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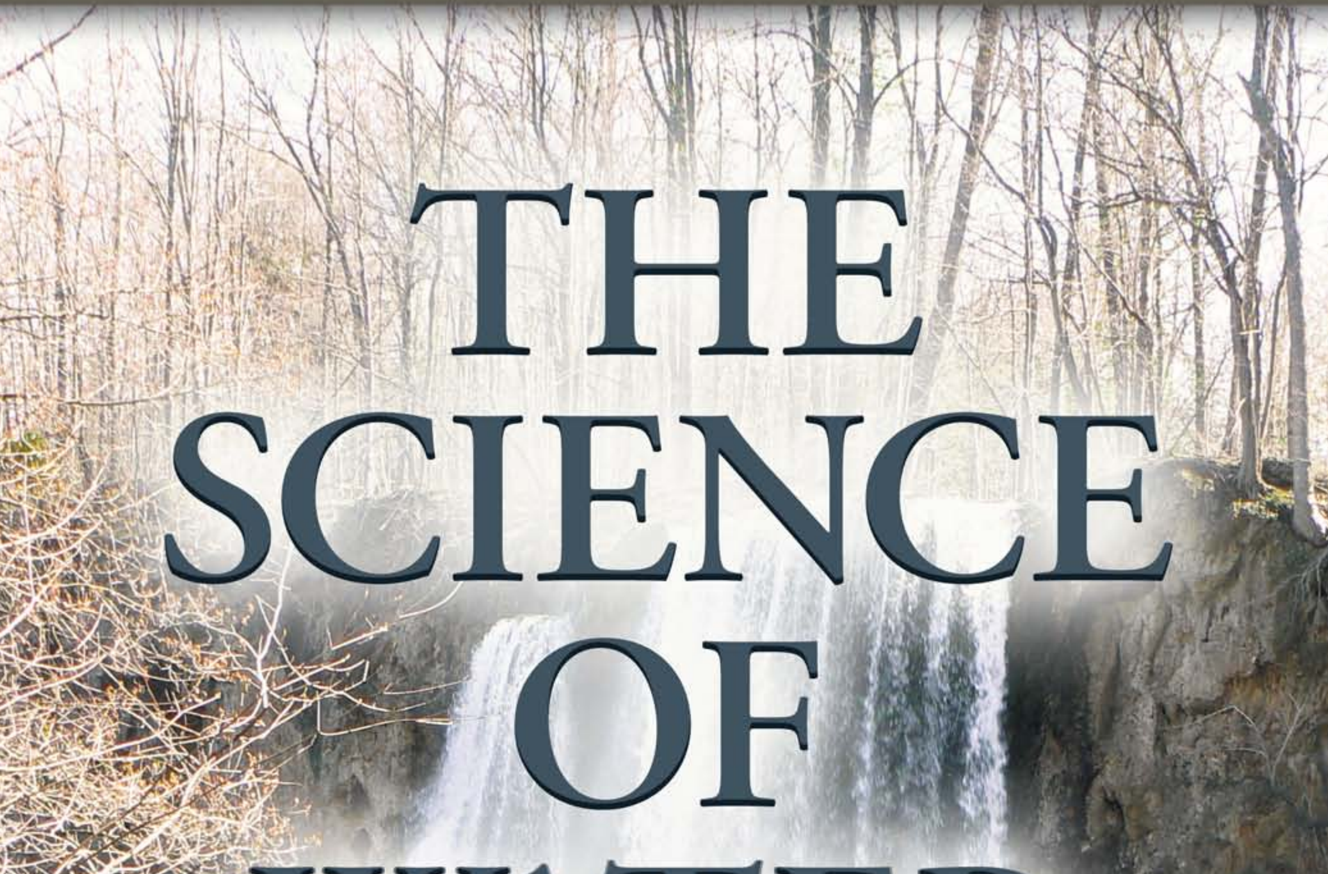

THE SCIENCE OF WATER

Concepts and Applications

Frank R. Spellman

CRC Press
Taylor & Francis Group

Second Edition

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For Revonna M. Bieber

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Preface

Hailed on its first publication as a masterful account for both the general reader and student, *The Science of Water* continues to ask the same questions: water, water, water … water everywhere, right? In addition, it asks: the Earth's supply of finite water resources can be increased constantly to meet growing demand, right? Despite these absurdities, a belief actually does prevail that the Earth's finite water resources can be increased constantly to meet growing demand. History has demonstrated that consumption and waste increase in response to rising supply. However, the fact of the matter is that freshwater is a finite resource that can be increased only slightly through desalinization or some other practices, all at tremendous cost.

In addition to asking the same questions, this standard synthesis has now been completely revised and expanded for the second edition. The text still deals with the essence of water, that is, what water is all about. Further, while this text points out that water is one of the simplest and most common chemical compounds on Earth, it also shows water to be one of the most mysterious and awe-inspiring substances we know. Important to this discussion about water and its critical importance on Earth is man—man and his use, misuse, and reuse of freshwater and wastewater. Furthermore, this text takes the view that since water is the essence of all life on Earth, it is precious—too precious to abuse, misuse, and ignore. Thus, as you might guess, the common thread woven throughout the fabric of this presentation is water resource utilization and its protection.

The text follows a pattern that is nontraditional; that is, the paradigm (model or prototype) used here is based on real-world experience—not on theoretical gobbledygook. Clearly written and user friendly, this timely revision of *The Science of Water* builds on the remarkable success of the first edition. Still written as an information source, it should be pointed out that this text is not limited in its potential for other uses. For example, while this work can be utilized by the water/wastewater practitioner to provide valuable insight into the substance he/she works hard to collect, treat, and supply for its intended purpose, it can just as easily provide important information for the policymaker who may be tasked with making decisions concerning water resource utilization. Consequently, this book will serve a varied audience—students, lay personnel, regulators, technical experts, attorneys, business leaders, and concerned citizens.

The question thus becomes: Why a text on the science of water? This leads to another question: Is it not the case that water treatment, wastewater treatment, and other work with water are more of an art than a science? In answering this first question, it should be pointed out that the study of water is a science. It is a science that is closely related/interrelated to other scientific disciplines such as biology, microbiology, chemistry, mathematics, and hydrology. Therefore, to solve the problems and understand the issues related to water, water practitioners need a broad base of scientific information from which to draw.

To answer the second question, with a finite answer, it might be easier to bring up another question or situation—for the purist, an analogy. Consider, for example, the thoracic surgeon (thoracic surgery is the major league of surgery, according to a thoracic surgeon I know), who has a reputation for being an artist with a scalpel. This information may be encouraging to the would-be patient who is to be operated on by such a surgeon. However, this same patient may further inquire about the surgeon's education, training, experience, and knowledge of the science of medicine. If I were the patient, I would want her (the artful surgeon) to understand the science of my heart and other vital organs before she took the scalpel in hand to perform her artful surgery. Wouldn't you?

Frank R. Spellman

To the Reader

In reading this text, you are going to spend some time
following a drop of water on its travels.
When you dip a finger in a basin of water and lift it up again, you
bring with it a small glistening drop out of the water below and
hold it before you.
Do you have any idea where this drop has been?
What changes it has undergone, during all the long ages water
has lain on and under the face of the Earth?

Running Water. White Oak Canyon Trail, Shenandoah National Forest, Virginia. [Photo by Revonna M. Bieber (November 29, 2006).]

About the Author

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Dr. Spellman writes on a range of topics in all areas of environmental science and occupational health. Several of his texts have been adapted/adopted for classroom use at major universities throughout the United States, Canada, Europe, and Russia; two are currently being translated into Spanish for South American markets.

Dr. Spellman has been cited in more than 400 publications. He serves as a professional expert witness for Domina Law Group, Omaha, Nebraska, and he consults on homeland security vulnerability assessments (VAs) for water/wastewater facilities nationwide. He receives numerous requests to collaborate with well-recognized experts on publications in various scientific fields. He is a contributing author to *The Engineering Handbook*, 2nd edition, published by Taylor & Francis.

1 Introduction

> When color photographs of the earth as it appears from space were first published, it was a revelation: they showed our planet to be astonishingly beautiful. We were taken by surprise. What makes the earth so beautiful is its abundant water. The great expanses of vivid blue ocean with swirling, sunlit clouds above them should not have caused surprise, but the reality exceeded everybody's expectations. The pictures must have brought home to all who saw them the importance of water to our planet.
>
> **—E. C. Pielou (1998, Preface)**

Whether we characterize it as ice, rainbow, steam, frost, dew, soft summer rain, fog, flood or avalanche, or as stimulating as a stream or cascade, water is special—water is strange—water is different.

Water is the most abundant inorganic liquid in the world; moreover, it occurs naturally anywhere on Earth. Literally awash with it, life depends on it, and yet water is so very different.

Water is scientifically different. With its rare and distinctive property of being denser as a liquid than as a solid, it is different. Water is different in that it is the only chemical compound found naturally in solid, liquid, and gaseous states. Water is sometimes called the *universal solvent*. This is a fitting name, especially when you consider that water is a powerful reagent that is capable in time of dissolving everything on Earth.

Water is different. It is usually associated with all the good things on Earth. For example, water is associated with quenching thirst, with putting out fires, and with irrigating the Earth. The question is: Can we really say emphatically, definitively that water is associated with only those things that are good?

Not really!

Remember, water is different; nothing, absolutely nothing, is safe from it.

Water is different. This unique substance is odorless, colorless, and tasteless. Water covers 71% of the Earth completely. Even the driest dust ball contains 10–15% water.

Water and life—life and water—inseparable.

The prosaic becomes wondrous as we perceive the marvels of water.

Three hundred and twenty-six million cubic miles of water cover the Earth, but only 3% of this total is fresh with most locked up in polar ice caps, glaciers, in lakes; in flows through soil and in river and stream systems back to an ever-increasing saltier sea (only 0.027% is available for human consumption). Water is different.

Saltwater is different from freshwater. Moreover, this text deals with freshwater and ignores saltwater because saltwater fails its most vital duty, which is to be pure, sweet, and serve to nourish us.

Standing at a dripping tap, water is so palpably wet, one can literally hear the drip-drop-plop.

Water is special—water is strange—water is different—more importantly, water is critical for our survival, yet we abuse it, discard it, fowl it, curse it, dam it, and ignore it. At least, this is the way we view the importance of water at this moment in time … however, because water is special, strange, and different, the dawn of tomorrow is pushing for quite a different view.

Along with being special, strange, and different, water is also a contradiction, a riddle.

How?

Consider the Chinese proverb "Water can both float and sink a ship."

The presence of water everywhere feeds these contradictions. Lewis (1996, p. 90) points out that "water is the key ingredient of mother's milk and snake venom, honey and tears."

Leonardo da Vinci gave us insight into more of water's apparent contradictions:

> Water is sometimes sharp and sometimes strong, sometimes acid and sometimes bitter;
> Water is sometimes sweet and sometimes thick or thin;
> Water sometimes brings hurt or pestilence, sometimes
> health-giving, sometimes poisonous.
> Water suffers changes into as many natures as are the
> different places through which it passes.
> Water, as with the mirror that changes with the color of its object,
> so it alters with the nature of the place, becoming noisome,
> laxative, astringent, sulfurous, salt, incarnadined, mournful, raging,
> angry, red, yellow, green, black, blue, greasy, fat or slim.
> Water sometimes starts a conflagration, sometimes it extinguishes one.
> Water is warm and is cold.
> Water carries away or sets down.
> Water hollows out or builds up.
> Water tears down or establishes.
> Water empties or fills.
> Water raises itself or burrows down.
> Water spreads or is still.
> Water is the cause at times of life or death, or increase of privation,
> nourishes at times and at others does the contrary.
> Water, at times has a tang, at times it is without savor.
> Water sometimes submerges the valleys with great flood.
> In time and with water, everything changes.

Water's contradictions can be summed up by simply stating that though the globe is awash in it, water is no single thing, but an elemental force that shapes our existence. Leonardo's last contradiction, "In time and with water, everything changes," concerns us most in this text.

Many of Leonardo's water contradictions are apparent to most observers. But with water there are other factors that do not necessarily stand out, that are not always so apparent. This is made clear by the following example—what you see on the surface is not necessarily what lies beneath.

STILL WATER

Consider a river pool, isolated by fluvial processes and time from the mainstream flow. We are immediately struck by one overwhelming impression: It appears so still … so very still … still enough to soothe us. The river pool provides a kind of poetic solemnity, if only at the pool's surface. No words of peace, no description of silence or motionlessness can convey the perfection of this place, in this moment stolen out of time.

We ask ourselves, "The water is still, but does the term 'still' correctly describe what we are viewing … is there any other term we can use besides still—is there any other kind of still?"

Yes, of course, we know many ways to characterize still. For sound or noise, 'still' can mean inaudible, noiseless, quiet, or silent. With movement (or lack of movement), still can mean immobile, inert, motionless, or stationary. At least, this is how the pool appears to the casual visitor on the surface. The visitor sees no more than water and rocks.

How is the rest of the pool? We know very well that a river pool is more than just a surface. How does the rest of the pool (for example, the subsurface) fit the descriptors we tried to use to characterize its surface? Maybe they fit, maybe they do not. In time, we will go beneath the surface, through the liquid mass, to the very bottom of the pool to find out. For now, remember that images retained from first glances are almost always incorrectly perceived, incorrectly discerned, and never fully understood.

On second look, we see that the fundamental characterization of this particular pool's surface is correct enough. Wedged in a lonely riparian corridor—formed by river bank on one side and sand bar on the other—between a youthful, vigorous river system on its lower end and a glacier- and artesian-fed lake on its headwater end, almost entirely overhung by mossy old Sitka spruce, the surface of the large pool, at least at this particular location, is indeed still. In the proverbial sense, the pool's surface is as still and as flat as a flawless sheet of glass.

The glass image is a good one, because, like perfect glass, the pool's surface is clear, crystalline, unclouded, definitely transparent, yet perceptively deceptive as well. The water's clarity, accentuated by its bone-chilling coldness, is apparent at close range. Further back, we see only the world reflected in the water—the depths are hidden and unknown. Quiet and reflective, the polished surface of the water perfectly reflects in mirror-image reversal the spring greens of the forest at the pond's edge, without the slightest ripple. Up close, looking straight into the bowels of the pool we are struck by the water's transparency. In the motionless depths, we do not see a deep, slow-moving reach with muddy bottom typical of a river or stream pool; instead, we clearly see the warm variegated tapestry of blues, greens, and blacks stitched together with threads of fine, warm-colored sand that carpets the bottom, at least 12 ft below. Still waters can run deep.

No sounds emanate from the pool. The motionless, silent water does not, as we might expect, lap against its bank or bubble or gurgle over the gravel at its edge. Here, the river pool, held in temporary bondage, is patient, quiet, waiting, withholding all signs of life from its surface visitor.

Then the reality check: the present stillness, like all feelings of calm and serenity, could be fleeting, momentary, temporary, you think. And you would be correct, of course, because there is nothing still about a healthy river pool.

At this exact moment, true clarity is present, it just needs to be perceived … and it will be.

We toss a small stone into the river pool, and watch the concentric circles ripple outward as the stone drops through the clear depths to the pool bottom. For a brief instant, we are struck by the obvious: the stone sinks to the bottom, following the laws of gravity, just as the river flows according to those same inexorable laws—downhill in its search for the sea. As we watch, the ripples die away leaving as little mark as the usual human lifespan creates in the waters of the world, then disappears as if it had never been. Now the river water is as before, still. At the pool's edge, we look down through the massy depth to the very bottom—the substrate.

We determine that the pool bottom is not flat or smooth, but instead is pitted and mounded occasionally with discontinuities. Gravel mounds alongside small corresponding indentations—small, shallow pits—make it apparent to us that gravel was removed from the indentations and piled into slightly higher mounds. From our topside position, as we look down through the cool, quiescent liquid, the exact height of the mounds and the depth of the indentations is difficult for us to judge; our vision is distorted through several feet of water.

However, we can detect near the low gravel mounds (where female salmon buried their eggs, and where their young grow until they are old enough to fend for themselves), and actually through the gravel mounds, movement—water flow—an upwelling of groundwater. This water movement explains our ability to see the variegated color of pebbles. The mud and silt that would normally cover these pebbles have been washed away by the water's subtle, inescapable movement. Obviously, in the depths, our still water is not as still as it first appeared.

The slow, steady, inexorable flow of water in and out of the pool, along with the up-flowing of groundwater through the pool's substrate and through the salmon redds (nests) is only a small part of the activities occurring within the pool, including the air above it, the vegetation surrounding it, and the damp bank and sandbar forming its sides.

Let's get back to the pool itself. If we could look at a cross-sectional slice of the pool, at the water column, the surface of the pool may carry those animals that can literally walk on water. The body of the pool may carry rotifers and protozoa and bacteria—tiny microscopic animals—as well as many fish. Fish will also inhabit hidden areas beneath large rocks and ledges, to escape predators. Going down further in the water column, we come to the pool bed. This is called the benthic zone, and certainly the greatest number of creatures lives here, including larvae and nymphs of all sorts, worms, leeches, flatworms, clams, crayfish, dace, brook lampreys, sculpins, suckers, and water mites.

We need to go down even further, down into the pool bed, to see the whole story. How far this goes and what lives here, beneath the water, depends on whether it is a gravelly bed, or a silty or muddy one. Gravel will allow water, with its oxygen and food, to reach organisms that live underneath the pool. Many of the organisms that are found in the benthic zone may also be found underneath, in the hyporheal zone.

But to see the rest of the story we need to look at the pool's outlet, and where its flow enters the main river. These are the riffles—shallow places where water runs fast and is disturbed by rocks. Only organisms that cling very well, such as net-winged midges, caddisflies, stoneflies, some mayflies, dace, and sculpins can spend much time here, and the plant life is restricted to diatoms and small algae. Riffles are a good place for mayflies, stoneflies, and caddisflies to live because they offer plenty of gravel to hide.

At first, we struggled to find the "proper" words to describe the river pool. Eventually, we settled on "still waters." We did this because of our initial impression, and because of our lack of understanding—lack of knowledge. Even knowing what we know now, we might still describe the river pool as still waters. However, in reality, we must call the pool what it really is: a dynamic habitat. This is true, of course, because each river pool has its own biological community, all members interwoven with one another in complex fashion, all depending on one another. Thus, our river pool habitat is part of a complex, dynamic ecosystem. On reflection, we realize, moreover, that anything dynamic certainly can't be accurately characterized as "still"—including our river pool.

Maybe you have not had the opportunity to observe a river pool like the one described above. Maybe such an opportunity does not interest you. However, the author's point can be made in a different manner.

Take a moment out of your hectic schedule and perform an action most people never think about doing. Hold a glass of water (like the one in Figure 1.1) and think about the substance within the glass—about the substance you are getting ready to drink. You are aware that the water inside a drinking glass is not one of those items people usually spend much thought on, unless they are tasked with providing the drinking water—or dying of thirst.

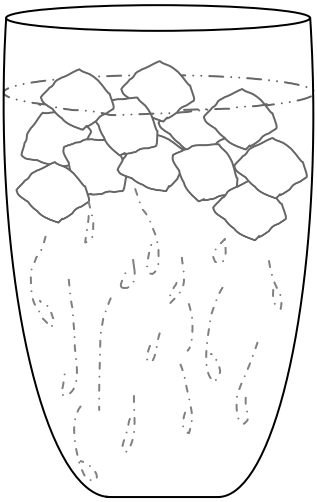

FIGURE 1.1 A glass of drinking water.

As mentioned earlier, water is special, strange, and different. Some of us find water fascinating—a subject worthy of endless interest, because of its unique behavior, limitless utility, and ultimate and intimate connection with our existence. Perhaps you might agree with Tom Robbins (1976, pp. 1–2), whose description of water follows:

> Stylishly composed in any situation—solid, gas or liquid—speaking in penetrating dialects understood by all things—animal, vegetable or mineral—water travels intrepidly through four dimensions, *sustaining* (Kick a lettuce in the field and it will yell "Water!"), *destroying* (The Dutch boy's finger remembered the view from Ararat) and *creating* (It has even been said that human beings were invented by water as a device for transporting itself from one place to another, but that's another story). Always in motion, ever-flowing (whether at stream rate or glacier speed), rhythmic, dynamic, ubiquitous, changing and working its changes, a mathematics turned wrong side out, a philosophy in reverse, the ongoing odyssey of water is irresistible.

As Robbins said, water is always in motion. One of the most essential characteristic of water is that it is dynamic. Water constantly evaporates from sea, lakes, and soil and transpires from foliage; is transported through the atmosphere; falls to the Earth; runs across the land; and filters down to flow along rock strata into aquifers. Eventually, water finds its way to the sea again—indeed, water never stops moving.

A thought that might not have occurred to most people as they look at our glass of water is, "Who has tasted this same water before us?" Before us? Absolutely. Remember, water is almost a finite entity. What we have now is what we have had in the past. The same water consumed by Cleopatra, Aristotle, Leonardo da Vinci, Napoleon, Joan of Arc (and several billion other folks who preceded us), we are drinking now—because water is dynamic (never at rest), and because water constantly cycles and recycles, as discussed in another section.

Water never goes away, disappears, or vanishes; it always returns in one form or another. As Dove (1989) points out, "all water has a perfect memory and is forever trying to get back to where it was."

SETTING THE STAGE

The availability of a water supply adequate in terms of both quantity and quality is essential to our very existence. One thing is certain: History has shown that the provision of an adequate quantity of quality potable water has been a matter of major concern since the beginning of civilization.

Water—especially clean, safe water—we know we need it to survive—we know a lot about it—however, the more we know the more we discover we don't know.

Modern technology has allowed us to tap potable water supplies and to design and construct elaborate water distribution systems. Moreover, we have developed technology to treat used water (wastewater); that is, water we foul, soil, pollute, discard, and flush away.

Have you ever wondered where the water goes when you flush the toilet? Probably not.

An entire technology has developed around treating water and wastewater. Along with technology, of course, technological experts have been developed. These experts range from environmental/structural/civil engineers to environmental scientists, geologists, hydrologists, chemists, biologists, and others.

Along with those who design and construct water/wastewater treatment works, there is a large cadre of specialized technicians, spread worldwide, who operate water- and wastewater-treatment plants. These operators are tasked, obviously, with providing a water product that is both safe and palatable for consumption and with treating (cleaning) a waste stream before it is returned to its receiving body (usually a river or stream). It is important to point out that not only are water practitioners who treat potable and used water streams responsible for ensuring quality, quantity, and reuse of their product, because of the events of 9/11, they are also tasked with protecting this essential resource from terrorist acts.

The fact that most water practitioners know more about water than the rest of us comes as no surprise. For the average person, knowledge of water usually extends to knowing no more than that water is good or bad; it is terrible tasting, just great, wonderful, clean and cool and sparkling, or full of scum/dirt/rust/chemicals, great for the skin or hair, very medicinal, and so on. Thus, to say the water "experts" know more about water than the average person is probably an accurate statement.

At this point, the reader is probably asking: What does all this have to do with anything? Good question.

What it has to do with water is quite simple. We need to accept the fact that we simply do not know what we do not know about water.

As a case in point, consider this: Have you ever tried to find a text that deals exclusively and extensively with the science of water? Such texts are few, far flung, imaginary, nonexistent—there is a huge gap out there.

Then the question shifts to—why would you want to know anything about water in the first place? Another good question.

This text makes an effort to answer this question.

To start with, let's talk a little about the way in which we view water.

Earlier brief mention was made about the water contents of a simple drinking water glass. Let's face it, drinking a glass of water is something that normally takes little effort and even less thought. The trouble is, our view of water and its importance is relative.

The situation could be different—even more relative, however. For example, consider the young woman who is an adventurer, an outdoor person. She likes to jump into her four-wheel-drive vehicle and head out for new adventure. On this particular day, she decides to drive through Death Valley, California—one end to another and back on a seldom-used dirt road. She has done this a few times before. During her transit of this isolated region, she decides to take a side road that seems to lead to the mountains to her right.

She travels along this isolated, hardpan road for approximately 50 miles—then the motor in her four-wheel-drive vehicle quits. No matter what she does, the vehicle will not start. Eventually, the vehicle's battery dies; she had cranked on it too much.

Realizing that the vehicle was not going to start, she also realized she was alone and deep inside an inhospitable area. What she did not know was that the nearest human being was about 60 miles to the west.

She had another problem—a problem more pressing than any other. She did not have a canteen or container of water—an oversight on her part. Obviously, she told herself, this is not a good situation.

What an understatement that turned out to be.

Just before noon, on foot, she started back down the same road she had traveled. She reasoned she did not know what was in any other direction other than the one she had just traversed. She also knew the end of this side road intersected the major highway that bisected Death Valley. She could flag down a car or truck or bus; she would get help, she reasoned.

She walked—and walked—and walked some more. "Gee, if it wasn't so darn hot," she muttered to herself, to sagebrush, to scorpions, to rattlesnakes, and to cacti. The point is it was hot; about 107°F.

She continued on for hours, but now she was not really walking; instead, she was forcing her body to move along. Each step hurt. She was burning up. She was thirsty. How thirsty was she? Well, right about now just about anything liquid would do, thank you very much!

Later that night, after hours of walking through that hostile land, she couldn't go on. Deep down in her heat-stressed mind, she knew she was in serious trouble. Trouble of the life-threatening variety.

Just before passing out, she used her last ounce of energy to issue a dry pathetic scream.

This scream of lost hope and imminent death was heard—but only by the sagebrush, the scorpions, the rattlesnakes, and the cacti—and by the vultures that were now circling above her parched, dead remains. The vultures were of no help, of course. They had heard these screams before. They were indifferent; they had all the water they needed; their food supply wasn't all that bad either.

This case sheds light on a completely different view of water. Actually, it is a very basic view that holds: we cannot live without it.

HISTORICAL PERSPECTIVE

An early human, wandering alone from place to place, hunting and gathering to subsist, probably would have had little difficulty in obtaining drinking water, because such a person would—and could—only survive in an area where drinking water was available with little travail.

The search for clean, fresh, and palatable water has been a human priority from the very beginning. The author takes no risk in stating that when humans first walked the Earth, many of the steps they took were in the direction of water.

When early humans were alone or in small numbers, finding drinking water was a constant priority, to be sure, but it is difficult for us to imagine today just how big a priority finding drinking water became as the number of humans proliferated.

Eventually communities formed, and with their formation came the increasing need to find clean, fresh, and palatable drinking water, and also to find a means of delivering it from the source to the point of use.

Archeological digs are replete with the remains of ancient water systems (man's early attempts to satisfy that never-ending priority). Those digs (spanning the history of the past 20 or more centuries) testify to this. For well over 2000 years, piped water supply systems have been in existence. Whether the pipes were fashioned from logs or clay or carved from stone or other materials is not the point—the point is they were fashioned to serve a vital purpose, one universal to the community needs of all humans: to deliver clean, fresh, and palatable water to where it was needed.

These early systems were not arcane. Today, we readily understand their intended purpose. As we might expect, they could be rather crude, but they were reasonably effective, though they lacked in two general areas what we take for granted today.

First, of course, they were not pressurized, but instead relied on gravity flow, since the means to pressurize the mains was not known at the time—and even if such pressurized systems were known, they certainly would not have been used to pressurize water delivered via hollowed-out logs and clay pipe.

The second general area early civilizations lacked that we do not suffer today (that is, in the industrialized world) is sanitation. Remember, to know the need for something exists (in this case, the ability to sanitize, to disinfect water supplies), the nature of the problem must be defined. Not until the mid-1800s (after countless millions of deaths from waterborne disease over the centuries) did people realize that a direct connection between contaminated drinking water and disease existed. At that point, sanitation of water supply became an issue.

When the relationship between waterborne diseases and the consumption of drinking water was established, evolving scientific discoveries led the way toward the development of technology for processing and disinfection. Drinking water standards were developed by health authorities, scientists, and sanitary engineers.

With the current lofty state of effective technology that we in the United States and the rest of the developed world enjoy today, we could sit on our laurels, so to speak, and assume that because of the discoveries developed over time (and at the cost of countless people who died [and still die] from waterborne-diseases) that all is well with us—that problems related to providing us with clean, fresh, and palatable drinking water are problems of the past.

Are they really problems of the past? Have we solved all the problems related to ensuring that our drinking water supply provides us with clean, fresh, and palatable drinking water? Is the water delivered to our tap as clean, fresh, and palatable as we think it is … as we hope it is? Does anyone really know?

What we do know is that we have made progress. We have come a long way from the days of gravity flow water delivered via mains of logs and clay or stone … Many of us on this Earth have come a long way from the days of cholera epidemics.

However, to obtain a definitive answer to those questions, perhaps we should ask those who boiled their water for weeks on end in Sydney, Australia in fall of 1998. Or better yet, we should speak with those who drank the "city water" in Milwaukee in 1993 or in Las Vegas, Nevada—those who suffered and survived the onslaught of *Cryptosporidium,* from contaminated water out of their taps.

Or if we could, we should ask these same questions of a little boy named Robbie, who died of acute lymphatic leukemia, the probable cause of which is far less understandable to us: toxic industrial chemicals, unknowingly delivered to him via his local water supply.

If water is so precious, so necessary for sustaining life, then two questions arise: (1) Why do we ignore water? (2) Why do we abuse it (pollute or waste it)?

We ignore water because it is so common, so accessible, so available, so unexceptional (unless you are lost in the desert without a supply of it). Again, why do we pollute and waste water? There are several reasons; many will be discussed later in this text.

You might be asking yourself: Is water pollution really that big of a deal? Simply stated, yes, it is. Man has left his footprint (in the form of pollution) on the environment, including on our water sources. Man has a bad habit of doing this. What it really comes down to is "out of sight out of mind" thinking. Or when we abuse our natural resources in any manner, maybe we think to ourselves: "Why worry about it. Let someone else sort it all out."

As this text proceeds, it will lead you down a path strewn with abuse and disregard for our water supply—then all (excepting the water) will become clear. Hopefully, we will not have to wait until someone does sort it … and us out. Because, with time and everything else, there might be a whole lot of sorting out going on.

Let us get back to that gap in knowledge dealing with the science of water. This text is designed to show how this obvious and unsatisfactory gap in information about water is to be filled in. Having said this, now it is to welcome you the gap-filler: *The Science of Water: Concepts and Applications.*

Finally, before moving on with the rest of the text, it should be pointed out that the view held throughout this work is that water is special, strange, and different—and very vital. This view is held for several reasons, but the most salient factor driving this view is the one that points to the fact that on this planet, *water is life.*

REFERENCES

Dove, R., 1989. *Grace Notes.* New York: Norton.

Lewis, S.A., 1996. *The Sierra Club Guide to Safe Drinking Water.* San Francisco: Sierra Club Books.

Pielou, E.C., 1998. *Fresh Water.* Chicago: University of Chicago.

Robbins, T., 1976. *Even Cowgirls Get the Blues.* Boston: Houghton Mifflin Company.

FURTHER READING

DeZuane, J., 1997. *Handbook of Drinking Water Quality*, 2nd ed. New York: Wiley.

Gerba, C.P., 1996. Risk Assessment. In *Pollution Science*, Pepper, I.L., Gerba, C.P., and Brusseau, M.L. (eds.). San Diego: Academic Press.

Hammer, M.J. and Hammer, M.J., Jr., 1996. *Water and Wastewater Technology*, 3rd ed. Englewood Cliffs, NJ: Prentice-Hall.

Harr, J., 1995. *A Civil Action.* New York: Vintage Books.

Metcalf & Eddy, Inc., 1991. *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd ed. New York: McGraw-Hill, Inc.

Meyer, W.B., 1996. *Human Impact on Earth*. New York: Cambridge University Press.

Nathanson, J.A., 1997. *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*. Upper Saddle River, NJ: Prentice-Hall.

Running Water. White Oak Canyon Trail, Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

2 All about Water

Water can both float and sink a ship.

—Chinese Proverb

Unless you are thirsty, in real need of refreshment, when you look upon that glass of water shown in Figure 1.1, you might ask—well, what could be more boring? The curious might wonder what physical and chemical properties of water make it so unique and necessary for living things. Again you might ask, when you look at that glass of water, taste, and smell it—well, what could be more boring? Pure water is virtually colorless and has no taste or smell. But the hidden qualities of water make it a most interesting subject.

When the uninitiated becomes initiated to the wonders of water, one of the first surprises is that the total quantity of water on the Earth is much the same now as it was more than 3 or 4 billion years ago, when the 320+ million cubic miles of it were first formed. Ever since then, the water reservoir has gone round and round, building up, breaking down, cooling, and then warming. Water is very durable, but remains difficult to explain because it has never been isolated in a completely undefiled state.

Remember, water is special, strange, and different.

HOW SPECIAL, STRANGE, AND DIFFERENT IS WATER?

Have you ever wondered what the nutritive value of water is? Well, the fact is water has no nutritive value. Yet it is the major ingredient of all living things. Consider yourself, for example. Think of what you need to survive—just to survive. Food? Air? PS-3? MTV? Water? Naturally, water, which is the focus of this text. Water is of major importance to all living things; up to 90% of the body weight of some organisms comes from water. Up to 60% of the human body is water, the brain is composed of 70% water, the lungs are nearly 90% water, and about 83% of our blood is water. It helps digest our food, transport waste, and control body temperature. Each day humans must replace 2.4 L of water, some through drinking and the rest taken by the body from the foods we eat.

There wouldn't be any you, me, or Lucy the dog without the existence of an ample liquid water supply on the Earth. The unique qualities and properties of water are what make it so important and basic to life. The cells in our bodies are full of water. The excellent ability of water to dissolve so many substances allows our cells to use valuable nutrients, minerals, and chemicals in biological processes.

Water's "stickiness" (from surface tension) plays a part in our body's ability to transport these materials all through ourselves. The carbohydrates and proteins that our bodies use as food are metabolized and transported by water into the bloodstream. No less important is the ability of water to transport waste material out of our bodies.

Water is used to fight forest fires, yet we use water spray on coal in a furnace to make it burn better.

Chemically, water is hydrogen oxide. However, on more advanced analysis it turns out to be a mixture of more than 30 possible compounds. In addition, all of its physical constants are abnormal (strange).

At a temperature of 2900°C some substances that contain water cannot be forced to part with it. And yet others that do not contain water will liberate it even when slightly heated.

When liquid, water is virtually incompressible; as it freezes, it expands by an eleventh of its volume.

For the above stated reasons, and for many others, we can truly say that water is special, strange, and different.

CHARACTERISTICS OF WATER

Up to this point many things have been said about water; however, it has not been said that water is plain. This is the case because nowhere in nature is plain water to be found. Here on the Earth, with a geologic origin dating back over 3–5 billion years, water found in even its purest form is composed of many constituents. You probably know the chemical description of water is H_2O—that is, one atom of oxygen bound to two atoms of hydrogen. The hydrogen atoms are "attached" to one side of the oxygen atom, resulting in a water molecule having a positive charge on the side where the hydrogen atoms are and a negative charge on the other side where the oxygen atom is. Since opposite electrical charges attract, water molecules tend to attract one another, making water kind of "sticky"—the hydrogen atoms (positive charge) attract the oxygen side (negative charge) of a different water molecule.

√ **Important Point:** All these water molecules attracting one another means they tend to clump together. This is why water drops are, in fact, "drops"! If it weren't for some of the Earth's forces, such as gravity, a drop of water would be ball shaped—a perfect sphere. Even if it doesn't form a perfect sphere on the Earth, we should be happy water is sticky.

Along with H_2O molecules, hydrogen (H^+), hydroxyl (OH^-), sodium, potassium, and magnesium, there are other ions and elements present in water. Additionally, water contains dissolved compounds including various carbonates, sulfates, silicates, and chlorides. Rainwater, often assumed to be the equivalent of distilled water, is not immune to contamination as it descends through the atmosphere. The movement of water across the face of land contributes to its contamination, taking up dissolved gases, such as carbon dioxide and oxygen, and a multitude of organic substances and minerals leached from the soil. Don't let that crystal clear lake or pond fool you. These are not filled with water alone but are composed of a complex mixture of chemical ingredients far exceeding the brief list presented here; it is a special medium in which highly specialized life can occur.

How important is water to life? To answer this question, all we need do is to take a look at the common biological cell. It easily demonstrates the importance of water to life.

Living cells comprise a number of chemicals and organelles within a liquid substance, the cytoplasm, and the cell's survival may be threatened by changes in the proportion of water in the cytoplasm. This change in the proportion of water in the cytoplasm can occur through desiccation (evaporation), oversupply, or the loss of either nutrients or water to the external environment. A cell that is unable to control and maintain homeostasis (i.e., the correct equilibrium/proportion of water) in its cytoplasm may be doomed—it may not survive.

√ **Important Point:** As mentioned, water is called the "universal solvent" because it dissolves more substances than any other liquid. This means that wherever water goes, either through the ground or through our bodies, it takes along valuable chemicals, minerals, and nutrients.

INFLAMMABLE AIR + VITAL AIR = WATER

In 1783 the brilliant English chemist and physicist Henry Cavendish was "playing with" electric current. Specifically, Cavendish was passing electric current through a variety of substances to see what happened. Eventually, he got around to water. He filled a tube with water and sent electric current through it. The water vanished.

To say that Cavendish was flabbergasted by the results of this experiment would be a mild understatement. "The tube has to have a leak in it," he reasoned.

He repeated the experiment again—same result.

Then again—same result.

The fact is he made the water disappear again and again. Actually, what Cavendish had done was convert the liquid water to its gaseous state—into an invisible gas.

When Cavendish analyzed the contents of the tube, he found it contained a mixture of two gases, one of which was *inflammable air* and the other a heavier gas. This heavier gas had only been discovered a few years earlier by his colleague, the English chemist and clergyman Joseph Priestly, who, finding that it kept a mouse alive and supported combustion, called it *vital air.*

JUST TWO H's AND ONE O

Cavendish was able to separate the two main constituents that make up water. All that remained was for him to put the ingredients back together again. He accomplished this by mixing a measured volume of inflammable air with different volumes of its vital counterpart, and setting fire to both. He found that most mixtures burned well enough, but when the proportions were precisely two to one, there was an explosion and the walls of his test tubes were covered with liquid droplets. He quickly identified these as water.

Cavendish made an announcement: Water was not water. Moreover, water is not just an odorless, colorless, and tasteless substance that lies beyond the reach of chemical analysis. Water is not an element in its own right, but a compound of two independent elements, one a supporter of combustion and the other combustible. When united, these two elements become the preeminent quencher of thirst and flames.

It is interesting to note that a few years later, the great French genius Antoine Lavoisier tied the compound neatly together by renaming the ingredients *hydrogen*—"the water producer"—and *oxygen*. In a fitting tribute to his guillotined corpse (he was a victim of the French Revolution), his tombstone came to carry a simple and telling epitaph, a fitting tribute to the father of a new age in chemistry—*just two H's and one O.*

SOMEWHERE BETWEEN 0 AND 105°

We take water for granted now. Every high-school level student knows that water is a chemical compound of two simple and abundant elements. And yet scientists continue to argue the merits of rival theories on the structure of water. The fact is we still know only little about water. For example, we don't know how water works.

Part of the problem lies in the fact that no one has ever seen a water molecule. It is true that we have theoretical diagrams and equations. We also have a disarmingly simple formula—H_2O. The reality, however, is that water is very complex. X-rays, for example, have shown that the atoms in water are intricately laced.

It has been said over and over again that water is special, strange, and different. Water is also almost indestructible. Sure, we know that electrolysis can separate water atoms, but we also know that once they get together again they must be heated up to more than 2900°C to separate them again.

Water is also idiosyncratic. This can be seen in the way in which the two atoms of hydrogen in a water molecule (see Figure 2.1) take up a very precise and strange (different) alignment to each

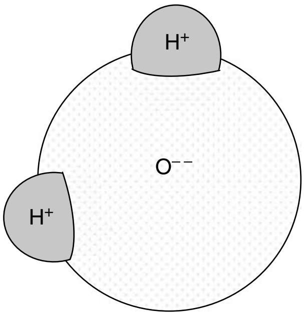

FIGURE 2.1 Molecule of water.

other. Not at all at angles of 45°, 60°, or 90°—oh no, not water. Remember, water is different. The two hydrogen atoms always come to rest at an angle of approximately 105° from each other, making all diagrams of their attachment to the larger oxygen atom look like Mickey Mouse ears on a very round head (see Figure 2.1; remember that everyone's favorite mouse is mostly water, too).

This 105° relationship makes water lopsided, peculiar, and eccentric—it breaks all the rules. You're not surprised, are you?

One thing is certain, however; this 105° angle is crucial to all life as we know it. Thus, the answer to defining why water is special, strange, different, and vital, lies somewhere between 0 and 105°.

WATER'S PHYSICAL PROPERTIES

Water has several unique physical properties. These properties are:

- Water is unique in that it is the only natural substance that is found in all three states—liquid, solid (ice), and gas (steam)—at the temperatures normally found on the Earth. The Earth's water is constantly interacting, changing, and in motion.
- Water freezes at 32°F and boils at 212°F at sea level but boils at 186.4°F at 14,000 feet. In fact, water's freezing and boiling points are the baseline with which temperature is measured: 0° on the Celsius scale is water's freezing point and 100° is water's boiling point. Water is unusual in that the solid form, ice, is less dense than the liquid form, which is why ice floats.
- Water has a high specific heat index. This means that water can absorb a lot of heat before it begins to get hot. This is why water is valuable to industries and in your car's radiator as a coolant. The high specific heat index of water also helps regulate the rate at which air changes temperature, which is why the temperature change between seasons is gradual rather than sudden, especially near the oceans.
- Water has a very high surface tension. In other words and as previously mentioned, water is sticky and elastic, and tends to clump together in drops rather than spread out in a thin film. Surface tension is responsible for capillary action (discussed in detail later), which allows water (and its dissolved substances) to move through the roots of plants and through the thin blood vessels in our bodies.
- Here's a quick rundown of some of water's properties:
  - Weight: 62.416 lb/ft^3 at 32°F
  - Weight: 61.998 lb/ft^3 at 100°F
  - Weight: 8.33 lb/gal, 0.036 lb/in^3.
  - Density: 1 g/cm^3 at 39.2°F, 0.95865 g/cm^3 at 212°F
  - 1 gal = 4 Qt = 8 Pt = 128 Oz = 231 in^3.
  - 1 L = 0.2642 gal = 1.0568 Qt = 61.02 in^3.
  - 1 million gal = 3.069 acre-ft = 133,685.64 ft^3

CAPILLARY ACTION

If we were to mention the term "capillary action" to men or women on the street, they might instantly nod their heads and respond that their bodies are full of them—that capillaries are the tiny blood vessels that connect the smallest arteries and the smallest of the veins. This would be true, of course. But in the context of water science, capillary is something different from capillary action in the human body.

Even if you've never heard of capillary action, it is still important in your life. Capillary action is important for moving water (and all of the things that are dissolved in it) around. It is defined as the movement of water within the spaces of a porous material due to the forces of adhesion, cohesion, and surface tension.

Surface tension is a measure of the strength of the water's surface film. The attraction between the water molecules creates a strong film, which among other common liquids is only surpassed by that of mercury. This surface tension permits water to hold up substances heavier and denser than itself. A steel needle carefully placed on the surface of a glass of water will float. Some aquatic insects such as the water strider rely on surface tension to walk on water.

Capillary action occurs because water is sticky, thanks to the forces of cohesion (water molecules like to stay close together) and adhesion (water molecules are attracted and stick to other substances). So, water tends to stick together, as in a drop, and it sticks to glass, cloth, organic tissues, and soil. Dip a paper towel into a glass of water and the water will "climb" onto the paper towel. In fact, it will keep going up the towel until the pull of gravity is too much for it to overcome.

THE WATER CYCLE

The natural *water cycle* or *hydrological cycle* is the means by which water in all three forms—solid, liquid, and vapor—circulates through the biosphere. The water cycle is all about describing how water moves above, on, and through the Earth. A lot more water, however, is "in storage" for long periods of time than is actually moving through the cycle. The storehouses for the vast majority of all water on the Earth are the oceans. It is estimated that of the 332,500,000 mi^3 of the world's water supply, about 321,000,000 mi^3 is stored in oceans. That is about 96.5%. It is also estimated that the oceans supply about 90% of the evaporated water that goes into the water cycle.

Water—lost from the Earth's surface to the atmosphere either by evaporation from the surface of lakes, rivers, and oceans or through the transpiration of plants—forms clouds that condense to deposit moisture on the land and sea. Evaporation from the oceans is the primary mechanism supporting the surface-to-atmosphere portion of the water cycle. Note, however, that a drop of water may travel thousands of miles between the time it evaporates and the time it falls to the Earth again as rain, sleet, or snow. The water that collects on land flows to the ocean in streams and rivers or seeps into the Earth's surface, joining groundwater. Even groundwater eventually flows toward the ocean for recycling (see Figure 2.2).

The cycle constantly repeats itself, a cycle without end.

√ **Note:** How long water that falls from the clouds takes to return to the atmosphere varies tremendously. After a short summer shower, most of the rainfall on land can evaporate into the atmosphere in only a matter of minutes. A drop of rain falling on the ocean may take as long as 37,000 years before it returns to the atmosphere and some water has been in the ground or caught in glaciers for millions of years.

√ **Important Point:** Only about 2% of the water absorbed into plant roots is used in photosynthesis. Nearly all of it travels through the plant to the leaves, where transpiration to the atmosphere begins the cycle again.

SPECIFIC WATER MOVEMENTS

After having reviewed the water cycle in very simple terms to provide foundational information, it is important to point out that the actual movement of water on the Earth is much more complex. Three different methods of transport are involved in this water movement: *evaporation, precipitation*, and *run-off.*

Evaporation of water is a major factor in hydrologic systems. Evaporation is a function of temperature, wind velocity, and relative humidity. Evaporation (or vaporization) is, as the name implies, the formation of vapor. Dissolved constituents such as salts remain behind when water evaporates. Evaporation of the surface water of oceans provides most of the water vapor. It should be pointed out, however, that water can also vaporize through plants, especially from leaf surfaces. This process

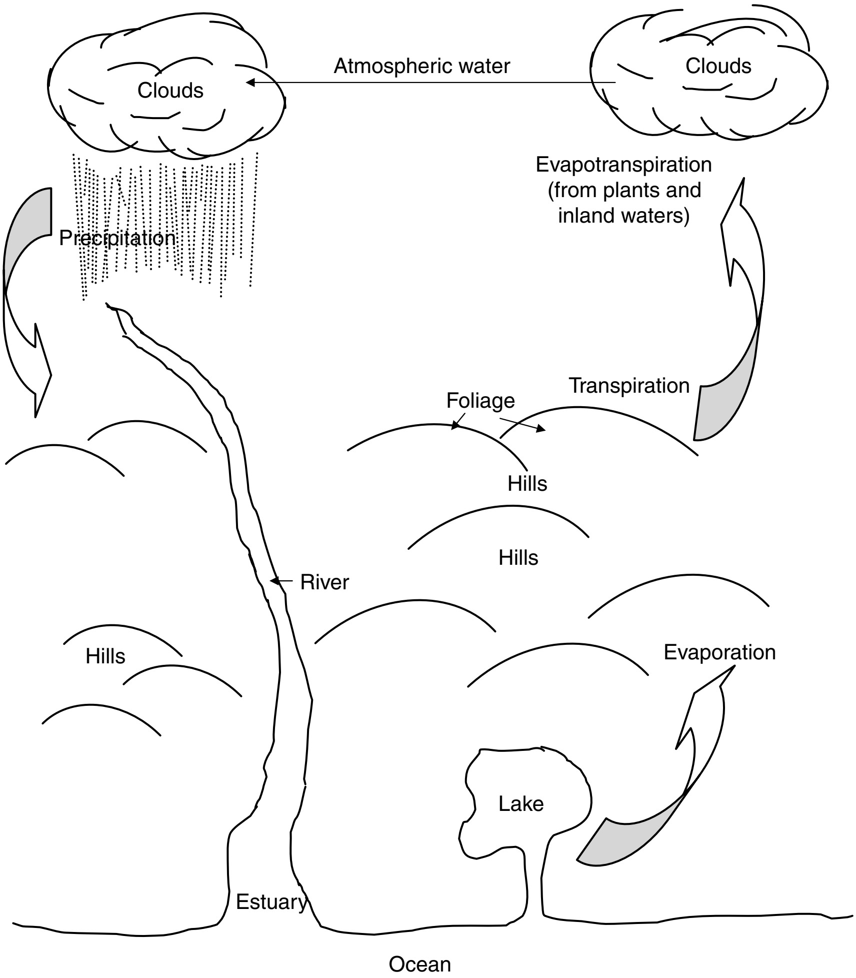

FIGURE 2.2 Water cycle.

is called *evapotranspiration*. Plant transpiration is pretty much an invisible process—since the water is evaporating from the leaf surfaces, you don't just go out and see the leaves "breathe." During a growing season, a leaf will transpire many times more water than its own weight. A large oak tree can transpire 40,000 gal (151,000 L)/year (USGS, 2006).

USGS (2006) points out that the amount of water that plants transpire varies greatly over time and geographically. There are a number of factors that determine transpiration rates:

- **Temperature:** transpiration rates go up as the temperature goes up, especially during the growing season when the air is warmer due to stronger sunlight and warmer air masses.
- **Relative humidity:** As the relative humidity of the air surrounding the plant rises, the transpiration rate falls. It is easier for water to evaporate into drier air than into more saturated air.
- **Wind and air movement:** Increased movement of the air around a plant will result in a higher transpiration rate.
- **Soil–moisture availability:** When moisture is lacking, plants begin to senesce (i.e., premature aging, which can result in leaf loss) and transpire less water.

- **Type of plant:** Plants transpire water at different rates. Some plants, which grow in arid regions, such as cacti and succulents, conserve precious water by transpiring less water than other plants.

√ **Interesting Point:** It may surprise you that ice can also vaporize without melting first; however, this *sublimation* process is slower than vaporization of liquid water.

Evaporation rates are measured with evaporation pans. These evaporation pans provide data that indicate the atmospheric evaporative demand of an area and can be used to estimate (1) the rates of evaporation from ponds, lakes, and reservoirs, and (2) evapotranspiration rates. It is important to note that several factors affect the rate of pan evaporation. These factors include the type of pan, type of pan environment, method of operating the pan, exchange of heat between pan and ground, solar radiation, air temperature, wind, and temperature of the water surface (Jones, 1992).

Precipitation includes all forms by which atmospheric moisture descends to the Earth—rain, snow, sleet, and hail. Before precipitation can occur, the water that enters the atmosphere by vaporization must first condense into liquid (clouds and rain) or solid (snow, sleet, and hail) before it can fall. This vaporization process absorbs energy. This energy is released in the form of heat when the water vapor condenses. You can best understand this phenomenon when you compare it to what occurs when water that evaporates from your skin absorbs heat, making you feel cold.

√ **Note:** The annual evaporation from ocean and land areas is the same as the annual precipitation.

Run-off is the flow back to the oceans of the precipitation that falls on land. This journey to the oceans is not always unobstructed—flow back may be intercepted by vegetation (from which it later evaporates), a portion is held in depressions, and a portion infiltrates into the ground. A part of the infiltrated water is taken up by plant life and returned to the atmosphere through evapotranspiration, while the remainder either moves through the ground or is held by capillary action. Eventually, water drips, seeps, and flows its way back into the oceans.

Assuming that the water in the oceans and ice caps and glaciers is fairly constant when averaged over a period of years, the water balance of the Earth's surface can be expressed by the following relationship: Water lost = Water gained (Turk and Turk, 1988).

Q AND Q FACTORS

While potable water practitioners must have a clear and complete understanding of the natural water cycle, they must, as previously mentioned, also factor in two major considerations (Quantity and Quality—the Q and Q factors): (1) providing a "quality" potable water supply—one that is clean, wholesome, and safe to drink; and (2) finding a water supply available in adequate "quantities" to meet the anticipated demand.

√ **Important Point:** Two central facts important to our discussion of freshwater supplies are: (1) water is very much a local or regional resource, and (2) problems of its shortage or pollution are equally local problems. Human activities affect the quantity of water available at a locale at any time by changing either the total volume that exists there, or aspects of quality that restrict or devalue it for a particular use. Thus, the total human impact on water supplies is the sum of the separate human impacts on the various drainage basins and groundwater aquifers. In the global system, the central, critical fact about water is the natural variation in its availability (Meyer, 1996). Simply put—*not all lands are watered equally.*

To meet the Q and Q requirements of a potential water supply, the potable water "practitioner" (whether the design engineer, community planner, plant manager, plant administrator, plant engineer, or other responsible person in charge) must determine the answers to a number of questions, including:

1. Does a potable water supply with the capacity to be distributed at all times in sufficient quantity and pressure exist nearby?
2. Will constructing a centralized treatment and distribution system for the whole community be best, or would using individual well supplies be better?
3. If a centralized water treatment facility is required, will the storage capacity at the source as well as at intermediate points of the distribution system maintain the water pressure and flow (Quantity) within the conventional limits, particularly during loss-of-pressure "events"—major water main breaks, rehabilitation of the existing system, or major fires, for example?
4. Is a planned or preventive maintenance program in place (or anticipated) for the distribution system that can be properly planned, implemented, and controlled at the optimum level possible?
5. Is the type of water treatment process selected in compliance with federal and state drinking water standards?

√ **Important Point:** Water from a river or a lake usually requires more extensive treatment than groundwater to remove bacteria and suspended particles.

√ **Important Point:** The primary concern for the drinking water practitioner involved with securing an appropriate water supply, treatment process, and distribution system must be the protection of public health. Contaminants must be eliminated or reduced to a safe level to minimize menacing waterborne diseases (to prevent another Milwaukee *Cryptosporidium* event) and to avoid forming long-term or chronic injurious health effects.

6. Has the optimum hydraulic design of the storage, pumping, and distribution network been determined, once the source and treatment processes are selected, to ensure that sufficient quantities of water can be delivered to consumers at adequate pressures?
7. Have community leaders and consumers (the general public) received continuing and realistic information about the functioning of the proposed drinking water service?

√ **Important Point:** Drinking water practitioners are wise to follow the guidance given in point 7, simply because public "buying into" any proposed drinking water project that involves new construction or retrofitting, expansion or upgrade of an existing facility is essential—to ensure that necessary financing is forthcoming. In addition to the finances needed for any type of waterworks construction project, public and financial support are also required to ensure the safe operation, maintenance, and control of the entire water supply system. The acronym POTW begins with the word "public" and the public foots the bills.

8. Does planning include steps to ensure elimination of waste, leakages, and unauthorized consumption?

√ **Important Point:** Industry-wide operational experience has shown that the cost per cubic foot, cubic meter, liter, or gallon of water delivered to the customer has steadily increased because of manpower, automation, laboratory, and treatment costs. To counter these increasing costs, treatment works must meter consumers, measure the water supply flow, and should evaluate the entire system annually.

9. Does the waterworks or proposed water works physical plant include adequate laboratory facilities to ensure proper monitoring of water quality?

√ **Note:** Some waterworks facilities routinely perform laboratory work. However, water pollution control technologists must ensure that the waterworks laboratory or other laboratories used is approved by the appropriate health authority. Keep in mind that the laboratory selected to test and analyze the waterworks samples must be able to analyze chemical, microbiologic, and radionuclide parameters.

10. Are procedures in place to evaluate specific problems such as the lead content in the distribution system and at the consumer's faucet or suspected contamination due to cross-connection potentials?
11. Is a cross-connection control program in place to make sure that the distribution system (in particular) is protected from plumbing errors and illegal connections that may lead to injection of nonpotable water into public or private supplies of drinking water?
12. Are waterworks operators and laboratory personnel properly trained and licensed?
13. Are waterworks managers properly trained and licensed?
14. Are proper operating records and budgetary records mantained?

SOURCES OF WATER

Approximately 40 million mi^3 of water cover or reside within the Earth. The oceans contain about 97% of all water on the Earth. The other 3% is fresh water: (1) snow and ice on the surface of the Earth contains about 2.25% of the water; (2) usable groundwater is approximately 0.3%; and (3) surface fresh water is less than 0.5%.

In the United States, for example, average rainfall is approximately 2.6 ft (a volume of 5900 km^3). Of this amount, approximately 71% evaporates (about 4200 cm^3), and 29% goes to stream flow (about 1700 km^3).

Beneficial freshwater uses include manufacturing, food production, domestic and public needs, recreation, hydroelectric power production, and flood control. Stream flow withdrawn annually is about 7.5% (440 km^3). Irrigation and industry use almost half of this amount (3.4% or 200 km^3/year). Municipalities use only about 0.6% (35 km^3/year) of this amount.

Historically, in the United States, water usage has been on the increase (as might be expected). For example, in 1975, 40 billion gallons of fresh water was used. In 1990, the total increased to 455 billion gallons. Projected use in 2002 was about 725 billion gallons.

The primary sources of fresh water include the following:

1. Captured and stored rainfall in cisterns and water jars
2. Groundwater from springs, artesian wells, and drilled or dug wells
3. Surface water from lakes, rivers, and streams
4. Desalinized seawater or brackish groundwater
5. Reclaimed wastewater

Current federal drinking water regulations actually define three distinct and separate sources of fresh water. They are surface water, groundwater, and groundwater under the direct influence of surface water (GUDISW). This last classification is the result of the Surface Water Treatment Rule (SWTR). The definition of the conditions that constitute GUDISW, while specific, is not obvious. This classification is discussed in detail later.

WATERSHED PROTECTION

Watershed protection is one of the barriers in the multiple-barrier approach to protecting source water. In fact, watershed protection is the primary barrier, the first line of defense against contamination of drinking water at its source.

MULTIPLE-BARRIER CONCEPT

On August 6, 1996, during the Safe Drinking Water Act Reauthorization signing ceremony, President Bill Clinton stated:

> "A fundamental promise we must make to our people is that the food they eat and the water they drink are safe."

No rational person could doubt the importance of the promise made in this statement.

The Safe Drinking Water Act (SWDA), passed in 1974 and amended in 1986 and (as stated above) reauthorized in 1996, gives the United States Environmental Protection Agency (USEPA) the authority to set drinking water standards. This document is important for many reasons, but is even more important because it describes how the USEPA establishes these standards.

Drinking water standards are regulations that the USEPA sets to control the level of contaminants in the nation's drinking water. These standards are part of the SWDA's "multiple-barrier approach" to drinking water protection. The multiple-barrier approach includes the following elements.

1. Assessing and protecting drinking water sources—Means doing everything possible to prevent microbes and other contaminants from entering water supplies. Minimizing human and animal activity around our watersheds is one part of this barrier.
2. Optimizing treatment processes—Provides a second barrier. This usually means filtering and disinfecting the water. It also means making sure that the people who are responsible for our water are properly trained and certified and knowledgeable of the public health issues involved.
3. Ensuring the integrity of distribution systems—Consists of maintaining the quality of water as it moves through the system on its way to the customer's tap.
4. Effecting correct cross-connection control procedures—Is a critical fourth element in the barrier approach. It is critical because the greatest potential hazard in water distribution systems is associated with cross-connections to nonpotable waters. There are many connections between potable and nonpotable systems—every drain in a hospital constitutes such a connection—but cross-connections are those through which backflow can occur (Angele, 1974).
5. Continuous monitoring and testing of the water before it reaches the tap—Monitoring water quality is a critical element in the barrier approach. It should include having specific procedures to follow should potable water ever fail to meet quality standards.

With the involvement of the USEPA, local governments, drinking water utilities, and citizens, these multiple barriers ensure that the tap water in the United States and territories is safe to drink. Simply, in the multiple-barrier concept, we employ a holistic approach to water management that begins at the source and continues with treatment, through disinfection and distribution.

The bottom line on the multiple-barrier approach to protecting the watershed is best summed up in the following (Spellman, 2003):

> Ideally, under the general concept of "quality in, means quality out," a protected watershed ensures that surface runoff and inflow to the source waters occur within a pristine environment.

WATERSHED MANAGEMENT

Water regulates population growth, influences world health and living conditions, and determines biodiversity. For thousands of years, people have tried to control the flow and quality of water. Water provided resources and a means of transportation for development in some areas. Even today, the presence or absence of water is critical in determining how we can use land.

Yet, despite this long experience in water use and water management, humans often fail to manage water well. Sound water management was pushed aside by the rapid, never-ending economic development in many countries. Often, optimism about the applications of technology (e.g., dam building, wastewater treatment, or irrigation measures) exceeded concerns for, or even interest in, environmental shortcomings. Pollution was viewed as the inevitable consequence of development, the price that must be paid to achieve economic progress.

Clearly, we now have reached the stage of our development when the need for management of water systems is apparent, beneficial, and absolutely imperative. Land use and activities in the watershed directly impact raw water quality. Effective watershed management improves raw water quality, controls treatment costs, and provides additional health safeguards. Depending on goals, watershed management can be simple or complex.

This section discusses the need for watershed management on a multiple-barrier basis and a brief overview of the range of techniques and approaches that can be used to investigate the biophysical, social, and economic forces affecting water and its use.

Water utility directors are charged with providing potable water in a quantity and quality that meet the public's demand. They are also charged with providing effective management on a holistic basis of the entire water supply system; such management responsibility includes proper management of the area's watershed.

√ **Key Point:** Integrated water management means putting all of the pieces together, including considering social, environmental, and technical aspects.

[Note: Much of the information provided in this section is adapted from W. Viessman, Jr. (1991).]

Remarkable consensus exists among worldwide experts over the current issues confronted by waterworks managers and others. These issues include the following:

1. Water availability, requirements, and use
    - Protection of aquatic and wetland habitat
    - Management of extreme events (droughts, floods, etc.)
    - Excessive extractions from surface and groundwater
    - Global climate change
    - Safe drinking water supply
    - Waterborne commerce
2. Water quality
    - Coastal and ocean water quality
    - Lake and reservoir protection and restoration
    - Water quality protection, including effective enforcement of legislation
    - Management of point- and nonpoint-source pollution
    - Impacts on land/water/air relationships
    - Health risks
3. Water management and institutions
    - Coordination and consistency
    - Capturing a regional perspective
    - Respective roles of federal and state/provincial agencies
    - Respective roles of projects and programs
    - Economic development philosophy that should guide planning
    - Financing and cost sharing
    - Information and education
    - Appropriate levels of regulation and deregulation

- Water rights and permits
- Infrastructure
- Population growth
- Water resources planning, including
    i. Consideration of the watershed as an integrated system
    ii. Planning as a foundation for, not a reaction to, decision making
    iii. Establishment of dynamic planning processes incorporating periodic review and redirection
    iv. Sustainability of projects beyond construction and early operation
    v. A more interactive interface between planners and the public
    vi. Identification of sources of conflict as an integral part of planning
    vii. Fairness, equity, and reciprocity between affected parties

WATER QUALITY IMPACT

Generally, water quality of a typical river system is impacted by about 60% nonpoint pollution, 21% municipal discharge, 18% industrial discharge, and about 1% sewer overflows. Of the nonpoint pollution, about 67% is from agriculture, 18% urban, and 15% from other sources.

Land use directly impacts water quality. The impact of land use on water quality is clearly evident in Table 2.1.

From the waterworks operator point of view, water quality issues for nutrient contamination can be summarized quite simply:

1. Nutrients + algae = taste and odor problems
2. Nutrients + algae + macrophytes + decay = trihalomethanes (THM) precursors

WATERSHED PROTECTION AND REGULATIONS

The Clean Water Act (CWA) and Safe Drinking Water Act (SDWA) reauthorization addresses source water protection. Implementation of regulatory compliance requirements (with guidance provided by the U.S. Department of Health) is left up to the state and local health department officials to implement.

Water protection regulations in force today not only provide guidance and regulation for watershed protection but they also provide additional benefits for those tasked with managing drinking water utilities.

TABLE 2.1
Land Use That Directly Impacts Water Quality

Source	Sediment	Nutrients	Viruses, Bacteria	THM	Fe, Mn
Urban	x	x	x	x	x
Agriculture	x	x	x	x	x
Logging	x	x		x	x
Industrial	x	x		x	x
Septic Tanks		x	x	x	
Construction	x	x			

Source: From Spellman, F.R., *The Handbook for Wastewater Operator Certification*, CRC Press, Boca Raton, FL, 2001.

The typical drinking water utility (which provides safe drinking water to the consumer) has two choices in water pollution control: “Keep it out or take it out.” The “keep it out” part pertains to the watershed management, of course; otherwise, if the water supply contains contaminants, they must be removed by treatment, “take it out.” Obviously, utility directors and waterworks managers are concerned with controlling treatment costs. An effective watershed management program can reduce treatment costs by reducing source water contamination. The “take it out” option is much more expensive and time consuming than keeping it out in the first place.

Proper watershed management also works to maintain consumer confidence. If the consumer is aware that the water source from the area’s watershed is of the highest quality, then logically, confidence in the quality of the water is high. High-quality water also works directly to reduce public health risks.

A WATERSHED PROTECTION PLAN

Watershed protection begins with planning. The watershed protection plan consists of several elements, which include the need to:

1. Inventory and characterize water sources
2. Identify pollutant sources
3. Assess vulnerability of intake
4. Establish program goals
5. Develop protection strategies
6. Implement program
7. Monitor and evaluate program effectiveness

RESERVOIR MANAGEMENT PRACTICES

To ensure an adequate and safe supply of drinking water for a municipality, watershed management includes proper reservoir management practices. These practices include proper lake aeration, harvesting, dredging, and use of algicide. Water quality improvements by lake aeration include reduction in iron, manganese, phosphorus, ammonia, and sulfide content. Lake aeration also reduces cost of capital and operation for water supply treatment. Algicide treatment controls algae, which in turn reduces taste and odor problems. The drawback of using algicides is that they are successful for only a brief period.

POTABLE WATER SOURCE

Because of the huge volume and flow conditions, the quality of natural water cannot be modified significantly within the body of water. Accordingly, humans must augment nature’s natural purification processes with physical, chemical, and biological treatment procedures. Essentially, this quality control approach is directed to the water withdrawn, which is treated from a source for a specific use.

POTABLE WATER

Potable water is water fit for human consumption and domestic use, which is sanitary and normally free of minerals, organic substances, and toxic agents in excess or in reasonable amounts for domestic usage in the area served, and normally adequate in quantity for the minimum health requirements of the persons served.

With regard to a potential potable water supply, the key words, as previously mentioned, are “quality and quantity.” Obviously, if we have a water supply that is unfit for human consumption, we have a quality problem. If we do not have an adequate supply of quality water, we have a quantity problem.

In this section, the focus is on surface water and groundwater hydrology and the mechanical components associated with collection and conveyance of water from its source to the public water supply system for treatment. Well supplies are also discussed.

KEY DEFINITIONS

Annular space The space between the casing and the wall of the hole.

Aquifer A porous, water-bearing geologic formation.

Caisson Large pipe placed in a vertical position.

Cone of depression As the water in a well is drawn down, the water near the well drains or flows into it. The water will drain further back from the top of the water table into the well as drawdown increases.

Confined aquifer An aquifer that is surrounded by formations of less permeable or impermeable material.

Contamination The introduction into water of toxic materials, bacteria, or other deleterious agents that make the water unfit for its intended use.

Drainage basin An area from which surface runoff or groundwater recharge is carried into a single drainage system. It is also called catchment area, watershed, and drainage area.

Drawdown The distance or difference between the static level and the pumping level. When the drawdown for any particular capacity well and rate pump bowls is determined, the pumping level is known for that capacity. The pump bowls are located below the pumping level so that they will always be underwater. When the drawdown is fixed or remains steady, the well is then furnishing the same amount of water as is being pumped.

Groundwater Subsurface water occupying a saturated geological formation from which wells and springs are fed.

Hydrology The applied science pertaining to properties, distribution, and behavior of water.

Impermeable A material or substance that water will not pass through.

Overland flow The movement of water on and just under the Earth's surface.

Permeable A material or substance that water can pass through.

Porosity The ratio of pore space to total volume. That portion of a cubic foot of soil that is air space and could therefore contain moisture.

Precipitation The process by which atmospheric moisture is discharged onto the Earth's crust. Precipitation takes the form of rain, snow, hail, and sleet.

Pumping level The level at which the water stands when the pump is operating.

Radius of influence The distance from the well to the edge of the cone of depression, the radius of a circle around the well from which water flows into the well.

Raw water The untreated water to be used after treatment as drinking water.

Recharge area An area from which precipitation flows into underground water sources.

Specific yield The geologist's method for determining the capacity of a given well and the production of a given water-bearing formation. It is expressed as gal/min/ft of drawdown.

Spring A surface feature where without the help of man, water issues from rock or soil onto the land or into a body of water, the place of issuance being relatively restricted in size.

Static level The height to which the water will rise in the well when the pump is not operating.

Surface runoff The amount of rainfall that passes over the surface of the Earth.

Surface water The water on the Earth's surface as distinguished from water underground (groundwater).

Unconfined aquifer An aquifer that sits on an impervious layer, but is open on the top to local infiltration. The recharge for an unconfined aquifer is local. It is also called a water table aquifer.

Water rights The rights, acquired under the law, to use the water accruing in surface or groundwater, for a specified purpose in a given manner and usually within the limits of a given time period.

Watershed A drainage basin from which surface water is obtained.

Water table The average depth or elevation of the groundwater over a selected area. The upper surface of the zone of saturation, except where that surface is formed by an impermeable body.

SURFACE WATER

From where do we get our potable water? From what water source is our drinking water provided? To answer these questions, we would most likely turn to one of two possibilities: our public water is provided by a groundwater or surface-water source because these two sources are, indeed, the primary sources of most water supplies.

From the earlier discussion of the hydrologic or water cycle, we know that from whichever of the two sources we obtain our drinking water, the source is constantly being replenished (we hope) with a supply of fresh water. This water cycle phenomenon was best summed up by Heraclitus of Ephesus, who said, "You could not step twice into the same rivers; for other waters are ever flowing on to you."

In this section, we discuss one of the primary duties of the drinking water practitioner (and humankind in general)—to find and secure a source of potable water for human use.

LOCATION! LOCATION! LOCATION!

In the real estate business, location is everything. The same can be said when it comes to sources of water. In fact, the presence of water defines "location" for communities. Although communities differ widely in character and size, all have the common concerns of finding water for industrial, commercial, and residential use. Freshwater sources that can provide stable and plentiful supplies for a community don't always occur where we wish. Simply put, on land, the availability of a regular supply of potable water is the most important factor affecting the presence—or absence—of many life-forms. A map of the world immediately shows us that surface waters are not uniformly distributed over the Earth's surface. U.S. land holds rivers, lakes, and streams on only about 4% of its surface. The heaviest populations of any life forms, including humans, are found in regions of the United States (and the rest of the world) where potable water is readily available because lands barren of water simply won't support large populations. One thing is certain: if a local supply of potable water is not readily available, the locality affected will seek a source. This is readily apparent (absolutely crystal clear), for example, when one studies the history of water "procurement" for the communities located within the Los Angeles basin.

√ **Important Point:** The volume of freshwater sources depends on geographic, landscape, and temporal variations, and on the impact of human activities.

HOW READILY AVAILABLE IS POTABLE WATER?

Approximately 326 million mi^3 of water comprise the Earth's entire water supply. Of this massive amount of water—though providing us indirectly with fresh water through evaporation from the oceans—only about 3% is fresh. Also, most of the minute percentage of fresh water the Earth holds is locked up in polar ice caps and in glaciers. The rest is held in lakes, in flows through soil, and in river and stream systems. Only 0.027% of the Earth's fresh water is available for human consumption (see Table 2.2 for the distribution percentages of the Earth's water supply).

TABLE 2.2
World Water Distribution

Location	Percent of Total
Land areas	
Freshwater lakes	0.009
Saline lakes and inland seas	0.008
Rivers (average instantaneous volume)	0.0001
Soil moisture	0.005
Groundwater (above depth of 4000 m)	0.61
Ice caps and glaciers	2.14
Total land areas	**2.8**
Atmosphere (water vapor)	0.001
Oceans	97.3
Total all locations (rounded)	**100**

Source: From USGS, 2006.

We see from Table 2.2 that the major sources of drinking water are from surface water, groundwater, and from GUDISW (i.e., springs or shallow wells).

Again, surface water is that water that is open to the atmosphere and results from overland flow (i.e., runoff that has not yet reached a definite stream channel). Put a different way, surface water is the result of surface runoff.

For the most part, however, surface (as used in the context of this text) refers to water flowing in streams and rivers, as well as water stored in natural or artificial lakes, man-made impoundments such as lakes made by damming a stream or river, springs that are affected by a change in level or quantity, shallow wells that are affected by precipitation, wells drilled next to or in a stream or river, rain catchments, and muskeg and tundra ponds.

Specific sources of surface water include:

1. Rivers
2. Streams
3. Lakes
4. Impoundments (man-made lakes made by damming a river or stream)
5. Very shallow wells that receive input via precipitation
6. Springs affected by precipitation (flow or quantity directly dependent upon precipitation)
7. Rain catchments (drainage basins)
8. Tundra ponds or muskegs (peat bogs)

Surface water has advantages as a source of potable water. Surface-water sources are usually easy to locate, unlike groundwater. Finding surface water does not take a geologist or hydrologist and normally it is not tainted with minerals precipitated from the Earth's strata.

Ease of discovery aside, surface water also presents some disadvantages: surface-water sources are easily contaminated (polluted) with microorganisms that can cause waterborne diseases (anyone who has suffered from "hiker's disease" or "hiker's diarrhea" can attest to this), and from chemicals that enter from surrounding runoff and upstream discharges. Water rights can also present problems.

As mentioned, most surface water is the result of surface runoff. The amount and flow rate of this surface water is highly variable, for two main reasons: (1) human interferences (influences) and (2) natural conditions. In some cases, surface water runs quickly off land surfaces. From a water resources standpoint, this is generally undesirable, because quick runoff does not provide enough time for the water to infiltrate the ground and recharge groundwater aquifers. Surface water that quickly runs off land also causes erosion and flooding problems. Probably the only good thing that can be said about surface water that runs off quickly is that it usually does not have enough contact time to increase in mineral content. Slow surface water off land has all the opposite effects.

Drainage basins collect surface water and direct it on its gravitationally influenced path to the ocean. The drainage basin is normally characterized as an area measured in square miles, acres, or sections. Obviously, if a community is drawing water from a surface-water source, the size of its drainage basin is an important consideration.

Surface-water runoff, like the flow of electricity, flows or follows the path of least resistance. Surface water within the drainage basin normally flows toward one primary watercourse (river, stream, brook, creek, etc.), unless some man-made distribution system (canal or pipeline) diverts the flow.

√ **Important Point:** Many people probably have an overly simplified idea that precipitation falls on the land, flows overland (runoff), and runs into rivers, which then empty into the oceans. That is "overly simplified" because rivers also gain and lose water to the ground. Still, it is true that much of the water in rivers comes directly from runoff from the land surface, which is defined as surface runoff.

Surface-water runoff from land surfaces depends on several factors, including:

- *Rainfall duration*: Even a light, gentle rain, if it lasts long enough, can, with time, saturate soil and allow runoff to take place.
- *Rainfall intensity*: With increases in intensity, the surface of the soil quickly becomes saturated. This saturated soil can hold no more water; as more rain falls and water builds up on the surface, it creates surface runoff.
- *Soil moisture*: The amount of existing moisture in the soil has a definite impact on surface runoff. Soil already wet or saturated from a previous rain causes surface runoff to occur sooner than if the soil were dry. Surface runoff from frozen soil can be up to 100% of snowmelt or rain runoff because frozen ground is basically impervious.
- *Soil composition*: The composition of the surface soil directly affects the amount of runoff. For example, hard rock surfaces, obviously, result in 100% runoff. Clay soils have very small void spaces that swell when wet; the void spaces close and do not allow infiltration. Coarse sand possesses large void spaces that allow easy flow of water, which produces the opposite effect, even in a torrential downpour.
- *Vegetation cover*: Groundcover limits runoff. Roots of vegetation and pine needles, pine cones, leaves, and branches create a porous layer (a sheet of decaying natural organic substances) above the soil. This porous "organic" sheet readily allows water into the soil. Vegetation and organic waste also act as cover to protect the soil from hard, driving rains, which can compact bare soils, close off void spaces, and increase runoff. Vegetation and groundcover work to maintain the soil's infiltration and water-holding capacity, and also work to reduce soil moisture evaporation.
- *Ground slope*: When rain falls on steeply sloping ground, up to 80+% may become surface runoff. Gravity moves the water down the surface more quickly than it can infiltrate the surface. Water flow off flat land is usually slow enough to provide opportunity for a higher percentage of the rainwater to infiltrate the ground.

- *Human influences*: Various human activities have a definite impact on surface-water runoff. Most human activities tend to increase the rate of water flow. For example, canals and ditches are usually constructed to provide steady flow, and agricultural activities generally remove groundcover that would work to retard the runoff rate. On the opposite extreme, man-made dams are generally built to retard the flow of runoff.

Paved streets, tarmac, paved parking lots, and buildings are impervious to water infiltration, greatly increasing the amount of storm-water runoff from precipitation events. These man-made surfaces (which work to hasten the flow of surface water) often cause flooding to occur, sometimes with devastating consequences. In badly planned areas, even relatively light precipitation can cause local flooding. Impervious surfaces not only present flooding problems, but they also do not allow water to percolate into the soil to recharge groundwater supplies—often another devastating blow to a location's water supply.

ADVANTAGES AND DISADVANTAGES OF SURFACE WATER

The biggest advantage of using a surface-water supply as a water source is that these sources are readily located; finding surface-water sources does not demand sophisticated training or equipment. Many surface-water sources have been used for decades and even centuries (in the United States, for example), and considerable data are available on the quantity and quality of the existing water supply. Surface water is also generally softer (not mineral-laden), which makes its treatment much simpler.

The most significant disadvantage of using surface water as a water source is pollution. Surface waters are easily contaminated (polluted) with microorganisms that cause waterborne diseases and chemicals that enter the river or stream from surface runoff and upstream discharges.

Another problem with many surface-water sources is turbidity, which fluctuates with the amount of precipitation. Increases in turbidity increase treatment cost and operator time.

Surface-water temperatures can be a problem because they fluctuate with ambient temperature, making consistent water quality production at a waterworks plant difficult.

Drawing water from a surface-water supply might also present problems. Intake structures may clog or become damaged from winter ice, or the source may be so shallow that it completely freezes in the winter.

Water rights cause problems too—removing surface water from a stream, lake, or spring requires a legal right. The lingering, seemingly unanswerable question is: Who owns the water?

Using surface water as a source means that the purveyor is obligated to meet the requirements of the SWTR and Interim Enhanced Surface Water Treatment Rule (IESWTR). (Note: This rule only applies to large public water systems [PWS], that serve more than 10,000 people. It tightened controls on DBPs, turbidity and regulation of *Cryptosporidium*.)

SURFACE WATER HYDROLOGY

To properly manage and operate water systems, a basic understanding of the movement of water and the things that affect water quality and quantity are important: in other words, hydrology. A discipline of applied science, hydrology includes several components such as the physical configuration of the watershed, geology, soils, vegetation, nutrients, energy, wildlife, and water itself.

As mentioned, the area from which surface water flows is called a drainage basin or catchment area. With a surface water source, this drainage basin is most often called, in nontechnical terms, a watershed (when dealing with groundwater, we call this area a recharge area).

√ **Key Point:** The area that directly influences the quantity and quality of surface water is called the drainage basin or watershed.

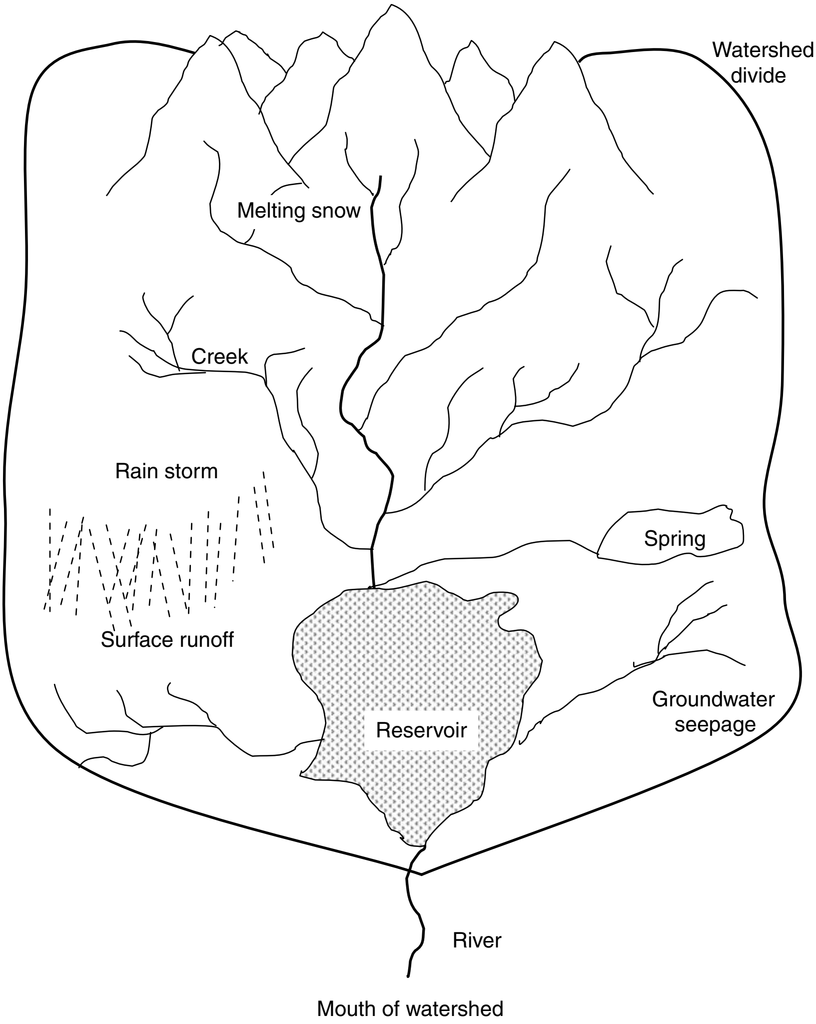

FIGURE 2.3 Watershed.

When you trace on a map the course of a major river from its meager beginnings on its seaward path, that its flow becomes larger and larger is apparent. While every tributary brings a sudden increase, between tributaries, the river grows gradually from the overland flow entering it directly (see Figure 2.3).

Not only does the river grow its whole watershed or drainage basin, the land it drains into grows too in the sense that it embraces an ever-larger area.

The area of the watershed is commonly measured in square miles, sections, or acres. When taking water from a surface-water source, knowing the size of the watershed is desirable.

RAW WATER STORAGE

Raw water (i.e., water that has not been treated) is stored for single or multiple uses, such as navigation, flood control, hydroelectric power, agriculture, water supply, pollution abatement, recreation, and flow augmentation. The primary reason for storing water is to meet peak demands, or to store water to meet demands when the flow of the source is below the demand. Raw water is stored in natural storage sites (such as lakes, muskeg, and tundra ponds) or in man-made storage areas such as dams. Man-made dams are either masonry or embankment dams. If embankment dams are used, they are typically constructed of local materials with an impermeable clay core.

SURFACE WATER INTAKES

Withdrawing water from a river, lake, or reservoir so that it may be conveyed to the first unit of treatment process requires an intake structure. Intakes have no standard design and range from a simple-pump suction pipe sticking out into the lake or stream to expensive structures costing several thousands of dollars. Typical intakes include submerged intakes, floating intakes, infiltration galleries, spring boxes, and roof catchments. Their primary functions are to supply the highest quality water from the source and to protect piping and pumps from clogging as a result of wave action, ice formation, flooding, and submerged debris. A poorly conceived or constructed intake can cause many problems. Failure of the intake could result in water-system failure.

On a small stream, the most common intake structures used are small gravity dams placed across the stream or a submerged intake. In the gravity dam type, a gravity line or pumps can remove water behind the dam. In the submerged intake type, water is collected in a diversion and carried away by gravity or pumped from a caisson.

Another common intake used on small and large streams is an end-suction centrifugal pump or submersible pump placed on a float. The float is secured to the bank and the water is pumped to a storage area.

Often, the intake structure placed in a stream is an infiltration gallery. The most common infiltration galleries are built by placing well screens or perforated pipe into the streambed. The pipe is covered with clean, graded gravel. When water passes through the gravel, coarse filtration removes a portion of the turbidity and organic material. The water collected by the perforated pipe then flows to a caisson placed next to the stream and is removed from the caisson by gravity or pumping.

Intakes used in springs are normally implanted into the water-bearing strata, then covered with clean, washed rock and sealed, usually with clay. The outlet is piped into a spring box.

In some locations, rainwater is a primary source of water. Rainwater is collected from the roofs of buildings with a device called a roof catchment.

After determining that a water source provides a suitable quality and quantity of raw water, choosing an intake location includes determining the following:

1. Best quality water location
2. Dangerous currents
3. Sandbar formation
4. Wave action
5. Ice storm factors
6. Flood factors
7. Navigation channel avoidance
8. Intake accessibility
9. Power availability
10. Floating or moving object damage factors
11. Distance from pumping station
12. Upstream uses that may affect water quality

SURFACE-WATER SCREENS

Generally, screening devices are installed to protect intake pumps, valves, and piping. A coarse screen of vertical steel bars, with openings of 1–3 in., placed in a near-vertical position excludes large objects. It may be equipped with a trash truck rack rake to remove accumulated debris.

A finer screen, one with 3/8-in. openings, removes leaves, twigs, small fish, and other material passing through the bar rack. Traveling screens consist of wire mesh trays that retain solids as the water passes through them. Drive chain and sprockets raise the trays into a head enclosure, where the debris is removed by water sprays. The screen travel pattern is intermittent and controlled by the amount of accumulated material.

√ **Note:** When considering what type of screen should be employed, the most important consideration is ensuring that the screen can be easily maintained.

SURFACE-WATER QUALITY

Surface waters should be of adequate quality to support aquatic life and be aesthetically pleasing, and waters used as sources of supply should be treatable by conventional processes to provide potable supplies that can meet the drinking water standards. Many lakes, reservoirs, and rivers are maintained at a quality suitable for swimming, water skiing, boating as well as for drinking water.

Whether the surface-water supply is taken from a river, stream, lake, spring, impoundment, reservoir, or dam, surface-water quality varies widely, especially in rivers, streams, and small lakes. These water bodies are not only susceptible to waste discharge contamination but also to “flash” contamination (can occur almost immediately and not necessarily over time). Lakes are subject to summer/winter stratification (turnover) and to algal blooms. Pollution sources range from runoff (agricultural, residential, and urban) to spills, municipal and industrial wastewater discharges, recreational users, and natural occurrences. Surface-water supplies are difficult to protect from contamination and must always be treated.

PWS must comply with applicable federal and state regulations and must provide quantity and quality water supplies including proper treatment (where/when required) and competent/qualified waterworks operators.

The USEPA’s regulatory requirements insist that all public water systems using any surface or groundwater under the direct influence of surface water must disinfect and may be required by the state to filter, unless the water source meets certain requirements and site-specific conditions. Treatment technique requirements are established in lieu of Maximum Contaminant Levels (MCLs) for *Giardia*, viruses, heterotrophic plate count bacteria, *Legionella*, and turbidity. Treatment must achieve at least 99.9% removal (3-log removal) or inactivation of *Giardia lamblia* cysts and 99.9% removal or inactivation of viruses.

GROUNDWATER SUPPLY

Unbeknownst to most of us, our Earth possesses an unseen ocean. This ocean, unlike the surface oceans that cover most of the globe, is fresh water: the groundwater that lies contained in aquifers beneath the Earth’s crust. This gigantic water source forms a reservoir that feeds all the natural fountains and springs of the Earth. But how does water travel into the aquifers that lie under the Earth’s surface?

Groundwater sources are replenished from a percentage of the average approximately 3 ft of water that falls to the Earth each year on every square foot of land. Water falling to the Earth as precipitation follows three courses. Some runs off directly to rivers and streams (roughly 6 in. of that 3 ft), eventually working back to the sea. Evaporation and transpiration through vegetation takes up about 2 ft. The remaining 6 in. seeps into the ground, entering, and filling every interstice, hollow, and cavity. Gravity pulls water toward the center of the Earth. That means that water on the surface will try to seep into the ground below it. Although groundwater comprises only one sixth of the total (1,680,000 miles of water), if we could spread out this water over the land, it would blanket it to a depth of 1000 feet.

AQUIFERS

As mentioned, part of the precipitation that falls on land infiltrates the land surface, percolates downward through the soil under the force of gravity, and becomes groundwater. Groundwater, like surface water, is extremely important to the hydrologic cycle and to our water supplies. Almost half of the people in the United States drink public water from groundwater supplies. Overall, more water exists as groundwater than surface water in the United States, including the water in the Great Lakes. But sometimes, pumping it to the surface is not economical, and in recent years, pollution of groundwater supplies from improper disposal has become a significant problem.

We find groundwater in saturated layers called aquifers under the Earth's surface. Three types of aquifers exist: unconfined, confined, and springs.

Aquifers are made up of a combination of solid material such as rock and gravel and open spaces called pores. Regardless of the type of aquifer, the groundwater in the aquifer is in a constant state of motion. This motion is caused by gravity or by pumping.

The actual amount of water in an aquifer depends upon the amount of space available between the various grains of material that make up the aquifer. The amount of space available is called porosity. The ease of movement through an aquifer is dependent upon how well the pores are connected. For example, clay can hold a lot of water and has high porosity, but the pores are not connected, so water moves through the clay with difficulty. The ability of an aquifer to allow water to infiltrate is called permeability.

The aquifer that lies just under the Earth's surface is called the zone of saturation, an unconfined aquifer (see Figure 2.4). The top of the zone of saturation is the water table. An unconfined aquifer is only contained on the bottom and is dependent on local precipitation for recharge. This type of aquifer is often called a water table aquifer.

Unconfined aquifers are the primary source of shallow well water (see Figure 2.4). These wells are shallow (and not desirable as a public drinking water source). They are subject to local contamination from hazardous and toxic materials—fuel and oil, septic tanks, and agricultural runoff providing increased levels of nitrates and microorganisms. These wells may be classified as GUDISW, and therefore require treatment for control of microorganisms.

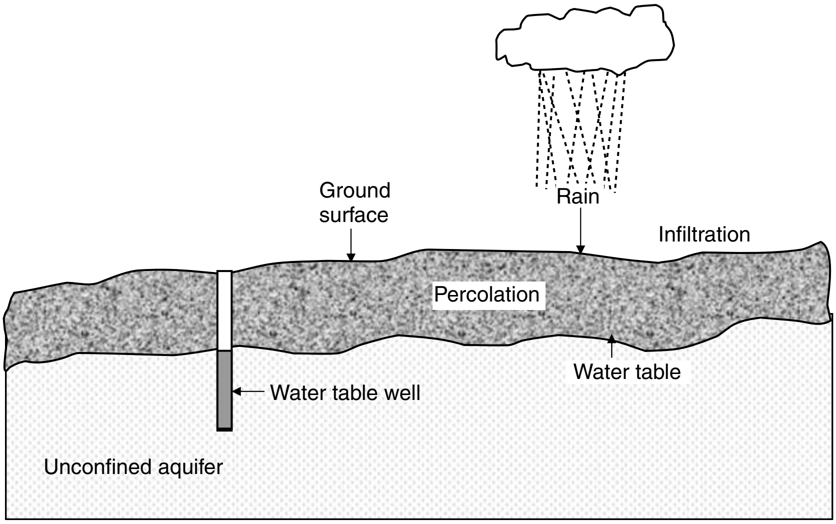

FIGURE 2.4 Unconfined aquifer. (From Spellman, F.R. 1996. *Stream Ecology and Self-Purification: An Introduction for Wastewater and Water Specialists*, Lancaster, PA, Technomic Publishing Company.)

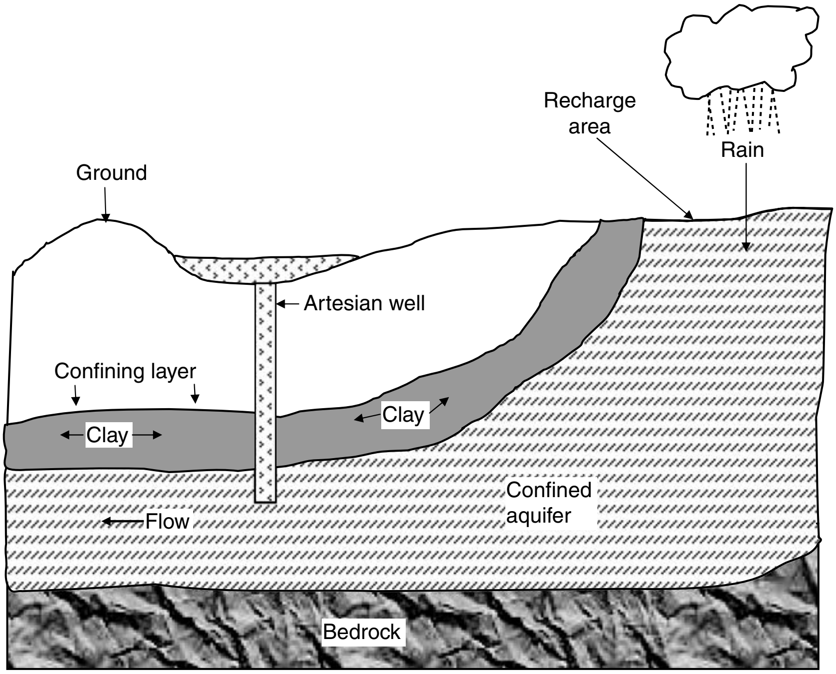

FIGURE 2.5 Confined aquifer. (From Spellman, F.R. 1996. *Stream Ecology and Self-Purification: An Introduction for Wastewater and Water Specialists*, Lancaster, PA, Technomic Publishing Company.)

A confined aquifer is sandwiched between two impermeable layers that block the flow of water. The water in a confined aquifer is under hydrostatic pressure. It does not have a free water table (see Figure 2.5).

Confined aquifers are called artesian aquifers. Wells drilled into artesian aquifers are called artesian wells and commonly yield large quantities of high quality water. An artesian well is any well where the water in the well casing would rise above the saturated strata. Wells in confined aquifers are normally referred to as deep wells and are not generally affected by local hydrological events.

A confined aquifer is recharged by rain or snow in the mountains where the aquifer lies close to the surface of the Earth. Because the recharge area is some distance from areas of possible contamination, the possibility of contamination is usually very low. However, once contaminated, confined aquifers may take centuries to recover.

Groundwater naturally exits the Earth's crust in areas called springs. The water in a spring can originate from a water table aquifer or from a confined aquifer. Only water from a confined spring is considered desirable for a public water system.

GROUNDWATER QUALITY

Generally, groundwater possesses high chemical, bacteriological, and physical quality. Groundwater pumped from an aquifer composed of a mixture of sand and gravel, if not directly influenced by surface water, is often used without filtration. It can also be used without disinfection if it has a low coliform count. However, as mentioned, groundwater can become contaminated. When septic systems fail, saltwater intrudes, improper disposal of wastes occurs, improperly stockpiled chemicals leach, underground storage tanks leak, and hazardous materials spill. Fertilizers and pesticides are misplaced, and when mines are improperly abandoned, groundwater can become contaminated.

To understand how an underground aquifer becomes contaminated, you must understand what occurs when pumping is taking place within the well. When groundwater is removed from its underground source (i.e., from the water-bearing stratum) via a well, water flows toward the center of the well. In a water table aquifer, this movement causes the water table to sag toward the well. This sag is called the cone of depression. The shape and size of the cone depends on the relationship between the pumping rate and the rate at which water can move toward the well. If the rate is high, the cone is shallow, and its growth stabilizes. The area that is included in the cone of depression is called the cone of influence, and any contamination in this zone will be drawn into the well.

GUDISW

GUDISW is not classified as a groundwater supply. A supply designated as GUDISW must be treated under the state's surface water rules rather than the groundwater rules.

The SWTR of the Safe Drinking Water Act requires each site to determine which groundwater supplies are influenced by surface water (i.e., when surface water can infiltrate a groundwater supply and could contaminate it with *Giardia*, viruses, turbidity, and organic material from the surface water source). To determine whether a groundwater supply is under the direct influence of surface water, the USEPA has developed procedures that focus on significant and relatively rapid shifts in water quality characteristics, including turbidity, temperature, and pH. When these shifts can be closely correlated with rainfall or other surface-water conditions, or when certain indicator organisms associated with surface water are found, the source is said to be under the direct influence of surface water.

Almost all groundwater is in constant motion through the pores and crevices of the aquifer in which it occurs. The water table is rarely level; it generally follows the shape of the ground surface. Groundwater flows in the downhill direction of the sloping water table. The water table sometimes intersects low points of the ground, where it seeps out into springs, lakes, or streams.

Usual groundwater sources include wells and springs that are not influenced by surface water or local hydrologic events.

As a potable water source, groundwater has several advantages over surface water. Unlike surface water, groundwater is not easily contaminated. Groundwater sources are usually lower in bacteriological contamination than surface waters. Groundwater quality and quantity usually remains stable throughout the year. In the United States, groundwater is available in most locations.

As a potable water source, groundwater does present some disadvantages compared to surface water sources. Operating costs are usually higher because groundwater supplies must be pumped to the surface. Any contamination is often hidden from view. Removing any contaminants is very difficult. Groundwater often possesses high mineral levels, and thus an increased level of hardness because it is in contact longer with minerals. Near coastal areas, groundwater sources may be subject to saltwater intrusion.

√ **Important Point:** Groundwater quality is influenced by the quality of its source. Changes in source waters or degraded quality of source supplies may seriously impair the quality of the groundwater supply.

Prior to moving onto water use, it is important to point out that our freshwater supplies are constantly renewed through the hydrologic cycle, but the balance between the normal ratio of freshwater to salt water is not subject to our ability to change. As our population grows and we move into lands without ready freshwater supplies, we place an ecological strain upon those areas, and on their ability to support life.

Communities that build in areas without adequate local water supply are at risk in the event of emergency. Proper attention to our surface and groundwater sources, including remediation, pollution control, and water reclamation and reuse can help ease the strain, but technology cannot fully replace adequate local freshwater supplies, whether from surface or groundwater sources.

WELL SYSTEMS

The most common method for withdrawing groundwater is to penetrate the aquifer with a vertical well, then pump the water up to the surface.

In the past, when someone wanted a well, they simply dug (or hired someone to dig) and hoped (gambled) that they would find water in a quantity suitable for their needs. Today, in most locations in the United States, for example, developing a well supply usually involves a more complicated step-by-step process.

Local, state, and federal requirements specify the actual requirements for development of a well supply in the United States. The standard sequence for developing a well supply generally involves a seven-step process. This process includes:

Step 1: Application—Depending on the location, filling out and submitting an application (to the applicable authorities) to develop a well supply is standard procedure.
Step 2: Well site approval—Once the application has been made, local authorities check various local geological and other records to ensure that the siting of the proposed well coincides with mandated guidelines for approval.
Step 3: Well drilling—The well is then drilled.
Step 4: Preliminary engineering report—After the well is drilled and the results documented, a preliminary engineering report is prepared on the suitability of the site to serve as a water source. This procedure involves performing a pump test to determine if the well can supply the required amount of water. The well is generally pumped for at least 6 h at a rate equal to or greater than the desired yield. A stabilized drawdown should be obtained at that rate and the original static level should be recovered within 24 h after pumping stops. During this test period, samples are taken and tested for bacteriological and chemical quality.
Step 5: Submission of documents for review and approval—The application and test results are submitted to an authorized reviewing authority that determines if the well site meets approval criteria.
Step 6: Construction permit—If the site is approved, a construction permit is issued.
Step 7: Operation permit—When the well is ready for use, an operation permit is issued.

WELL SITE REQUIREMENTS

To protect the groundwater source and provide high-quality safe water, the waterworks industry has developed standards and specifications for wells. The following listing includes industry standards and practices, as well as those items included in the State Department of Environmental Compliance regulations, for example.

√ **Note:** Check with your local regulatory authorities to determine well site requirements.

1. Minimum well lot requirements
    a. 50 ft from well to all property lines
    b. All-weather access road provided
    c. Lot graded to divert surface runoff
    d. Recorded well plat and dedication document
2. Minimum well location requirements
    a. At least 50-ft horizontal distance from any actual or potential sources of contamination involving sewage
    b. At least 50-ft horizontal distance from any petroleum or chemical storage tank or pipeline or similar source of contamination, except where plastic type well casing is used, the separation distance must be at least 100 ft

3. Vulnerability assessment
    a. Wellhead area = 1000-ft radius from the well
    b. What is the general land use of the area (residential, industrial, livestock, crops, undeveloped, other)?
    c. What are the geologic conditions (sinkholes, surface, subsurface)?

TYPE OF WELLS

Water supply wells may be characterized as shallow or deep. In addition, wells are classified as follows:

1. Class I—cased and grouted to 100 ft
2. Class II A—cased to a minimum of 100 ft and grouted to 20 ft
3. Class II B—cased and grouted to 50 ft

Note: During the well-development process, mud/silt forced into the aquifer during the drilling process is removed, allowing the well to produce the best-quality water at the highest rate from the aquifer.

SHALLOW WELLS

Shallow wells are those that are less than 100 ft deep. Such wells are not particularly desirable for municipal supplies since the aquifers they tap are likely to fluctuate considerably in depth, making the yield somewhat uncertain. Municipal wells in such aquifers cause a reduction in the water table (or phreatic surface) that affects nearby private wells, which are more likely to utilize shallow strata. Such interference with private wells may result in damage suits against the community. Shallow wells may be dug, bored, or driven.

Dug Wells

Dug wells are the oldest type of well and date back many centuries; they are dug by hand or by a variety of unspecialized equipment. They range in size from approximately 4–15 ft in diameter and are usually about 20–40 ft deep. Such wells are usually lined or cased with concrete or brick. Dug wells are prone to failure from drought or heavy pumpage. They are vulnerable to contamination and are not acceptable as a public water supply in many locations.

Driven Wells

Driven wells consist of a pipe casing terminating at a point slightly greater in diameter than the casing. The pointed well screen and the lengths of pipe attached to it are pounded down or driven in the same manner as a pile, usually with a drop hammer, to the water-bearing strata. Driven wells are usually 2–3 in. in diameter and are used only with unconsolidated materials. This type of shallow well is not acceptable as a public water supply.

Bored Wells

Bored wells range from 1 to 36 in. in diameter and are constructed with unconsolidated materials. The boring is accomplished with augers (either hand or machine driven) that fill with soil and then are drawn to the surface to be emptied. The casing may be placed after the well is completed (in relatively cohesive materials), but must advance with the well into the noncohesive strata. Bored wells are not acceptable as a public water supply.

DEEP WELLS

Deep wells are the usual source of groundwater for municipalities. Deep wells tap thick and extensive aquifers that are not subject to rapid fluctuations in water (piezometric surface—the height to which water will rise in a tube penetrating a confined aquifer) level and that provide a large and uniform yield. Deep wells typically yield water of a more constant quality than shallow wells, although the quality is not necessarily better. Deep wells are constructed by a variety of techniques; we discuss two of these techniques (jetting and drilling) below.

Jetted Wells

Jetted well construction commonly employs a jetting pipe with a cutting tool. This type of well cannot be constructed in clay, hardpan, or where boulders are present. Jetted wells are not acceptable as a public water supply.

Drilled Wells

Drilled wells are usually the only type of well allowed for use in most public water supply systems. Several different methods of drilling are available; all of which are capable of drilling wells of extreme depth and diameter. Drilled wells are constructed using a drilling rig that creates a hole into which the casing is placed. Screens are installed at one or more levels when water-bearing formations are encountered.

COMPONENTS OF A WELL

The components that make up a well system include the well itself, the building and the pump, and the related piping system. In this section, we focus on the components that make up the well itself. Many of these components are shown in Figure 2.6.

WELL CASING

A well is a hole in the ground called the borehole. The hole is protected from collapse by placing a casing inside it. The well casing prevents the walls of the hole from collapsing and prevents contaminants (either surface or subsurface) from entering the water source. The casing also provides a column of stored water and housing for the pump mechanisms and pipes. Well casings constructed of steel or plastic material are acceptable. The well casing must extend a minimum of 12 in. above grade.

GROUT

To protect the aquifer from contamination, the casing is sealed to the borehole near the surface and near the bottom where it passes into the impermeable layer with grout. This sealing process keeps the well from being polluted by surface water and seals out water from water-bearing strata that have undesirable water quality. Sealing also protects the casing from external corrosion and restrains unstable soil and rock formations.

Grout consists of near cement that is pumped into the annular space (it is completed within 48 h of well construction). It is pumped under continuous pressure starting at the bottom and progressing upward in one continuous operation.

WELL PAD

The well pad provides a ground seal around the casing. The pad is constructed of reinforced concrete 6 ft × 6 ft (6 in. thick) with the wellhead located in the middle. The well pad prevents contaminants from collecting around the well and seeping down into the ground along the casing.

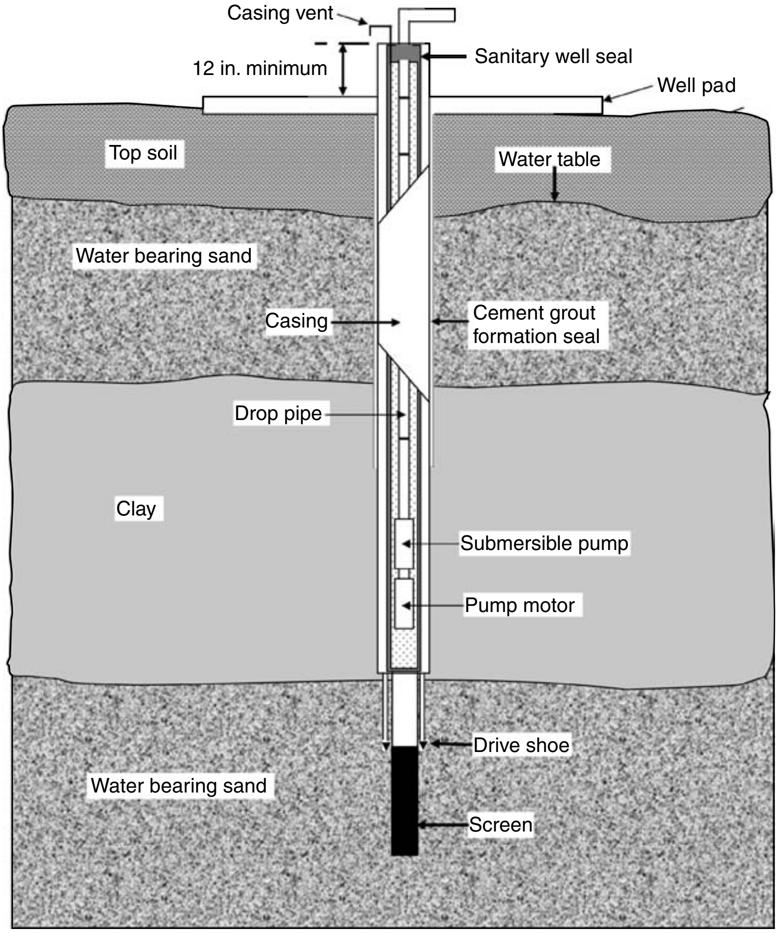

FIGURE 2.6 Components of a well.

SANITARY SEAL

To prevent contamination of the well, a sanitary seal is placed at the top of the casing. The type of seal varies depending upon the type of pump used. The sanitary seal contains openings for power and control wires, pump support cables, a drawdown gauge, discharge piping, pump shaft, and air vent, while providing a tight seal around them.

WELL SCREEN

Screens can be installed at the intake point(s) on the end of a well casing or on the end of the inner casing on gravel-packed well. These screens perform two functions: (1) supporting the borehole and (2) reducing the amount of sand that enters the casing and the pump. They are sized to allow the maximum amount of water while preventing the passage of sand/sediment/gravel.

CASING VENT

The well casing must have a vent to allow air into the casing as the water level drops. The vent terminates 18 in. above the floor with a return bend pointing downward. The opening of the vent must be screened with no. 24 mesh of stainless steel to prevent entry of vermin and dust.

DROP PIPE

The drop pipe or riser is the line leading from the pump to the wellhead. It ensures adequate support so that an aboveground pump does not move and a submersible pump is not lost down the well. This pipe is either made of steel or PVC. Steel is the most desirable.

MISCELLANEOUS WELL COMPONENTS

These include:

Gauge and air line Measures the water level of the well.

Check valve Located immediately after the well. It prevents system water from returning to the well. It must be located above the ground and be protected from freezing.

Flowmeter Required to monitor the total amount of water withdrawn from the well, including any water blown off.

Control switches Controls for well pump operation.

Blowoff Valved and located between the well and the storage tank; used to flush the well of sediment or turbid or super-chlorinated water.

Sample taps (a) Raw water sample tap—located before any storage or treatment to permit sampling of the water directly from the well. (b) Entry point sample tap—located after treatment.

Control valves Isolates the well for testing or maintenance or used to control water flow.

WELL EVALUATION

After a well is developed, a pump test must be conducted to determine if the well can supply the required amount of water. The well is generally pumped for at least 6 h (many states require a 48-h yield and drawdown test) at a rate equal to or greater than the desired yield.

Yield is the volume or quantity of water per unit of time discharged from a well (GPM, ft^3/sec). Regulations usually require that a well produce a minimum of 0.5 gal/min/residential connection.

Drawdown is the difference between the static water level (level of the water in the well when it has not been used for some time and has stabilized) and the pumping water level in a well. Drawdown is measured by using an airline and pressure gauge to monitor the water level during the 48 h of pumping.

The procedure calls for the airline to be suspended inside the casing down into the water. At the other end are the pressure gauge and a small pump. Air is pumped into the line (displacing the water) until the pressure stops increasing. The gauge's highest-pressure reading is recorded.

During the 48 h of pumping, the yield and drawdown are monitored more frequently during the beginning of the testing period because the most dramatic changes in flow and water level usually occur then.

The original static level should be recovered within 24 h after pumping stops.

Testing is accomplished on a bacteriological sample for analysis by the MPN method every half hour during the last 10 h of testing. The results are used to determine if chlorination is required or if chlorination alone will be sufficient to treat the water. Chemical, physical, and radiological samples are collected for analyses at the end of the test period to determine if treatment other than chlorination may be required.

√ **Note:** Recovery from the well should be monitored at the same frequency as during the yield and drawdown testing and for at least the first 8 h, or until 90% of the observed drawdown is obtained.

Specific capacity (often called productivity index) is a test method for determining the relative adequacy of a well, and over a period of time is a valuable tool in evaluating the well production. Specific capacity is expressed as a measure of well yield per unit of drawdown (yield divided by drawdown). When conducting this test, if possible, always run the pump for the same length of time and at the same pump rate.

WELL PUMPS

Pumps are used to move the water out of the well and deliver it to the storage tank/distribution system. The type of pump chosen for use should provide optimum performance based on location and operating conditions, required capacity, and total head.

Two types of pumps commonly installed in groundwater systems are lineshaft turbines and submersible turbines. Regardless of the type of pump used, pumps are rated on the basis of the pumping capacity expressed in gpm (e.g., 40 gal/min) and not on horsepower.

ROUTINE OPERATION AND RECORDKEEPING REQUIREMENTS

Ensuring the proper operation of a well requires close monitoring; wells should be visited regularly. During routine monitoring visits, check for any unusual sounds in the pump, line, or valves, and for any leaks. In addition, cycle valves routinely to ensure good working condition. Check motors to make sure they are not overheating. Check the well pump to guard against short cycling. Collect a water sample for a visual check for sediment. Also, check chlorine residual and treatment equipment. Measure gallons on the installed meter for 1 min to obtain pump rate in gpm (look for gradual trends or big changes). Check water level in the well at least monthly (maybe more often in summer or during periods of low rainfall). Finally, from recorded meter readings, determine gallons used and compare with the water consumed to determine possible distribution system leaks.

Along with meter readings, other records must be accurately and consistently maintained for water supply wells. This record keeping is absolutely imperative. The records (an important resource for troubleshooting) can be useful when problems develop or helpful in identifying potential problems. A properly operated and managed waterworks facility keeps the following records of well operation.

WELL LOG

The well log provides documentation of what materials were found in the borehole and at what depth. It also includes the depths at which water was found, the casing length and type, what type of soils were found at which depth, testing procedure, well development techniques, and well production. In general, the following items should be included in the well log:

1. Well location
2. Who drilled the well?
3. When the well was completed
4. Well class
5. Total depth to bedrock
6. Hole and casing size
7. Casing material and thickness
8. Screen size and locations
9. Grout depth and type
10. Yield and drawdown (test results)
11. Pump information (type, HP, capacity, intake depth, and model number)
12. Geology of the hole
13. A record of yield and drawdown data

WELL MAINTENANCE

Wells do not have an infinite life, and their output is likely to reduce with time as a result of hydrological and mechanical factors.

Protecting the well from possible contamination is an important consideration. If proper well location (based on knowledge of the local geological conditions and a vulnerability assessment of the area) is maintained, potential problems can be minimized.

During the initial assessment, it is important to ensure that the well is not located in a sinkhole area. A determination of where unconsolidated or bedrock aquifers may be subject to contamination must be made. Several other important determinations must be made. Is the well located on a floodplain? Is it located next to a drainfield for septic systems or near a landfill? Are petroleum/gasoline storage tanks nearby? Is pesticide/plastic manufacturing conducted near the well site?

Along with proper well location, proper well design and construction prevent wells from acting as conduits for vertical migration of contaminants into the groundwater. Basically, the pollution potential of a well equals how well it was constructed. Contamination can occur during the drilling process, and an unsealed or unfinished well is an avenue for contamination. Any opening in the sanitary seal or break in the casing may cause contamination, as can reversal of water flow.

In routine well maintenance operations, corroded casing or screens are sometimes withdrawn and replaced but this is difficult and not always successful. Simply constructing a new well may be cheaper.

WELL ABANDONMENT

In the past, the common practice was simply to walk away and forget about a well when it ran dry. Today, while dry or failing wells are still abandoned, we know that they must be abandoned with care (and not completely forgotten). An abandoned well can become a convenient (and dangerous) receptacle for wastes, thus contaminating the aquifer. An improperly abandoned well could also become a haven for vermin, or worse, a hazard for children.

A temporarily abandoned well must be sealed with a watertight cap or wellhead seal. The well must be maintained so that it does not become a source or channel of contamination during temporary abandonment.

When a well is permanently abandoned all casing and screen materials may be salvaged. The well should be checked from top to bottom to assure that no obstructions interfere with plugging/sealing operations. Prior to plugging, the well should be thoroughly chlorinated. Bored wells should be completely filled with cement grout. If the well was constructed in an unconsolidated formation, it should be completely filled with cement grout or clay slurry introduced through a pipe that initially extends to the bottom of the well. As the pipe is raised, it should remain submerged in the top layers of grout as the well is filled.

Wells constructed in consolidated rock or those that penetrate zones of consolidated rock can be filled with sand or gravel opposite zones of consolidated rock. The sand or gravel fill is terminated 5 ft below the top of the consolidated rock. The remainder of the well is filled with sand–cement grout.

WATER USE

In the United States, rainfall averages approximately 4250×10^9 gal/d. About two thirds of this returns to the atmosphere through evaporation directly from the surface of rivers, streams, and lakes and transpiration from plant foliage. This leaves approximately 1250×10^9 gal/d to flow across or through the Earth to the sea.

USGA (2004) points out that estimates in the United States indicate that about 408 billion gal/d (one thousand million gallons per day, abbreviated Bgal/d) were withdrawn from all uses during

2000. This total has varied less than 3% since 1985 as withdrawals have stabilized for the two largest uses—thermoelectric power and irrigation. Fresh groundwater withdrawals (83.3 Bgal/d) during 2000 were 14% more than during 1985. Fresh surface-water withdrawals in 2000 were 262 Bgal/d, varying less than 2% since 1985.

About 195 Bgal/d, or 8% of all freshwater and saline-water withdrawals in 2000 were used for thermoelectric power. Most of this water was derived from surface water and used for once-through cooling at power plants. About 52% of fresh surface-water withdrawals and about 96% of saline-water withdrawals were for thermoelectric-power use. Withdrawals for thermoelectric power have been relatively stable since 1985.

Irrigation remained the largest use of fresh water in the United States and totaled 137 Bgal/d in 2000. Since 1950, irrigation has accounted for about 65% of total water withdrawals, excluding those for thermoelectric power. Historically, more surface water than groundwater has been used for irrigation. However, the percentage of total irrigation withdrawals from groundwater has continued to increase, from 23% in 1950 to 42% in 2000. Total irrigation withdrawals were 2% more in 2000 than in 1995 because of a 16% increase in groundwater withdrawals and a small decrease in surface-water withdrawals. Irrigated acreage more than doubled between 1950 and 1980, then remained constant before increasing nearly 7% between 1995 and 2000. The number of acres irrigated with sprinkler and microirrigation systems has continued to increase and now comprises more than one half the total irrigated acreage.

Public-supply withdrawals were more than 43 Bgal/d in 2000. Public-supply withdrawals during 1950 were 14 Bgal/d. During 2000, about 85% of the population in the United States obtained drinking water from public suppliers, compared to 62% during 1950. Surface water provided 63% of the total during 2000, whereas surface water provided 74% during 1950.

Self-supplied industrial withdrawals totaled nearly 20 Bgal/d in 2000, or 12% less than in 1995. Compared to 1985, industrial self-supported withdrawals declined by 24%. Estimates of industrial water use in the United State were largest during the years 1965–1980. But during 2000, estimates were at the lowest level since reporting began in 1950. Combined withdrawals for self-supplied domestic, livestock, aquaculture, and mining were less than 13 Bgal/d in 2000, and represented about 3% of total withdrawals.

California, Texas, and Florida accounted for one quarter of all water withdrawals in 2000. States with the largest surface-water withdrawals were California, which has large withdrawals for irrigation and thermoelectric power, and Texas and Nebraska, all of which had large withdrawals for irrigation.

In this text, the primary concern with water use is with regard to municipal applications (demand). Municipal water demand is usually classified according to the nature of the user. These classifications are:

1. *Domestic*: Domestic water is supplied to houses, schools, hospitals, hotels, restaurants, etc. for culinary, sanitary, and other purposes. Use varies with the economic level of the consumer, the range being 20–100 gal/capita/d. It should be pointed out that these figures include water used for watering gardens and lawns, and for washing cars.
2. *Commercial and industrial*: Commercial and industrial water is supplied to stores, offices, and factories. The importance of commercial and industrial demand is based, of course, on whether there are large industries that use water supplied from the municipal system. These large industries demand a quantity of water directly related to the number of persons employed, to the actual floor space or area of each establishment, and to the number of units manufactured or produced. Industry in the United States uses an average of 150 Bgal/d of water.
3. *Public use*: Public use water is the water furnished to public buildings and used for public services. This includes water for schools, public buildings, fire protection, and for flushing streets.

4. *Loss and waste*: Water that is lost or wasted (i.e., unaccounted for) is attributable to leaks in the distribution system, inaccurate meter readings, and for unauthorized connections. Loss and waste of water can be expensive. To reduce loss and waste a regular program that includes maintenance of the system and replacement or recalibration of meters is required (McGhee, 1991).

REFERENCES

Angele, F.J., Sr., 1974. *Cross Connections and Backflow Protection*, 2nd ed. Denver: American Water Association.

Jones, F.E., 1992. *Evaporation of Water.* Chelsea, MI: Lewis Publishers.

McGhee, T.J., 1991. *Water Supply and Sewerage*, 6th ed. New York: McGraw-Hill.

Meyer, W.B., 1996. *Human Impact on Earth*. New York: Cambridge University Press.

Spellman, F.R., 2003. *Handbook of Water and Wastewater Treatment Plant Operations*. Boca Raton, FL: Lewis Publishers.

Turk, J. and Turk, A., 1988. *Environmental Science*, 4th ed. Philadelphia: Saunders College Publishing.

USGS, 2006. *Water Science in Schools.* Washington, DC: U.S. Geological Survey.

Viessman, W., Jr., 1991. Water management issues for the nineties. *Water Resources Bulletin*, 26(6):883–981.

FURTHER READING

Lewis, S.A., 1996. *The Sierra Club Guide to Safe Drinking Water.* San Francisco: Sierra Club Books.

Peavy, H.S. et al., 1985. *Environmental Engineering.* New York: McGraw-Hill.

Pielou, E.C., 1998. *Fresh Water.* Chicago: University of Chicago Press.

Powell, J.W., 1904. *Twenty-Second Annual Report of the Bureau of American Ethnology to the Secretary of the Smithsonian Institution, 1900–1901.* Washington, DC: Government Printing Office.

USEPA, 2006. *Watersheds.* Accessed 12/06@http://www.epa.gov/owow/watershed/whatis.html.

USGS, 2004. *Estimated Use of Water in the United States in 2000.* Washington, DC: U.S. Geological Survey.

Running water. White Oak Canyon Trail, Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

3 Water Hydraulics

> Anyone who has tasted natural spring water knows that it is different from city water, which is used over and over again, passing from mouth to laboratory and back to mouth again, without ever being allowed to touch the earth. We need to practice such economics these days, but in several thirsty countries, there are now experts in hydrodynamics who are trying to solve the problem by designing flowforms that copy the earth, producing rhythmic and spiral motions in moving water. And these pulsations do seem to vitalize and energize the liquid in some way, changing its experience, making it taste different and produce better crops.
>
> **—L. Watson (1988)**

√ **Important Point:** The practice and study of water hydraulics are not new. Even in medieval times, water hydraulics was not new. "Medieval Europe had inherited a highly developed range of Roman hydraulic components" (Magnusson, 2001). The basic conveyance technology, based on low-pressure systems of pipe and channels, was already established. In studying "modern" water hydraulics, it is important to remember, as Magnusson puts it, that the science of water hydraulics is the direct result of two immediate and enduring problems: "The acquisition of freshwater and access to continuous strip of land with a suitable gradient between the source and the destination."

TERMINOLOGY

- *Friction head*—The energy needed to overcome friction in the piping system. It is expressed in terms of the added system head required.
- *Head*—The equivalent distance water must be lifted to move from the supply tank or inlet to the discharge. Head can be divided into three components: *static head, velocity head*, and *friction head.*
- *Pressure*—The force exerted per square unit of surface area. May be expressed in pounds per square inch.
- *Static head*—The actual vertical distance from the system inlet to the highest discharge point.
- *Total dynamic head*—The total of the static head, friction head, and velocity head.
- *Velocity*—The speed of a liquid moving through a pipe, channel, or tank. May be expressed in feet per second.
- *Velocity head*—The energy needed to keep the liquid moving at a given velocity. It is expressed in terms of the added system head required.

WHAT IS WATER HYDRAULICS?

The word "hydraulic" is derived from the Greek words *hydro* (meaning water) and *aulis* (meaning pipe). Originally, the term referred only to the study of water at rest and in motion (flow of water in pipes or channels). Today, it means the flow of *any* "liquid" in a system.

What is a liquid? In terms of hydraulics, a liquid can be either oil or water. In fluid power systems used in modern industrial equipment, the hydraulic liquid of choice is oil. Some common examples of hydraulic fluid power systems include automobile braking and power steering systems, hydraulic elevators, and hydraulic jacks or lifts. Probably the most familiar hydraulic fluid power systems in water/wastewater operations are used in dump trucks, front-end loaders, graders, and earth-moving and excavations equipment. In this text, we are concerned with liquid water.

Many find the study of water hydraulics difficult and puzzling; however, it is not mysterious or difficult. It is the function or output of practical applications of the basic principles of water physics.

BASIC CONCEPTS

Air pressure (at sea level) = 14.7 pounds per square inch (psi)

The relationship shown above is important because our study of hydraulics begins with air. A blanket of air, many miles thick, surrounds the Earth. The weight of this blanket on a given square inch of the Earth's surface will vary according to the thickness of the atmospheric blanket above that point. As shown above, at sea level, the pressure exerted is 14.7 pounds per square inch (psi). On a mountaintop, air pressure decreases because the blanket is not as thick.

$$1 \text{ ft}^3 \text{ H}_2\text{O} = 62.4 \text{ lb}$$

The relationship shown above is also important: both cubic feet and pounds are used to describe the volume of water. There is a defined relationship between these two methods of measurement. The specific weight of water is defined relative to a cubic foot. One cubic foot of water weighs 62.4 lb. This relationship is true only at a temperature of 4°C and at a pressure of 1 atmosphere (known as standard temperature and pressure [STP]—14.7 psi at sea level containing 7.48 gallons [gal]). The weight varies so little that, for practical purposes, this weight is used for a temperature from 0 to 100°C. One cubic inch of water weighs 0.0362 lb. Water 1 ft deep will exert a pressure of 0.43 psi on the bottom area (12 in. × 0.0362 lb/in.^{3}). A column of water 2 ft high exerts 0.86 psi, 10 ft high exerts 4.3 psi, and 55 ft high exerts

$$55 \text{ ft} \times 0.43 \text{ psi/ft} = 23.65 \text{ psi}$$

A column of water 2.31 ft high will exert 1.0 psi. To produce a pressure of 50 psi requires a water column of

$$50 \text{ psi} \times 2.31 \text{ ft/psi} = 115.5 \text{ ft}$$

√ **Remember:** The important points being made here are

1. 1 ft^3 H_2O = 62.4 lb (see Figure 3.1).
2. A column of water 2.31 ft high will exert 1.0 psi.

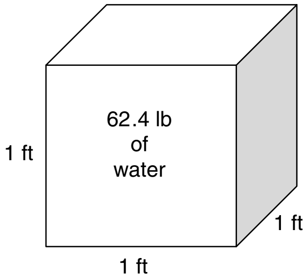

FIGURE 3.1 One cubic foot of water weighs 62.4 lb.

Another relationship is also important:

$$1 \text{ gal } H_2O = 8.34 \text{ lb}$$

At STP, 1 ft^3 of water contains 7.48 gal. With these two relationships, we can determine the weight of 1 gal of water. This is accomplished by

$$\text{Wt. of gallon of water} = \frac{62.4 \text{ lb}}{7.48 \text{ gal}} = 8.34 \text{ lb/gal}$$

Thus,

$$1 \text{ gal } H_2O = 8.34 \text{ lb}$$

√ **Important Point:** Further, this information allows cubic feet to be converted into gallons by simply multiplying the number of cubic feet by 7.48 gal/ft^3.

EXAMPLE 3.1

Problem:

Find the number of gallons in a reservoir that has a volume of 855.5 ft^3.

Solution:

$$855.5 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 6399 \text{ gal (rounded)}$$

√ **Important Point:** The term *head* is used to designate water pressure in terms of the height of a column of water in feet. For example, a 10-ft column of water exerts 4.3 psi. This can be called 4.3-psi pressure or 10 ft of head.

STEVIN'S LAW

Stevin's law deals with water at rest. Specifically, it states: "The pressure at any point in a fluid at rest depends on the distance measured vertically to the free surface and the density of the fluid." Stated as a formula, this becomes

$$p = wh \tag{3.1}$$

where
p = Pressure in pounds per square foot, psf
w = Density in pounds per cubic foot, lb/ft^3
h = Vertical distance in feet

EXAMPLE 3.2

Problem:

What is the pressure at a point 18 ft below the surface of a reservoir?

Solution:

√ **Note:** To calculate this, we must know that the density of the water, w, is 62.4 lb/ft^3.

$$\begin{aligned} p &= wh \\ &= 62.4\ \text{lb/ft}^3 \times 18\ \text{ft} \\ &= 1123\ \text{lb/ft}^2 \text{ or } 1123\ \text{psf} \end{aligned}$$

Waterworks operators generally measure pressure in pounds per square *inch* rather than pounds per square *foot*; to convert, divide by 144 in.^{2}/ft^2 (12 in. × 12 in. = 144 in.^{2}):

$$P = \frac{1123\ \text{psf}}{144\ \text{in.}^2/\text{ft}} = 7.8\ \text{lb/in.}^2 \text{ or psi (rounded)}$$

PROPERTIES OF WATER

Table 3.1 shows the relationship between temperature, specific weight, and density of water.

DENSITY AND SPECIFIC GRAVITY

When it is said that iron is heavier than aluminum, it means that iron has greater density than aluminum. In practice, what is really being said is that a given volume of iron is heavier than the same volume of aluminum.

√ **Important Point:** What is density? *Density* is the *mass per unit volume* of a substance.

Suppose you had a tub of lard and a large box of cold cereal, each having a mass of 600 g. The density of the cereal would be much less than the density of the lard because the cereal occupies a much larger volume than the lard occupies.

The density of an object can be calculated by using the formula:

$$\text{Density} = \frac{\text{mass}}{\text{volume}} \tag{3.2}$$

In water treatment operations, perhaps the most common measures of density are pounds per cubic foot (lb/ft^3) and pounds per gallon (lb/gal).

TABLE 3.1
Water Properties (temperature, specific weight, and density)

Temperature (°F)	Specific Weight (lb/ft^3)	Density (slugs/ft^3)	Temperature (°F)	Specific Weight (lb/ft^3)	Density (slugs/ft^3)
32	62.4	1.94	130	61.5	1.91
40	62.4	1.94	140	61.4	1.91
50	62.4	1.94	150	61.2	1.90
60	62.4	1.94	160	61.0	1.90
70	62.3	1.94	170	60.8	1.89
80	62.2	1.93	180	60.6	1.88
90	62.1	1.93	190	60.4	1.88
100	62.0	1.93	200	60.1	1.87
110	61.9	1.92	210	59.8	1.86
120	61.7	1.92			

- 1 ft^3 of water weighs 62.4 lb—density = 62.4 lb/ft^3
- 1 gal of water weighs 8.34 lb—density = 8.34 lb/gal

The density of a dry material, such as cereal, lime, soda, and sand, is usually expressed in pounds per cubic foot. The density of a liquid, such as liquid alum, liquid chlorine, or water, can be expressed either as pounds per cubic foot or as pounds per gallon. The density of a gas, such as chlorine gas, methane, carbon dioxide, or air, is usually expressed in pounds per cubic foot.

As shown in Table 3.1, the density of a substance like water changes slightly as the temperature of the substance changes. This occurs because substances usually increase in volume (size—they expand) as they become warmer. Because of this expansion due to warming, the same weight is spread over a larger volume, so the density is low when a substance is warm compared to when it is cold.

√ **Important Point:** What is specific gravity? *Specific gravity is the weight (or density) of a substance compared to the weight (or density) of an equal volume of water.* (Note: The specific gravity of water is 1.)

This relationship is easily seen when 1 ft^3 of water, which weighs 62.4 lb as shown earlier, is compared to 1 ft^3 of aluminum, which weighs 178 lb. Aluminum is 2.7 times as heavy as water.

It is not that difficult to find the specific gravity of a piece of metal. All you have to do is to weigh the metal in air, then weigh it under water. Its loss of weight is the weight of an equal volume of water. To find the specific gravity, divide the weight of the metal by its loss of weight in water.

$$\text{Specific gravity} = \frac{\text{weight of a substance}}{\text{weight of equal volume of water}} \tag{3.3}$$

Example 3.3

Problem:

Suppose a piece of metal weighs 150 lb in air and 85 lb under water. What is the specific gravity?

Solution:

Step 1: (150–85) lb = 65 lb loss of weight in water.

Step 2: $\text{Specific gravity} = \frac{150}{65} = 2.3$

√ **Important Point:** In a calculation of specific gravity, it is *essential* that the densities be expressed in the same units.

As stated earlier, the specific gravity of water is 1, which is the standard, the reference to which all other liquid or solid substances are compared. Specifically, any object that has a specific gravity >1 will sink in water (rocks, steel, iron, grit, floc, sludge). Substances with a specific gravity <1 will float (wood, scum, gasoline). Considering the total weight and volume of a ship, its specific gravity is <1; therefore, it can float.

The most common use of specific gravity in water treatment operations is in gallons-to-pounds conversions. In many cases, the liquids being handled have a specific gravity of 1.00 or very nearly 1.00 (between 0.98 and 1.02), so 1.00 may be used in the calculations without introducing significant error. However, in calculations involving a liquid with a specific gravity <0.98 or >1.02, the conversions from gallons to pounds must consider specific gravity. The technique is illustrated in the following example.

EXAMPLE 3.4

Problem:

There are 1455 gal of a certain liquid in a basin. If the specific gravity of the liquid is 0.94, how many pounds of liquid are in the basin?

Solution:

Normally, for a conversion from gallons to pounds, we would use the factor 8.34 lb/gal (the density of water) if the substance's specific gravity was between 0.98 and 1.02. However, in this instance, the substance has a specific gravity outside this range, so the 8.34 factor must be adjusted.

Step 1: Multiply 8.34 lb/gal by the specific gravity to obtain the adjusted factor:

$$8.34\text{ lb/gal} \times 0.94 = 7.84\text{ lb/gal (rounded)}$$

Step 2: Then convert 1455 gal into pounds using the corrected factor:

$$(1455\text{ gal})(7.84\text{ lb/gal}) = 11{,}407\text{ lb (rounded)}$$

FORCE AND PRESSURE

Water exerts force and pressure against the walls of its container, whether it is stored in a tank or flowing in a pipeline. There is a difference between force and pressure, though they are closely related. Force and pressure are defined below.

Force is the push or pull influence that causes motion. In the English system, force and weight are often used in the same way. The weight of 1 ft^3 of water is 62.4 lb. The force exerted on the bottom of a 1-ft cube is 62.4 lb (see Figure 3.1). If we stack two cubes on top of each other, the force on the bottom will be 124.8 lb.

Pressure is a force per unit of area. In equation form, this can be expressed as:

$$P = \frac{F}{A} \tag{3.4}$$

where
P = pressure
F = force
A = area over which the force is distributed

As mentioned, pounds per square inch or pounds per square foot are common expressions of pressure. The pressure on the bottom of the cube is 62.4 lb/ft^2 (see Figure 3.1). It is common to express pressure in pounds per square inch. This is easily accomplished by determining the weight of 1 in.^2 of a cube 1 ft high. If we have a cube that is 12 in. on each side, the number of square inches on the bottom surface of the cube is $12 \times 12 = 144\text{ in.}^2$ Dividing the weight by the number of square inches determines the weight on each square inch:

$$\text{psi} = \frac{62.4\text{ lb/ft}}{144\text{ in.}^2} = 0.433\text{ psi/ft}$$

This is the weight of a 1-in.^2 and 1-ft-tall column of water. If the column of water were 2 ft tall, the pressure would be 2 ft × 0.433 psi/ft = 0.866.

√ **Important Point:** 1 ft of water = 0.433 psi.

With the above information, feet of head can be converted into pounds per square inch by multiplying the feet of head times 0.433 psi/ft.

Example 3.5

Problem:

A tank is mounted at a height of 90 ft. Find the pressure at the bottom of the tank.

Solution:

$$90\,\text{ft} \times 0.433\,\text{psi/ft} = 39\,\text{psi (rounded)}$$

√ **Note:** To convert pounds per square inch into feet, you would divide the pounds per square inch by 0.433 psi/ft.

Example 3.6

Problem:

Find the height of water in a tank if the pressure at the bottom of the tank is 22 psi.

Solution:

$$\text{Height (ft)} = \frac{22\,\text{psi}}{0.433\,\text{psi/ft}} = 51\,\text{ft (rounded)}$$

√ **Important Point:** One of the problems encountered in a hydraulic system is storing the liquid. Unlike air, which is readily compressible and is capable of being stored in large quantities in relatively small containers, a liquid such as water cannot be compressed. Therefore, it is not possible to store a large amount of water in a small tank—62.4 lb of water occupies a volume of 1 ft^3, regardless of the pressure applied to it.

HYDROSTATIC PRESSURE

Figure 3.2 shows a number of differently shaped, connected, open containers of water. Note that the water level is the same in each container, regardless of the shape or size of the container. This occurs because pressure is developed, within water (or any other liquid), by the weight of the water above. If the water level in any one container were to be momentarily higher than that in any of the other

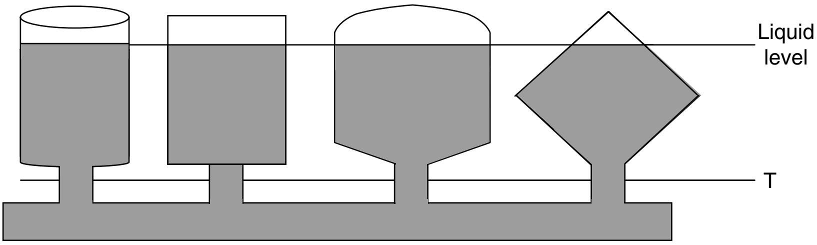

FIGURE 3.2 Hydrostatic pressure.

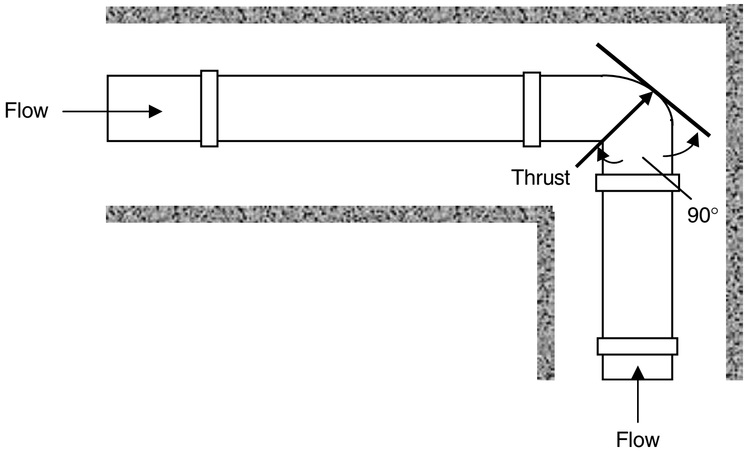

FIGURE 3.3 Shows direction of thrust in a pipe in a trench (viewed from above).

containers, the higher pressure at the bottom of this container would cause some water to flow into the container having the lower liquid level. In addition, the pressure of the water at any level (such as Line T) is the same in each of the containers. Pressure increases because of the weight of the water. The farther down from the surface, the greater the pressure created. This illustrates that the *weight*, not the volume, of water contained in a vessel determines the pressure at the bottom of the vessel.

Nathanson (1997) points out some very important principles that always apply for hydrostatic pressure.

1. The pressure depends only on the depth of water above the point in question (not on the water surface area).
2. The pressure increases in direct proportion to the depth.
3. The pressure in a continuous volume of water is the same at all points that are at the same depth.
4. The pressure at any point in the water acts in all directions at the same depth.

EFFECTS OF WATER UNDER PRESSURE*

According to Hauser (1993), water under pressure and in motion can exert tremendous forces inside a pipeline. One of these forces, called hydraulic shock or *water hammer*, is the momentary increase in pressure that occurs when there is a sudden change of direction or velocity of the water.

When a rapidly closing valve suddenly stops water flowing in a pipeline, pressure energy is transferred to the valve and pipe wall. Shock waves are set up within the system. Waves of pressure move in horizontal yo-yo fashion—back and forth—against any solid obstacles in the system. Neither the water nor the pipe will compress to absorb the shock, which may result in damage to pipes, valves, and shaking of loose fittings.

Another effect of water under pressure is called thrust. *Thrust* is the force that water exerts on a pipeline as it rounds a bend. As shown in Figure 3.3, thrust usually acts perpendicular (at 90°) to the inside surface it pushes against. As stated, it affects bends, but also reducers, dead ends, and tees. Uncontrolled, the thrust can cause movement in the fitting or pipeline, which will lead to separation of the pipe coupling away from both sections of pipeline, or at some other nearby coupling upstream or downstream of the fitting.

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* This section is adapted from Hauser, B.A. (1993), *Hydraulics for Operators*, Lewis Publishers, Boca Raton, FL, pp. 16–18, and American Water Works Association (1995), *Basic Science Concepts and Applications: Principles and Practices of Water Supply Operations*, 2nd ed., American Water Works Association, Denver, pp. 351–353.

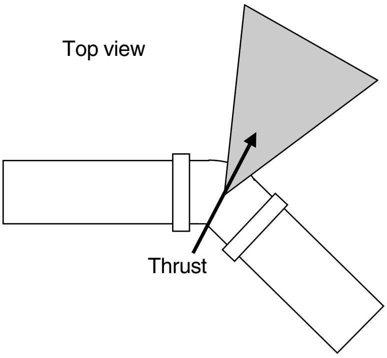

FIGURE 3.4 Thrust block.

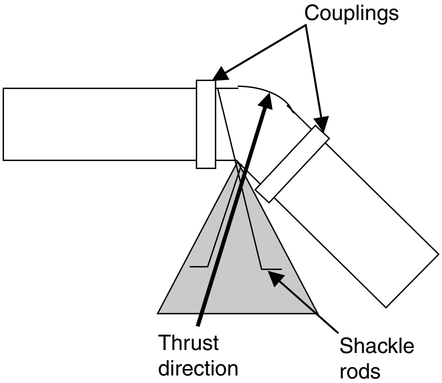

FIGURE 3.5 Thrust anchor.

There are two types of devices commonly used to control thrust in larger pipelines: thrust blocks and thrust anchors. A *thrust block* is a mass of concrete cast in place onto the pipe and around the outside bend of the turn. An example is shown in Figure 3.4. These are used for pipes with tees or elbows that turn left or right or slant upward. The thrust is transferred to the soil through the larger bearing surface of the block.

A *thrust anchor* is a massive block of concrete, often a cube, cast in place below the fitting to be anchored (see Figure 3.5). As shown in Figure 3.5, imbedded steel shackle rods anchor the fitting to the concrete block, effectively resisting upward thrusts.

The size and shape of a thrust control device depends on pipe size, type of fitting, water pressure, water hammer, and soil type.

HEAD

Head is defined as the vertical distance through which water must be lifted from the supply tank to the discharge, or as the height a column of water would rise due to the pressure at its base. A perfect vacuum plus atmospheric pressure of 14.7 psi would lift the water 34 ft. If the top of the sealed tube is opened to the atmosphere and the reservoir is enclosed, the pressure in the reservoir is increased; the water will rise in the tube. Because atmospheric pressure is essentially universal, we usually ignore the first 14.7 psi of actual pressure measurements and measure only the difference between the water pressure and the atmospheric pressure; we call this *gauge pressure*. For example, water in an open reservoir is subjected to the 14.7 psi of atmospheric pressure, but subtracting this

14.7 psi leaves a gauge pressure of 0 psi. This shows that the water would rise 0 ft above the reservoir surface. If the gauge pressure in a water main were 120 psi, the water would rise in a tube connected to the main:

$$120\ \text{psi} \times 2.31\ \text{ft/psi} = 277\ \text{ft}\ \ \text{(rounded)}$$

The *total head* includes the vertical distance through which the liquid must be lifted (static head), the loss to friction (friction head), and the energy required to maintain the desired velocity (velocity head).

$$\text{Total head} = \text{static head} + \text{friction head} + \text{velocity head} \tag{3.5}$$

STATIC HEAD

Static head is the actual *vertical* distance the liquid must be lifted.

$$\text{Static head} = \text{discharge elevation} - \text{supply elevation} \tag{3.6}$$

EXAMPLE 3.7

Problem:

The supply tank is located at an elevation of 118 ft. The discharge point is at an elevation of 215 ft. What is the static head in feet?

Solution:

$$\text{Static head (ft)} = 215\ \text{ft} - 118\ \text{ft} = 97\ \text{ft}$$

FRICTION HEAD

Friction head is the equivalent distance of the energy that must be supplied to overcome friction. Engineering references include tables showing the equivalent vertical distance for various sizes and types of pipes, fittings, and valves. The total friction head is the sum of the equivalent vertical distances for each component.

$$\text{Friction head (ft)} = \text{energy loss due to friction} \tag{3.7}$$

VELOCITY HEAD

Velocity head is the equivalent distance of the energy consumed in achieving and maintaining the desired velocity in the system.

$$\text{Velocity head (ft)} = \text{energy loss to maintain velocity} \tag{3.8}$$

TOTAL DYNAMIC HEAD (TOTAL SYSTEM HEAD)

$$\text{Total head} = \text{static head} + \text{friction head} + \text{velocity head} \tag{3.9}$$

PRESSURE/HEAD

The pressure exerted by water/wastewater is directly proportional to its depth or head in the pipe, tank, or channel. If the pressure is known, the equivalent head can be calculated.

$$\text{Head (ft)} = \text{pressure (psi)} \times 2.31\ \text{ft/psi} \tag{3.10}$$

EXAMPLE 3.8

Problem:

The pressure gauge on the discharge line from the influent pump reads 72.3 psi. What is the equivalent head in feet?

Solution:

$$\text{Head (ft)} = 72.3 \times 2.31 \text{ ft/psi} = 167 \text{ ft}$$

HEAD/PRESSURE

If the head is known, the equivalent pressure can be calculated by

$$\text{Pressure (psi)} = \frac{\text{head (ft)}}{2.31 \text{ ft/psi}} \tag{3.11}$$

EXAMPLE 3.9

Problem:

The tank is 22 ft deep. What is the pressure in pounds per square inch at the bottom of the tank when it is filled with water?

Solution:

$$\text{Pressure (psi)} = \frac{22 \text{ ft}}{2.31 \text{ ft/psi}} = 9.52 \text{ psi (rounded)}$$

FLOW/DISCHARGE RATE: WATER IN MOTION

The study of fluid flow is much more complicated than that of fluids at rest, but it is important to have an understanding of these principles because the water in a waterworks system is nearly always in motion.

Discharge (or flow) is the quantity of water passing a given point in a pipe or channel during a given period. Stated another way for open channels: The flow rate through an open channel is directly related to the velocity of the liquid and the cross-sectional area of the liquid in the channel.

$$Q = AV \tag{3.12}$$

where

Q = flow—discharge in cubic feet per second, cfs
A = cross-sectional area of the pipe or channel, ft^2
V = water velocity in feet per second, fps or ft/s

EXAMPLE 3.10

Problem:

The channel is 6 ft wide and the water depth is 3 ft. The velocity in the channel is 4 ft/s. What is the discharge or flow rate in cubic feet per second?

Solution:

$$\text{Flow (cfs)} = 6\,\text{ft} \times 3\,\text{ft} \times 4\,\text{ft/s} = 72\,\text{cfs}$$

Discharge or flow can be recorded as gallons per day (gpd), gallons per minute (gpm), or cubic feet per second. Flows treated by many waterworks plants are large and often referred to in million gallons per day (MGD). The discharge or flow rate can be converted from cfs to other units such as gallons per minute or million gallons per day by using appropriate conversion factors.

EXAMPLE 3.11

Problem:

A pipe, 12 in. in diameter, has water flowing through it at 10 ft/s. What is the discharge in (a) cubic feet per second; (b) gallons per minute; and (c) million gallons per day?

Solution:

Before we can use the basic formula (3.13), we must determine the area A of the pipe. The formula for the area of a circle is

$$A = \pi \frac{D^2}{4} = \pi r^2 \tag{3.13}$$

where π is the constant, of value 3.14159 or, simply, 3.14 and D is the diameter of the circle in feet and r the radius of the circle in feet.

Therefore, the area of the pipe is

$$A = \pi \frac{D^2}{4} = 3.14 \frac{(1\,\text{ft})^2}{4} = 0.785\,\text{ft}^2$$

Now, we can determine the discharge in cfs for part (a)

$$Q = VA = 10\,\text{ft/s} \times 0.785\,\text{ft}^2 \times 7.85\,\text{ft}^3/\text{s or cfs}$$

For part (b), we need to know that 1 cfs is 449 gpm, so 7.85 cfs × 449 gpm/cfs = 3525 gpm (rounded).

Finally, for part (c), 1 million gal per day is 1.55 cfs, so

$$\frac{7.85\,\text{cfs}}{1.55\,\text{cfs/MGD}} = 5.06\,\text{MGD}$$

√ **Important Point:** Flow may be *laminar* (streamline—see Figure 3.6) or *turbulent* (see Figure 3.7). Laminar flow occurs at extremely low velocities. The water moves in straight parallel lines, called streamlines, or laminae, which slide upon each other as they travel, rather than mixing up. Normal pipe flow is turbulent flow, which occurs because of friction encountered on the inside of the pipe. The outside layers of the flow are thrown into the inner layers; the result is that all the layers mix and move in different directions at different velocities. However, the direction of the flow is forward.

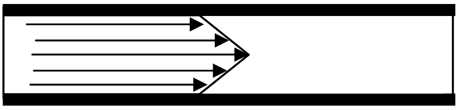

FIGURE 3.6 Laminar (streamline) flow.

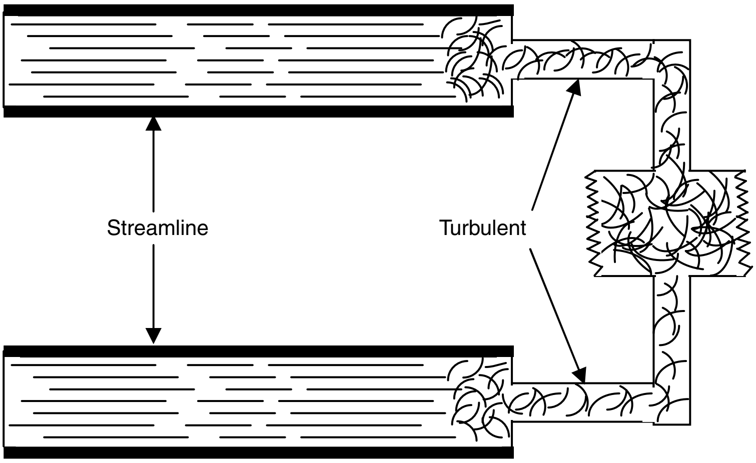

FIGURE 3.7 Turbulent flow.

√ **Important Point:** Flow may be steady or unsteady. For our purposes, we consider steady-state flow only; most of the hydraulic calculations in this manual assume steady-state flow.

AREA/VELOCITY

The *law of continuity* states that the discharge at each point in a pipe or channel is the same as the discharge at any other point (if water does not leave or enter the pipe or channel). That is, under the assumption of steady-state flow, the flow that enters the pipe or channel is the same flow that exits the pipe or channel. In equation form, this becomes

$$Q_1 = Q_2 \quad \text{or} \quad A_1V_1 = A_2V_2 \tag{3.14}$$

√ **Note:** In regard to the area/velocity relationship, Equation 3.14 also makes clear that for a given flow rate, the velocity of the liquid varies indirectly with changes in cross-sectional area of the channel or pipe. This principle provides the basis for many of the flow measurement devices used in open channels (weirs, flumes, and nozzles).

EXAMPLE 3.12

Problem:

A pipe, 12 in. in diameter, is connected to a 6-in. diameter pipe. The velocity of the water in the 12-in. pipe is 3 fps. What is the velocity in the 6-in. pipe?

Solution:

Using the equation, $A_1V_1 = A_2V_2$, we need to determine the area of each pipe:

$$12\,\text{in.}: A = \pi\frac{D^2}{4}$$

$$= 3.14\frac{1\,\text{ft}^2}{4}$$

$$= 0.785\,\text{ft}^2$$

$$6\,\text{in.}: A = 3.14\frac{(0.5)^2}{4}$$

$$= 0.196\,\text{ft}^2$$

The continuity equation now becomes

$$(0.785\,\text{ft}^2)\left(3\frac{\text{ft}}{\text{s}}\right) = (0.196\,\text{ft}^2)V_2$$

Solving for V_2

$$V^2 = \frac{(0.785\,\text{ft}^2)(3\,\text{ft/s})}{(0.196\,\text{ft}^2)}$$

$$= 12\,\text{ft/s or fps}$$

PRESSURE/VELOCITY

In a closed pipe flowing full (under pressure), the pressure is indirectly related to the velocity of the liquid. This principle, when combined with the principle discussed in the previous section, forms the basis for several flow measurement devices (Venturi meters and rotameters) as well as the injector used for dissolving chlorine into water:

$$\text{Velocity}_1 \times \text{pressure}_1 = \text{velocity}_2 \times \text{pressure}_2$$

or

$$V_1P_1 = V_2P_2 \tag{3.15}$$

PIEZOMETRIC SURFACE AND BERNOULLI'S THEOREM

> They will take your hand and lead you to the pearls of the desert, those secret wells swallowed by oyster crags of wadi, underground caverns that bubble rusty salt water you would sell your own mothers to drink.
>
> **—S. Holman (1998)**

To keep the systems in waterworks operating properly and efficiently, the operators must understand the basics of hydraulics—the laws of force, motion, and others. As stated previously, most applications of hydraulics in water treatment systems involve water in motion—in pipes under pressure or in open channels under the force of gravity. The volume of water flowing past any given point in the pipe or channel per unit time is called the flow rate or discharge—or just *flow*.

With regard to flow, *continuity of flow* and the *continuity equation* have been discussed (i.e., Equation 3.15). Along with the continuity of flow principle and continuity equation, the law of conservation of energy, piezometric surface, and Bernoulli's theorem (or principle) are also important to our study of water hydraulics.

CONSERVATION OF ENERGY

Many of the principles of physics are important for the study of hydraulics. When applied to problems involving the flow of water, few principles of physical science are more important and useful to us than the *law of conservation of energy*. Simply put, the law of conservation of energy states that energy can neither be created nor destroyed, but it can be converted from one form into another. In a given closed system, the total energy is constant.

ENERGY HEAD

Two types of energy—kinetic and potential—and three forms of mechanical energy—potential energy due to elevation, potential energy due to pressure, and kinetic energy due to velocity—exist in hydraulic systems. Energy has the unit of foot pounds (ft-lb). It is convenient to express hydraulic energy in terms of *energyhead*, in feet of water. This is equivalent to foot-pounds per pound of water (ft-lb/lb = ft).

PIEZOMETRIC SURFACE

As mentioned earlier, we have seen that when a vertical tube, open at the top, is installed onto a vessel of water, the water will rise in the tube to the water level in the tank. The water level to which the water rises in a tube is the *piezometric surface*. That is, the piezometric surface is an imaginary surface that coincides with the level of the water to which water in a system would rise in a *piezometer* (an instrument used to measure pressure).

The surface of water that is in contact with the atmosphere is known as *free water surface*. Many important hydraulic measurements are based on the difference in height between the free water surface and some point in the water system. The *piezometric surface* is used to locate this free water surface in a vessel, where it cannot be observed directly.

To understand how a piezometer actually measures pressure, consider the following example.

If a clear, see-through pipe is connected to the side of a clear glass or plastic vessel, the water will rise in the pipe to indicate the level of the water in the vessel. Such a see-through pipe, the piezometer, allows you to see the level of the top of the water in the pipe; this is the piezometric surface.

In practice, a piezometer is connected to the side of a tank or pipeline. If the water-containing vessel is not under pressure (as is the case in Figure 3.8), the piezometric surface will be the same

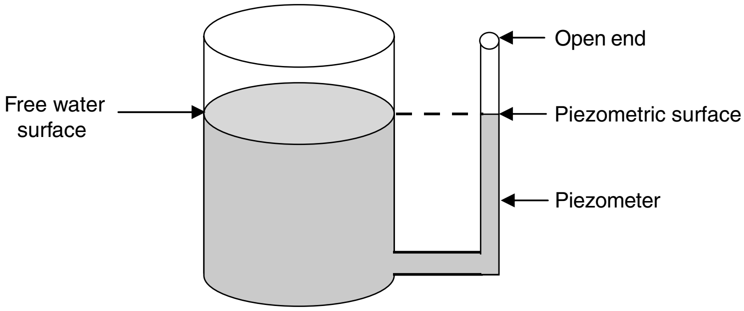

FIGURE 3.8 A container not under pressure where the piezometric surface is the same as the free water surface in the vessel.

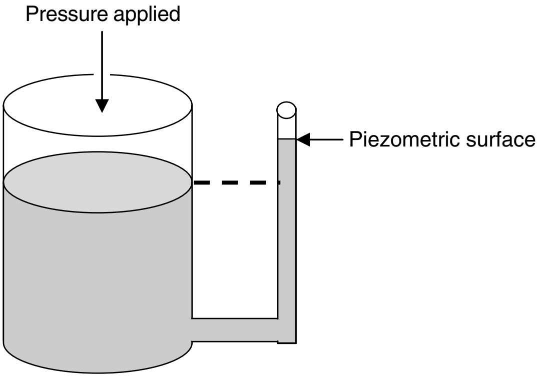

FIGURE 3.9 A container under pressure where the piezometric surface is above the level of the water in the tank.

as the free water surface in the vessel, just as it would if a drinking straw (the piezometer) were left standing in a glass of water.

When pressurized in a tank and pipeline system, as they often are, the pressure will cause the piezometric surface to rise above the level of the water in the tank. The greater the pressure, the higher the piezometric surface (see Figure 3.9). An increased pressure in a water pipeline system is usually obtained by elevating the water tank.

√ **Important Point:** In practice, piezometers are not installed on pipelines or on water towers because water towers are hundreds of feet high. Instead, pressure gauges are used that record pressure of water in feet or in pounds per square inch.

Water only rises to the level of the main body of water when it is at rest (static or standing water). The situation is quite different when water is flowing. Consider, for example, an elevated storage tank feeding a distribution system pipeline. When the system is at rest, all valves closed, all the piezometric surfaces are the same height as the free water surface in storage. In contrast, when the valves are opened and the water begins to flow, the piezometric surface changes. This is an important point because as water continues to flow down a pipeline, less and less pressure is exerted. This happens because some pressure is lost (used up) keeping the water moving over the interior surface of the pipe (friction). The pressure that is lost is called *head loss.*

HEAD LOSS

Head loss is best explained by an example. Figure 3.10 shows an elevated storage tank feeding a distribution system pipeline. When the valve is closed (Figure 3.10a), all the piezometric surfaces are the same height as the free water surface in storage. When the valve opens and water begins to flow (Figure 3.10b), the piezometric surfaces *drop.* The farther along the pipeline, the lower the piezometric surface, because some of the pressure is used up keeping the water moving over the rough interior surface of the pipe. Thus, pressure is lost and is no longer available to push water up in a piezometer; this is the *head loss.*

HYDRAULIC GRADE LINE

When the valve is opened in Figure 3.10, flow begins with a corresponding energy loss due to friction. The pressures along the pipeline can measure this loss. In Figure 3.10b, the difference in pressure heads between sections 1, 2, and 3 can be seen in the piezometer tubes attached to the pipe. A line connecting the water surface in the tank with the water levels at sections 1–3 shows the pattern of continuous pressure loss along the pipeline. This is called the *hydraulic grade line* (*HGL*)

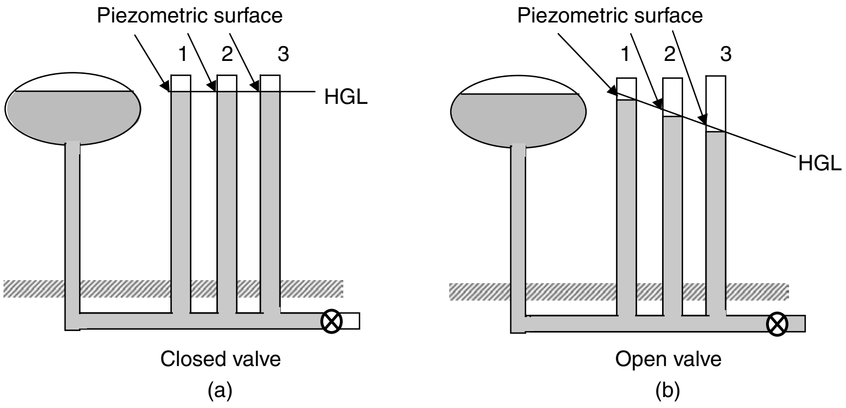

FIGURE 3.10 Shows head loss and piezometric surface changes when water is flowing.

or *hydraulic gradient* of the system. (Note: It is important to point out that in a static water system, the HGL is always horizontal.) The HGL is a very useful graphical aid when analyzing pipe flow problems.

√ **Important Point:** During the early design phase of a treatment plant, it is important to establish the HGL across the plant because both the proper selection of the plant site elevation and the suitability of the site depend on this consideration. Typically, most conventional water treatment plants required 16–17 ft of head loss across the plant.

√ **Key Point:** Changes in the piezometric surface occur when water is flowing.

BERNOULLI'S THEOREM*

Swiss physicist and mathematician Samuel Bernoulli developed the calculation for the total energy relationship from point to point in a steady-state fluid system in the 1700s. Before discussing Bernoulli's energy equation, it is important to understand the basic principle behind Bernoulli's equation.

Water (and any other hydraulic fluid) in a hydraulic system possesses two types of energy—kinetic and potential. *Kinetic energy* is present when the water is in motion. The faster the water moves, the more the kinetic energy used. *Potential energy* is a result of the water pressure. The *total energy* of the water is the sum of the kinetic and potential energy. Bernoulli's principle states that the total energy of the water (fluid) always remains constant. Therefore, when the water flow in a system increases, the pressure must decrease. When water starts to flow in a hydraulic system, the pressure drops. When the flow stops, the pressure rises again. The pressure gauges shown in Figure 3.11 indicate this balance more clearly.

√ **Note:** The basic principle explained above ignores friction losses from point to point in a fluid system employing steady-state flow.

BERNOULLI'S EQUATION

In a hydraulic system, total energy head is equal to the sum of three individual energy heads. This can be expressed as

$$\text{Total head} = \text{elevation head} + \text{pressure head} + \text{velocity head}$$

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* The section is adapted from Nathanson, J.A. (1997), *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 2nd ed., Prentice-Hall, Upper Saddle River, NJ.

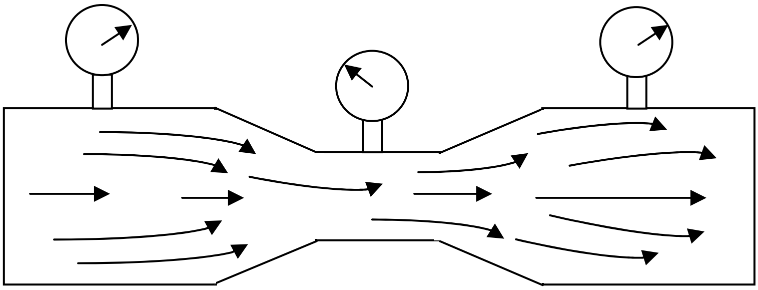


FIGURE 3.11 Demonstration of Bernoulli's principle.

where
elevation head = pressure due to the elevation of the water
pressure head = height of a column of water that a given hydrostatic pressure in a system could support
velocity head = energy present due to the velocity of the water

This can be expressed mathematically as

$$E = z + \frac{P}{w} + \frac{v^2}{2g} \tag{3.16}$$

where
E = total energy head
z = height of the water above a reference plane, ft
P = pressure, psi
w = unit weight of water, 62.4 lb/ft^3
v = flow velocity, ft/s
g = acceleration due to gravity, 32.2 ft/s^2

Consider the constriction in the section of pipe shown in Figure 3.12. We know, based on the *law of energy conservation*, that the total energy head at section A, E_1 must equal the total energy head at section B, E_2, and using Equation 3.16, we get Bernoulli's equation.

$$z_A + \frac{P_A}{w} + \frac{v_A^2}{2g} = z_B + \frac{P_B}{w} + \frac{v_B^2}{2g} \tag{3.17}$$

The pipeline system shown in Figure 3.12 is horizontal; therefore, we can simplify Bernoulli's equation because $z_A = z_B$.

Because they are equal, the elevation heads cancel out from both sides, leaving:

$$\frac{P_A}{w} + \frac{v_A^2}{2g} = \frac{P_B}{w} + \frac{v_B^2}{2g} \tag{3.18}$$

As water passes through the constricted section of the pipe (section B), we know from continuity of flow that the velocity at section B must be greater than the velocity at section A because of the

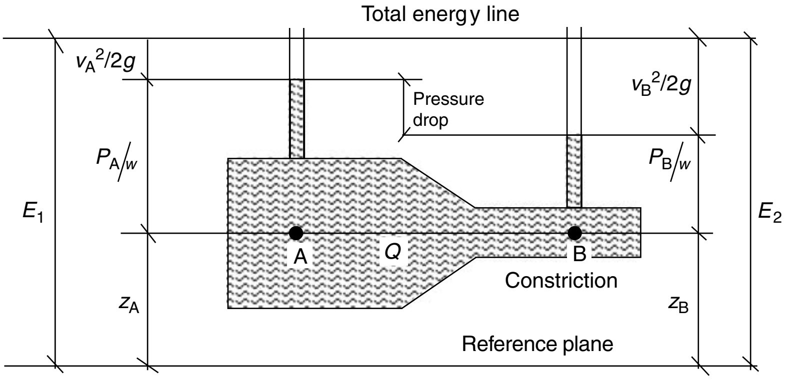


FIGURE 3.12 The result of the law of conservation. Since the velocity and kinetic energy of the water flowing in the constricted section must increase, the potential energy may decrease. This is observed as a pressure drop in the constriction. (Adapted from Nathanson, J.A., *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 2nd ed., Prentice-Hall, Upper Saddle River, NJ, 1997.)

smaller flow area at section B. This means that the velocity head in the system increases as the water flows into the constricted section. However, the total energy must remain constant. For this to occur, the pressure head, and therefore the pressure, must drop. In effect, pressure energy is converted into kinetic energy in the constriction.

The fact that the pressure in the narrower pipe section (constriction) is less than the pressure in the bigger section seems to defy common sense. However, it does follow logically from continuity of flow and conservation of energy. The fact that there is a pressure difference allows measurement of flow rate in the closed pipe.

EXAMPLE 3.13

Problem:

In Figure 3.12, the diameter at section A is 8 in., and at section B it is 4 in. The flow rate through the pipe is 3.0 cfs and the pressure at section A is 100 psi. What is the pressure in the constriction at section B?

Solution:

Step 1: Compute the flow area at each section, as follows:

$$A_A = \frac{\lambda(0.666\,\text{ft})^2}{4} = 0.394\,\text{ft}^2(\text{rounded})$$

$$A_B = \frac{\lambda(0.333\,\text{ft})^2}{4} = 0.087\,\text{ft}^2(\text{rounded})$$

Step 2: From $Q = AV$ or Q/A or, we get

$$V_A = \frac{3.0\,\text{ft}^3/\text{s}}{0.349\,\text{ft}^2} = 8.6\,\text{ft/s (rounded)}$$

$$V_B = \frac{3.0\,\text{ft}^3/\text{s}}{0.087\,\text{ft}^2} = 34.5\,\text{ft/s (rounded)}$$

Step 3: Applying Equation 3.18, we get

$$\frac{100\times144}{62.4}+\frac{(8.6)^2}{2\times32.2}=\frac{P_\mathrm{B}\times144}{62.4}+\frac{(34.5)}{2\times32.2}$$

√ **Note:** The pressures are multiplied by 144 in^2/ft^2 to convert from psi to lb/ft^2 to be consistent with the units for *w*; the energy head terms are in feet of head.

Continuing, we get

$$231+1.15=2.3P_\mathrm{B}+18.5$$

and

$$P_\mathrm{B}=\frac{232.2-18.5}{2.3}=\frac{213.7}{2.3}=93\,\text{psi (rounded)}$$

HYDRAULIC MACHINES (PUMPS)

Conveying water to and from process equipment is an integral part of the water industry that requires energy consumption. The amount of energy required depends on the height to which the water is raised, the length and diameter of the conveying conduits, the rate of flow, and the water's physical properties (in particular, viscosity and density). In some applications, external energy for transferring water is not required. For example, when water flows to a lower elevation under the influence of gravity, a partial transformation of the water's potential energy into kinetic energy occurs. However, when conveying water or wastewater through horizontal conduits, especially to higher elevations within a system, mechanical devices such as pumps are employed. Requirements vary from small units used to pump only a few gallons per minute to large units capable of handling several hundred cubic feet per second. Table 3.2 lists pump applications in water/wastewater treatment operations.

TABLE 3.2
Pump Applications in Water/Wastewater Systems

Application	Function	Pump Type
Low service	To lift water from the source to treatment processes, or from storage to filter-backwashing system	Centrifugal
High service	To discharge water under pressure to distribution system; to pump collected or intercepted wastewater and pump to treatment facility	Centrifugal
Booster	To increase pressure in the distribution/collection system or to supply elevated storage tanks	Centrifugal
Well	To lift water from shallow or deep wells and discharge it to the treatment plant, storage facility, or distribution system	Centrifugal or jet
Chemical feed	To add chemical solutions at desired dosages for treatment processes	Positive displacement
Sampling	To pump water/wastewater from sampling points to the laboratory or automatic analyzers	Positive displacement or centrifugal
Sludge/biosolids	To pump sludge or biosolids from sedimentation facilities to further treatment or disposal	Positive displacement or centrifugal

Source: Adapted from American Water Works Association, *Water Transmission and Distribution*, American Water Works Association, Denver, 1996, p. 358.

√ **Note:** In determining the amount of pressure or force a pump must provide to move the water, the term *pump head* was established.

Several methods are available for transporting water, wastewater, and chemicals for treatment between process equipment:

- Centrifugal force inducing fluid motion
- Volumetric displacement of fluids, either mechanically, or with other fluids
- Transfer of momentum from another fluid
- Mechanical impulse
- Gravity induced

Depending on the facility and unit processes contained within, all the above methods may be important to the maintenance operator.

PUMPING HYDRAULICS

Arasmith (1993) points out that during operation, water enters a pump on the suction side, where the pressure is lower. Since the function of the pump is to add pressure to the system, discharge pressure will always be higher. An important concept to keep in mind is in pump systems, measurements are taken from the point of reference to the centerline of the pump (horizontal line drawn through the center of the pump).

To understand pump operation, or *pumping hydraulics*, we need to be familiar with certain basic terms and then relate these terms pictorially (as we do in Figure 3.13) to illustrate how water is pumped from one point to another.

- *Static head*—The distance between the suction and discharge water levels when the pump is shut off. We indicate static head conditions with the letter Z (see Figure 3.13).
- *Suction lift*—The distance between the suction water level and the center of the pump impeller. This term is only used when the pump is in a suction lift condition; the pump

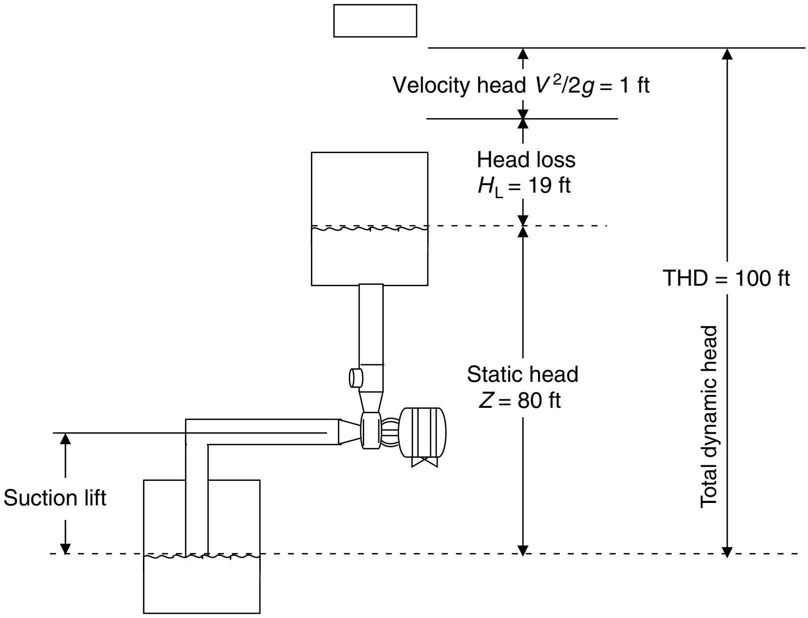


FIGURE 3.13 Components of total dynamic head.

must have the energy to provide this lift. A pump is said to be in a suction lift condition any time the center (eye) of the impeller is above the water being pumped (see Figure 3.13).

- *Suction head*—A pump is said to be in a suction head condition any time the center (eye) of the impeller is below the water level being pumped. Specifically, suction head is the distance between the suction water level and the center of the pump impeller when the pump is in a suction head condition (see Figure 3.13).
- *Velocity head*—The amount of energy required to bring water or wastewater from standstill to its velocity. For a given quantity of flow, the velocity head will vary indirectly with the pipe diameter. Velocity head is often shown mathematically as $V^2/2g$ (see Figure 3.13).
- *Total dynamic head*—The total energy needed to move water from the centerline of a pump (eye of the first impeller of a lineshaft turbine) to some given elevation or to develop some given pressure. This includes the static head, velocity head, and the head loss due to friction (see Figure 3.13).

WELL AND WET WELL HYDRAULICS

When the source of water for a water distribution system is from a groundwater supply, knowledge of well hydraulics is important to the operator. Basic well hydraulics terms are presented and defined, and they are related pictorially (see Figure 3.14). Also discussed are wet wells, which are important in both water and wastewater operations.

WELL HYDRAULICS

- *Static water level*—The water level in a well when no water is being taken from the groundwater source (i.e., the water level when the pump is off; see Figure 3.14). Static water level is normally measured as the distance from the ground surface to the water surface. This is an important parameter because it is used to measure changes in the water table.
- *Pumping water level*—The water level when the pump is off. When water is pumped out of a well, the water level usually drops below the level in the surrounding aquifer and eventually stabilizes at a lower level; this is the pumping level (see Figure 3.14).
- *Drawdown*—The difference, or the drop, between the static water level and the pumping water level, measured in feet. Simply stated, it is the distance the water level drops once pumping begins (see Figure 3.14).

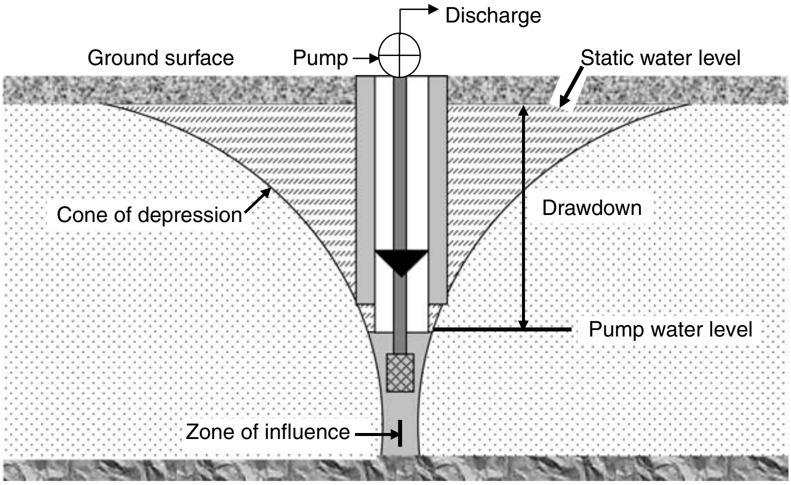


FIGURE 3.14 Hydraulic characteristics of a well.

- *Cone of depression*—In unconfined aquifers, there is a flow of water in the aquifer from all directions toward the well during pumping. The free water surface in the aquifer then takes the shape of an inverted cone or a curved funnel line. The curve of the line extends from the pumping water level to the static water level at the outside edge of the zone (or radius) of influence (see Figure 3.14).

√ **Important Point:** The shape and size of the cone of depression is dependent on the relationship between the pumping rate and the rate at which water can move toward the well. If the rate is high, the cone will be shallow and its growth will stabilize. If the rate is low, the cone will be sharp and continue to grow in size.

- *Zone (or radius) of influence*—the distance between the pump shaft and the outermost area affected by drawdown (see Figure 3.14). The distance depends on the porosity of the soil and other factors. This parameter becomes important in well fields with many pumps. If wells are set too close together, the zones of influence will overlap, increasing the drawdown in all wells. Obviously, pumps should be spaced apart to prevent this from happening.

√ **Note:** Two important parameters not shown in Figure 3.14 are well yield and specific capacity.

1. *Well yield* is the rate of water withdrawal that a well can supply over a long period. Alternatively, simply, it is the maximum pumping rate that can be achieved without increasing the drawdown. The yield of small wells is usually measured in gallons per minute (liters per minute) or gallons per hour (liters per hour). For large wells, it may be measured in cubic feet per second (cubic meters per second).
2. *Specific capacity* is the pumping rate per foot of drawdown (gpm/ft), or

$$\text{Specific capacity} = \frac{\text{well yield}}{\text{drawdown}} \tag{3.19}$$

Example 3.14

Problem:

If the well yield is 300 gpm and the drawdown is measured to be 20 ft, what is the specific capacity?

Solution:

$$\text{Specific capacity} = \frac{300}{20}$$

$$= 15\,\text{gpm/ft of drawdown}$$

Specific capacity is one of the most important concepts in well operation and testing. The calculation should be made frequently in the monitoring of well operation. A sudden drop in specific capacity indicates problems such as pump malfunction, screen plugging, or other problems that can be serious. Such problems should be identified and corrected as soon as possible.

WET WELL HYDRAULICS

Water pumped from a wet well by a pump set above the water surface exhibits the same phenomena as the groundwater well. In operation, a slight depression of the water surface forms right at the intake line (drawdown), but in this case it is minimal because there is free water at the pump entrance at all times (at least there should be). The most important consideration in wet well operations is to ensure that the suction line is submerged far enough below the surface so that air entrained by the active movement of the water at this section is not able to enter the pump.

Because water flow is not always constant or at the same level, variable speed pumps are commonly used in wet well operations, or several pumps are installed for single or combined operation. In many cases, pumping is accomplished in an on/off mode. Control of pump operation is in response to water level in the well. Level control devices such as mercury switches are used to sense a high and low level in the well and transmit the signal to pumps for action.

FRICTION HEAD LOSS

Materials or substances capable of flowing cannot flow freely. Nothing flows without encountering some type of resistance. Consider electricity, the flow of free electrons in a conductor. Whatever type of conductor used (i.e., copper, aluminum, silver, etc.) offers some resistance. In hydraulics, the flow of water is analogous to the flow of electricity. Within a pipe or open channel, for instance, flowing water, like electron flow in a conductor, encounters resistance. However, resistance to the flow of water is generally termed friction loss (or more appropriately, head loss).

FLOW IN PIPELINES

The problem of waste flow in pipelines—the prediction of flow rate through pipes of given characteristics, the calculation of energy conversions therein, and so forth—is encountered in many applications of water/wastewater operations and practice. Although the subject of pipe flow embraces only those problems in which pipes flow completely full (as in water lines), in this section we also address pipes that flow partially full (wastewater lines, normally treated as open channels).

The solution of practical pipe flow problems resulting from application of the energy principle, the equation of continuity, and the principle and equation of water resistance are also discussed. Resistance to flow in pipes is not only the result of long reaches of pipe but is also offered by pipe fittings, such as bends and valves, which dissipate energy by producing relatively large-scale turbulence.

PIPE AND OPEN FLOW BASICS

To understand what friction head loss is all about, it is necessary to review a few terms presented earlier in the text and to introduce some new terms pertinent to the subject.

- *Laminar and turbulent flow—laminar flow*—Is ideal flow; that is, water particles moving along straight, parallel paths, in layers or streamlines. Moreover, in laminar flow there is no turbulence in the water and no friction loss. This is not typical of normal pipe flow because the water velocity is too great, but it is typical of groundwater flow.
- *Turbulent flow* (characterized as "normal" for a typical water system)—Occurs when water particles move in a haphazard fashion and continually cross each other in all directions resulting in pressure losses along a length of pipe.
- *HGL*—Recall that the HGL (shown in Figure 3.15) is a line connecting two points to which the liquid would rise at various places along any pipe or open channel if piezometers were inserted in the liquid. It is a measure of the pressure head available at these various points.

√ **Note:** When water flows in an open channel, the HGL coincides with the profile of the water surface.

- *Energy grade line*—The total energy of flow in any section with reference to some datum (i.e., a reference line, surface or point) is the sum of the elevation head z, the pressure head y,

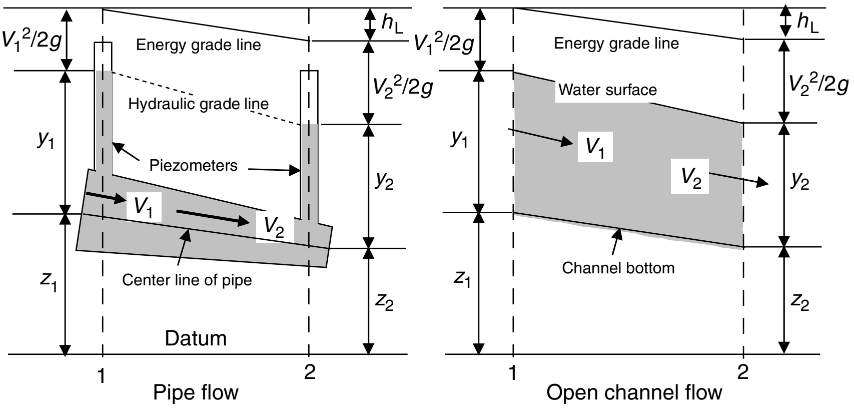


FIGURE 3.15 Comparison of pipe flow and open-channel flow. (Adapted from Metcalf & Eddy, *Wastewater Engineering: Collection and Pumping of Wastewater*, McGraw-Hill, New York, 1981.)

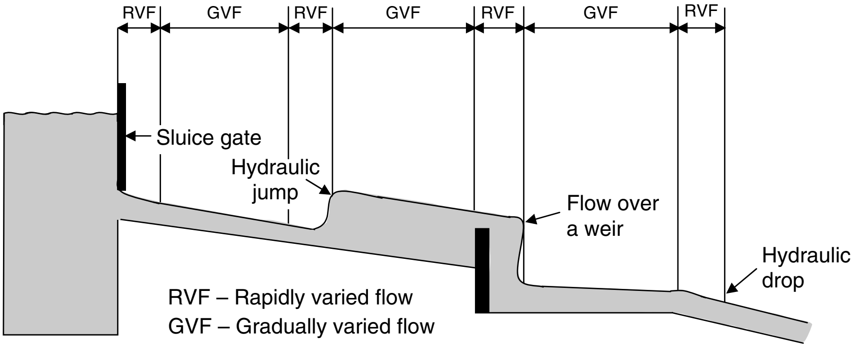


FIGURE 3.16 Varied flow.

and the velocity head $V^2/2g$. Figure 3.15 shows the *energy grade line* or *energy gradient*, which represents the energy from section to section. In the absence of frictional losses, the energy grade line remains horizontal, although the relative distribution of energy may vary between the elevation, pressure, and velocity heads. In all real systems, however, losses of energy occur because of resistance to flow, and the resulting energy grade line is *sloped* (i.e., the energy grade line is the slope of the specific energy line).

- *Specific energy (E)*—Sometimes called *specific head*, is the sum of the pressure head y and the velocity head $V^2/2g$. The specific energy concept is especially useful in analyzing flow in open channels.
- *Steady flow*—Occurs when the discharge or rate of flow at any cross section is constant.
- *Uniform flow*—Occurs when the depth, cross-sectional area, and other elements of flow are substantially constant from section to section.
- *Nonuniform flow*—Occurs when the slope, cross-sectional area, and velocity change from section to section. The flow through a Venturi section used for measuring flow is a good example.
- *Varied flow*—Flow in a channel is considered varied if the depth of flow changes along the length of the channel. The flow may be gradually varied or rapidly varied (i.e., when the depth of flow changes abruptly), as shown in Figure 3.16.
- *Slope* (gradient)—The head loss per foot of channel.

MAJOR HEAD LOSS

Major head loss consists of pressure decreases along the length of pipe caused by friction created as water encounters the surfaces of the pipe. It typically accounts for most of the pressure drop in a pressurized or dynamic water system.

Components of Major Head Loss

The components that contribute to major head loss are roughness, length, diameter, and velocity.

Roughness

Even when new, the interior surfaces of pipes are rough. The roughness varies, of course, depending on pipe material, corrosion (tuberculation and pitting), and age. Because normal flow in a water pipe is turbulent, the turbulence increases with pipe roughness, which, in turn, causes pressure to drop over the length of the pipe.

Pipe Length

With every foot of pipe length, friction losses occur. The longer the pipe, the more the head loss. Friction loss because of pipe length must be factored into head loss calculations.

Pipe Diameter

Generally, small diameter pipes have more head loss than large diameter pipes. This is the case because in large diameter pipes less of the water actually touches the interior surfaces of the pipe (encountering less friction) than in a small diameter pipe.

Water Velocity

Turbulence in a water pipe is directly proportional to the speed (or velocity) of the flow. Thus, the velocity head also contributes to head loss.

√ **Note:** For the same diameter pipe, when flow increases, head loss increases.

Calculating Major Head Loss

Darcy, Weisbach, and others developed the first practical equation used to determine pipe friction in about 1850. The equation or formula now known as the *Darcy–Weisbach* equation for circular pipes is:

$$h_\mathrm{f} = f\frac{LV^2}{D2g} \tag{3.20}$$

In terms of the flow rate Q, the equation becomes:

$$h_\mathrm{f} = \frac{8fLQ^2}{\lambda^2 gD^5} \tag{3.21}$$

where

h_f = head loss, ft
f = coefficient of friction
L = length of pipe, ft
V = mean velocity, ft/s
D = diameter of pipe, ft
g = acceleration due to gravity, 32.2 ft/s^2
Q = flow rate, ft^3/s

The Darcy–Weisbach formula as such was meant to apply to the flow of any fluid and into this friction factor was incorporated the degree of roughness and an element called the *Reynolds number*, which was based on the viscosity of the fluid and the degree of turbulence of flow.

The Darcy–Weisbach formula is used primarily for determining head loss calculations in pipes. For making this determination in open channels, the *Manning equation* was developed during the later part of the 19th century. Later, this equation was used for both open channels and closed conduits.

In the early 1900s, a more practical equation, the *Hazen–Williams* equation, was developed for use in making calculations related to water pipes and wastewater force mains:

$$Q = 0.435 \times CD^{2.63} \times S^{0.54} \tag{3.22}$$

where

Q = flow rate, ft^3/s
C = coefficient of roughness (C decreases with roughness)
D = hydraulic radius R, ft
S = slope of energy grade line, ft/ft

C FACTOR

C factor, as used in the Hazen–Williams formula, designates the coefficient of roughness. C does not vary appreciably with velocity, and by comparing pipe types and ages, it includes only the concept of roughness, ignoring fluid viscosity and Reynolds number.

Based on experience (experimentation), accepted tables of C factors have been established for pipe (see Table 3.3). Generally, C factor decreases by one with each year of pipe age. Flow for a newly designed system is often calculated with a C factor of 100, based on averaging it over the life of the pipe system.

√ **Note:** A high C factor means a smooth pipe. A low C factor means a rough pipe.

√ **Note:** An alternate to calculating the Hazen–Williams formula, called an alignment chart, has become quite popular for fieldwork. The alignment chart can be used with reasonable accuracy.

SLOPE

Slope is defined as the head loss per foot. In open channels, where the water flows by gravity, slope is the amount of incline of the pipe, and is calculated as feet of drop per foot of pipe length (ft/ft). Slope is designed to be just enough to overcome frictional losses, so that the velocity remains constant, the water keeps flowing, and solids will not settle in the conduit. In piped systems, where pressure loss for every foot of pipe is experienced, slope is not provided by slanting the pipe but instead by pressure added to overcome friction.

MINOR HEAD LOSS

In addition to the head loss caused by friction between the fluid and the pipe wall, losses also are caused by turbulence created by obstructions (i.e., valves and fittings of all types) in the line, changes in direction, and changes in flow area.

√ **Note:** In practice, if minor head loss is less than 5% of the total head loss, it is usually ignored.

TABLE 3.3
***C* Factors**

Type of Pipe	*C* Factor
Asbestos cement	140
Brass	140
Brick sewer	100
Cast iron	
10 years old	110
20 years old	90
Ductile iron (cement lined)	140
Concrete or concrete lined	
Smooth, steel forms	140
Wooden forms	120
Rough	110
Copper	140
Fire hose (rubber lined)	135
Galvanized iron	120
Glass	140
Lead	130
Masonry conduit	130
Plastic	150
Steel	
Coal-tar enamel lined	150
New unlined	140
Riveted	110
Tin	130
Vitrified	120
Wood stave	120

Source: Adapted from Lindeburg, M.R., *Civil Engineering Reference Manual*, Professional Publications, Inc., San Carlos, CA, 1986.

BASIC PUMPING HYDRAULICS

Water, regardless of the source, is conveyed to the waterworks for treatment and distributed to the users. Conveyance from the source to the point of treatment occurs by aqueducts, pipelines, or open channels, but the treated water is normally distributed in pressurized closed conduits. After use, whatever the purpose, the water becomes wastewater, which must be disposed of somehow, but almost always ends up being conveyed back to a treatment facility before being outfalled to some water body, to begin the cycle again.

We call this an urban water cycle, because it provides a human-generated imitation of the natural water cycle. Unlike the natural water cycle, however, without pipes, the cycle would be nonexistent or, at least, short-circuited.

PIPING

For use as water mains in a distribution system, pipes must be strong and durable in order to resist applied forces and corrosion. The pipe is subjected to internal pressure from the water and to external pressure from the weight of the backfill (soil) and vehicles above it. The pipe may also have to withstand water hammer. Damage due to corrosion or rusting may also occur internally because of the water quality or externally because of the nature of the soil conditions.

Of course, pipes must be constructed to withstand the expected conditions of exposure, and pipe configuration systems for water distribution systems must be properly designed and installed in terms of water hydraulics. Because the water/wastewater operator should have a basic knowledge of water hydraulics related to commonly used standard piping configurations, piping basics are briefly discussed in this section.

PIPING NETWORKS

It would be far less costly and make for more efficient operation if municipal water systems were built with separate single pipe networks extending from treatment plant to user's residence. Unfortunately, this ideal single-pipe scenario is not practical for real world applications. Instead of a single piping system, a network of pipes is laid under the streets. Each of these piping networks is composed of different materials that vary (sometimes considerably) in diameter, length, and age. These networks range in complexity to varying degrees, and each of these joined-together pipes contribute energy losses to the system.

ENERGY LOSSES IN PIPE NETWORKS

Water flow networks may consist of pipes arranged in series, parallel, or some complicated combination. In any case, an evaluation of friction losses for the flows is based on energy conservation principles applied to the flow junction points. Methods of computation depend on the particular piping configuration. In general, however, they involve establishing a sufficient number of simultaneous equations or employing a friction loss formula where the friction coefficient depends only on the roughness of the pipe (e.g., Hazen–Williams equation—Equation 3.22). (Note: Demonstrating the procedure for making these complex computations is beyond the scope of this text.)

PIPES IN SERIES

When two pipes of different sizes or roughnesses are connected in series (see Figure 3.17), head loss for a given discharge, or discharge for a given head loss, may be calculated by applying the appropriate equation between the bonding points, taking into account all losses in the interval. Thus, head losses are cumulative.

Series pipes may be treated as a single pipe of constant diameter to simplify the calculation of friction losses. The approach involves determining an "equivalent length" of a constant diameter pipe that has the same friction loss and discharge characteristics as the actual series pipe system. In addition, application of the continuity equation to the solution allows the head loss to be expressed in terms of only one pipe size.

√ **Note:** In addition to the head loss caused by friction between the water and the pipe wall, losses also are caused by minor losses: obstructions in the line, changes in directions, and changes in flow area. In practice, the method of equivalent length is often used to determine these losses. The method of equivalent length uses a table to convert each valve or fitting into an equivalent length of straight pipe.

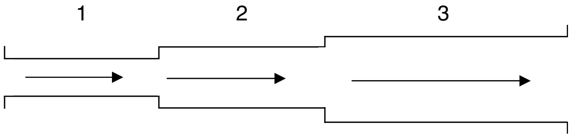


FIGURE 3.17 Pipes in series.

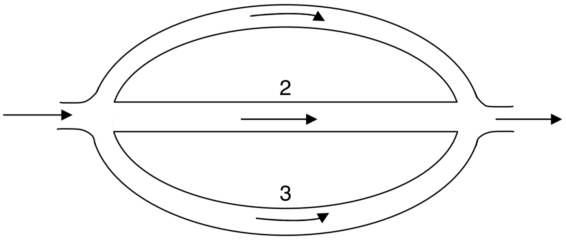


FIGURE 3.18 Pipe in parallel.

In making calculations involving pipes in series, remember these two important basic operational tenets:

1. The same flow passes through all pipes connected in series.
2. The total head loss is the sum of the head losses of all of the component pipes.

In some operations involving series networks where the flow is given and the total head loss is unknown, we can use the Hazen–Williams formula to solve for the slope and the head loss of each pipe as if they were separate pipes. Adding up the head losses to get the total head loss is then a simple matter.

Other series network calculations may not be as simple to solve using the Hazen–Williams equation. For example, one problem we may be faced with is what diameter to use with varying sized pipes connected together in a series combination. Moreover, head loss is applied to both pipes (or other multiples), and it is not known how much loss originates from each one; thus, determining slope would be difficult—but not impossible.

In such cases the *equivalent pipe theory,* as mentioned earlier, can be used. Again, one single "equivalent pipe" is created which will carry the correct flow. This is practical because the head loss through it is the same as that in the actual system. The equivalent pipe can have any *C* factor and diameter, just as long as those same dimensions are maintained all the way through to the end. Keep in mind that the equivalent pipe must have the correct length, so that it will allow the correct flow through, which yields the correct head loss (the given head loss).

PIPES IN PARALLEL

Two or more pipes connected (as in Figure 3.18) so that flow is first divided among the pipes and is then rejoined comprise a parallel pipe system. A parallel pipe system is a common method for increasing the capacity of an existing line. Determining flows in pipes arranged in parallel are also made by application of energy conservation principles—specifically, energy losses through all pipes connecting common junction points must be equal. Each leg of the parallel network is treated as a series piping system and converted to a single equivalent length pipe. The friction losses through the equivalent length parallel pipes are then considered equal and the respective flows determined by proportional distribution.

√ **Note:** Computations used to determine friction losses in parallel combinations may be accomplished using a simultaneous solution approach for a parallel system that has only two branches. However, if the parallel system has three or more branches, a modified procedure using the Hazen–Williams loss formula is easier.

OPEN-CHANNEL FLOW

> Water is transported over long distances through aqueducts to locations where it is to be used and/or treated. Selection of an aqueduct type rests on such factors as topography, head availability, climate, construction practices, economics, and water quality protection. Along with pipes and tunnels, aqueducts may also include or be solely composed of open channels.
>
> **—W. Viessman, Jr. and M.J. Hammer (1998)**

In this section, water passage in open channels, which allow part of the water to be exposed to the atmosphere, is discussed. This type of channel—an open-flow channel—includes natural waterways, canals, culverts, flumes, and pipes flowing under the influence of gravity.

CHARACTERISTICS OF OPEN-CHANNEL FLOW

McGhee (1991) points out that basic hydraulic principles apply in open-channel flow (with water depth constant) although there is no pressure to act as the driving force. Velocity head is the only natural energy this water possesses, and at normal water velocities, this is a small value ($V^2/2g$).

Several parameters can be (and often are) used to describe open-channel flow. However, we begin our discussion with a few characteristics including laminar or turbulent, uniform or varied, and subcritical, critical, or supercritical.

LAMINAR AND TURBULENT FLOW

Laminar and *turbulent* flow in open channels is analogous to that in closed pressurized conduits (i.e., pipes). It is important to point out, however, that flow in open channels is usually turbulent. In addition, there is no important circumstance in which laminar flow occurs in open channels in either water or wastewater unit processes or structures.

UNIFORM AND VARIED FLOW

Flow can be a function of time and location. If the flow quantity is invariant, it is said to be steady. *Uniform* flow is flow in which the depth, width, and velocity remain constant along a channel. That is, if the flow cross section does not depend on the location along the channel, the flow is said to be uniform. *Varied* or *nonuniform* flow involves a change in these, with a change in one producing a change in the others. Most circumstances of open-channel flow in water/wastewater systems involve varied flow. The concept of uniform flow is valuable, however, in that it defines a limit that the varied flow may be considered to be approaching in many cases.

√ **Note:** Uniform channel construction does not ensure uniform flow.

CRITICAL FLOW

Critical flow (i.e., flow at the critical depth and velocity) defines a state of flow between two flow regimes. Critical flow coincides with minimum specific energy for a given discharge and maximum discharge for a given specific energy. Critical flow occurs in flow measurement devices at or near free discharges, and establishes controls in open-channel flow. Critical flow occurs frequently in water/wastewater systems and is very important in their operation and design.

√ **Note:** Critical flow minimizes the specific energy and maximizes discharge.

PARAMETERS USED IN OPEN-CHANNEL FLOW

The three primary parameters used in open-channel flow are hydraulic radius, hydraulic depth, and slope, S.

Hydraulic Radius

The *hydraulic radius* is the ratio of area in flow to wetted perimeter.

$$r_H = \frac{A}{P} \tag{3.23}$$

where

r_H = hydraulic radius
A = cross-sectional area of the water
P = wetted perimeter

Why is hydraulic radius important? Good question.

Probably the best way in which to answer this question is by illustration. Consider, for example, that in open channels it is of primary importance to maintain the proper velocity. This is the case, of course, because if velocity is not maintained then flow stops (theoretically). In order to maintain velocity at a constant level, the channel slope must be adequate to overcome friction losses. As with other flows, calculation of head loss at a given flow is necessary, and the Hazen–Williams equation is useful ($Q = 0.435Cd^{2.63}S^{0.54}$). Keep in mind that the concept of slope has not changed. The difference? We are now measuring, or calculating for, the physical slope of a channel (ft/ft), equivalent to head loss.

The preceding seems logical, makes sense—but there is a problem. The problem is with the diameter. In conduits that are not circular (grit chambers, contact basins, streams and rivers), or in pipes only partially full (drains, wastewater gravity mains, sewers, etc.) where the cross-sectional area of the water is not circular, there is no diameter.

If there is no diameter (and there is not), then what do we do? Another good question.

Because there is no diameter in a situation where the cross-sectional area of the water is not circular, we must use another parameter to designate the size of the cross section, and the amount of it that contacts the sides of the conduit. This is where the *hydraulic radius* (r_H) comes in. The hydraulic radius is a measure of the efficiency with which the conduit can transmit water. Its value depends on pipe size and amount of fullness. Simply stated, we use the hydraulic radius to measure how much of the water is in contact with the sides of the channel, or how much of the water is not in contact with the sides (see Figure 3.19).

√ **Note:** For a circular channel flowing either full or half-full, the hydraulic radius is (D/4). Hydraulic radii of other channel shapes are easily calculated from the basic definition.

Hydraulic Depth

The *hydraulic depth* is the ratio of area in flow to the width of the channel at the fluid surface. (Note that another name for hydraulic depth is the *hydraulic mean depth* or hydraulic radius.)

$$d_H = \frac{A}{w} \tag{3.24}$$

where

d_H = hydraulic depth
A = area in flow
w = width of the channel at the fluid surface

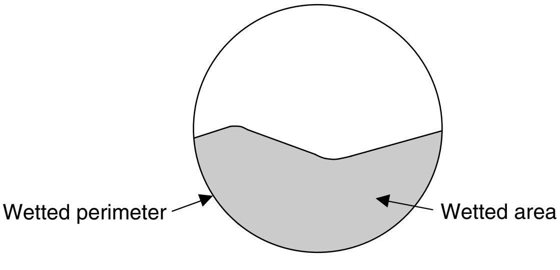


FIGURE 3.19 Hydraulic radius.

Slope (S)

The *slope, S*, in open-channel equations is the slope of the energy line. If the flow is uniform, the slope of the energy line will parallel the water surface and channel bottom. In general, the slope can be calculated from the Bernoulli equation as the energy loss per unit length of channel.

$$S = \frac{D\mathrm{h}}{D\mathrm{l}} \tag{3.25}$$

OPEN-CHANNEL FLOW CALCULATIONS

As mentioned, the calculation for head loss at a given flow is typically accomplished by using the Hazen–Williams equation. In addition, in open-channel flow problems although the concept of slope has not changed, the problem arises with the diameter. Again, in pipes only partially full where the cross-sectional area of the water is not circular, there is no diameter. Thus, the hydraulic radius is used for these noncircular areas.

In the original version of the Hazen–Williams equation, the hydraulic radius was incorporated. Moreover, similar versions developed by Chezy (pronounced "Shay-zee") and Manning and others incorporated the hydraulic radius. In open channels, *Manning's formula* has become most commonly used:

$$Q = \frac{1.5}{n} A R^{0.66} S^{0.5} \tag{3.26}$$

where

Q = channel discharge capacity, ft^3/s
1.5 = constant
n = channel roughness coefficient
A = cross-sectional flow, ft^2
R = hydraulic radius of the channel, ft
S = slope of the channel bottom, dimensionless

The hydraulic radius of a channel is defined as the ratio of the flow area to the wetted perimeter P. In formula form, $R = A/P$. The new component is n (the roughness coefficient) and depends on the material and age for a pipe or lined channel and on topographic features for a natural streambed. It approximates roughness in open channels and can range from a value of 0.01 for a smooth clay pipe to 0.1 for a small natural stream. The value of n commonly assumed for concrete pipes or lined channels is 0.013. *A*s the channels get smoother n values decrease (see Table 3.4).

The following example illustrates the application of Manning's formula for a channel with a rectangular cross section.

EXAMPLE 3.15

Problem:

A rectangular drainage channel is 3 ft wide and is lined with concrete, as illustrated in Figure 3.20. The bottom of the channel drops in elevation at a rate of 0.5/100 ft. What is the discharge in the channel when the depth of water is 2 ft?

Solution:

Assume $n = 0.013$

TABLE 3.4
Manning Roughness Coefficient (n)

Type of Conduit	n	Type of Conduit	n
Pipe			
Cast iron (coated)	0.012–0.014	Cast iron (uncoated)	0.013–0.015
Wrought iron (galvanized)	0.015–0.017	Wrought iron (black)	0.012–0.015
Steel (riveted and spiral)	0.015–0.017	Corrugated	0.021–0.026
Wood stave	0.012–0.013	Cement surface	0.010–0.013
Concrete	0.012–0.017	Vitrified	0.013–0.015
Clay (drainage tile)	0.012–0.014		
Lined Channels			
Metal (smooth semicircular)	0.011–0.015	Metal (corrugated)	0.023–0.025
Wood (planed)	0.010–0.015	Wood (unplanned)	0.011–0.015
Cement lined	0.010–0.013	Concrete	0.014–0.016
Cement rubble	0.017–0.030	Grass	up to 0.020
Unlined Channels			
Earth (straight and uniform)	0.017–0.025	Earth (dredged)	0.025–0.033
Earth (winding)	0.023–0.030	Earth (stony)	0.025–0.040
Rock (smooth and uniform)	0.025–0.035	Rock (jagged and irregular)	0.035–0.045

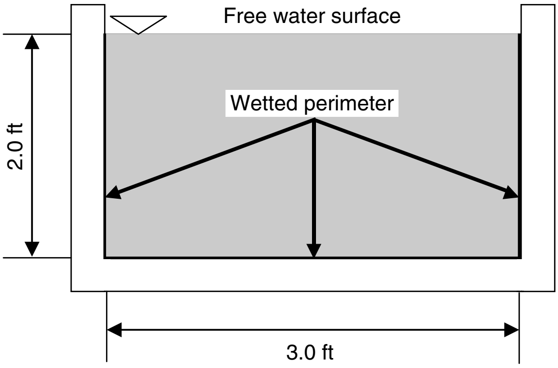


FIGURE 3.20 Refer to Figure 3.15.

Referring to Figure 3.20, we see that the cross-sectional flow area $A = 3\text{ ft} \times 2\text{ ft} = 6\text{ ft}^2$ and the wetted perimeter $P = (2 + 3 + 2)\text{ ft} = 7\text{ ft}$. The hydraulic radius $R = A/P = 6\text{ ft}^2/7\text{ ft} = 0.86\text{ ft}$. The slope $S = 0.5/100 = 0.005$.

Applying Manning's formula, we get:

$$Q = \frac{2.0}{0.013} \times 6 \times 0.866^{0.66} \times 0.005^{0.5}$$

$$Q = 59\,\text{cfs}$$

OPEN-CHANNEL FLOW: THE BOTTOM LINE

To this point, we have set the stage for explaining (in the simplest possible way) what open-channel flow is—what it is all about. Thus, now that we have explained the necessary foundational material and important concepts, we are ready to explain open-channel flow in a manner whereby it will be easily understood.

We stated that when water flows in a pipe or channel with a *free surface* exposed to the atmosphere, it is called *open-channel flow*. We also know that gravity provides the motive force, the constant push, while friction resists the motion and causes energy expenditure. River and stream flow is open-channel flow. Flow in sanitary sewers and storm water drains is open-channel flow, except in force mains where the water is pumped under pressure.

The key to solving storm water and sanitary sewer routine problems is a condition known as *steady uniform flow*; that is, we assume steady uniform flow. Steady flow, of course, means that the discharge is constant with time. Uniform flow means that the slope of the water surface and the cross-sectional flow area are also constant. It is common practice to call a length of channel, pipeline, or stream that has a relatively constant slope and cross section a *reach* (Nathanson, 1997).

The slope of the water surface, under steady uniform flow conditions, is the same as the slope of the channel bottom. The HGL lies along the water surface and, as in pressure flow in pipes, the HGL slopes downward in the direction of flow. Energy loss is evident as the water surface elevation drops. Figure 3.20 illustrates a typical profile view of uniform steady flow. The slope of the water surface represents the rate of energy loss.

√ **Note:** Rate of energy loss (see Figure 3.21) may be expressed as the ratio of the drop in elevation of the surface in the reach to the length of the reach.

Figure 3.22 shows typical cross sections of open-channel flow. In Figure 3.22a, the pipe is only partially filled with water and there is a free surface of atmospheric pressure. This is still

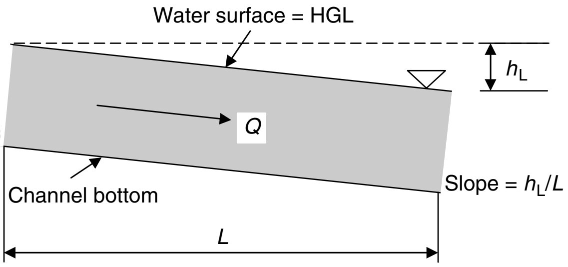


FIGURE 3.21 Steady uniform open-channel flow—where the slope of the water surface (or HGL) is equal to the slope of the channel bottom.

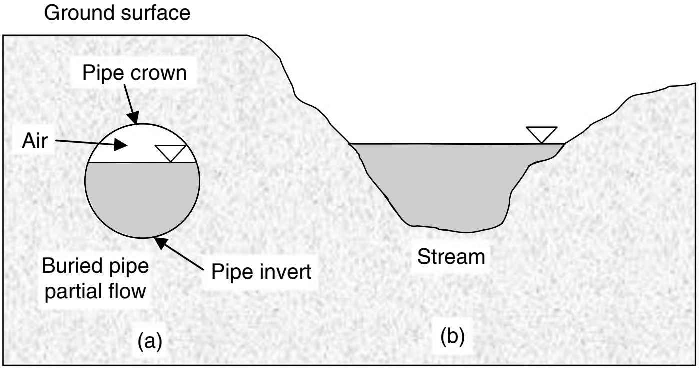


FIGURE 3.22 Open-channel flow in an underground pipe (a) or a surface stream (b). (Adapted from Nathanson, J.A., *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 2nd ed., Prentice-Hall, Upper Saddle River, NJ, 1997.)

open-channel flow, although the pipe is a closed underground conduit. Remember, the important point is that gravity and not a pump is moving the water.

FLOW MEASUREMENT

> While it is clear that maintaining water/wastewater flow is at the heart of any treatment process, clearly, it is the measurement of flow that is essential to ensuring the proper operation of a water/wastewater treatment system. Few knowledgeable operators would argue with this statement. Hauser (1996) asks: "Why measure flow?" Then she explains: "The most vital activities in the operation of water and wastewater treatment plants are dependent on a knowledge of how much water is being processed."

In the statement above, Hauser makes clear that flow measurement is not only important but also routine in water/wastewater operations. Routine, yes, but also the most important variable measured in a treatment plant. Hauser also pointed out that there are several reasons to measure flow in a treatment plant. The American Water Works Association (1995) lists several additional reasons to measure flow:

- The flow rate through the treatment processes needs to be controlled so that it matches distribution system use.
- It is important to determine the proper feed rate of chemicals added in the processes.
- The detention times through the treatment processes must be calculated. This is particularly applicable to surface water plants that must meet $C \times T$ values required by the Surface Water Treatment Rule.
- Flow measurement allows operators to maintain a record of water furnished to the distribution system for periodic comparison with the total water metered to customers. This provides a measure of "water accounted for," or conversely (as pointed out earlier by Hauser), the amount of water wasted, leaked, or otherwise not paid for; that is, lost water.
- Flow measurement allows operators to determine the efficiency of pumps. Pumps that are not delivering their designed flow rate are probably not operating at maximum efficiency, and so power is being wasted.
- For well systems, it is very important to maintain records of the volume of water pumped and the hours of operation for each well. The periodic computation of well pumping rates can identify problems such as worn pump impellers and blocked well screens.
- Reports that must be furnished to the state by most water systems must include records of raw- and finished water pumpage.
- Wastewater generated by a treatment system must also be measured and recorded.
- Individual meters are often required for the proper operation of individual pieces of equipment. For example, the makeup water to a fluoride saturator is always metered to assist in tracking the fluoride feed rate.

√ **Note:** Simply put, measurement of flow is essential for operation, process control, and recordkeeping of water and wastewater treatment plants.

All of the uses just discussed create the need, obviously, for a number of flow-measuring devices, often with different capabilities. In this section, we discuss many of the major flow measuring devices currently used in water/wastewater operations.

FLOW MEASUREMENT: THE OLD-FASHIONED WAY

An approximate but very simple method to determine open-channel flow has been used for many years. The procedure involves measuring the velocity of a floating object moving in a straight uniform reach of the channel or stream. If the cross-sectional dimensions of the channel are known and the depth of flow is measured, then flow area can be computed. From the relationship $Q = AV$, the discharge Q can be estimated.

In preliminary fieldwork, this simple procedure is useful in obtaining a ballpark estimate for the flow rate, but is not suitable for routine measurements.

EXAMPLE 3.16

Problem:

A floating object is placed on the surface of water flowing in a drainage ditch and is observed to travel a distance of 20 m downstream in 30 s. The ditch is 2 m wide and the average depth of flow is estimated to be 0.5 m. Estimate the discharge under these conditions.

Solution:

The flow velocity is computed as distance over time, or

$$V = \frac{D}{T} = 20\text{ m}/30\text{ s} = 0.67\text{ m/s}$$

The channel area $A = 2\text{ m} \times 0.5\text{ m} = 1.0\text{ m}^2$
The discharge $Q = A \times V = 1.0\text{ m}^2 \times 0.66\text{ m}^2 = 0.66\text{ m}^3/\text{s}$

BASIS OF TRADITIONAL FLOW MEASUREMENT

Flow measurement can be based on flow rate or flow amount. *Flow rate* is measured in gallons per minute, million gallons per day, or cubic feet per second. Water/wastewater operations need flow rate meters to determine process variables within the treatment plant, in wastewater collection, and in potable water distribution. Typically, flow rate meters used are pressure differential meters, magnetic meters, and ultrasonic meters. Flow rate meters are designed for metering flow in closed pipe or open-channel flow.

Flow amount is measured in either gallons or in cubic feet. Typically, a totalizer, which sums up the gallons or cubic feet that pass through the meter, is used. Most service meters are of this type. They are used in private, commercial, and industrial activities where the total amount of flow measured is used in determining customer billing. In wastewater treatment, where sampling operations are important, automatic composite sampling units—flow proportioned to grab a sample every so many gallons—are used. Totalizer meters can be the velocity (propeller or turbine), positive displacement, or compound types. In addition, weirs and flumes are used extensively for measuring flow in wastewater treatment plants because they are not affected (to a degree) by dirty water or floating solids.

FLOW MEASURING DEVICES

In recent decades, flow measurement technology has evolved rapidly from the "old-fashioned way" of measuring flow to the use of simple practical measuring devices too much more sophisticated devices. Physical phenomena discovered centuries ago have been the starting point for many of the viable flowmeter designs used today. Moreover, the recent technology explosion has enabled flowmeters to handle many more applications than could have been imagined centuries ago.

Before selecting a particular type of flow measurement device, Kawamura (2000) recommends consideration of several questions.

1. Is liquid or gas flow being measured?
2. Is the flow occurring in a pipe or in an open channel?

3. What is the magnitude of the flow rate?
4. What is the range of flow variation?
5. Is the liquid being measured clean, or does it contain suspended solids or air bubbles?
6. What is the accuracy requirement?
7. What is the allowable head loss by the flowmeter?
8. Is the flow corrosive?
9. What types of flowmeters are available to the region?
10. What types of postinstallation service are available to the area?

DIFFERENTIAL PRESSURE FLOWMETERS

Kawamura (2000) points out that for many years *differential pressure* flowmeters have been the most widely applied flow-measuring device for water flow in pipes that require accurate measurement at reasonable cost. The differential pressure type of flowmeter makes up the largest segment of the total flow-measurement devices currently being used. Differential pressure-producing meters currently on the market are the Venturi, Dall type, Herschel Venturi, universal Venturi, and venture inserts.

The differential pressure-producing device has a flow restriction in the line that causes a differential pressure or “head” to be developed between the two measurement locations. Differential pressure flowmeters are also known as head meters, and, of all the head meters, the orifice flowmeter is the most widely applied device.

The advantages of differential pressure flowmeters include the following:

- Simple construction
- Relatively inexpensive
- No moving parts
- Transmitting instruments are external
- Low maintenance
- Wide application of flowing fluid; suitable for measuring both gas and liquid flow
- Ease of instrument and range selection
- Extensive product experience and performance database

The disadvantages include the following:

- Flow rate is a nonlinear function of the differential pressure
- Low flow rate rangeability with normal instrumentation

OPERATING PRINCIPLE

Differential pressure flowmeters operate on the principle of measuring pressure at two points in the flow, which provides an indication of the rate of flow that is passing by. The difference in pressures between the two measurement locations of the flowmeter is the result of the change in flow velocities. Simply, there is a set relationship between the flow rate and volume, so the meter instrumentation automatically translates the differential pressure into a volume of flow. The volume of flow rate through the cross-sectional area is given by

$$Q = AV \text{ (average)}$$

where
Q = volumetric flow rate
A = flow in the cross-sectional area
V = average fluid velocity

TYPES OF DIFFERENTIAL PRESSURE FLOWMETERS

Differential pressure flowmeters operate on the principle of developing a differential pressure across a restriction that can be related to the fluid flow rate.

√ **Important Point:** Optimum measurement accuracy is maintained when the flowmeter is calibrated, the flowmeter is installed in accordance with standards and codes of practice, and the transmitting instruments are periodically calibrated.

The most commonly used differential pressure flowmeter types used in water/wastewater treatment are

1. Orifice
2. Venturi
3. Nozzle
4. Pitot-static tube

Orifice

The most commonly applied *orifice* is a thin, *concentric*, flat metal plate with an opening in the plate (see Figure 3.23), installed perpendicular to the flowing stream in a circular conduit or pipe. Typically, a sharp-edged hole is bored in the center of the orifice plate. As the flowing water passes through the orifice, the restriction causes an increase in velocity. A concurrent decrease in pressure occurs as potential energy (static pressure) is converted into kinetic energy (velocity). As the water leaves the orifice, its velocity decreases and its pressure increases as kinetic energy is converted back into potential energy according to the laws of conservation of energy. However, there is always some permanent pressure loss due to friction, and the loss is a function of the ratio of the diameter of the orifice bore (d) to the pipe diameter (D).

For dirty water applications (i.e., wastewater), a concentric orifice plate will eventually have impaired performance due to dirt buildup at the plate. Instead, *eccentric* or *segmental* orifice plates (see Figure 3.24) are often used. Measurements are typically less accurate than those obtained from the concentric orifice plate. Eccentric or segmental orifices are rarely applied in current practice.

The orifice differential pressure flowmeter is the lowest cost differential flowmeter, is easy to install, and has no moving parts. However, it also has high permanent head loss (ranging from

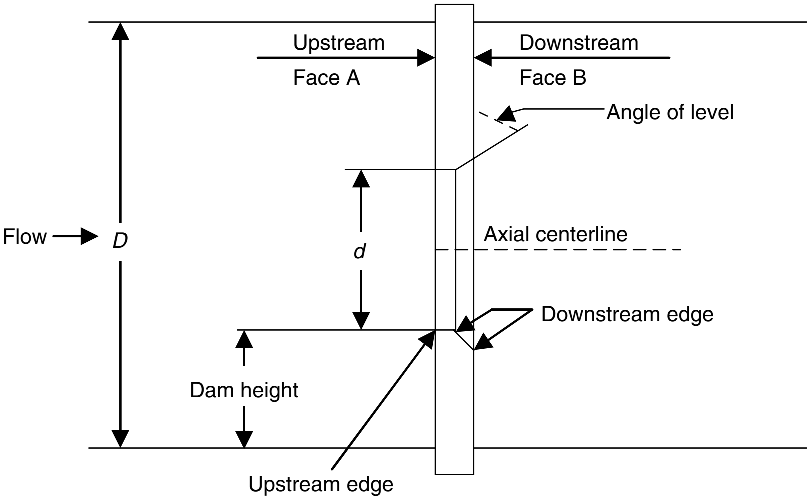


FIGURE 3.23 Orifice plate.

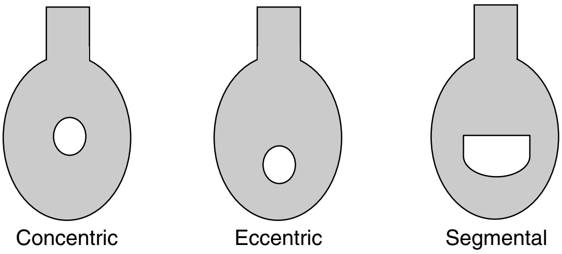


FIGURE 3.24 Types of orifice plate.

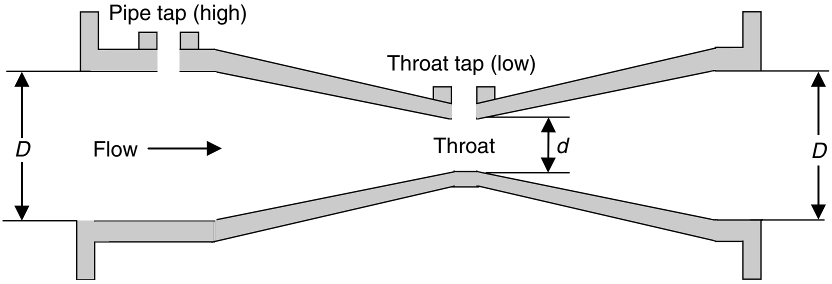


FIGURE 3.25 Venturi tube.

40 to 90%) higher pumping costs, an accuracy of ±2% for a flow range of 4:1, and is affected by wear or damage.

√ **Important Point:** Orifice meters are not recommended for permanent installation to measure wastewater flow; solids in the water easily catch on the orifice, throwing off accuracy. For installation, it is necessary to have ten diameters of straight pipe ahead of the orifice meter to create a smooth flow pattern, and five diameters of straight pipe on the discharge side.

Venturi

A *Venturi* is a restriction with a relatively long passage with smooth entry and exit (see Figure 3.25). It has long life expectancy, simplicity of construction, relatively high-pressure recovery (i.e., produces less permanent pressure loss than a similar sized orifice), but is more expensive, is not linear with flow rate, and is the largest and heaviest differential pressure flowmeter. It is often used in wastewater flows since the smooth entry allows foreign material to be swept through instead of building up as it would in front of an orifice. The accuracy of this type of flowmeter is ±1% for a flow range of 10:1. The head loss across a Venturi flowmeter is relatively small, ranging from 3 to 10% of the differential, depending on the ratio of the throat diameter to the inlet diameter (a.k.a. beta ratio).

Nozzle

Flow nozzles (flow tubes) have a smooth entry and sharp exit (see Figure 3.26). For the same differential pressure, the permanent pressure loss of a nozzle is of the same order as that of an orifice, but it can handle wastewater and abrasive fluids better than an orifice can. Note that for the same line size and flow rate, the differential pressure at the nozzle is lower (head loss ranges from 10 to 20% of the differential) than the differential pressure for an orifice; hence, the total pressure loss is lower than that of an orifice. Nozzles are primarily used in steam service because of their rigidity, which makes them dimensionally more stable at high temperatures and velocities than orifices.

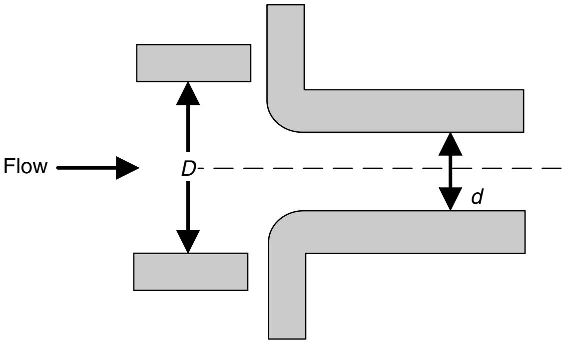


FIGURE 3.26 Long-radius flow nozzle.

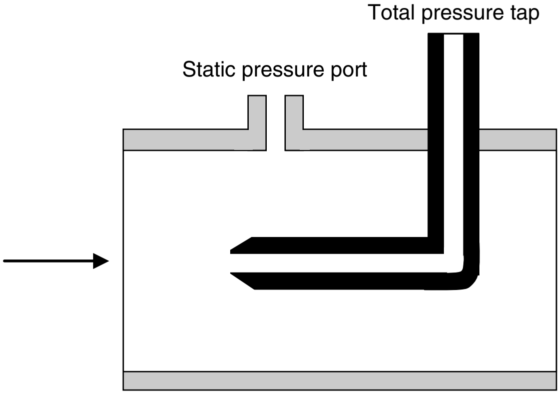


FIGURE 3.27 Pitot tube.

√ **Important Point:** A useful characteristic of nozzles is that they reach a critical flow condition, that is, a point at which further reduction in downstream pressure does not produce a greater velocity through the nozzle. When operated in this mode, nozzles are very predictable and repeatable.

Pitot Tube

A *Pitot tube* is a point velocity-measuring device (see Figure 3.27). It has an impact port; as fluid hits the port, its velocity is reduced to zero and kinetic energy (velocity) is converted to potential energy (pressure head). The pressure at the impact port is the sum of the static pressure and the velocity head. The pressure at the impact port is also known as stagnation pressure or total pressure. The pressure difference between the impact pressure and the static pressure measured at the same point is the velocity head. The flow rate is the product of the measured velocity and the cross-sectional area at the point of measurement. Note that the Pitot tube has negligible permanent pressure drop in the line, but the impact port must be located in the pipe where the measured velocity is equal to the average velocity of the flowing water through the cross section.

MAGNETIC FLOWMETERS

Magnetic flowmeters are relatively new to the water/wastewater industry. They are volumetric flow devices designed to measure the flow of electrically conductive liquids in a closed pipe. They measure the flow rate based on the voltage created between two electrodes (in accordance with Faraday's law

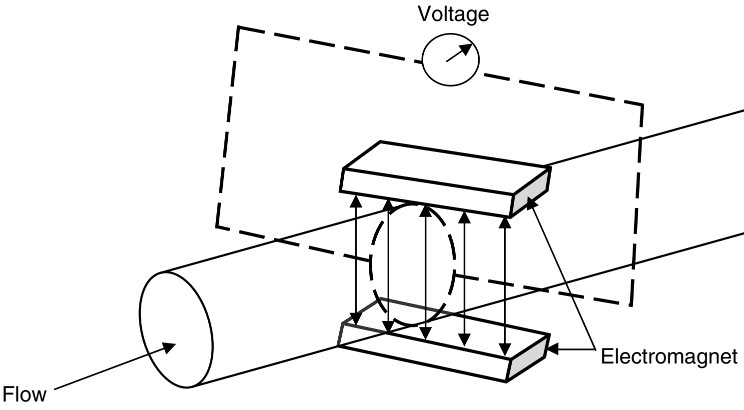


FIGURE 3.28 Magnetic flowmeter.

of electromagnetic induction) as the water passes through an electromagnetic field (see Figure 3.28). Induced voltage is proportional to flow rate. Voltage depends on magnetic field strength (constant), distance between electrodes (constant), and velocity of flowing water (variable).

Properties of the magnetic flowmeter include (1) minimal headloss (no obstruction with line size meter); (2) no effect on flow profile; (3) suitable for size range between 0.1 and 120 in.; (4) have an accuracy rating of from 0.5 to 2% of flow rate; and (5) it measures forward or reverse flow.

The advantages of magnetic flowmeters include the following:

- Obstruction less flow
- Minimal head loss
- Wide range of sizes
- Bi-directional flow measurement
- Variations in density, viscosity, pressure, and temperature yield negligible effect
- Can be used for wastewater
- No moving parts

The disadvantages include the following:

- Metered liquid must be conductive (but you would not use this type meter on clean fluids anyway)
- Bulky, expensive in smaller sizes, and may require periodic calibration to correct drifting of the signal

The combination of the magnetic flowmeter and the transmitter is considered as a system. A typical system, schematically illustrated in Figure 3.29, shows a transmitter mounted remote from the magnetic flowmeter. Some systems are available with transmitters mounted integral to the magnetic flowmeter. Each device is individually calibrated during the manufacturing process, and the accuracy statement of the magnetic flowmeter includes both pieces of equipment. One is not sold or used without the other (Water and Wastewater Instrumentation Testing Association and United States Environmental Protection Agency, 1991).

It is also interesting to note that since 1983 almost every manufacturer has offered the microprocessor-based transmitter.

Regarding minimum piping straight run requirements, magnetic flowmeters are quite forgiving of piping configuration. The downstream side of the magnetic flowmeter is much less critical than the upstream side. Essentially, all that is required of the downstream side is that sufficient

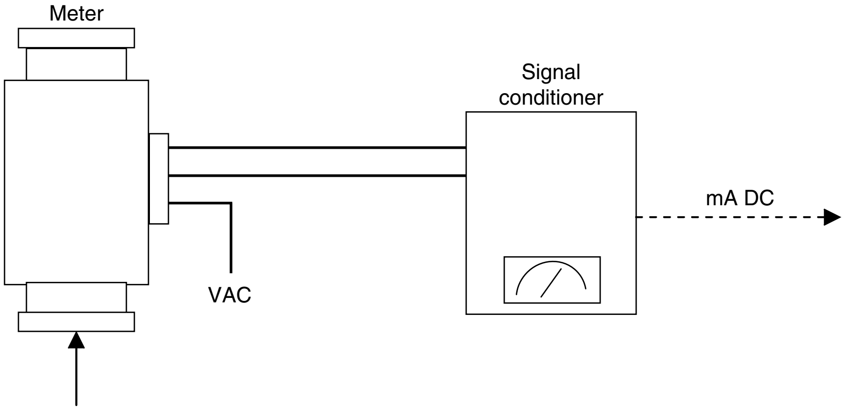


FIGURE 3.29 Magnetic flowmeter system.

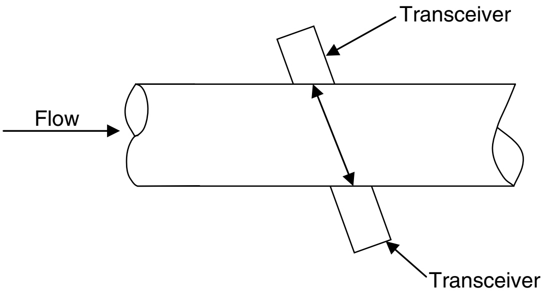


FIGURE 3.30 Time-of-flight ultrasonic flowmeter.

backpressure is provided to keep the magnetic flowmeter full of liquid during flow measurement. Two diameters downstream should be acceptable (Mills, 1991).

√ **Note:** Magnetic flowmeters are designed to measure conductive liquids only. If air or gas is mixed with the liquid, the output becomes unpredictable.

ULTRASONIC FLOWMETERS

Ultrasonic flowmeters use an electronic transducer to send a beam of ultrasonic sound waves through the water to another transducer on the opposite side of the unit. The velocity of the sound beam varies with the liquid flow rate, so the beam can be electronically translated to indicate flow volume. The accuracy is ±1% for a flow velocity ranging from 1 to 25 ft/s, but the meter reading is greatly affected by a change in the fluid composition.

Two types of ultrasonic flowmeters are in general use for closed pipe flow measurements. The first (time of flight or transit time) usually uses pulse transmission and is for clean liquids, while the second (Doppler) usually uses continuous wave transmission and is for dirty liquids.

Time-of-Flight Ultrasonic Flowmeters

Time-of-flight flowmeters make use of the difference in the time for a sonic pulse to travel a fixed distance, first in the direction of flow and then against the flow. This is accomplished by opposing transceivers positioned on diagonal path across meter spool as shown in Figure 3.30. Each transmits and receives ultrasonic pulses with flow and against flow. The fluid velocity is directly proportional to time difference of pulse travel.

The time-of-flight ultrasonic flowmeter operates with minimal head loss and it has an accuracy range of 1–2.5% full scale. It can be mounted as integral spool piece transducers or as externally mountable clamp-ons. It can measure flow accurately when properly installed and applied (Brown, 1991).

The advantages of time of flight ultrasonic flowmeters include the following:

- No obstruction to flow
- Minimal head loss
- Clamp-ons
    - Can be portable
    - No interruption of flow
- No moving parts
- Linear over wide range
- Wide range of pipe sizes
- Bi-directional flow measurement

The disadvantages include the following:

- Sensitive to solids or bubble content
    - Interfere with sound pulses
- Sensitive to flow disturbances
- Alignment of transducers is critical
- Clamp-on—pipe walls must freely pass ultrasonic pulses

Doppler-Type Ultrasonic Flowmeters

Doppler ultrasonic flowmeters make use of the Doppler frequency shift caused by sound scattered or reflected from moving particles in the flow path. Doppler meters are not considered to be as accurate as time of flight flowmeters. However, they are very convenient to use and generally more popular and less expensive than time-of-flight flowmeters.

In operation, a propagated ultrasonic beam is interrupted by particles in moving fluid and reflected toward a receiver. The difference of propagated and reflected frequencies is directly proportional to fluid flow rate.

Ultrasonic Doppler flowmeters feature minimal head loss with an accuracy of 2–5% full scale. They are either of the integral spool piece transducer type or externally mountable clamp-ons.

The advantages of the Doppler ultrasonic flowmeter include the following:

- No obstruction to flow
- Minimal head loss
- Clamp-on
    - Can be portable
    - No interruption of flow
- No moving parts
- Linear over wide range
- Wide range of pipe sizes
- Low installation and operating costs
- Bi-directional flow measurement

The disadvantages include the following:

- Requires minimum concentration and size of solids or bubbles for reliable operation (see Figure 3.31)
- Requires a minimum speed to maintain suspension
- Clamp-on type limited to sonically conductive pipe

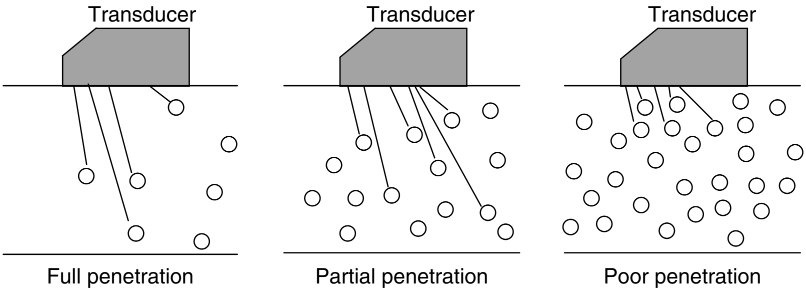


FIGURE 3.31 Particle concentration effect; the greater the number of particles, the greater the number of errors.

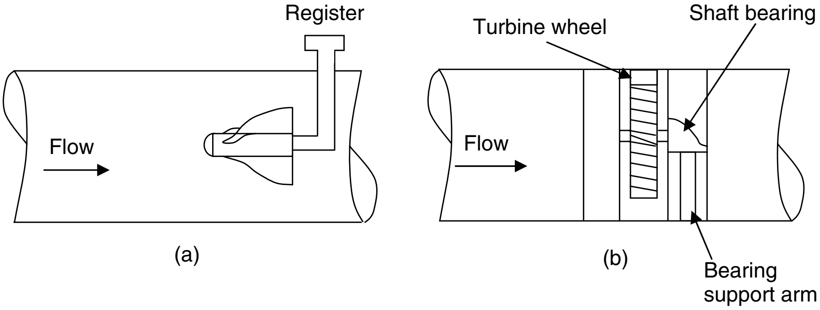


FIGURE 3.32 (a) Propeller meter; (b) Turbine meter.

VELOCITY FLOWMETERS

Velocity or *turbine* flowmeters use a propeller or turbine to measure the velocity of the flow passing the device (see Figure 3.32). The velocity is then translated into a volumetric amount by the meter register. Sizes are available from a variety of manufacturers to cover the flow range from 0.001 to over 25,000 gpm for liquid service. End connections are available to meet the various piping systems. The flowmeters are typically manufactured of stainless steel but are also available in a wide variety of materials, including plastic. Velocity meters are applicable to all clean fluids. Velocity meters are particularly well suited for measuring intermediate flow rates on clean water (Oliver, 1991).

The advantages of the velocity meter include the following:

- Highly accurate
- Corrosion-resistant materials
- Long-term stability
- Liquid or gas operation
- Wide operating range
- Low pressure drop
- Wide temperature and pressure limits
- High-shock capability
- Wide variety of electronics available

As shown in Figure 3.32, a turbine flowmeter consists of a rotor mounted on a bearing and shaft in a housing. The fluid to be measured is passed through the housing, causing the rotor to spin with a rotational speed proportional to the velocity of the flowing fluid within the meter. A device to measure the speed of the rotor is employed to make the actual flow measurement. The sensor can be a mechanically gear-driven shaft to a meter or an electronic sensor that detects the passage of each rotor blade generating a pulse. The rotational speed of the sensor shaft and the frequency of the pulse are proportional to the volumetric flow rate through the meter.

POSITIVE-DISPLACEMENT FLOWMETERS

Positive-displacement flowmeters are most commonly used for customer metering; they have long been used to measure liquid products. These meters are very reliable and accurate for low flow rates because they measure the exact quantity of water passing through them. Positive-displacement flowmeters are frequently used for measuring small flows in a treatment plant because of their accuracy. Repair or replacement is easy because they are so common in the distribution system.

In essence, a positive-displacement flowmeter is a hydraulic motor with high volumetric efficiency that absorbs a small amount of energy from the flowing stream. This energy is used to overcome internal friction in driving the flowmeter and its accessories and is reflected as a pressure drop across the flowmeter. Pressure drop is regarded as an unavoidable feature that must be minimized. It is the pressure drop across the internals of a positive displacement flowmeter that actually creates a hydraulically unbalanced rotor, which causes rotation (Barnes, 1991).

Simply stated, a positive-displacement flowmeter is one that continuously divides the flowing stream into known volumetric segments, isolates the segments momentarily, and returns them to the flowing stream while counting the number of displacements.

A positive-displacement flowmeter can be broken down into three basic components: the external housing, the measuring unit, and the counter drive train.

The external housing is the pressure vessel that contains the product being measured.

The measuring unit is a precision metering element made up of the measuring chamber and the displacement mechanism. The most common displacement mechanisms include the oscillating piston, sliding vane, oval gear, trirotor, birotor, and nutating disc types (see Figure 3.33).

The counter drive train is used to transmit the internal motion of the measuring unit into a usable output signal. Many positive-displacement flowmeters use a mechanical gear train that requires a rotary shaft seal or packing gland where the shaft penetrates the external housing.

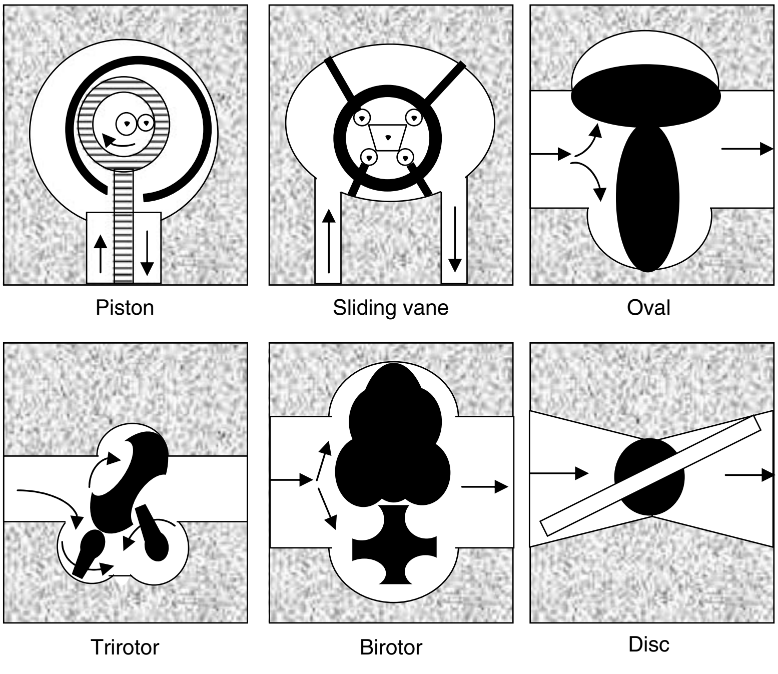


FIGURE 3.33 Six common positive displacement meter principles.

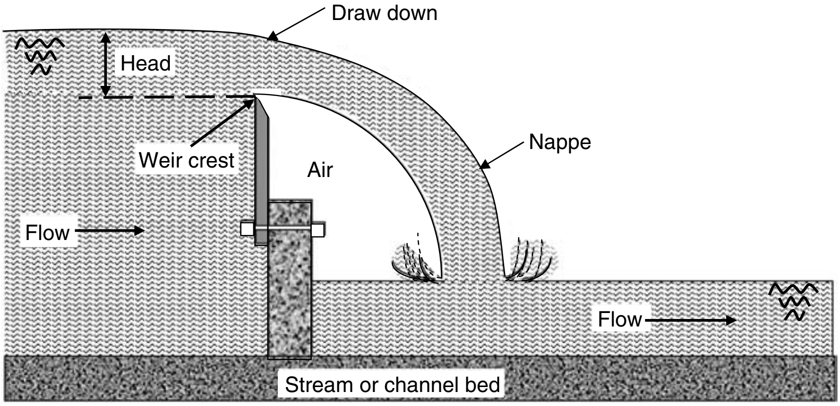


FIGURE 3.34 Side view of a weir.

The positive-displacement flowmeter can offer excellent accuracy, repeatability, and reliability in many applications.

The positive-displacement flowmeter has satisfied many needs in the past and should play a vital role in serving the future needs as required.

OPEN-CHANNEL FLOW MEASUREMENT

The majority of industrial liquid flows are carried in closed conduits that flow completely full and under pressure. However, this is not the case for high-volume flows of liquids in waterworks, sanitary, and stormwater systems that are commonly carried in open channels. Low system heads and high volumetric flow rates characterize flow in open channels.

The most commonly used method of measuring the rate of flow in open-channel flow configurations is that of *hydraulic structures*. In this method, flow in an open channel is measured by inserting a hydraulic structure into the channel, which changes the level of liquid in or near the structure. By selecting the shape and dimensions of the hydraulic structure, the rate of flow through or over the restriction will be related to the liquid level in a known manner. Thus, the flow rate through the open channel can be derived from a single measurement of the liquid level in or near the structure (Grant, 1991).

The hydraulic structures used in measuring flow in open channels are known as primary measuring devices and may be divided into two broad categories—weirs and flumes, which are covered in the following subsections.

WEIRS

The *weir* is a widely used device to measure open-channel flow. As shown in Figure 3.34, a weir is simply a dam or obstruction placed in the channel so that water backs up behind it and then flows over it. The sharp crest or edge allows the water to spring clear of the weir plate and to fall freely in the form of a *nappe*.

As Nathanson (1997) points out, when the nappe discharges freely into the air, there is a hydraulic relationship between the height or depth of water flowing over the weir crest and the flow rate. This height, the vertical distance between the crest and the water surface, is called the *head on the weir*; it can be measured directly with a meter or yardstick or automatically by float-operated recording devices. Two common weirs, rectangular and triangular, are shown in Figure 3.35.

Rectangular weirs are commonly used for large flows (see Figure 3.35A). The formula used to make rectangular weir computations is:

$$Q = 3.33Lh^{1.5} \tag{3.27}$$

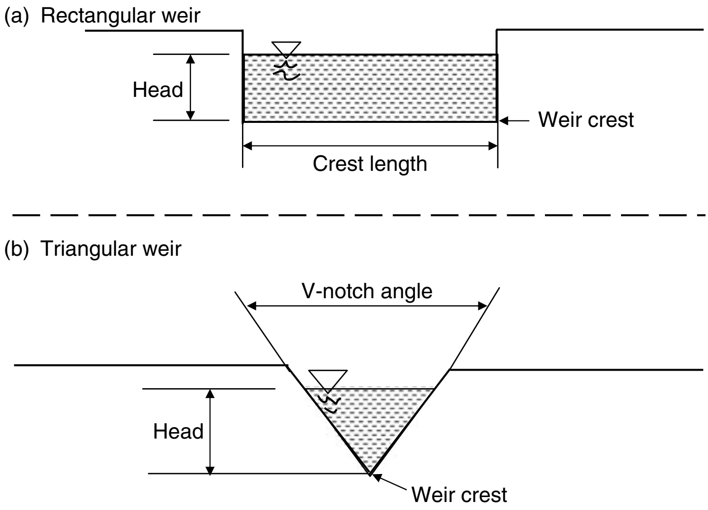


FIGURE 3.35 (a) Rectangular weir; (b) triangular V-notch weir.

where
Q = flow
L = width of weir
h = head on weir (measured from edge of weir in contact with the water, up to the water surface)

EXAMPLE 3.17

Problem:

A weir 4 ft high extends 15 ft across a rectangular channel in which there are 80 cfs flowing. What is the depth just upstream from the weir?

Solution:

$$Q = 3.33Lh^{1.5}$$

$$80 = 3.33 \times 15h^{1.5}$$

$$h = 1.4 \text{ ft (w/calculator: 1.6 INV } y^{1.5} = 1.36 \text{ or } 1.4)$$

$$\text{4-ft high weir} + 1.4 \text{ ft head of water} = 5.4 \text{ ft depth}$$

Triangular weirs, also called V-notch weirs, can have notch angles ranging from 22.5 to 90°, but right angle notches are the most common (see Figure 3.35B).

The formula used to make V-notch (90°) weir calculations is

$$Q = 2.5h^{2.5} \tag{3.28}$$

where Q is the flow and h the head on weir (measured from bottom of notch to water surface).

EXAMPLE 3.18

Problem:

What should be the minimum weir height for measuring a flow of 1200 gpm with a 90° V-notch weir, if the flow is now moving at 4 ft/s in a 2.5-ft wide rectangular channel?

Solution:

$$\frac{1200\,\text{gpm}}{60\ \text{s/min} \times 7.48\ \text{gal/ft}^3} = 2.67\text{cfs}$$

$$Q = A\text{V}$$

$$2.67 = 2.5d4$$

$$d = 0.27\ \text{ft}$$

$$Q = 2.5h^{2.5}$$

$$2.67 = 2.5h^{2.5}$$

$$h = 1.03\ (\text{calculator: } 1.06\ \text{INV}\ y^{2.5} = 1.026\ \text{or}\ 1.03)$$

$$0.27\ \text{ft (original depth)} + 1.03\ \text{(head on weir)} = 1.3\ \text{ft}$$

It is important to point out that weirs, aside from being operated within their flow limits, must also be operated within the available system head. In addition, the operation of the weir is sensitive to the approach velocity of the water, often necessitating a stilling basin or pound upstream of the weir. Weirs are not suitable for water that carries excessive solid materials or silt, which deposit in the approach channel behind the weir and destroy the conditions required for accurate discharge measurements.

√ **Important Point:** Accurate flow rate measurements with a weir cannot be expected unless the proper conditions and dimensions are maintained.

FLUMES

A *flume* is a specially shaped constricted section in an open channel (similar to the Venturi tube in a pressure conduit). The special shape of the flume (see Figure 3.36) restricts the channel area or changes the channel slope, resulting in an increased velocity and a change in the level of the liquid flowing through the flume. The flume restricts the flow, and then expands it in a definite fashion. The flow rate through the flume may be determined by measuring the head on the flume at a single point, usually at some distance downstream from the inlet.

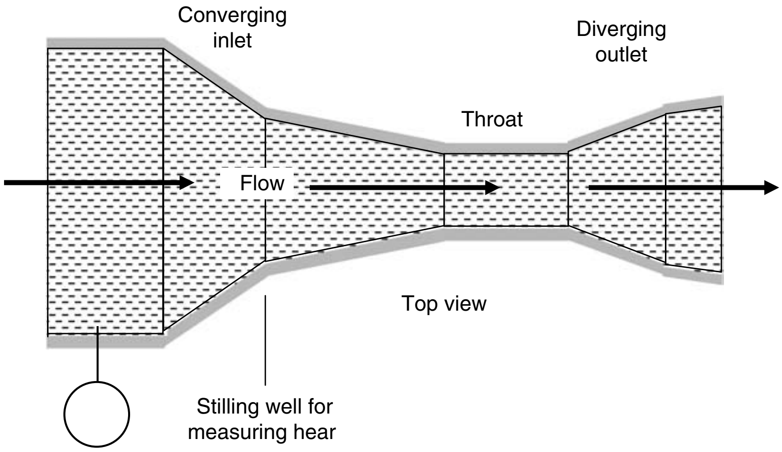


FIGURE 3.36 Parshall flume.

Flumes can be categorized as belonging to one the three general families, depending on the state of flow induced—subcritical, critical, or supercritical. Typically, flumes that induce a critical or supercritical state of flow are most commonly used. This is because when critical or supercritical flow occurs in a channel, one head measurement can indicate the discharge rate if it is made far enough upstream so that the flow depth is not affected by the drawdown of the water surface as it achieves or passes through a critical state of flow. For critical or supercritical states of flow, a definitive head–discharge relationship can be established and measured, based on a single head reading. Thus, most commonly encountered flumes are designed to pass the flow from subcritical through critical or near the point of measurement.

The most common flume used for a permanent wastewater flow-metering installation is called the *Parshall flume*, shown in Figure 3.36.

Formulas for flow through Parshall flumes differ, depending on throat width. The formula below can be used for widths of 1–8 ft, and applies to a medium range of flows.

$$Q = 4WH_a^{1.52}W^{0.026} \tag{3.29}$$

where

Q = flow

H_a = depth in stilling well upstream

W = width of throat

√ **Note:** Parshall flumes are low maintenance items.

REFERENCES

American Water Works Association, 1995a. *Basic Science Concepts and Applications: Principles and Practices of Water Supply Operations*, 2nd ed. Denver: American Water Works Association.

American Water Works Association, 1995b. *Water Treatment: Principles and Practices of Water Supply Operations*, 2nd ed. Denver, CO: American Water Works Association, pp. 449–450.

American Water Works Association, 1996. *Water Transmission and Distribution*, 2nd ed. Denver: American Water Works Association, p. 358.

Arasmith, S., 1993. *Introduction to Small Water Systems*. Albany, OR: ACR Publications, Inc., pp. 59–61.

Barnes, R.G., 1991. Positive Displacement Flowmeters for Liquid Measurement. In *Flow Measurement*, Spitzer, D.W. (ed.). Research Triangle Park, NC: Instrument Society of America, pp. 315–322.

Brown, A.E., 1991. Ultrasonic Flowmeters. In *Flow Measurement*, Spitzer, D.W. (ed.). Research Triangle Park, NC: Instrument Society of America, pp. 415–432.

Grant, D.M., 1991. Open Channel Flow Measurement. In *Flow Measurement*, Spitzer, D.W. (ed). Research Triangle Park, NC: Instrument Society of America, pp. 252–290.

Hauser, B.A., 1993. *Hydraulics for Operators*. Boca Raton, FL: Lewis Publishers.

Hauser, B.A., 1996. *Practical Hydraulics Handbook*, 2nd ed. Boca Raton, FL: Lewis Publishers, p. 91.

Holman, S., 1998. *A Stolen Tongue*. New York: Anchor Press, Doubleday, p. 245.

Kawamura, S., 2000. *Integrated Design and Operation of Water Treatment Facilities*, 2nd ed. New York: Wiley.

Magnusson, R.J., 2001. *Water Technology in the Middle Ages*. Baltimore: The John Hopkins University Press.

McGhee, T.J., 1991. *Water Supply and Sewerage*, 2nd ed. New York: McGraw-Hill.

Mills, R.C., 1991. Magnetic Flowmeters. In *Flow Measurement*, Spitzer, D.W. (ed.). Research Triangle Park, NC: Instrument Society of America.

Nathanson, J.A., 1997. *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 2nd ed. Upper Saddle River, NJ: Prentice-Hall.

Oliver, P.D., 1991. Turbine Flowmeters. In *Flow Measurement*, Spitzer, D.W. (ed.). Research Triangle Park, NC: Instrument Society of America, pp. 373–414.

Viessman, W., Jr. and Hammer, M.J., 1998. *Water Supply and Pollution Control*, 6th ed. Menlo Park, CA: Addison-Wesley.

Water and Wastewater Instrumentation Testing Association and United States Environmental Protection Agency, 1991. *Flow Instrumentation: A Practical Workshop on Making Them Work*. Sacramento, CA:

Water and Wastewater Instrumentation Testing Association and United States Environmental Protection Agency, Section A, May 16–17.

Watson, L., 1988. *The Water Planet: A Celebration of the Wonder of Water.* New York: Crown Publishers, Inc.

FURTHER READING

Cheremisinoff, N.P. and Cheremisinoff, P.N., 1989. *Pumps/Compressors/Fans: Pocket Handbook*. Lancaster, PA: Technomic Publishing Company, p. 3.

Garay, P.N., 1990. *Pump Application Desk Book*. Lilburn, GA: The Fairmont Press (Prentice-Hall), p. 10.

Grimes, A.S., 1976. Supervisory and Monitoring Instrumentation. In *Pump Handbook*, Karassik, I.J. et al. (eds.). New York: McGraw-Hill.

Husain, Z.D. and Sergesketter, M.J., 1991. Differential Pressure Flowmeters. In *Flow Measurement*, Spitzer, D.W. (ed.). Research Triangle Park, NC: Instrument Society of America, pp. 119–160.

Hydraulic Institute, 1990. *The Hydraulic Institute Engineering Data Book*, 2nd ed. Cleveland: Hydraulic Institute.

Hydraulic Institute, 1994. *Hydraulic Institute Complete Pump Standards*, 4th ed. Cleveland: Hydraulic Institute.

Krutzsch, W.C., 1976. Introduction and Classification of Pumps. In *Pump Handbook*, Karassik, I.J. et al. (eds.). New York: McGraw-Hill, p. 1.1.

Lindeburg, M.R., 1986. *Civil Engineering Reference Manual,* 4th ed. San Carlos, CA: Professional Publications, Inc.

Metcalf & Eddy, 1981. *Wastewater Engineering: Collection and Pumping of Wastewater.* New York: McGraw-Hill.

Onondaga County Department of Drainage and Sanitation, 1986. *Basic Maintenance Training Course*. North Syracuse, NY: Onondaga County Department of Drainage and Sanitation.

Spellman, F.R., 2000. *The Handbook for Waterworks Operator Certification, Volume 2: Intermediate Level.* Lancaster, PA: Technomic Publishing Company.

Texas Utilities Association, 1988. *Texas Manual. Manual of Water Utility Operations*, 8th ed. Research Triangle Park, NC: Instrument Society of America, pp. 175–219.

Wahren, U., 1997. *Practical Introduction to Pumping Technology.* Houston: Gulf Publishing Company.

Running Water. White Oak Canyon Trail, Shenandoah National Forest, Virginia (Photo by Revonna M. Bieber.)

4 Water Chemistry

> Chemical testing can be divided into two types. The first type measures a bulk physical property of the sample such as volume, temperature, melting point, or mass. These measurements are normally performed with an instrument, and one simply has to calibrate the instrument to perform the test. Most analyses, however, are of the second type, in which a chemical property of the sample is determined that generates information about how much of what is present.
>
> **—R.K. Smith (1993)**

As mentioned previously, although no one has seen a water molecule, we have determined through x-rays that atoms in water are elaborately meshed. Moreover, although it is true that we do not know as much as we need to know about water—our growing knowledge of water is a work in progress—we have determined many things about water. A large amount of our current knowledge comes from studies of water chemistry.

Water chemistry is important because several factors about water to be treated and then distributed or returned to the environment are determined through simple chemical analysis. Probably the most important determination that the water practitioner makes about water is its hardness.

Why chemistry? "I'm not a chemist," you might say.

Simply put, when you add chlorine to water to make it safe to drink or safe to discharge into a receiving body (usually a river or lake), you are a chemist. Chemistry is the study of substances and the changes they undergo. Water specialists and those interested in the study of water must possess a fundamental knowledge of chemistry.

Before beginning our discussion of water chemistry, it is important for the reader to have some basic understanding of chemistry concepts and chemical terms. The following section presents a review of terms, definitions, and concepts in chemistry.

CHEMISTRY CONCEPTS AND DEFINITIONS

Chemistry, like the other sciences, has its own language; thus, to understand chemistry, you must understand the following concepts and key terms.

CONCEPTS

"Miscible," "Solubility"

1. *Miscible* means capable of being mixed in all proportions. Simply stated, when two or more substances disperse uniformly in all proportions when brought into contact they are said to be completely soluble in one another, or completely miscible. The precise chemistry definition is "homogenous molecular dispersion of two or more substances" (Jost, 1992). Examples are:
   - All gases are completely miscible.
   - Water and alcohol are completely miscible.
   - Water and mercury (in its liquid form) are immiscible liquids.
2. Between the two extremes of miscibility, there is a range of solubility; that is, various substances mix with one another up to a certain proportion. In many environmental situations,

a rather small amount of contaminant is soluble in water in contrast to the complete miscibility of water and alcohol. The amounts are measured in parts per million (ppm).

"Suspension," "Sediment," "Particles," "Solids"

Often water carries solids or particles in suspension. These dispersed particles are much larger than molecules and may be composed of millions of molecules. The particles may be suspended in flowing and initial quiescent conditions but eventually gravity causes settling of the particles. The resultant accumulation by settling is often called sediment or biosolids (sludge) or residual solids in wastewater treatment vessels. Between this extreme of readily falling out by gravity and permanent dispersal as a solution at the molecular level, there are intermediate types of dispersion or suspension. Particles can be so finely milled or of such small intrinsic size as to remain in suspension almost indefinitely and can in some respects be similar to solutions.

"Emulsion"

Emulsions represent a special case of a suspension. As you know, oil and water do not mix. Oil and other hydrocarbons derived from petroleum generally float on water with negligible solubility in water. In many instances, oils may be dispersed as fine oil droplets (an emulsion) in water and not readily separated by floating because of size or the addition of dispersal promoting additives. Oil and, in particular, emulsions, can prove detrimental to many treatment technologies and must be treated in the early steps of a multi-step treatment train.

"Ion"

An ion is an electrically charged particle. For example, sodium chloride or table salt forms charged particles on dissolution in water; sodium is positively charged (a cation), and chloride is negatively charged (an anion). Many salts similarly form cations and anions on dissolution in water.

"Mass Concentration"

Concentration is often expressed in terms of parts per million (ppm) or mg/L. Sometimes parts per thousand (ppt) or parts per billion (ppb) are also used.

$$\text{ppm} = \frac{\text{mass of substance}}{\text{mass of solutions}} \tag{4.1}$$

Because 1 kg of solution with water as a solvent has a volume of approximately 1 L,

$$1\,\text{ppm} \approx 1\,\text{mg/L}$$

DEFINITIONS

- *Chemistry*—The science that deals with the composition and changes in composition of substances. Water is an example of this composition; it is composed of two gases, hydrogen and oxygen. Water also changes form from liquid to solid to gas, but does not necessarily change composition.
- *Matter*—Anything that has weight (mass) and occupies space. Kinds of matter include elements, compounds, and mixtures.

- *Solids*—Substances that maintain definite size and shape. Solids in water fall into one of the following categories:
  1. Dissolved
  2. Colloidal
  3. Suspended

  Dissolved solids are in solution and pass through a filter. The solution consisting of the dissolved components and water forms a single phase (a homogenous solution).

  Colloidal solids (sols) are uniformly dispersed in solution but they form a solid phase that is distinct from the water phase.

  Suspended solids are also a separate phase from the solution. Some suspended solids are classified as *settleable solids*. Placing a sample in a cylinder and measuring the amount of solids that have settled after a set amount of time determines settleable solids. The size of solids increases going from dissolved solids to suspended solids.
- *Liquids*—Having a definite volume, but not shape, liquids will fill containers to certain levels and form free level surfaces.
- *Gases*—Of neither definite volume nor shape, they completely fill any container in which they are placed.
- *Element*—The simplest form of chemical matter. Each element has chemical and physical characteristics different from all other kinds of matter.
- *Compound*—A substance of two or more chemical elements chemically combined. Examples: water (H_2O) is a compound formed by hydrogen and oxygen. Carbon dioxide (CO_2) is composed of carbon and oxygen.
- *Mixture*—A physical, not chemical, intermingling of two or more substances. Sand and salt stirred together form a mixture.
- *Atom*—The smallest particle of an element that can unite chemically with other elements. All the atoms of an element are the same in chemical behavior although they may differ slightly in weight. Most atoms can combine chemically with other atoms to form molecules.
- *Molecule*—The smallest particle of matter or a compound that possesses the same composition and characteristics as the rest of the substance. A molecule may consist of a single atom, two or more atoms of the same kind, or two or more atoms of different kinds.
- *Radical*—Two or more atoms that unite in a solution and behave chemically as if a single atom.
- *Solvent*—The component of a solution that does the dissolving.
- *Solute*—The component of a solution that is dissolved by the solvent.
- *Ion*—An atom or group of atoms that carries a positive or negative electric charge as a result of having lost or gained one or more electrons.
- *Ionization*—The formation of ions by splitting of molecules or electrolytes in solution. Water molecules are in continuous motion, even at lower temperatures. When two water molecules collide, a hydrogen ion is transferred from one molecule to the other. The water molecule that loses the hydrogen ion becomes a negatively charged hydroxide ion. The water molecule that gains the hydrogen ion becomes a positively charged hydronium ion. This process is commonly referred to as the self-ionization of water.
- *Cation*—A positively charged ion.
- *Anion*—A negatively charged ion.
- *Organic*—Chemical substances of animal or vegetable origin made of carbon structure.
- *Inorganic*—Chemical substances of mineral origin.
- *Solids*—As pertaining to water—suspended and dissolved material in water.
- *Dissolved solids*—The material in water that will pass through a glass fiber filter and remain in an evaporating dish after evaporation of the water.

- *Suspended solids*—The quantity of material deposited when a quantity of water, sewage, or other liquid is filtered through a glass fiber filter.
- *Total solids*—The solids in water, sewage, or other liquids; it includes the suspended solids (largely removable by a filter) and filterable solids (those which pass through the filter).
- *Saturated solution*—The physical state in which a solution will no longer dissolve more of the dissolving substance—solute.
- *Colloidal*—Any substance in a certain state of fine division in which the particles are less than one micron in diameter.
- *Turbidity*—A condition in water caused by the presence of suspended matter, resulting in the scattering and absorption of light rays.
- *Precipitate*—A solid substance that can be dissolved, but is separated from the solution because of a chemical reaction or change in conditions such as pH or temperature.

CHEMISTRY FUNDAMENTALS

Whenever water practitioners add a substance to another substance (from adding sugar to a cup of tea to adding chlorine to water to make it safe to drink) they perform chemistry. Water operators (as well as many others) are chemists, because they are working with chemical substances—and how those substances react is important for them to know and to understand.

MATTER

Going through a day without coming in contact with many kinds of *matter* would be impossible. Paper, coffee, gasoline, chlorine, rocks, animals, plants, water, and air—all the materials of which the world is made—are all different forms or kinds of matter. Previously, matter was defined as anything that has mass (weight) and occupies space—matter is distinguishable from empty space by its presence. Thus, obviously, the statement about going through a day without coming into contact with matter is not only correct, but avoiding some form of matter is virtually impossible. Not all matter is the same, even though we narrowly classify all matter into three groups: solids, liquids, and gases. These three groups are called the *physical states of matter* and are distinguishable from one another by means of two general features, shape and volume.

√ **Important Point:** *Mass* is closely related to the concept of *weight*. On Earth, the weight of matter is a measure of the force with which it is pulled by gravity toward the Earth's center. As we leave Earth's surface, the gravitational pull decreases, eventually becoming virtually insignificant, while the weight of matter accordingly reduces to zero. Yet, the matter still possesses the same amount of "mass." Hence, the mass and weight of matter are proportional to each other.

√ **Important Point:** Since matter occupies space, a given form of matter is also associated with a definite volume. Space should not be confused with air, since air is itself a form of matter. *Volume* refers to the actual amount of space that a given form of matter occupies.

Solids have a definite, rigid shape with their particles closely packed together and sticking firmly to each other. A solid does not change its shape to fit a container. Put a solid on the ground and it will keep its shape and volume—it will never spontaneously assume a different shape. Solids also possess a definite volume at a given temperature and pressure.

Liquids maintain a constant volume, but change shape to fit the shape of their container; they do not possess a characteristic shape. The particles of the liquid move freely over one another, but still stick together enough to maintain a constant volume. Consider a glass of water. If we pour the water into a drinking glass, the water takes the shape of the glass; if we pour it into a bowl, the water takes the shape of the bowl. Thus, if space is available, any liquid assumes the shape of the container.

Like solids, liquids possess a definite volume at a given temperature and pressure, and they tend to maintain this volume when they are exposed to a change in either of these conditions.

Gases have no definite fixed shape and their volume can be expanded or compressed to fill different sizes of containers. A gas or mixture of gases like air can be put into a balloon, and will take the shape of the balloon. Particles of gases do not stick together at all and move about freely, filling containers of any shape and size.

A gas is also identified by its lack of a characteristic volume. When confined to a container with nonrigid, flexible walls, for example, the volume that a confined gas occupies depends on its temperature and pressure. When confined to a container with rigid walls, however, the volume of the gas is forced to remain constant.

Internal linkages among its units, including between one atom and another, maintain the constant composition associated with a given substance. These linkages are called *chemical bonds*. When a particular process occurs that involves the making and breaking of these bonds, we say that a *chemical reaction* or a *chemical change* has occurred.

Let us take a closer look at both chemical and physical changes of matter.

Chemical changes occur when new substances are formed that have entirely different properties and characteristics. When wood burns or iron rusts, a chemical change has occurred; the linkages—the chemical bonds—are broken.

Physical changes occur when matter changes its physical properties such as size, shape, and density, as well as when it changes its state, i.e., from gas to liquid to solid. When ice melts or when a glass window breaks into pieces, a physical change has occurred.

THE CONTENT OF MATTER: THE ELEMENTS

Matter is composed of pure basic substances. Earth is made up of the fundamental substances of which all matter is composed. These substances that resist attempts to decompose them into simpler forms of matter are called *elements*. To date, there are more than 100 known elements. They range from simple, lightweight elements to very complex, heavyweight elements. Some of these elements exist in nature in pure form; others are combined. The smallest unit of an element is the *atom*.

The simplest atom possible consists of a nucleus having a single proton with a single electron traveling around it. This is an atom of hydrogen, which has an atomic weight of one because of the single proton. The *atomic weight* of an element is equal to the total number of protons and neutrons in the nucleus of an atom of an element.

To gain an understanding of the basic atomic structure and related chemical principles, it is useful to compare the atom to our solar system. In our solar system, the sun is the center of everything. The *nucleus* is the center in the atom. The sun has several planets orbiting it. The atom has *electrons* orbiting the nucleus. It is interesting to note that the astrophysicist, who would likely find this analogy overly simplistic, is concerned mostly with activity within the nucleus. This is not the case, however, with the chemist. The chemist deals principally with the activity of the planetary electrons; chemical reactions between atoms or molecules involve only electrons, with no changes in the nuclei.

The nucleus is made up of positive electrically charged *protons* and *neutrons* that are neutral (no charge). The negatively charged electrons orbiting it balance the positive charge in the nucleus. An electron has negligible mass (less than 0.02% of the mass of a proton), which makes it practical to consider the weight of the atom as the weight of the nucleus.

Atoms are identified by name, atomic number, and atomic weight. The *atomic number* or *proton number* is the number of protons in the nucleus of an atom. It is equal to the positive charge on the nucleus. In a neutral atom, it is also equal to the number of electrons surrounding the nucleus. As mentioned, the atomic weight of an atom depends on the number of protons and neutrons in the nucleus, the electrons having negligible mass. Atoms (elements) received their names and symbols in interesting ways. The discoverer of the element usually proposes a name for it. Some elements get their symbols from languages other than English. The following is a list of common elements with their common names and the names from which the symbol is derived.

• chlorine	Cl
• copper	Cu (*Cuprum*—Latin)
• hydrogen	H
• iron	Fe (*Ferrum*—Latin)
• nitrogen	N
• oxygen	O
• phosphorus	P
• sodium	Na (*Natrium*—Latin)
• sulfur	S

As shown above, a unique capital letter or a unique combination of capital letter and a small letter designates each unique element. These are called chemical symbols. As is apparent from the list above, most of the time the symbol is easily recognized as an abbreviation of the atom name, such as O for oxygen.

Typically, we do not find most of the elements as single atoms. They are more often found in combinations of atoms called *molecules*. Basically, a molecule is the least common denominator of making a substance what it is.

A system of formulae has been devised to show how atoms are combined into molecules.

When a chemist writes the symbol for an element, it stands for one atom of the element. A subscript following the symbol indicates the number of atoms in the molecule. O_2 is the chemical formula for an oxygen molecule. It shows that oxygen occurs in molecules consisting of two oxygen atoms. As you know, a molecule of water contains two hydrogen atoms and one oxygen atom, so the formula is H_2O.

√ **Important Point:** The chemical formula of the water molecule, H_2O, was defined in 1860 by the Italian scientist Stanislao Cannizzaro.

Some elements have similar chemical properties. For example, a chemical such as bromine (atomic number 35) has chemical properties that are similar to the chemical properties of the element chlorine (atomic number 17, which most water operators are familiar with) and iodine (atomic number 53).

In 1865, English chemist John Newlands arranged some of the known elements in an increasing order of atomic weights. Newlands' arrangement placed the lightest element he knew about at the top of his list and the heaviest element at the bottom. Newlands was surprised when he observed that starting from a given element, every eighth element repeated the properties of the given element.

Later, in 1869, Dmitri Mendeleev, a Russian chemist, published a table of the 63 known elements. In his table, Mendeleev, like Newlands, arranged the elements in an increasing order of atomic weights. He also grouped them in eight vertical columns so that the elements with similar chemical properties would be found in one column. It is interesting to note that Mendeleev left blanks in his table. He correctly hypothesized that undiscovered elements existed that would fill in the blanks when they were discovered. Because he knew the chemical properties of the elements above and below the blanks in his table, he was able to predict quite accurately the properties of some of the undiscovered elements.

Our modern form of the periodic table is based on work done by the English scientist Henry Moseley, who was killed during World War I. Following the work of the New Zealand physicist Ernest Rutherford and the Danish physicist Niels Bohr, Moseley used x-ray methods to determine the number of protons in the nucleus of an atom.

The atomic number, or the number of protons, of an atom is related to its atomic structure. In turn, atomic structure governs chemical properties. The atomic number of an element is more directly related to its chemical properties than is its atomic weight. It is more logical to arrange the periodic table according to atomic numbers than atomic weights. By demonstrating the atomic numbers of elements, Moseley enabled chemists to make a better periodic table.

In the periodic table, each box or section contains the atomic number, symbol, and atomic weight of an element. The numbers down the left side of the box show the arrangement, or configuration, of the electrons in the various shells around the nucleus. For example, the element carbon has an atomic number of 6, its symbol is C, and its atomic weight is 12.01.

In the periodic table, a horizontal row of boxes is called a *period* or *series.* Hydrogen is all by itself because of its special chemical properties. Helium is the only element in the first period. The second period contains lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, and neon. Other elements may be identified by looking at the table.

A vertical column is called a *group* or *family.* Elements in a group have similar chemical properties.

The periodic table is useful because by knowing where an element is located in the table, you can have a general idea of its chemical properties.

As mentioned, for convenience, elements have a specific name and symbol, but they are often identified by chemical symbol only. The symbols of the elements consist of either one or two letters, with the first letter capitalized.

We list the elements important to the water practitioner (about a third of the 100+ elements) below. Those elements most closely associated with water treatment are marked (*).

Element	**Symbol**
Aluminum*	Al
Arsenic	As
Barium	Ba
Cadmium	Ca
Carbon*	C
Calcium	Ca
Chlorine*	Cl
Chromium	Cr
Cobalt	Co
Copper	Cu
Fluoride*	F
Helium	He
Hydrogen*	H
Iodine	I
Iron*	Fe
Lead	Pb
Magnesium*	Mg
Manganese*	Mn
Mercury	Hg
Nitrogen*	N
Nickel	Ni
Oxygen*	O
Phosphorus	P
Potassium	K
Silver	Ag
Sodium*	Na
Sulfur*	S
Zinc	Zn

COMPOUND SUBSTANCES

If we take a pure substance like calcium carbonate (limestone) and heat it, the calcium carbonate ultimately crumbles to a white powder. However, careful examination of the heating process shows that carbon dioxide also evolves from the calcium carbonate. Substances like calcium carbonate that can be broken down into two or more simpler substances are called *compound substances* or simply *compounds*. Heating is a common way of decomposing compounds, but other forms of energy are often used as well.

Chemical elements that make up compounds such as calcium carbonate combine with each other in definite proportions. When atoms of two or more elements are bonded together to form a compound, the resulting particle is called a *molecule*.

√ **Important Point:** This law simply means that only a certain number of atoms or radicals of one element will combine with a certain number of atoms or radicals of a different element to form a chemical compound.

Water, H_2O, is a compound. As stated, compounds are chemical substances made up of two or more elements bonded together. Unlike elements, compounds can be separated into simpler substances by chemical changes. Most forms of matter in nature are composed of combinations of the 100+ pure elements.

If you have a particle of a compound, for example a crystal of salt (sodium chloride), and subdivide until you get the smallest unit of sodium chloride possible, you would have a molecule. As stated, a molecule (or least common denominator) is the smallest particle of a compound that still has the characteristics of that compound.

√ **Important Point:** Because the weights of atoms and molecules are relative and the units are extremely small, the chemist works with units he/she identifies as moles. A mole (symbol mol) is defined as the amount of a substance that contains as many elementary entities (atoms, molecules, and so on) as there are atoms in 12 g of the isotope carbon-12.

√ **Important Point:** An isotope of an element is an atom having the same structure as the element—the same electrons orbiting the nucleus, and the same protons in the nucleus, but having more or fewer neutrons.

One mole of an element that exists as a single atom weighs as many grams as its atomic number (so one mole of carbon weighs 12 g), and it contains 6.022045×10^{23} atoms, which is the *Avogadro's number.*

As stated previously, symbols are used to identify elements. This is a shorthand method for writing the names of the elements. This shorthand method is also used for writing the names of compounds. Symbols used in this manner show kinds and numbers of different elements in the compound. These shorthand representations of chemical compounds are called chemical *formulas*. For example, the formula for table salt (sodium chloride) is NaCl. The formula shows that one atom of sodium combines with one atom of chlorine to form sodium chloride. Let us look at a more complex formula for the compound sodium carbonate (soda ash): Na_2CO_3. The formula shows that this compound is made up of three elements: sodium, carbon, and oxygen. In addition, there are two atoms of sodium, one atom of carbon, and three atoms of oxygen in each molecule.

As mentioned, when depicting chemical reactions, chemical *equations* are used. The following equation shows a chemical reaction that most water/wastewater operators are familiar with: chlorine gas added to water. It shows the formulas of the molecules that react together and the formulas of the product molecules.

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$

As stated previously, a chemical equation tells what elements and compounds are present before and after a chemical reaction. Sulfuric acid poured over zinc will cause the release of hydrogen and the formation of zinc sulfate. This is shown by the following equation:

$$Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2$$

One atom (also one molecule) of zinc unites with one molecule sulfuric acid giving one molecule of zinc sulfate and one molecule (two atoms) of hydrogen. Notice that there is the same number of atoms of each element on each side of the arrow. However, the atoms are combined differently.

Let us look at another example.

When hydrogen gas is burned in air, the oxygen from the air unites with the hydrogen and forms water. The water is the product of burning hydrogen. This can be expressed as an equation.

$$2H_2 + O_2 \rightarrow 2H_2O$$

This equation indicates that two molecules of hydrogen unite with one molecule of oxygen to form two molecules of water.

WATER SOLUTIONS

A *solution* is a condition in which one or more substances are uniformly and evenly mixed or dissolved. A solution has two components, a solvent and a solute. The *solvent* is the component that does the dissolving. The *solute* is the component that is dissolved. In water solutions, water is the solvent. Water can dissolve many other substances—given enough time, there are not too many solids, liquids, and gases that water cannot dissolve. When water dissolves substances, it creates solutions with many impurities.

Generally, a solution is usually transparent and not cloudy. However, a solution may be colored when the solute remains uniformly distributed throughout the solution and does not settle with time.

When molecules dissolve in water, the atoms making up the molecules come apart (dissociate) in the water. This dissociation in water is called *ionization*. When the atoms in the molecules come apart, they do so as charged atoms (both negatively and positively charged) called *ions*. The positively charged ions are called *cations* and the negatively charged ions are called *anions*.

A good example of the ionization occurs when calcium carbonate ionizes:

$CaCO_3$	↔	Ca^{++}	+	CO_3^{-2}
calcium carbonate		calcium ion		carbonate ion
		(cation)		(anion)

Another good example is the ionization that occurs when table salt (sodium chloride) dissolves in water:

NaCl	↔	Na^+	+	Cl^-
sodium chloride		sodium ion		chloride ion
		(cation)		(anion)

Some of the common ions found in water are:

Ion	Symbol
Hydrogen	H^+
Sodium	Na^+
Potassium	K^+
Chloride	Cl^-
Bromide	Br^-
Iodide	I^-
Bicarbonate	HCO_3^-

Water dissolves polar substances better than nonpolar substances. This makes sense when you consider that water is a polar substance. Polar substances such as mineral acids, bases, and salts are easily dissolved in water—while nonpolar substances such as oils, fats, and many organic compounds do not dissolve easily in water.

Water dissolves polar substances better than nonpolar substances but only to a point. Polar substances dissolve in water up to a point—only so much solute will dissolve at a given temperature, for example. When that limit is reached, the resulting solution is saturated. When a solution becomes saturated, no more solute can be dissolved. For solids dissolved in water, if the temperature of the solution is increased, the amount of solids (solutes) required to reach saturation increases.

WATER CONSTITUENTS

Natural water can contain a number of substances (what we may call impurities) or constituents in water treatment operations. The concentrations of various substances in water in dissolved, colloidal, or suspended form are typically low but vary considerably. A hardness value of up to 400 ppm of calcium carbonate, for example, is sometimes tolerated in public supplies, whereas 1 ppm of dissolved iron would be unacceptable.

When a particular constituent can affect the good health of the water user or affect the environment, it is called a contaminant or pollutant. These contaminants, of course, are what the water operator works to prevent from entering or removes from the water supply. In this section, we discuss some of the more common constituents of water.

SOLIDS

Other than gases, all contaminants of water contribute to the solids content. Natural water carries many dissolved and undissolved solids. The undissolved solids are nonpolar substances and consist of relatively large particles of materials such as silt, which will not dissolve. Classified by their size and state, chemical characteristics, and size distribution, solids can be dispersed in water in both suspended and dissolved forms.

Size of solids in water can be classified as suspended solids, settleable, colloidal, or dissolved. Total solids are those that are suspended and dissolved solids that remain behind when the water is removed by evaporation. Solids are also characterized as volatile or nonvolatile.

The distribution of solids is determined by computing the percentage of filterable solids by size range. Solids typically include inorganic solids such as silt and clay from riverbanks and organic matter such as plant fibers and microorganisms from natural or human-made sources.

√ **Important Point:** Although not technically accurate from a chemical point of view because some finely suspended material can actually pass through the filter, suspended solids are defined as those that can be filtered out in the suspended solids laboratory test. The material that passes through the filter is defined as dissolved solids.

As mentioned, colloidal solids are extremely fine suspended solids (particles) of less than one micron in diameter; they are so small (though they still make water cloudy) that they will not settle even if allowed to sit quietly for days or weeks.

TURBIDITY

Simply stated, turbidity refers to how clear the water is. Water's clarity is one of the first characteristics people notice. Turbidity in water is caused by the presence of suspended matter, which results in the scattering and absorption of light rays. The greater the amount of total suspended solids (TSS) in the water, the murkier it appears and the higher the measured turbidity. Thus, simply stated, turbidity is a measure of the light-transmitting properties of water. Natural water that is very clear (low turbidity) allows you to see images at considerable depths. As mentioned, high turbidity water, on the other hand, appears cloudy. Keep in mind that water of low turbidity is not necessarily without dissolved solids. Dissolved solids do not cause light to be scattered or absorbed; thus, the water looks clear. High turbidity causes problems for the waterworks operator—components that cause high turbidity can cause taste and odor problems and will reduce the effectiveness of disinfection.

COLOR

Color in water can be caused by a number of contaminants such as iron, which changes in the presence of oxygen to yellow or red sediments. The color of water can be deceiving. First, color is considered an aesthetic quality of water with no direct health impact. Second, many of the colors associated with water are not true colors, but the result of colloidal suspension (apparent color). This apparent color can often be attributed to iron and to dissolved tannin extracted from decaying plant material. True color is the result of dissolved chemicals (most often organics) that cannot be seen. True color is distinguished from apparent color by filtering the sample.

DISSOLVED OXYGEN (DO)

Although water molecules contain an oxygen atom, this oxygen is not what is needed by aquatic organisms living in our natural waters. A small amount of oxygen, up to about ten molecules of oxygen per million of water, is actually dissolved in water. This dissolved oxygen is breathed by fish and zooplankton and is needed by them to survive. Other gases can also be dissolved in water. In addition to oxygen, carbon dioxide, hydrogen sulfide, and nitrogen are examples of gases that dissolve in water. Gases dissolved in water are important. For example, carbon dioxide is important because of the role it plays in pH and alkalinity. Carbon dioxide is released into the water by microorganisms and consumed by aquatic plants. However, dissolved oxygen (DO) in water is of utmost importance to us here, not only because it is important to most aquatic organisms, but also because DO is also an important indicator of water quality.

Like terrestrial life, aquatic organisms need oxygen to live. As water moves past their breathing apparatus, microscopic bubbles of oxygen gas in the water, DO, are transferred from the water to their blood. Like any other gas-diffusion process, the transfer is efficient only above certain concentrations. In other words, oxygen can be present in the water, but too low a concentration would not sustain aquatic life. Oxygen is also needed by virtually all algae and macrophytes, and for many chemical reactions that are important to water body functioning.

Rapidly moving water, such as a mountain stream or large river, tends to contain a lot of dissolved oxygen, while stagnant water contains little. Bacteria in water can consume oxygen as organic matter decays. Thus, excess organic material in our lakes and rivers can cause an oxygen-deficient situation to occur. Aquatic life can have a hard time in stagnant water that has a lot of rotting, organic material in it, especially in summer, when dissolved-oxygen levels are at a seasonal low.

√ **Important Point:** As mentioned, solutions can become saturated with solute. This is the case with water and oxygen. As with other solutes, the amount of oxygen that can be dissolved at saturation depends upon the temperature of the water. In the case of oxygen, the effect is just the opposite of other solutes. The higher the temperature, the lower the saturation level; the lower the temperature, the higher the saturation level.

METALS

Metals are elements, present in chemical compounds as positive ions or in the form of cations in solution. Metals with a density over 5 kg/dm^3 are known as *heavy metals*. Metals are one of the constituents or impurities often carried by water. Although most of the metals are not harmful at normal levels, a few metals can cause taste and odor problems in drinking water. In addition, some metals may be toxic to humans, animals, and microorganisms. Most metals enter water as part of compounds that ionize to release the metal as positive ions.

Table 4.1 lists some metals commonly found in water and their potential health hazards.

√ **Important Point:** Metals may be found in various physical and chemical forms. These forms, or "species," can be particles or simple organic compounds, organic complexes, or colloids. The dominating form is determined largely by the chemical composition of water, the matrix, and, in particular, the pH.

ORGANIC MATTER

Organic matter or compounds are those that contain the element carbon and that are derived from material that was once alive (i.e., plants and animals). Organic compounds include fats, dyes, soaps, rubber products, plastics, wood, fuels, cotton, proteins, and carbohydrates. Organic compounds in water are usually large, nonpolar molecules that do not dissolve well in water. They often provide large amounts of energy to animals and microorganisms.

√ **Important Point:** Natural organic matter (NOM) is used to describe the complex mixture of organic material, such as humic and hydrophilic acids present in all drinking water sources. NOM can cause major problems in the treatment of water as it reacts with chlorine to form disinfection by-products (DBPs). Many of the DBPs formed by the reaction of NOM with disinfectants are reported to be toxic and carcinogenic to humans if ingested over an extended period. The removal of NOM and hence reduction in DBPs is a major goal in the treatment of any water source.

TABLE 4.1
Common Metals Found in Water

Metal	Health Hazard
Barium	Circulatory system effects and increase in blood pressure
Cadmium	Concentration in the liver, kidneys, pancreas, and thyroid
Copper	Nervous system damage and kidney effects, toxic to humans
Lead	Same as copper
Mercury	Central nervous system (CNS) disorders
Nickel	CNS disorders
Selenium	CNS disorders
Silver	Turns skin gray
Zinc	Causes taste problems—is not a health hazard

INORGANIC MATTER

Inorganic matter or compounds are carbon free, not derived from living matter, and easily dissolved in water; they are of mineral origin. The inorganics include acids, bases, oxides, salts, etc. Several inorganic components are important in establishing and controlling water quality. Two important inorganic constituents in water are nitrogen and phosphorous.

ACIDS

Lemon juice, vinegar, and sour milk are acidic or contain acid. The common acids used in waterworks operations are hydrochloric acid (HCl), sulfuric acid (H_2SO_4), nitric acid (HNO_3), and carbonic acid (H_2CO_3). Note that in each of these acids, hydrogen (H) is one of the elements.

√ **Important Point:** An acid is a substance that produces hydrogen ions (H^+) when dissolved in water. Hydrogen ions are hydrogen atoms stripped of their electrons. A single hydrogen ion is nothing more than the nucleus of a hydrogen atom.

The relative strengths of acids in water (listed in descending order of strength) are classified in Table 4.2.

√ **Note:** Acids and bases become solvated—they loosely bond to water molecules.

BASES

A *base* is a substance that produces hydroxide ions (OH^-) when dissolved in water. Lye or common soap (bitter things) contains bases. The bases used in waterworks operations are calcium hydroxide ($Ca(OH)_2$), sodium hydroxide (NaOH), and potassium hydroxide (KOH). Note that the hydroxyl group (OH) is found in all bases. In addition, note that bases contain metallic substances, such as sodium (Na), calcium (Ca), magnesium (Mg), and potassium (K). These bases contain the elements that produce the alkalinity in water.

SALTS

When acids and bases chemically interact, they neutralize each other. The compound (other than water) that forms from the neutralization of acids and bases is called a *salt*. Salts constitute, by far, the largest group of inorganic compounds. A common salt used in waterworks operations, copper sulfate, is utilized to kill algae in water.

TABLE 4.2
Relative Strengths of Acids in Water

Perchloric acid	$HClO_4$
Sulfuric acid	H_2SO_4
Hydrochloric acid	HCl
Nitric acid	HNO_3
Phosphoric acid	H_3PO_4
Nitrous acid	HNO_2
Hydrofluoric acid	HF
Acetic acid	CH_3COOH
Carbonic acid	H_2CO_3
Hydrocyanic acid	HCN
Boric acid	H_3BO_3

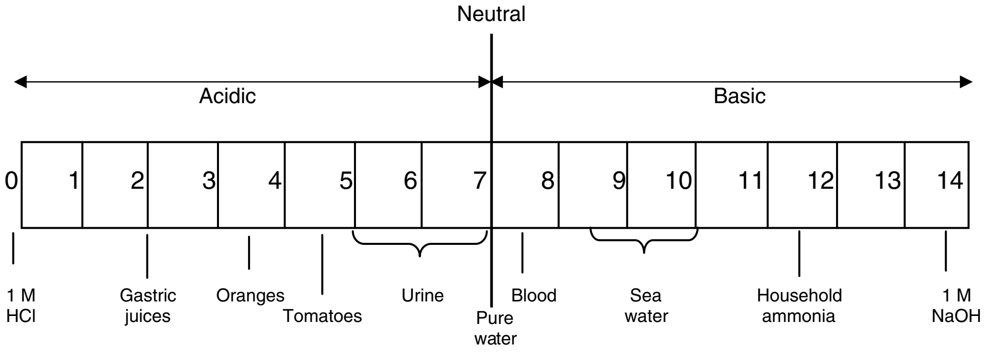


FIGURE 4.1 pH of selected liquids.

pH

pH is a measure of the hydrogen ion (H^+) concentration. Solutions range from very acidic (having a high concentration of H^+ ions) to very basic (having a high concentration of OH^- ions). The pH scale ranges from 0 to 14, with 7 being the neutral value (see Figure 4.1). The pH of water is important to the chemical reactions that take place within water, and pH values that are too high or low can inhibit the growth of microorganisms.

High pH values are considered basic and low pH values are considered acidic. Stated another way, low pH values indicate a high level of H^+ concentration, while high pH values indicate a low H^+ concentration. Because of this inverse logarithmic relationship, there is a tenfold difference in H^+ concentration.

Natural water varies in pH depending on its source. Pure water has a neutral pH, with an equal number H^+ and OH^-. Adding an acid to water causes additional positive ions to be released so that the H^+ ion concentration goes up and the pH value goes down.

$$HCl \leftrightarrow H^+ + Cl^-$$

To control coagulation and corrosion by water, the waterworks operator must test for the hydrogen ion concentration to determine the water's pH. In a test for coagulation, as more alum (acid) is added, the pH value lowers. If more lime (alkali) is added, the pH value rises. This relationship should be remembered—if a good floc is formed, the pH should then be determined and maintained at that pH value until the raw water changes.

Pollution can change water's pH, which in turn can harm animals and plants living in the water. For instance, water coming out of an abandoned coal mine can have a pH of 2, which is very acidic and would definitely affect any fish crazy enough to try to live in it. By using the logarithm scale, this mine-drainage water would be 100,000 times more acidic than neutral water—so stay out of abandoned mines.

√ **Important Point:** Seawater is slightly more basic (the pH value is higher) than most natural fresh water. Neutral water (such as distilled water) has a pH of 7, which is in the middle of being acidic and alkaline. Seawater happens to be slightly alkaline (basic), with a pH of about 8. Most natural water has a pH range of 6–8, although acid rain can have a pH as low as 4.

COMMON WATER MEASUREMENTS

Water practitioners/regulators such as waterworks operators and USEPA along with their scientific counterparts at the U.S. Geological Survey (USGS) have been measuring water for decades. Millions of measurements and analyses have been made. Some measurements are taken almost every time water is sampled and investigated, no matter where in the U.S. the water is being studied. Even these simple measurements can sometimes reveal something important about the water and the environment around it.

USGS (2006) points out that the results of a single measurement of a water's properties are actually less important than looking at how the properties vary over time. For example, if you take the pH of the river running through your town and find that it is 5.5, you might say "Wow, the water is acidic!" But a pH of 5.5 might be "normal" for that river. It is similar to how normal body temperature (when one is not ill) is about 97.5°F, but a youngster's normal temperature is "really normal"—right on the 98.6 mark. As with our temperatures, if the pH of your river begins to change, then you might suspect that something is going on somewhere that is affecting the water, and possibly, its quality. So, often, the changes in water measurements are more important than the actual measured values.

Up to this point, we have discussed important constituents and parameters of turbidity, dissolved oxygen, pH, and others. Now let us discuss parameters such as alkalinity, water temperature, specific conductance, and hardness.

ALKALINITY

Alkalinity is defined as the capacity of water to accept protons; it can also be defined as a measure of water's ability to neutralize an acid. Bicarbonates, carbonates, and hydrogen ions cause alkalinity and hydrogen compounds in a raw water supply. Bicarbonates are the major components of raw water because of the carbon dioxide action on basic materials of soil; borates, silicates, and phosphates may be minor components. Alkaline raw water may also contain salts formed from organic acids such as humic acids.

Alkalinity in water acts as a buffer that tends to stabilize and prevent fluctuations in pH. In fact, alkalinity is closely related to pH, but the two must not be confused. Total alkalinity is a measure of the amount of alkaline materials in water. The alkaline materials act as the buffer to changes in the pH. If the alkalinity to too low (below 80 ppm) there can be rapid fluctuations in pH—i.e., there is insufficient buffer to the pH. High alkalinity (above 200 ppm) results in the water being too buffered. Thus, having significant alkalinity in water is usually beneficial, because it tends to prevent quick changes in pH, which interfere with the effectiveness of common water treatment processes. Low alkalinity also contributes to water's corrosive tendencies.

√ **Note:** When alkalinity is below 80 mg/L, it is considered low.

WATER TEMPERATURE

Water temperature is not only important to fisherman, but also to industries, fish, and algae. A lot of water is used for cooling purposes in power plants that generate electricity. They need cool water to start with, and they generally release warmer water back to the environment. The temperature of the released water can affect downstream habitats. Temperature also can affect the ability of water to hold oxygen as well as the ability of organisms to resist certain pollutants.

SPECIFIC CONDUCTANCE

Specific conductance is a measure of the water's ability to conduct an electrical current. It is highly dependent on the amount of dissolved solids (such as salt) in the water. Pure water, such as distilled water, will have a very low specific conductance, and seawater will have a high specific conductance. Rainwater often dissolves airborne gases and airborne dust while it is in the air, and thus often has a higher specific conductance than distilled water. Specific conductance is an important water-quality measurement because it gives a good idea of the amount of dissolved material in the water.

TABLE 4.3
Water Hardness

Classification	mg/L $CaCO_3$
Soft	0–75
Moderately Hard	75–150
Hard	150–300
Very Hard	Over 300

When electrical wires are attached to a battery and light bulb and wires are put into a beaker of distilled water, the bulb will not light. However, the bulb does light up when the beaker contains saline (saltwater). In the saline water, the salt has dissolved, releasing free electrons, and the water will conduct an electric current.

HARDNESS

Hardness may be considered a physical or chemical characteristic or parameter of water. It represents the total concentration of calcium and magnesium ions, reported as calcium carbonate. Simply, the amount of dissolved calcium and magnesium in water determines its "hardness." Hardness causes soaps and detergents to be less effective and contributes to scale formation in pipes and boilers. Hardness is not considered a health hazard; however, water that contains hardness must often be softened by lime precipitation or ion exchange. Hard water can even shorten the life of fabrics and clothes. Low hardness contributes to the corrosive tendencies of water. Hardness and alkalinity often occur together because some compounds can contribute both alkalinity and hardness ions. Hardness is generally classified as shown in Table 4.3.

WATER TREATMENT CHEMICALS

To operate a water treatment process correctly and safely, water operators need to know the types of chemical used in the processes, what the purpose of each is, and the safety precautions required in the use of each. This section briefly discusses chemicals used in

- Disinfection
- Coagulation
- Taste and odor removal
- Water softening
- Recarbonation
- Ion exchange softening
- Scale and corrosion control

DISINFECTION

In water practice, disinfection is often accomplished using chemicals. The purpose of disinfection is to selectively destroy disease-causing organisms. Chemicals commonly used in disinfection include chlorine and its compounds (most widely used), ozone, bromide, iodine, hydrogen peroxide, and others.

Many factors must be considered when choosing the type of chemical to be used for disinfection. These factors include contact time, intensity and nature of the physical agent, temperature, and type and number of organisms.

COAGULATION

Chemical coagulation conditions water for further treatment by the removal of

- Turbidity, color, and bacteria
- Iron and manganese
- Tastes, odors, and organic pollutants

In water treatment, normal sedimentation processes do not always settle out particles efficiently. This is especially the case when attempting to remove particles less than 50 μm in diameter.

In some instances, it is possible to agglomerate (to make or form into a rounded mass) particles into masses or groups. These rounded masses are of increased size and therefore increased settling velocities, in some instances. For colloidal-sized particles, however, agglomeration is difficult—as colloidal particles are difficult to clarify without special treatment.

Chemical coagulation is usually accomplished by the addition of metallic salts such as aluminum sulfate (alum) or ferric chloride. Alum is the most commonly used coagulant in water treatment and is most effective between pH ranges of 5.0 and 7.5. Sometimes polymer is added to alum to help form small floc for faster settling. Ferric chloride, effective down to a pH of 4.5, is sometimes used.

In addition to pH, a variety of other factors influence the chemical coagulation process, including

1. Temperature
2. Influent quality
3. Alkalinity
4. Type and amount of coagulant used
5. Type and length of flocculation
6. Type and length of mixing

TASTE AND ODOR REMOVAL

Although odor can be a problem with wastewater treatment, the taste and odor parameter is only associated with potable water. Either organic or inorganic materials may produce tastes and odors in water. The perceptions of taste and odor are closely related and often confused by water practitioners as well as by consumers. Thus, it is difficult to precisely measure either one. Experience has shown that a substance that produces an odor in water almost invariably imparts a perception of taste as well. This is not the case, however. Taste is generally attributed to mineral substances in the water. Most of these minerals affect water taste but do not cause odors.

Along with the impact minerals can have on water taste, there are other substances or practices that can affect both water taste and odor (e.g., metals, salts from the soil, constituents of wastewater, and end products generated from biological reactions). When water has a distinct taste but no odor, the taste might be the result of inorganic substances. Anyone who has tasted alkaline water has also tasted its biting bitterness. Then there are the salts; they not only give water that salty taste but also contribute to its bitter taste. Other than from natural causes, water can take a distinctive color or taste, or both, from human contamination of the water.

Organic materials can produce both taste and odor in water. Petroleum-based products are probably the prime contributors to both these problems in water.

Biological degradation or decomposition of organics in surface waters also contributes to both taste and odor problems. Algae are another problem. Certain species of algae produce oily substances that may result in both taste and odor. Synergy can also work to produce taste and odor problems in water. Mixing water and chlorine is one example.

With regard to chemically treating water for odor and taste problems, oxidants such as chlorine, chlorine dioxide, ozone, and potassium permanganate can be used. These chemicals are especially effective when water is associated with an earthy or musty odor caused by the nonvolatile metabolic products of actinomycetes and blue-green algae. Tastes and odors associated with dissolved gases and some volatile organic materials are normally removed by oxygen in aeration processes.

WATER SOFTENING

The reduction of hardness, or softening, is a process commonly practiced in water treatment. Chemical precipitation and ion exchange are the two softening processes that are most commonly used. Softening of hard water is desired (for domestic users) to reduce the amount of soap used, increase the life of water heaters, and reduce encrustation of pipes (cementing together the individual filter media grains).

In chemical precipitation, it is necessary to adjust the pH. To precipitate the two ions most commonly associated with hardness in water, calcium (Ca^{2+}) and magnesium (Mg^{2+}), the pH must be raised to about 9.4 for calcium and about 10.6 for magnesium. To raise the pH to the required levels lime is added.

Chemical precipitation is accomplished by converting calcium hardness to calcium carbonate and magnesium hardness to magnesium hydroxide. This is normally accomplished by using the lime-soda ash or the caustic soda processes.

The lime-soda ash process reduces the total mineral content of the water, removes suspended solids, removes iron and manganese, and reduces color and bacterial numbers. The process, however, has a few disadvantages. McGhee (1991) points out, for example, that the process produces large quantities of sludge, requires careful operation, and, as stated earlier, if the pH is not properly adjusted, may create operational problems downstream of the process.

In the caustic soda process, the caustic soda reacts with the alkalinity to produce carbonate ions for reduction with calcium. The process works to precipitate calcium carbonate in a fluidized bed of sand grains, steel grit, marble chips, or some other similar dense material. As particles grow in size by deposition of $CaCO_3$, they migrate to the bottom of the fluidized bed from which they are removed. This process has the advantages of requiring short detention times (about 8 s) and producing no sludge.

RECARBONATION

Recarbonation (stabilization) is the adjustment of the ionic condition of water so that it will neither corrode pipes nor deposit calcium carbonate, which produces an encrusting film. During or after the lime-soda ash softening process, this recarbonation is accomplished through the reintroduction of carbon dioxide into the water. Lime softening of hard water supersaturates the water with calcium carbonate and may have a pH of greater than 10. Because of this, pressurized carbon dioxide is bubbled into the water, lowering the pH and removing calcium carbonate. The high pH can also create a bitter taste in drinking water. Recarbonation removes this bitterness.

ION EXCHANGE SOFTENING

Hardness can be removed by ion exchange. In water softening, ion exchange replaces calcium and magnesium with a nonhardness cation, usually sodium. Calcium and magnesium in solution are removed by an interchange with sodium within a solid interface (matrix) through which the flow is passed. Similar to the filter, the ion exchanger contains a bed of granular material, a flow distributor, and an effluent vessel that collects the product. The exchange media include greensand (a sand or sediment given a dark greenish color by grains of glauconite), aluminum silicates, synthetic siliceous gels, bentonite clay, sulfonated coal, and synthetic organic resins and are generally in particle form usually ranging up to a diameter of 0.5 mm. Modern applications more often employ artificial organic resins. These clear, BB-sized resins are sphere shaped and have the advantage of providing a greater number of exchange sites. Each of these resin spheres contains sodium ions, which are released into the water in exchange for calcium and magnesium. As long as exchange sites are available, the reaction is virtually instantaneous and complete.

When all the exchange sites have been utilized, hardness begins to appear in the influent (breakthrough). When breakthrough occurs, this necessitates the regeneration of the medium by bringing it in contact with a concentrated solution of sodium chloride.

Ion exchange used in water softening has both advantages and disadvantages. One of its major advantages is that it produces softer water than does chemical precipitation. Additionally, ion exchange does not produce the large quantity of sludge encountered in the lime-soda process. One disadvantage is that although it does not produce sludge, ion exchange does produce concentrated brine. Moreover, the water must be free of turbidity and particulate matter or the resin might function as a filter and become plugged.

Scaling and Corrosion Control

Controlling scale and corrosion is important in water systems. Carbonate and noncarbonate hardness constituents in water cause scale. It forms a chalky-white deposit frequently found on teakettle bottoms. When controlled, this scale can be beneficial, forming a protective coating inside tanks and pipelines. A problem arises when scale is not controlled. Excessive scaling reduces the capacity of pipelines and the efficiency of heat transfer in boilers.

Corrosion is the oxidation of unprotected metal surfaces. Of particular concern in water treatment is the corrosion of iron and its alloys (i.e., the formation of rust). Several factors contribute to the corrosion of iron and steel. Alkalinity, pH, DO, and carbon dioxide all can cause corrosion. Along with the corrosion potential of these chemicals, their corrosive tendencies are significantly increased when water temperature and flow are increased.

DRINKING WATER PARAMETERS: CHEMICAL

> Water, in any of its forms, also … [has] scant respect for the laws of chemistry.
>
> Most materials act either as acids or bases, settling on either side of a natural reactive divided. Not water. It is one of the few substances that can behave both as an acid and as a base, so that under certain conditions it is capable of reacting chemically with itself. Or with anything else.
>
> Molecules of water are off balance and hard to satisfy. They reach out to interfere with every other molecule they meet, pushing its atoms apart, surrounding them, and putting them into solution. Water is the ultimate solvent, wetting everything, setting other elements free from the rocks, making them available for life. Nothing is safe. There isn't a container strong enough to hold it
>
> **—L. Watson (1988)**

Water chemical parameters are categorized into two basic groups: Inorganic and organic chemicals. Both groups enter water from natural causes or pollution.

√ **Note:** The solvent capabilities of water are directly related to its chemical parameters.

In this section, we do not look at each organic/inorganic chemical individually. Instead, we look at general chemical parameter categories such as dissolved oxygen organics (BOD and COD), (DO), synthetic organic chemicals (SOCs), volatile organic chemicals (VOCs), total dissolved solids (TDS), fluorides, metals, and nutrients—the major chemical parameters of concern.

Organics

Natural organics contain carbon and consist of biodegradable organic matter such as wastes from biological material processing, human sewage, and animal feces. Microbes aerobically break down the complex organic molecules into simpler, more stable end products. Microbial degradation yields end products such as carbon dioxide, water, phosphate, and nitrate. Organic particles in water may harbor harmful bacteria and pathogens. Infection by microorganisms may occur if the water is used for primary contact or as a raw drinking water source. Treated drinking water will not present the same health risks. In a potable drinking water plant, all organics should be removed in the water before disinfection.

Organic chemicals also contain carbon; they are substances that come directly from, or are manufactured from, plant or animal matter. Plastics provide a good example of organic chemicals that are made from petroleum, which originally came from plant and animal matter. Some organic chemicals (like those discussed above) released by decaying vegetation, occur naturally and by themselves tend not to pose health problems when they get in our drinking water. However, more serious problems are caused by the 100,000 or more different manufactured or synthetic organic chemicals in commercial use today. They include paints, herbicides, synthetic fertilizers, pesticides, fuels, plastics, dyes, preservatives, flavorings and pharmaceuticals, to name a few.

Many organic materials are soluble in water, toxic, and many of them are found in public water supplies. According to Tchobanoglous and Schroeder (1987), the presence of organic matter in water is troublesome. Organic matter causes: (1) color formation; (2) taste and odor problems; (3) oxygen depletion in streams; (4) interference with water treatment process; and (5) the formation of halogenated compounds when chlorine is added to disinfect water.

Remember, organics in natural water systems may come from natural sources or may result from human activities. Generally, the principal source of organic matter in water is from natural sources including decaying leaves, weeds, and trees; the amount of these materials present in natural waters is usually low. Anthropogenic (man-made) sources of organic substances come from pesticides and other synthetic organic compounds.

Again, many organic compounds are soluble in water, and surface waters are more prone to contamination by natural organic compounds than are groundwaters. In water, dissolved organics are usually divided into two categories: *biodegradable* and *nonbiodegradable.*

Biodegradable (able to break down) material consists of organics that can be used for food (nutrients) by naturally occurring microorganisms within a reasonable length of time. Alcohols, acids, starches, fats, proteins, esters, and aldehydes are the main constituents of biodegradable materials. They may result from domestic or industrial wastewater discharges, or they may be end products of the initial microbial decomposition of plant or animal tissue. Biodegradable organics in surface waters cause problems mainly associated with the effects that result from the action of microorganisms. As the microbes metabolize organic material, they consume oxygen.

When this process occurs in water, the oxygen consumed is DO. If the oxygen is not continually replaced in the water by artificial means, the DO level will decrease as the organics are decomposed by the microbes. This need for oxygen is called the *biochemical oxygen demand* (BOD): the amount of DO demanded by bacteria to break down the organic materials during the stabilization action of the decomposable organic matter under aerobic conditions over a 5-day incubation period at 20°C (68°F). This bioassay test measures the oxygen consumed by living organisms using the organic matter contained in the sample and dissolved oxygen in the liquid. The organics are broken down into simpler compounds and the microbes use the energy released for growth and reproduction. A BOD test is not required for monitoring drinking water.

√ **Note:** The more organic material in the water, the higher the BOD exerted by the microbes. Note also that some biodegradable organics can cause color, taste, and odor problems.

Nonbiodegradable organics are resistant to biological degradation. The constituents of woody plants are a good example. These constituents, including tannin and lignic acids, phenols, and cellulose, are found in natural water systems, and are considered refractory (resistant to biodegradation). Some polysaccharides with exceptionally strong bonds, and benzene (for example, associated with the refining of petroleum) with its ringed structure are essentially nonbiodegradable.

Certain nonbiodegradable chemicals can react with oxygen dissolved in water. The *chemical oxygen demand* (COD) is a more complete and accurate measurement of the total depletion of dissolved oxygen in water. *Standard Methods* defines COD as a test that provides a measure of the oxygen equivalent of that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant. The procedure is detailed in *Standard Methods.*

√ **Note:** COD is not normally used for monitoring water supplies, but is often used for evaluating contaminated raw water.

SYNTHETIC ORGANIC CHEMICALS (SOCs)

Synthetic organic chemicals (SOCs) are man-made, and because they do not occur naturally in the environment, they are often toxic to humans. More than 50,000 SOCs are in commercial production, including common pesticides, carbon tetrachloride, chloride, dioxin, xylene, phenols, aldicarb, and thousands of other synthetic chemicals. Unfortunately, even though they are so prevalent, little data has been collected on these toxic substances. Determining definitively just how dangerous many of the SOCs are is rather difficult.

VOLATILE ORGANIC CHEMICALS (VOCs)

Volatile organic chemicals (VOCs) are organic chemicals that are particularly dangerous. VOCs are absorbed through the skin during contact with water—as in the shower or bath. Hot water exposure allows these chemicals to evaporate rapidly, and they are harmful if inhaled. VOCs can be found in any tap water, regardless of in what part of the country one lives and the water supply source.

TOTAL DISSOLVED SOLIDS (TDS)

Earlier we pointed out that solids in water occur either in solution or in suspension, and are distinguished by passing the water sample through a glass-fiber filter. By definition, the *suspended solids* are retained on top of the filter, and the *dissolved solids* pass through the filter with the water. When the filtered portion of the water sample is placed in a small dish and then evaporated, the solids in the water remain as residue in the evaporating dish. This material is called *total dissolved solids*, or TDS.

Dissolved solids may be organic or inorganic. Water may come into contact with these substances within the soil, on surfaces, and in the atmosphere. The organic dissolved constituents of water are from the decay products of vegetation, organic chemicals, and organic gases. Removing these dissolved minerals, gases, and organic constituents is desirable because they may cause physiological effects and produce aesthetically displeasing color, taste, and odors.

√ **Note:** In water distribution systems, a high TDS means high conductivity with consequent higher ionization in corrosion control. However, high TDS also means more likelihood of a protective coating, a positive factor in corrosion control.

FLUORIDES

According to Phyllis J. Mullenix, Ph.D., water fluoridation is not the safe public health measure we have been led to believe. Concerns about uncontrolled dosage, accumulation in the body over time, and effects beyond the teeth (brain as well as bones) have not been resolved for fluoride. The health of citizens necessitates that all the facts be considered, not just those that are politically expedient.

Most medical authorities would take issue with Dr. Mullenix's view on the efficacy of fluoride in reducing tooth decay. Most authorities seem to hold that a moderate amount of *fluoride* ions (F^-) in drinking water contributes to good dental health. Fluoride is seldom found in appreciable quantities of surface waters and appears in groundwater in only a few geographical regions, although it is sometimes found in a few types of igneous or sedimentary rocks. Fluoride is toxic to humans in large quantities (the key words are “large quantities” or in Dr. Mullenix’s view “uncontrolled dosages”) and also toxic to some animals.

Fluoride used in small concentrations (about 1.0 mg/L in drinking water) can be beneficial. Experience has shown that drinking water containing a proper amount of fluoride can reduce tooth decay by 65% in children between the ages of 12 and 15. However, when the concentration of fluorides in untreated natural water supplies is excessive, either an alternative water supply must be used or treatment to reduce the fluoride concentration must be applied because excessive amounts of fluoride cause mottled or discolored teeth, a condition called *dental fluorosis*.

HEAVY METALS

Heavy metals are elements with atomic weights between 63.5 and 200.5, and a specific gravity greater than 4.0. Living organisms require trace amounts of some heavy metals, including cobalt, copper, iron, manganese, molybdenum, vanadium, strontium, and zinc. Excessive levels of essential metals, however, can be detrimental to the organism. Nonessential heavy metals of particular concern to surface water systems are cadmium, chromium, mercury, lead, arsenic, and antimony.

Heavy metals in water are classified as either nontoxic or toxic. Only those metals that are harmful in relatively small amounts are labeled toxic; other metals fall into the nontoxic group. In natural waters (other than in groundwaters), sources of metals include dissolution from natural deposits and discharges of domestic, agricultural, or industrial wastes.

All heavy metals exist in surface waters in colloidal, particulate, and dissolved phases, although dissolved concentrations are generally low. The colloidal and particulate metal may be found in (1) hydroxides, oxides, silicates, or sulfides; or (2) adsorbed to clay, silica, or organic matter. The soluble forms are generally ions or unionized organometallic chelates or complexes. The solubility of trace metals in surface waters is predominately controlled by water pH, the type and concentration of liquids on which the metal could adsorb, the oxidation state of the mineral components, and the redox environment of the system.

The behavior of metals in natural waters is a function of the substrate sediment composition, the suspended sediment composition, and the water chemistry. Sediment composed of fine sand and silt will generally have higher levels of adsorbed metal than will quartz, feldspar, and detrital carbonate-rich sediment.

The water chemistry of the system controls the rate of adsorption and desorption of metals to and from sediment. Adsorption removes the metal from the water column and stores the metal in the substrate. Desorption returns the metal to the water column, where recirculation and bioassimilation may take place. Metals may be desorbed from the sediment if the water experiences an increase in salinity, a decrease in redox potential, or a decrease in pH.

Although heavy metals such as iron (Fe) and manganese (Mn) do not cause health problems, they do impart a noticeable bitter taste to drinking water, even at very low concentrations. These metals usually occur in groundwater in solution, and these and others may cause brown or black stains on laundry and on plumbing fixtures.

NUTRIENTS

Elements in water (such as carbon, nitrogen, phosphorous, sulfur, calcium, iron, potassium, manganese, cobalt, and boron—all essential to the growth and reproduction of plants and animals) are called *nutrients* (or biostimulants). The two nutrients that concern us in this text are nitrogen and phosphorous.

Nitrogen (N_2), an extremely stable gas, is the primary component of the Earth’s atmosphere (78%). The nitrogen cycle is composed of four processes. Three of the processes—fixation, ammonification, and nitrification—convert gaseous nitrogen into usable chemical forms. The fourth process—denitrification—converts fixed nitrogen back to the unusable gaseous nitrogen state.

Nitrogen occurs in many forms in the environment and takes part in many biochemical reactions. Major sources of nitrogen include runoff from animal feedlots, fertilizer runoff from agricultural fields, from municipal wastewater discharges, and from certain bacteria and blue-green algae that obtain nitrogen directly from the atmosphere. Certain forms of acid rain can also contribute nitrogen to surface waters.

Nitrogen in water is commonly found in the form of *nitrate* (NO_3), which indicates that the water may be contaminated with sewage. Nitrates can also enter the groundwater from chemical fertilizers used in agricultural areas. Excessive nitrate concentrations in drinking water pose an immediate health threat to infants, both human and animal, which can cause death. The bacteria commonly found in the intestinal tract of infants can convert nitrate to highly toxic nitrites (NO_2). Nitrite can replace oxygen in the bloodstream and results in oxygen starvation that causes a bluish discoloration of the infant ("blue baby" syndrome).

√ **Note:** Lakes and reservoirs usually have less than 2 mg/L of nitrate measured as nitrogen. Higher nitrate levels are found in groundwater ranging up to 20 mg/L, but much higher values are detected in shallow aquifers polluted by sewage and/or excessive use of fertilizers.

Phosphorus (P) is an essential nutrient that contributes to the growth of algae and the eutrophication of lakes, although its presence in drinking water has little effect on health. In aquatic environments, phosphorus is found in the form of phosphate and is a limiting nutrient. If all phosphorus is used, plant growth ceases, no matter the amount of nitrogen available. Many bodies of fresh water currently experience influxes of nitrogen and phosphorus from outside sources. The increasing concentration of available phosphorus allows plants to assimilate more nitrogen before the phosphorus is depleted. If sufficient phosphorus is available, high concentrations of nitrates will lead to phytoplankton (algae) and macrophyte (aquatic plant) production.

Major sources of phosphorus include phosphates in detergents, fertilizer and feedlot runoff, and municipal wastewater discharges. The USEPA 1976 Water Quality Standards—Criteria Summaries for phosphorus—recommended a phosphorus criterion of 0.10 μg/L (elemental) phosphorus for marine and estuarine waters, but no freshwater criterion.

The biological, physical, and chemical condition of our water is of enormous concern to us all because we must live in such intimate contact with water. When these parameters shift and change, the changes affect us, often in ways science cannot yet define for us. Water pollution is an external element that can and does significantly affect our water. But what exactly is water pollution? We quickly learn that water pollution does not always go straight from source to water. Controlling what goes into our water is difficult, because the hydrologic cycle carries water (and whatever it picks up along the way) through all of our environment's media, affecting the biological, physical, and chemical condition of the water we must drink to live.

REFERENCES

Greenberg, A.E. et al. (eds.), 1999. *Standard Methods for Examination of Water and Wastewater*, 20th ed. Washington, DC: American Public Health Association.

Jost, N.J., 1992. Surface and Ground Water Pollution Control Technology. In *Fundamentals of Environmental Science and Technology*, Knowles, P.C. (ed.). Rockville, MD: Government Institutes, Inc.

McGhee, T.J., 1991. *Water Supply and Sewerage*, 6th ed. New York: McGraw-Hill.

Mullenix, P.J., 1997. In *A Letter Sent to Operations and Environmental Committee*, City of Calgary, Canada.

Smith, R.K., 1993. *Water and Wastewater Laboratory Techniques*. Alexandria, VA: Water Environment Federation.

Tchobanoglous, G. and Schroeder, E.D., 1987. *Water Quality*. Reading, MA: Addison-Wesley Publishing Company.

USGS, 2006. *Water Science for Schools: Water Measurements*. Washington, DC: U.S. Geological Survey.

Watson, L., 1988. *The Water Planet: A Celebration of the Wonder of Water*. New York: Crown Publishers.

FURTHER READING

Metcalf & Eddy, Inc., 1991. *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd ed. New York: McGraw-Hill.

Spellman, F.R., 1997. *Wastewater Biosolids to Compost*. Boca Raton, FL: CRC Press.`

Running Water. White Oak Canyon Trail, Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

5 Water Biology

> Scientists picture the primordial Earth as a planet washed by a hot sea and bathed in an atmosphere containing water vapor, ammonia, methane and hydrogen. Testing this theory, Stanley Miller at the University of Chicago duplicated these conditions in the laboratory. He distilled seawater in a special apparatus, passed the vapor with ammonia, methane and hydrogen through an electrical discharge at frequent intervals, and condensed the "rain" to return to the boiling seawater. Within a week, the seawater had turned red. Analysis showed that it contained amino acids, which are the building blocks of protein substances.
>
> Whether this is what really happened early in the Earth's history is not important; the experiment demonstrated that the basic ingredients of life could have been made in some such fashion, setting the stage for life to come into existence in the sea. The saline fluids in most living things may be an inheritance from such early beginnings.
>
> **—F.N. Kemmer (1979)**

Because microorganisms are significant in water, in disease transmission they are the primary agents of water treatment processes. Water practitioners must have considerable knowledge of the biological characteristics of water. Simply put, waterworks operators and students of the science of water cannot fully comprehend the principles of effective water treatment and water science without knowing the fundamentals concerning microorganisms and their relationships to one another; their effect on the treatment process; and their impact on consumers, animals, and the environment.

Water practitioners must know what principal groups of microorganisms are typically found in water supplies (surface and groundwater). They must be able to identify those microorganisms that must be treated (pathogenic organisms) and removed or controlled for biological treatment processes. They must be able to identify the organisms used as indicators of pollution/contamination and know their significance, and they must know the methods used to enumerate the indicator organisms. Finally, water treatment operators must be familiar with those organisms that indicate process conditions to optimize process operation.

√ **Important Point:** To have microbiological activity the body of water or wastewater must possess the appropriate environmental conditions. The majority of wastewater treatment processes, for example, are designed to operate using an aerobic process. The conditions required for aerobic operation are (1) sufficient free, elemental oxygen; (2) sufficient organic matter (food); (3) sufficient water; (4) enough nitrogen and phosphorus (nutrients) to permit oxidation of the available carbon materials; (5) proper pH (6.5–9.0); and (6) lack of toxic materials.

BIOLOGY/MICROBIOLOGY: WHAT IS IT?

Biology is generally defined as the study of living organisms (i.e., the study of life). *Microbiology* is a branch of biology that deals with the study of microorganisms that are so small in size that they must be studied under a microscope. Microorganisms of interest to the water practitioners and students of the science of water include bacteria, protozoa, viruses, algae, and others.

√ **Note:** The science and study of bacteria is known as bacteriology.

As mentioned, the waterworks operator's primary concern is how to control microorganisms that cause waterborne diseases—waterborne pathogens—to protect the consumer (human and animal).

WATER MICROORGANISMS

Microorganisms of interest to water practitioners and students of the science of water include bacteria, protozoa, rotifers, viruses, algae, and fungi. These organisms are the most diverse group of living organisms on Earth and occupy important niches in the ecosystem. Their simplicity and minimal survival requirements allow them to exist in diverse situations.

Water practitioners, in particular, are concerned with water supply and water purification through a treatment process. In treating water, the primary concern, of course, is producing potable water that is safe to drink (free of pathogens), with no accompanying offensive characteristics—foul taste and odor. To accomplish this, the drinking water practitioner must possess a wide range of knowledge. In short, to correctly examine raw water for pathogenic microorganisms and to determine the type of treatment necessary to ensure that the quality of the end product—potable water—meets regulatory standards, as well as to accomplish all the other myriad requirements involved in drinking water processing, the water practitioner must be a combination of specialist/generalist.

As a generalist, the water practitioner requires a great deal of knowledge and skill to understand the "big picture," so to speak. At the same time, drinking water practitioners fine-tune their abilities to a narrow range of focus—a focus that can be zeroed in on a single target within a broad field.

If a practitioner's narrowly focused specialty is not water microbiology, he/she must at least have enough knowledge in biological science to enable full comprehension of the fundamental factors concerning microorganisms and their relationships to one another, their effect on the treatment process, and their impact on the environment, human beings, and other organisms.

In short, the water practitioner as a generalist must know the importance of microbiological parameters and what they indicate—the potential of waterborne diseases. Though true that microbiological contaminants are associated with undesirable tastes and odors, or generators of treatment problems in drinking water technology (for example, algae and fungi) that are not causes of waterborne diseases (and not regulated by public health regulations), they are still important enough to the practitioner that knowledge of them is also essential. This chapter provides fundamental knowledge of water biology (microbiology) for the water practitioner (primarily for the generalist).

As mentioned, because they are a major health concern, water treatment specialists are mostly concerned about how to control microorganisms that cause *waterborne diseases* (e.g., typhoid, tetanus, hepatitis, dysentery, gastroenteritis, and others). Waterborne diseases are carried by *waterborne pathogens* (e.g., bacteria, virus, protozoa, etc.).

To understand how to minimize or maximize growth of microorganisms and control pathogens one must study the structure and characteristics of the microorganisms. In the following sections, the major groups of microorganisms (those important to water practitioners and students of the science of water) are described and discussed in relation to their size, shape, types, nutritional needs, and control.

√ **Important Point:** In the water environment, Koren (1991) points out that water is not a medium for the growth of microorganisms, but is instead a means of transmission (a conduit for; hence, the name *waterborne*) of the pathogen to the place where an individual is able to consume it and there start the outbreak of disease. This is contrary to the view taken by the average person. That is, when the topic of waterborne disease is brought up, we might mistakenly assume that waterborne diseases are at home in water. Nothing could be further from the truth. A water-filled ambience is not the environment in which the pathogenic organism would choose to live, that is, if it has such a choice. The point is microorganisms do not normally grow, reproduce, languish, and thrive in watery surroundings. Pathogenic microorganisms temporarily residing in water are simply biding their time, going with the flow, waiting for their opportunity to meet up with their unsuspecting host or hosts. To a degree, when the pathogenic microorganism finds its host or hosts, it is finally home or may have found its final resting place.

KEY TERMS

Key terms related to the discussion to follow and their basic definitions are listed below.

Algae Simple plants, many microscopic, containing chlorophyll. Freshwater algae are diverse in shape, color, size, and habitat. They are the basic link in the conversion of inorganic constituents in water into organic constituents.

Algal bloom Sudden spurts of algal growth, which can affect water quality adversely and indicate potentially hazardous changes in local water chemistry.

Anaerobic Able to live and grow in the absence of free oxygen.

Autotrophic organisms Produce food from inorganic substances.

Bacteria Single cell, microscopic living organisms (single-celled microorganisms) that possess rigid cell walls. They may be aerobic, anaerobic, or facultative; they can cause disease; and some are important in pollution control.

Biogeochemical cycle The chemical interactions between the atmosphere, hydrosphere, and biosphere.

Coliform organism Microorganisms found in the intestinal tract of humans and animals. Their presence in water indicates fecal pollution and potentially adverse contamination by pathogens.

Denitrification The anaerobic biological reduction of nitrate to nitrogen gas.

Fungi Simple plants lacking in ability to produce energy through photosynthesis.

Heterotrophic organism Organisms that are dependent on organic matter for foods.

Prokaryotic cell The simple cell type, characterized by the lack of a nuclear membrane and the absence of mitochondria.

Virus The smallest form of microorganisms capable of causing disease.

MICROORGANISMS (IN GENERAL)

The microorganisms of concern to water specialists are tiny organisms that make up a large and diverse group of free-living forms; they exist either as single cells, cell bunches, or clusters.

Found in abundance almost anywhere on Earth, the vast majority of microorganisms are not harmful. Many microorganisms, or microbes, occur as single cells (unicellular). Some are multicellular; others, such as viruses, do not have a true cellular appearance.

Mostly, a single microbial cell exhibits the characteristic features common to other biological systems, such as metabolism, reproduction, and growth.

CLASSIFICATION

For centuries, scientists classified the forms of life visible to the naked eye as either animal or plant. The Swedish naturalist Carolus Linnaeus organized much of the current knowledge about living things in 1735.

The importance of organizing or classifying organisms cannot be overstated, for without a classification scheme, it would be difficult to establish a criteria for identifying organisms and to arrange similar organisms into groups. Probably the most important reason for classifying organisms is to make things less confusing (Wistreich and Lechtman, 1980).

Linnaeus was quite innovative in the classification of organisms. One of his innovations is still with us today: the *binomial system of nomenclature.* Under the binomial system, all organisms are generally described by a two-word scientific name, the *genus* and *species.* Genus and species are groups that are part of hierarchy of groups of increasing size, based on their taxonomy. This hierarchy follows:

Kingdom
Phylum

Class
Order
Family
Genus
Species

Using this system, a fruit fly might be classified as:

Animalia
Arthropoda
Insecta
Diptera
Drosophilidae
Drosophila
melanogaster

This means that this organism is the species *melanogaster* in the genus *Drosophila* in the Family Drosophilidae in the Order Diptera in the Class Insecta in the Phylum Arthropoda in the Kingdom Animalia.

To further illustrate how the hierarchical system is exemplified by the classification system, the standard classification of the mayfly (a burrowing macroinvertebrate) is provided below.

MAYFLY

Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Ephermeroptera
Family	Ephemeridae
Genus	*Hexagenia*
Species	*limbata*

Utilizing this hierarchy and Linnaeus's binomial system of nomenclature, the scientific name of any organism (as stated previously) includes both the generic and specific names. In the above instances, to uniquely name the species it is necessary to supply the genus and the species, *Drosophila melanogaster* (i.e., the fruit fly) and *Hexagenia limbata* (mayfly). As shown, the first letter of the generic name is usually capitalized; hence, for example, *E. coli* indicates that *coli* is the species and *Escherichia* (abbreviated to *E.*) is the genus. The largest, most inclusive category—the kingdom—is plant. The names are always in Latin, so they are usually printed in italics or underlined. Some organisms also have English common names. Microbe names of particular interest in water/wastewater treatment include:

- *E. coli*—a coliform bacterium
- *Salmonella typhi*—the typhoid bacillus
- *Giardia lamblia*—a protozoan
- *Shigella* spp.
- *Vibrio cholerae*
- *Campylobacter*
- *Leptospira* spp.
- *Entamoeba histolytica*
- *Crytosporidia*

TABLE 5.1
Simplified Classification of Microorganisms

Kingdom	Members	Cell Classification
Animal	Rotifers	
	Crustaceans	
	Worms and larvae	Eukaryotic
Plant	Ferns	
	Mosses	
Protista	Protozoa	
	Algae	
	Fungi	
	Bacteria	Prokaryotic
	Lower algae forms	

√ **Note:** *Escherichia coli* is commonly known as simply *E. coli*, while *Giardia lamblia* is usually referred to by only its genus name, *Giardia*.

Generally, we use a simplified system of microorganism classification in water science, breaking down classification into the kingdoms of animal, plant, and protista. As a rule, the animal and plant kingdoms contain all the multicelled organisms, and the protists contain all the single-celled organisms. Along with microorganism classification based on the animal, plant, and protista kingdoms, microorganisms can be further classified as being *eukaryotic* or *prokaryotic* (see Table 5.1).

√ **Note:** A eukaryotic organism is characterized by a cellular organization that includes a well-defined nuclear membrane. The prokaryotes have structural organization that sets them off from all other organisms. They are simple cells characterized by a nucleus *lacking* a limiting membrane, an endoplasmic reticulum, chloroplasts, and mitochondria. They are remarkably adaptable, existing abundantly in the soil, the sea, and fresh water.

DIFFERENTIATION

Differentiation among the higher forms of life is based almost entirely upon morphological (form or structure) differences. However, differentiation (even among the higher forms) is not as easily accomplished as you might expect, because normal variations among individuals of the same species occur frequently.

Because of this variation even within a species, securing accurate classification when dealing with single-celled microscopic forms that present virtually no visible structural differences becomes extremely difficult. Under these circumstances, it is necessary to consider physiological, cultural, and chemical differences, as well as structure and form. Differentiation among the smaller groups of bacteria is based almost wholly upon chemical differences.

THE CELL

Amoebas at the start
Were not complex;
They tore themselves apart
And started Sex.

—A. Guiterman (1871–1943)

Cells are the fundamental units of life. The cell retains a dual existence as distinct entity and a building block in the construction of organisms. These conclusions about cells were observed and published by Schleiden (1838). Later, Rudolph Virchow added the powerful dictum, "Omnis cellula e cellula" … "All cells only arise from preexisting cells." This important tenet, along with others, formed the basis of what we call cell theory. The modern tenets of the cell theory include the following:

- All known living things are made up of cells.
- The cell is structural and functional unit of all living things.
- All cells come from preexisting cells by division.
- Cells contain hereditary information, which is passed from cell to cell during cell division.
- All cells are basically the same in chemical composition.
- All energy flow of life occurs within cells.

The modern tenets, of course, postdated Robert Hooke's 1663 discovery of cells in a piece of cork, which he examined under his primitive microscope. Hooke drew the cell (actually it was the cell wall he observed) and coined the word *cell*. The word cell is derived from the Latin word *cellula*, which means small compartment.

Thus, since the 19th century, we have known that all living things, whether animal or plant, are made up of cells. Again, the fundamental unit of all living things, no matter how complex, is the cell. A typical cell is an entity isolated from other cells by a membrane or cell wall. The cell membrane contains protoplasm (the living material found within them) and the nucleus.

In a typical mature plant cell (see Figure 5.1), the cell wall is rigid and is composed of nonliving material, while in the typical animal cell (see Figure 5.2) the wall is an elastic living membrane.

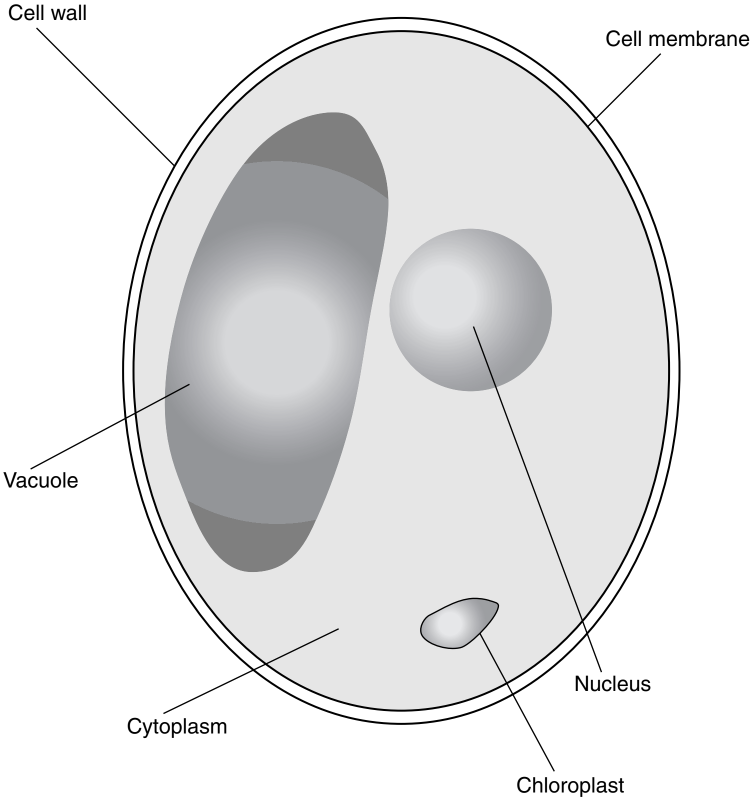


FIGURE 5.1 Plant cell.

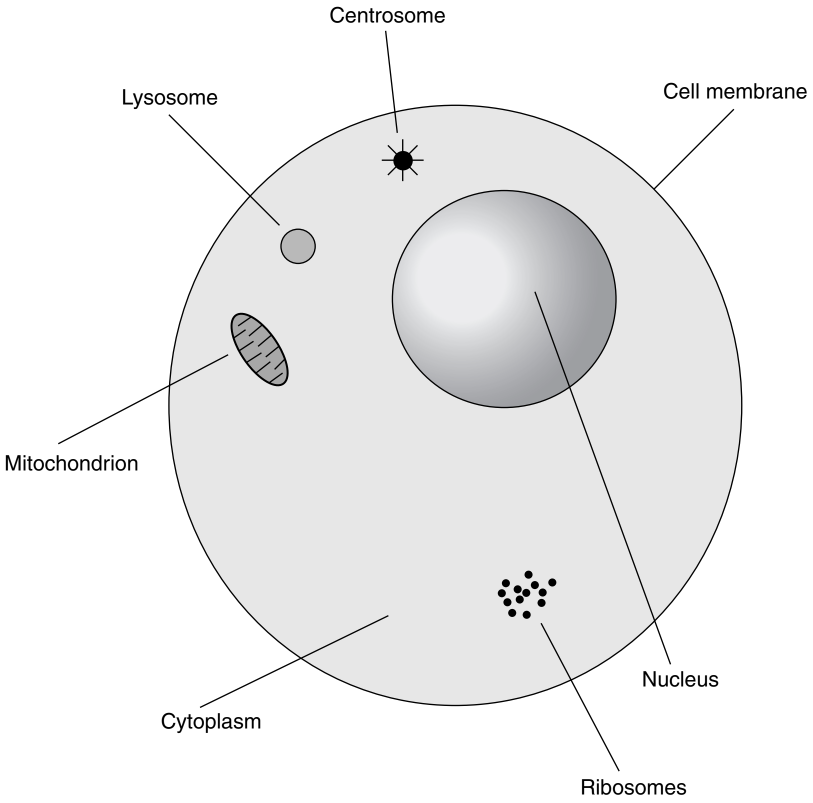


FIGURE 5.2 Animal cell.

Cells exist in a very great variety of sizes and shapes, as well as functions. The cell is the smallest functioning unit of a living thing that still has the characteristics of the whole organism. Size ranges from bacteria too small to be seen with the light microscope to the largest single cell known, the ostrich egg. Microbial cells also have an extensive size range, some being larger than human cells.

√ **Interesting Point:** The small size of a cell is limited by the volume capable of holding genetic material, proteins, etc., which are necessary to carry out the basic cell functions and reproduction. The large size of a cell is limited by metabolism. A cell must take in adequate amounts of oxygen and nutrients and get rid of wastes.

TYPES OF CELLS

Cells are of two fundamental types, prokaryotic and eukaryotic. *Prokaryotic* (meaning before nucleus) cells are simpler in design from eukaryotic cells, possessing neither a nucleus nor the organelles (i.e., internal cell structures, each of which has a specific function within the cells) found in the cytoplasm of eukaryotic (meaning true nucleus) cells. Because prokaryotes do not have a nucleus, DNA is in a "nucleiod" region. With the exception of archaebacteria, proteins are not associated with bacterial DNA. Bacteria are the best known and the most studied form of prokaryotic organisms (see Figure 5.3).

√ **Important Point:** Cells may exist as independent units, e.g., the protozoa, or as parts of multicellular organisms from which the cells may develop specializations and form tissues and organs with specific purposes.

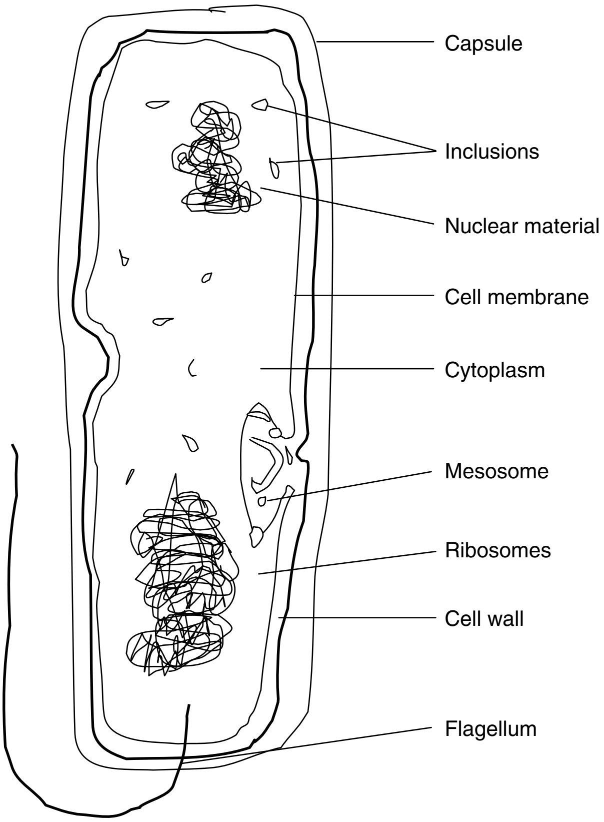


FIGURE 5.3 Bacterial cell.

Prokaryotes are unicellular organisms that do not develop or differentiate into multicellular forms. Some bacteria grow in filaments, or masses of cells, but each cell in the colony is identical and capable of independent existence. Prokaryotes are capable of inhabiting almost every place on the Earth, from the deep ocean to the edges of hot springs to just about every surface of our bodies.

√ **Important Point:** It is often stated that prokaryotic cells are among the most primitive forms of life on the Earth. However, it is important to point out that primitive does not mean they are outdated in the evolutionary sense because primitive bacteria may seem little changed, and thus may be viewed as well adapted.

As mentioned, prokaryotes are distinguished from eukaryotes on the basis of nuclear organization, specifically their lack of a nuclear membrane. Also, prokaryotes are smaller and simpler than eukaryotic cells. Again, prokaryotes also lack any of the intracellular organelles (i.e., internal cell structures, each of which has a specific function within the cell) and structures that are characteristic of eukaryotic cells. Most of the functions of organelles, such as mitochondria, chloroplasts, and the Golgi apparatus, are taken over by the prokaryotic plasma membrane. Prokaryotic cells have three architectural regions: appendages called *flagella* and *pili*—proteins attached to the cell surface; a *cell envelope* consisting of a *capsule*, a *cell wall*, and a *plasma membrane*; and a *cytoplasmic region* that contains the *cell genome* (DNA) and ribosomes and various sorts of inclusions.

Eukaryotic cells evolved about 1.5 billion years ago. Protists, fungi, plants, and animals have eukaryotic cells—all plants and animals are eukaryotes. They are larger, as much as 10 times the size of prokaryotic cells and most of their genetic material is found within a membrane-bound nucleus (a true nucleus), which is generally surrounded by several membrane-bound organelles.

TABLE 5.2
Comparison of Typical Prokaryotic and Eukaryotic Cells

Characteristic	Prokaryotic	Eukaryotic
Size	1–10 µm	10–100 µm
Nuclear envelope	Absent	Present
Cell wall (animals)	Usually	Present (plants)/absent
Plasma membrane	Present	Present
Nucleolus	Absent	Present
DNA	Present (single loop)	Present
Mitochondria	Absent	Present
Chloroplasts	Absent	Present (plants only)
Endoplasmic reticulum	Absent	Present
Ribosomes	Present	Present
Vacuoles	Absent	Present
Golgi apparatus	Absent	Present
Lysosomes	Absent	Often present
Cytoskeleton	Absent	Present

The presence of these membrane-bound organelles points to the significant difference between prokaryotes and eukaryotes. Although eukaryotes use the same genetic code and metabolic processes as prokaryotes, their higher level of organizational complexity has permitted the development of truly multicellular organisms.

√ **Important Point:** An enormous gap exists between prokaryotic and eukaryotic cells:

> … prokaryotes and eukaryotes are profoundly different from each other and clearly represent a marked dichotomy in the evolution of life … The organizational complexity of the eukaryotes is so much greater than that of prokaryotes that it is difficult to visualize how a eukaryote could have arisen from any known prokaryote.
>
> **—C.P. Hickman et al. (1997)**

Prokaryotic and eukaryotic cells also have their similarities. All cell types are bounded by a plasma membrane that encloses proteins and usually nucleic acids such as DNA and RNA. Table 5.2 shows a comparison of key features of both cell types.

√ **Interesting Point:** Plant cells can *generally* be distinguished from animal cells by (1) the *presence* of cell walls, chloroplasts, and central vacuoles in *plants* and their absence in animals; and (2) the *presence* of lysosomes and centrioles in *animals* and their absence in plants.

BACTERIA

The simplest wholly contained life systems are *bacteria* or *prokaryotes*, which are the most diverse group of microorganisms. As mentioned, they are among the most common microorganisms in water, are primitive, unicellular (single-celled) organisms, possessing no well-defined nucleus, and present a variety of shapes and nutritional needs. Bacteria contain about 85% water and 15% ash or mineral matter. The ash is largely composed of sulfur, potassium, sodium, calcium, and chlorides, with small amounts of iron, silicon, and magnesium. Bacteria reproduce by binary fission.

√ **Note:** *Binary fission* occurs when one organism splits or divides into two or more new organisms.

TABLE 5.3
Forms of Bacteria

Form	Technical Name		Example
	Singular	**Plural**	
Sphere	Coccus	Cocci	*Streptococcus*
Rod	Bacillus	Bacilli	*Bacillus typhosis*
Curved or spiral	Spirillum	Spirilla	*Spirillum cholera*

Bacteria, once called the smallest living organisms (now it is known that smaller forms of matter exhibit many of the characteristics of life), range in size from 0.5 to 2 μm in diameter and are about 1–10 μm long.

√ **Note:** A *micron* is a metric unit of measurement equal to 1 thousandth of a millimeter. To visualize the size of bacteria, consider that about 1000 bacteria lying side-by-side would reach across the head of a straight pin.

Bacteria are categorized into three general groups based on their physical form or shape (though almost every variation has been found; see Table 5.3). The simplest form is the sphere. Spherical-shaped bacteria are called *cocci*. Cocci mean "berries." They are not necessarily perfectly round, but may be somewhat elongated, flattened on one side, or oval. Rod-shaped bacteria is called *bacilli*. Spiral-shaped bacteria (called Spirilla), which have one or more twists and are never straight, make up the third group (see Figure 5.4). Such formations are usually characteristic of a particular genus or species. Within these three groups are many different arrangements. Some exist as single cells; others as pairs, as packets of four or eight, as chains, and as clumps.

Most bacteria require *organic food* to survive and multiply. Plant and animal material that gets into the water provides the food source for bacteria. Bacteria convert the food into energy and use the energy to make new cells. Some bacteria can use inorganics (e.g., minerals such as iron) as an energy source and exist and multiply even when organics (pollution) are not available.

STRUCTURE OF BACTERIAL CELL

The structural form and various components of the bacterial cell are probably best understood by referring to the simplified diagram of a rod-form bacterium shown in Figure 5.3. (Note: When studying Figure 5.3, keep in mind that cells of different species may differ greatly, both in structure and chemical composition; for this reason, no typical bacterium exists. Figure 5.3 shows a generalized bacterium used for the discussion that follows. Not all bacteria have all of the features shown in the figure, and some bacteria have structures not shown in the figure.)

Capsules

Bacterial *capsules* (see Figure 5.3) are organized accumulations of gelatinous materials on cell walls, in contrast to *slime layers* (a water secretion that adheres loosely to the cell wall and commonly diffuses into the cell), which are unorganized accumulations of similar material. The capsule is usually thick enough to be seen under the ordinary light microscope (macrocapsule), while thinner capsules (microcapsules) can be detected only by electron microscopy (Singleton and Sainsbury, 1994).

The production of capsules is determined largely by genetics as well as environmental conditions, and depends on the presence or absence of capsule-degrading enzymes and other growth factors. Varying in composition, capsules are mainly composed of water; the organic contents are made up of complex polysaccharides, nitrogen-containing substance, and polypeptides.

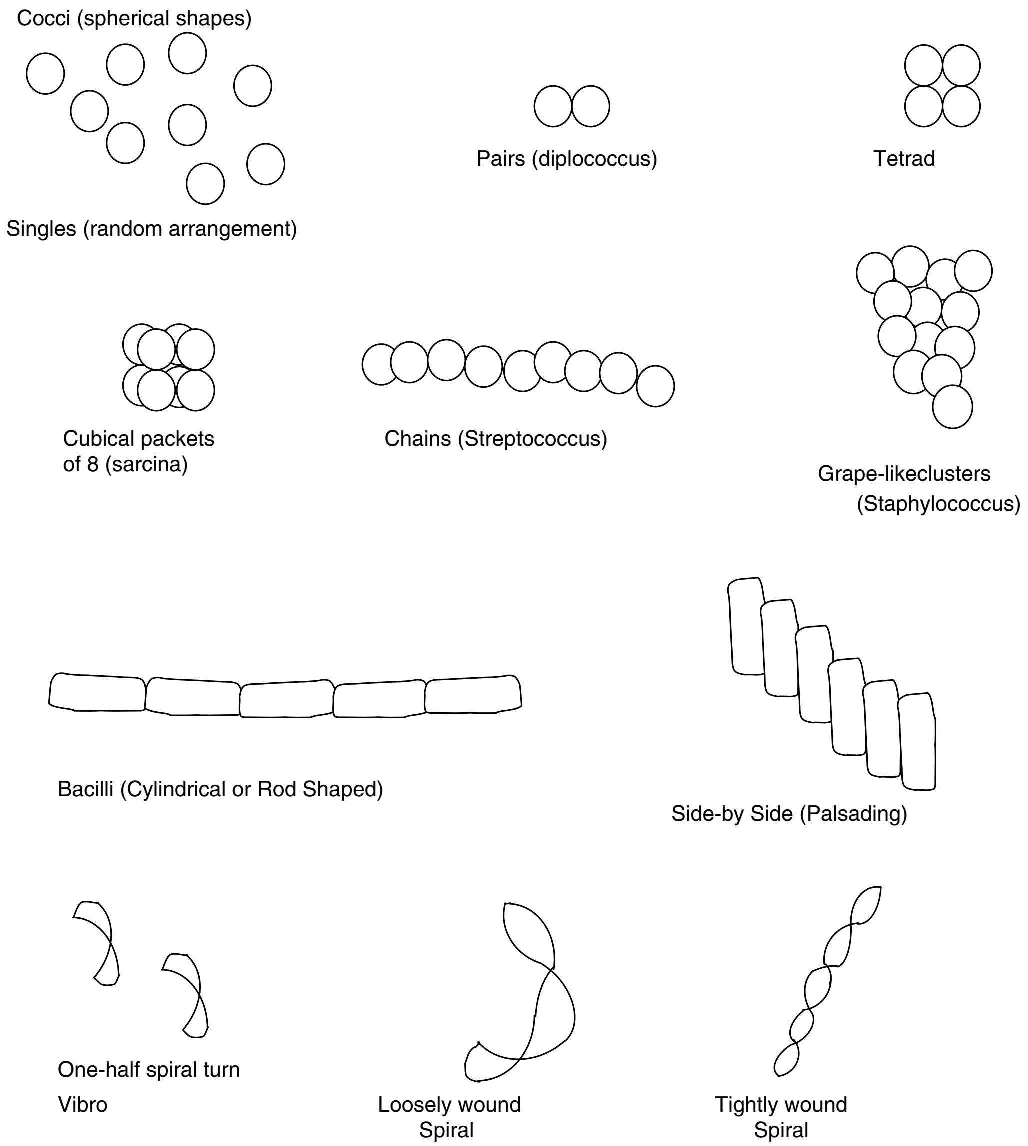


FIGURE 5.4 Bacterial shapes and arrangements.

Capsules confer several advantages when bacteria grow in their normal habitat. For example, they help (1) prevent desiccation; (2) resist phagocytosis by host phagocytic cells; (3) prevent infection by bateriophages; and (4) aid bacterial attachment to tissue surfaces in plant and animal hosts or to surfaces of solids objects in aquatic environments. Capsule formation often correlates with pathogenicity.

Flagella

Many bacteria are motile, and this ability to move independently is usually attributed to a special structure, the *flagella* (singular: flagellum). Depending on species, a cell may have a single flagellum (see Figure 5.3) (*monotrichous* bacteria; *trichous* means "hair"); one flagellum at each end (*amphitrichous* bacteria; *amphi* means "on both sides"); a tuft of flagella at one or both ends (*lophotrichous* bacteria; *lopho* means "tuft"); or flagella that arise all over the cell surface (*peritrichous* bacteria; *peri* means "around").

A flagellum is a threadlike appendage extending outward from the plasma membrane and cell wall. Flagella are slender, rigid, locomotor structures, about 20 µm across and up to 15–20 µm long.

Flagellation patterns are very useful in identifying bacteria and can be seen by light microscopy, but only after being stained with special techniques designed to increase their thickness. The detailed structure of flagella can be seen only in the electron microscope.

Bacterial cells benefit from flagella in several ways. They can increase the concentration of nutrients or decrease the concentration of toxic materials near the bacterial surfaces by causing a change in the flow rate of fluids. They can also disperse flagellated organisms to areas where colony formation can take place. The main benefit of flagella to organisms is their increased ability to flee from areas that might be harmful.

Cell Wall

The main structural component of most prokaryotes is the rigid *cell wall* (see Figure 5.3). Functions of the cell wall include (1) providing protection for the delicate protoplast from osmotic lysis (bursting); (2) determining a cell's shape; (3) acting as a permeability layer that excludes large molecules and various antibiotics and plays an active role in regulating the cell's intake of ions; and (4) providing a solid support for flagella.

Cell walls of different species may differ greatly in structure, thickness, and composition. The cell wall accounts for about 20–40% of a bacterium's dry weight.

Plasma Membrane (Cytoplasmic Membrane)

Surrounded externally by the cell wall and composed of a lipoprotein complex, the *plasma membrane* or cell membrane is the critical barrier, separating the inside from outside the cell (see Figure 5.3). About 7–8 µm thick and comprising 10–20% of a bacterium's dry weight, the plasma membrane controls the passage of all material into and out of the cell. The inner and outer faces of the plasma membrane are embedded with water-loving (hydrophilic) lips, whereas the interior is hydrophobic. Control of material into the cell is accomplished by screening, as well as by electric charge. The plasma membrane is the site of the surface charge of the bacteria.

In addition to serving as an osmotic barrier that passively regulates the passage of material into and out of the cell, the plasma membrane participates in the entire active transport of various substances into the bacterial cell. Inside the membrane, many highly reactive chemical groups guide the incoming material to the proper points for further reaction. This active transport system provides bacteria with certain advantages, including the ability to maintain a fairly constant intercellular ionic state in the presence of varying external ionic concentrations. In addition to participating in the uptake of nutrients, the cell membrane transport system participates in waste excretion and protein secretions.

Cytoplasm

Within a cell and bounded by the cell membrane is a complicated mixture of substances and structures called the *cytoplasm* (see Figure 5.3). The cytoplasm is a water-based fluid containing ribosomes, ions, enzymes, nutrients, storage granules (under certain circumstances), waste products, and various molecules involved in synthesis, energy metabolism, and cell maintenance.

Mesosome

A common intracellular structure found in the bacterial cytoplasm is the mesosome (see Figure 5.3). *Mesosomes* are invaginations of the plasma membrane in the shape of tubules, vesicles, or lamellae. Their exact function is unknown. Currently, many bacteriologists believe that mesosomes are artifacts generated during the fixation of bacteria for electron microscopy.

Nucleoid (Nuclear Body or Region)

The *nuclear region* of the prokaryotic cell is primitive and a striking contrast to that of the eukaryotic cell (see Figure 5.3). Prokaryotic cells lack a distinct nucleus; the function of the nucleus is carried out by a single, long, double-stranded DNA that is efficiently packaged to fit within the nucleoid. The nucleoid is attached to the plasma membrane. A cell can have more than one nucleoid when cell division occurs after the genetic material has been duplicated.

Ribosomes

The bacterial cytoplasm is often packed with ribosomes (see Figure 5.3). *Ribosomes* are minute, rounded bodies made of RNA and are loosely attached to the plasma membrane. Ribosomes are estimated to account for about 40% of a bacterium's dry weight; a single cell may have as many as 10,000 ribosomes. Ribosomes are the site of protein synthesis and are part of the translation process.

Inclusions

Inclusions (or storage granules) are often seen within bacterial cells (see Figure 5.3). Some inclusion bodies are not bound by a membrane and lie free in the cytoplasm. A single-layered membrane about 2–4 μm thick encloses other inclusion bodies. Many bacteria produce polymers that are stored as granules in the cytoplasm.

BACTERIAL GROWTH FACTORS

Several factors affect the rate at which bacteria grow, including temperature, pH, and oxygen levels. The warmer the environment, the faster the rate of growth. Generally, for each increase of 10°C, the growth rate doubles. Heat can also be used to kill bacteria.

Most bacteria grow best at neutral pH. Extreme acidic or basic conditions generally inhibit growth, though some bacteria may require acidic and some require alkaline conditions for growth.

Bacteria are aerobic, anaerobic, or facultative. If *aerobic*, they require free oxygen in the aquatic environment. *Anaerobic* bacteria exist and multiply in environments that lack dissolved oxygen. *Facultative* bacteria (e.g., iron bacteria) can switch from an aerobic to anaerobic growth or grow in an anaerobic or aerobic environment.

Under optimum conditions, bacteria grow and reproduce very rapidly. As stated previously, bacteria reproduce by *binary fission*.

An important point to consider in connection with bacterial reproduction is the rate at which the process can take place. The total time required for an organism to reproduce and the offspring to reach maturity is called *generation time*. Bacteria growing under optimal conditions can double their number about every 20 min. Obviously, this generation time is very short compared with that of higher plants and animals. Bacteria continue to grow at this rapid rate as long as nutrients hold out—even the smallest contamination can result in a sizable growth in a very short time.

√ **Note:** Even though wastewater can contain bacteria counts in the millions per milliliter, in wastewater treatment, under controlled conditions, bacteria can help destroy and identify pollutants. In such a process, bacteria stabilize organic matter (e.g., activated sludge processes), and thereby assist the treatment process in producing effluent that does not impose an excessive oxygen demand on the receiving body. Coliform bacteria can be used as an indicator of pollution by human or animal wastes.

DESTRUCTION OF BACTERIA

In water treatment, the destruction of bacteria is usually called *disinfection*.

√ **Important Point:** Inhibiting the growth of microorganisms is termed antisepsis, while destroying them is called disinfection.

Disinfection does not mean that all microbial forms are killed. That would be *sterilization*. However, disinfection does reduce the number of disease-causing organisms to an acceptable number. Growing bacteria are easy to control by disinfection. Some bacteria, however, form spores—survival structures—which are much more difficult to destroy.

WATERBORNE BACTERIA

All surface waters contain bacteria. Waterborne bacteria, as mentioned, are responsible for infectious epidemic diseases.

Bacterial numbers increase significantly during storm events when streams are high. Heavy rainstorms increase stream contamination by washing material from the ground surface into the stream. After the initial washing occurs, few impurities are left to be washed into the stream, which may then carry relatively "clean" water. A river of good quality shows its highest bacterial numbers during rainy periods; however, a much-polluted stream may show the highest numbers during low flows because of the constant influx of pollutants.

Water operators are primarily concerned with bacterial pathogens responsible for disease. These pathogens enter potential drinking water supplies through fecal contamination and are ingested by humans if the water is not properly treated and disinfected.

√ **Note:** Regulations require that owners of all public water supplies collect water samples and deliver them to a certified laboratory for bacteriological examination at least monthly. The number of samples required is usually in accordance with Federal Standards, which generally require that one sample per month be collected for each 1000 persons served by the waterworks.

PROTOZOA

Protozoans (or "first animals") are a large group of eukaryotic organisms of more than 50,000 known species belonging to the kingdom Protista that have adapted a form of cell to serve as the entire body. In fact, protozoans are one-celled, animal-like organisms with complex cellular structures. In the microbial world, protozoans are giants, many times larger than bacteria. They range in size from 4 µm to 500 µm. The largest ones can almost be seen by the naked eye. They can exist as solitary or independent organisms (for example, the stalked ciliates [see Figure 5.5] such as *Vorticella* sp.), or they can colonize like the sedentary *Carchesium* sp. Protozoa get their name because they employ the same type of feeding strategy as animals; that is, they are heterotrophic, meaning they obtain cellular energy from organic substances such as proteins. Most are harmless, but some are parasitic. Some forms have two life stages: active trophozoites (capable of feeding) and dormant cysts.

The major groups of protozoans are based on their method of locomotion (motility). For example, the *Mastigophora* are motile by means of one or more *flagella* (the whip-like projection that propels the free-swimming organisms—*G. lamblia* is a flagellated protozoan); the *Ciliophora* by means of shortened modified flagella called *cilia* (short hair-like structures that beat rapidly and propel them through the water); the *Sarcodina* by means of amoeboid movement (streaming or gliding action—the shape of amoebae change as they stretch, then contract, from place to place); and the *Sporozoa*, which are nonmotile; they are simply swept along, riding the current of the water.

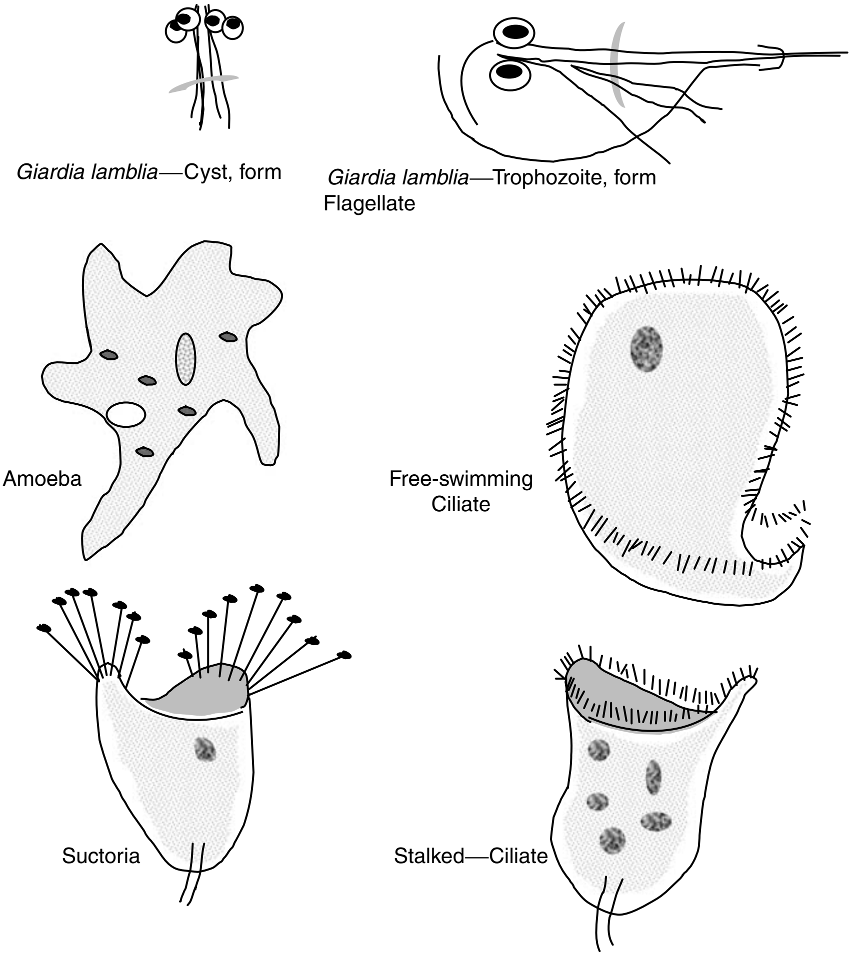


FIGURE 5.5 Protozoa.

Protozoa consume organics to survive; their favorite food is bacteria. Protozoa are mostly aerobic or facultative in regard to oxygen requirements. Toxic materials, pH, and temperature affect protozoan rates of growth in the same way as they affect bacteria.

Most protozoan life cycles alternate between an active growth phase (*trophozoites*) and a resting stage (*cysts*). Cysts are extremely resistant structures that protect the organism from destruction when it encounters harsh environmental conditions—including chlorination.

√ **Note:** Those protozoans not completely resistant to chlorination require higher disinfectant concentrations and longer contact time for disinfection than normally used in water treatment.

The three protozoans and the waterborne diseases associated with them of most concern to the waterworks operator are

- *Entamoeba histolytica*—amebic dysentery
- *G. lamblia*—giardiasis
- *Cryptosporidium*—cryptosporidiosis

In wastewater treatment, protozoa are a critical part of the purification process and can be used to indicate the condition of treatment processes. Protozoa normally associated with wastewater include amoeba, flagellates, free-swimming ciliates, and stalked ciliates.

Amoeba is associated with poor wastewater treatment of a young biosolids mass (see Figure 5.5). They move through wastewater by a streaming or gliding motion. Moving the liquids stored within the cell wall effects this movement. They are normally associated with an effluent high in BODs and suspended solids.

Flagellates (flagellated protozoa) have a single, long hair- or whip-like projection (flagella) that is used to propel the free-swimming organisms through wastewater and to attract food (see Figure 5.5). Flagellated protozoans are normally associated with poor treatment and a young biosolids. When the predominate organism is the flagellated protozoa, the plant effluent will contain large amounts of BODs and suspended solids.

The *free-swimming ciliated protozoan* uses its tiny, hair-like projections (cilia) to move itself through the wastewater and to attract food (see Figure 5.5). The free-swimming ciliated protozoan is normally associated with a moderate biosolids age and effluent quality. When the free-swimming ciliated protozoan is the predominate organisms, the plant effluent will normally be turbid and contain a high amount of suspended solids.

The *stalked-ciliated protozoan* attaches itself to the wastewater solids and uses its cilia to attract food (see Figure 5.5). The stalked ciliated protozoan is normally associated with a plant effluent that is very clear and contains low amounts of both BODs and suspended solids.

Rotifers make up a well-defined group of the smallest, simplest multicellular microorganisms and are found in nearly all aquatic habitats (see Figure 5.6). Rotifers are a higher life form associated with cleaner waters. Normally found in well-operated wastewater treatment plants, they can be used to indicate the performance of certain types of treatment processes.

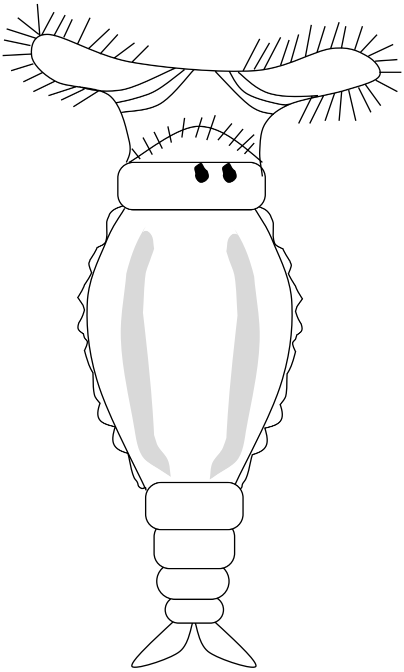


FIGURE 5.6 Philodina, a common rotifer.

MICROSCOPIC CRUSTACEANS

Because they are important members of freshwater zooplankton, microscopic *crustaceans* are of interest to water operators/practitioners. These microscopic organisms are characterized by a rigid shell structure. They are multicellular animals that are strict aerobes, and as primary producers, they feed on bacteria and algae. They are important as a source of food for fish. Additionally, microscopic crustaceans have been used to clarify algae-laden effluents from oxidation ponds.

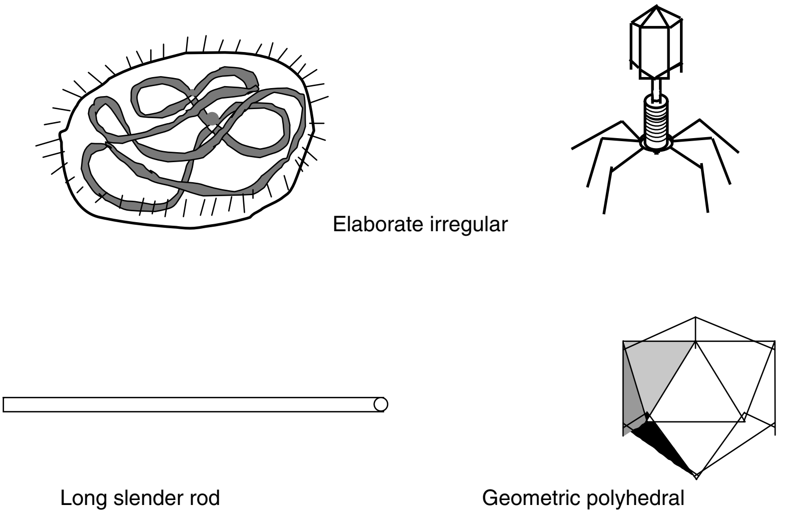
VIRUSES

Viruses are very different from other microorganisms. For example, consider their size relationship. Relative to size, if protozoans are the Goliaths of microorganisms, then viruses are the Davids. Stated more specifically and accurately, viruses are intercellular parasitic particles that are the smallest living infectious materials known—the midgets of the microbial world. Viruses are very simple life-forms consisting of a central molecule of genetic material surrounded by a protein shell called a capsid—and sometimes by a second layer called an envelope. They contain no mechanisms by which to obtain energy or reproduce on their own, thus to live, viruses must have a host. After they invade the cells of their specific host (animal, plant, insect, fish, or even bacteria), they take over the host's cellular machinery and force it to make more viruses. In the process, the host cell is destroyed and hundreds of new viruses are released into the environment.

The viruses of most concern to the water practitioners are the pathogens that cause hepatitis, viral gastroenteritis, and poliomyelitis.

Smaller and different from bacteria, viruses are prevalent in water contaminated with sewage. Detecting viruses in water supplies is a major problem because of the complexity of nonroutine procedures involved, but experience has shown that the normal coliform index can be used as a rough guide for viruses as for bacteria. However, more attention must be paid to viruses whenever surface water supplies have been used for sewage disposal.

Viruses occur in many shapes, including long slender rods, elaborate irregular shapes and geometric polyhedrals (see Figure 5.7).



Elaborate irregular

Long slender rod

Geometric polyhedral

FIGURE 5.7 Viral shapes.

Viruses are difficult to destroy by normal disinfection practices, requiring increased disinfectant concentration and contact time for effective destruction.

√ **Note:** Viruses that infect bacterial cells cannot infect and replicate within cells of other organisms. It is possible to utilize the specificity to identify bacteria, a procedure called phage typing.

ALGAE

You do not have to be a water operator to understand that algae can be a nuisance. Many ponds and lakes in the United States are currently undergoing *eutrophication*, the enrichment of an environment with inorganic substances (e.g., phosphorus and nitrogen), causing excessive algae growth and premature aging of the water body. The average person may not know what eutrophication means—however, when eutrophication occurs and especially when filamentous algae like *Caldophora* breaks loose in a pond or lake and washes ashore, algae makes its stinking, noxious presence known.

Algae are a form of aquatic plants and are classified by color (e.g., green algae, blue-green algae, golden-brown algae, etc.). Algae occur in many shapes and sizes (see Figure 5.8). Although they are not pathogenic, algae do cause problems with water/wastewater treatment plant operations. They grow easily on the walls of troughs and basins, and heavy growth can plug intakes and screens. Additionally, some algae release chemicals that give off undesirable tastes and odors.

As mentioned, algae are usually classified by their color. However, they are also commonly classified based on their cellular properties or characteristics. Several characteristics are used to classify algae including (1) cellular organization and cell wall structure; (2) the nature of the chlorophyll(s); (3) the type of motility, if any; (4) the carbon polymers that are produced and stored; and (5) the reproductive structures and methods.

Many algae (in mass) are easily seen by the naked eye—others are microscopic. They occur in fresh and polluted water as well as in salt water. Since they are plants, they are capable of using energy from the sun in photosynthesis. They usually grow near the surface of the water because light cannot penetrate very far through the water.

Algae are controlled in raw waters with chlorine and potassium permanganate. Algae blooms in raw water reservoirs are often controlled with copper sulfate.

√ **Note:** By producing oxygen, which is utilized by other organisms including animals, algae play an important role in the balance of nature.

FUNGI

Fungi are of relatively minor importance in water operations (except for biosolids composting, where they are critical). Fungi, like bacteria, are also extremely diverse. Most fungi are found in the

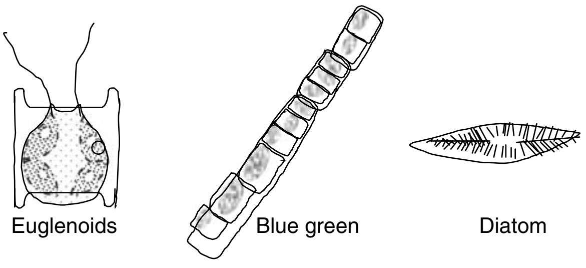


FIGURE 5.8 Algae.

soil and on other organisms, and a few are aquatic. However, many can be spread by water through soil erosion and as spores in aerosols. They are multicellular, autotrophic, photosynthetic protists. They grow as filamentous, mold-like forms or as yeast-like (single-celled) organisms. They feed on organic material.

√ **Note:** Aquatic fungi grow as parasites on living plants or animals and as saprophytes on those that are dead.

MICROBIOLOGICAL PROCESSES/ASPECTS

As mentioned, the primary goal in water treatment is to protect the consumer of potable drinking water from disease. Drinking water safety is a worldwide concern. Drinking nontreated or improperly treated water is a major cause of illness in developing countries.

Water contains several biological (as well as chemical) contaminants that must be removed efficiently to produce safe drinking water that is also aesthetically pleasing to the consumer. The finished water must be free of microbial pathogens and parasites, turbidity, color, taste, and odor. To achieve this goal, raw surface water or groundwater is subjected to a series of treatment processes that will be described in detail later. Disinfection alone is sufficient if the raw water originates from a protected source. More commonly, several processes are used to treat water. For example, disinfection may be combined with coagulation, flocculation, and filtration.

As mentioned, several unit processes are used in the water treatment process to produce microbiologically (and chemically) safe drinking water. The extent of treatment depends on the source of raw water; surface waters generally require more treatment than groundwaters. With the exception of disinfection, the other unit processes in the treatment train do not specifically address the destruction or removal of pathogens.

Water treatment unit processes include (1) storage of raw water; (2) prechlorination; (3) coagulation-flocculation; (4) water softening; (5) filtration; and (6) disinfection. Although filtration and disinfection are the primary means of removing contaminants and pathogens from drinking water supplies, in each of these unit processes, reduction or destruction of pathogens is accomplished but is variable and is influenced by a number of factors such as sunlight, sedimentation, and temperature.

The water treatment unit processes mentioned above are important and are described in detail later in this text. For the moment, because of relatively recent events involving pathogenic protozoans causing adverse reactions, including death, to consumers in various locations in the United States (and elsewhere), it is important to turn our attention to these pathogenic protozoans. One thing is certain: these pathogenic protozoans have the full attention of water treatment operators everywhere.

PATHOGENIC PROTOZOA

As mentioned, certain types of protozoans can cause disease. Of particular interest to the drinking water practitioner are the *E. histolytica* (amebic dysentery and amebic hepatitis), *G. lamblia* (giardiasis), *Cryptosporidium* (cryptosporidiosis), and the emerging *Cyclospora* (cyclosporosis). Sewage contamination transports eggs, cysts, and oocysts of parasitic protozoa and helminthes (tapeworms, hookworms, etc.) into raw water supplies, leaving water treatment (in particular filtration) and disinfection as the means by which to diminish the danger of contaminated water for the consumer.

To prevent the occurrence of *Giardia* and *Cryptosporidium* spp. in surface water supplies, and to address increasing problems with waterborne diseases, the USEPA implemented its Surface Water Treatment Rule (SWTR) in 1989. The rule requires both filtration and disinfection of all surface water supplies as a means of primarily controlling *Giardia* spp. and enteric viruses. Since implementation of its SWTR, the USEPA has also recognized that *Cryptosporidium* spp. is an agent of waterborne disease. In 1996, in its next series of surface water regulations, the USEPA included *Cryptosporidium*.

To test the need for and the effectiveness of the USEPA's SWTR, LeChevallier et al. conducted a study on the occurrence and distribution of *Giardia* and *Cryptosporidium* organisms in raw water supplies to 66 surface water filter plants. These plants were located in 14 states and 1 Canadian province. A combined immunofluorescence test indicated that cysts and oocysts were widely dispersed in the aquatic environment. *Giardia* spp. was detected in more than 80% of the samples. *Cryptosporidium* spp. was found in 85% of the sample locations. Taking into account several variables, *Giardia* or *Cryptosporidium* spp. were detected in 97% of the raw water samples. After evaluating their data, the researchers concluded that the SWTR might have to be upgraded (subsequently, it has been) to require additional treatment (LeChevallier et al., 1991).

Giardia

Giardia (gee-ar-dee-ah) *lamblia* (also known as hiker's/traveler's scourge or disease) is a microscopic parasite that can infect warm-blooded animals and humans. Although *Giardia* was discovered in the 19th century, not until 1981 did the World Health Organization (WHO) classify *Giardia* as a pathogen. An outer shell called a cyst, that allows it to survive outside the body for long periods, protects *Giardia*. If viable cysts are ingested, *Giardia* can cause the illness known as *giardiasis*, an intestinal illness that can cause nausea, anorexia, fever, and severe diarrhea.

In the United States, *Giardia* is the most commonly identified pathogen in waterborne disease outbreaks. Contamination of a water supply by *Giardia* can occur in two ways: (1) by the activity of animals in the watershed area of the water supply or (2) by the introduction of sewage into the water supply. Wild and domestic animals are major contributors in contaminating water supplies. Studies have also shown that, unlike many other pathogens, *Giardia* is not host-specific. In short, *Giardia* cysts excreted by animals can infect and cause illness in humans. Additionally, in several major outbreaks of waterborne diseases, the *Giardia* cyst source was sewage-contaminated water supplies.

Treating the water supply, however, can effectively control waterborne *Giardia*. Chlorine and ozone are examples of two disinfectants known to effectively kill *Giardia* cysts. Filtration of the water can also effectively trap and remove the parasite from the water supply. The combination of disinfection and filtration is the most effective water treatment process available today for prevention of *Giardia* contamination.

In drinking water, *Giardia* is regulated under the SWTR. Although the SWTR does not establish a maximum contaminant level (MCL) for *Giardia,* it does specify treatment requirements to achieve at least 99.9% (3-log) removal and inactivation of *Giardia*. This regulation requires that all drinking water systems using surface water or groundwater under the influence of surface water must disinfect and filter the water. The Enhanced Surface Water Treatment Rule (ESWTR), which includes *Cryptosporidium* and further regulates *Giardia,* was established in December 1996.

GIARDIASIS

During the past 15 years, giardiasis (CDC, 1995) has been recognized as one of the most frequently occurring waterborne diseases in the United States. *G. lamblia* cysts have been discovered in the United States in places as far apart as Estes Park, Colorado (near the Continental Divide); Missoula, Montana; Wilkes-Barre, Scranton, and Hazleton, Pennsylvania; and Pittsfield and Lawrence, Massachusetts, just to name a few.

Giardiasis is characterized by intestinal symptoms that usually last 1 week or more and may be accompanied by one or more of the following: diarrhea, abdominal cramps, bloating, flatulence, fatigue, and weight loss. Although vomiting and fever are commonly listed as relatively frequent symptoms, people involved in waterborne outbreaks in the United States have not commonly reported them.

While most *Giardia* infections persist only for 1 or 2 months, some people undergo a more chronic phase, which can follow the acute phase or may become manifest without an antecedent acute illness. Loose stools and increased abdominal gassiness with cramping, flatulence, and burping characterize the chronic phase. Fever is not common, but malaise, fatigue, and depression may ensue (Weller, 1985). For a small number of people, the persistence of infection is associated with the development of marked malabsorption and weight loss. Similarly, lactose (milk) intolerance can be a problem for some people. This can develop coincidentally with the infection or be aggravated by it, causing an increase in intestinal symptoms after ingestion of milk products.

Some people may have several of these symptoms without evidence of diarrhea or have only sporadic episodes of diarrhea every 3 or 4 days. Still others may not have any symptoms at all. Therefore, the problem may not be whether you are infected with the parasite or not, but how harmoniously you both can live together or how to get rid of the parasite (either spontaneously or by treatment) when the harmony does not exist or is lost.

√ **Note:** Three prescription drugs are available in the United States to treat giardiasis: quinacrine, metronidazole, and furazolidone. In a recent review of drug trials in which the efficacies of these drugs were compared, quinacrine produced a cure in 93% of patients, metronidazole cured 92%, and furazolidone cured about 84% of patients (Davidson, 1984).

Giardiasis occurs worldwide. In the United States, *Giardia* is the parasite most commonly identified in stool specimens submitted to state laboratories for parasitologic examination. During a 3-year period, approximately 4% of 1 million stool specimens submitted to state laboratories tested positive for *Giardia* (CDC, 1979). Other surveys have demonstrated *Giardia* prevalence rates ranging from 1 to 20%, depending on the location and ages of persons studied. Giardiasis ranks among the top 20 infectious diseases that cause the greatest morbidity in Africa, Asia, and Latin America; it has been estimated that about 2 million infections occur per year in these regions (Walsh and Warren, 1979; Walsh, 1981). People who are at highest risk for acquiring *Giardia* infection in the United States may be placed into five major categories:

1. People in cities whose drinking water originates from streams or rivers, and whose water treatment process does not include filtration, or where filtration is ineffective because of malfunctioning equipment
2. Hikers/campers/outdoor people
3. International travelers
4. Children who attend day-care centers, day-care center staff, and parents and siblings of children infected in day-care centers
5. Homosexual men

People in categories 1–3 have in common the same general source of infection, i.e., they acquire *Giardia* from fecally contaminated drinking water. The city resident usually becomes infected because the municipal water treatment process does not include the filter necessary to physically remove the parasite from the water. The number of people in the United States at risk (i.e., the number who receive municipal drinking water from unfiltered surface water) is estimated to be 20 million. International travelers may also acquire the parasite from improperly treated municipal waters in cities or villages in other parts of the world, particularly in developing countries. In Eurasia, only travelers to Leningrad appear to be at increased risk. In prospective studies, 88% of U.S. and 35% of Finnish travelers to Leningrad who had negative stool tests for *Giardia* on departure to the Soviet Union developed symptoms of giardiasis and had positive test for *Giardia* after they returned home (Brodsky et al., 1974; Jokipii and Jokipii, 1974). With the exception of visitors to Leningrad, however, *Giardia* has not been implicated as a major cause of traveler's diarrhea—it has been detected in fewer than 2% of travelers who develop diarrhea. However, hikers and campers risk infection every time they drink untreated raw water from a stream or river.

Persons in categories 4 and 5 become exposed through more direct contact with feces or an infected person; exposure to soiled of an infected child (day-care center–associated cases), or through direct or indirect anal–oral sexual practices in the case of homosexual men.

Although community waterborne outbreaks of giardiasis have received the greatest publicity in the United States during the past decade, about half of the *Giardia* cases discussed with the staff of the Centers for Disease Control (CDC) over a 3-year period had a day-care exposure as the most likely source of infection. Numerous outbreaks of *Giardia* in day-care centers have been reported in recent years. Infection rates for children in day-care center outbreaks range from 21 to 44% in the United States and from 8 to 27% in Canada (Black et al., 1981; Pickering et al., 1984). The highest infection rates are usually observed in children who wear diapers (1–3 years of age).

Local health officials and managers or water utility companies need to realize that sources of *Giardia* infection other than municipal drinking water exist. Armed with this knowledge, they are less likely to make a quick (and sometimes wrong) assumption that a cluster of recently diagnosed cases in a city is related to municipal drinking water. Of course, drinking water must not be ruled out as a source of infection when a larger than expected number of cases is recognized in a community, but the possibility that the cases are associated with a day-care center outbreak, drinking untreated stream water, or international travel should also be entertained.

To understand the finer aspects of *Giardia* transmission and strategies for control, the drinking water practitioner must become familiar with several aspects of the parasite's biology. Two forms of the parasite exist: a *trophozoite* and a *cyst*, both of which are much larger than bacteria (see Figure 5.9). Trophozoites live in the upper small intestine where they attach to the intestinal wall by means of a disc-shaped suction pad on their ventral surface. Trophozoites actively feed and reproduce here. At some time during the trophozoite's life, it releases its hold on the bowel wall and

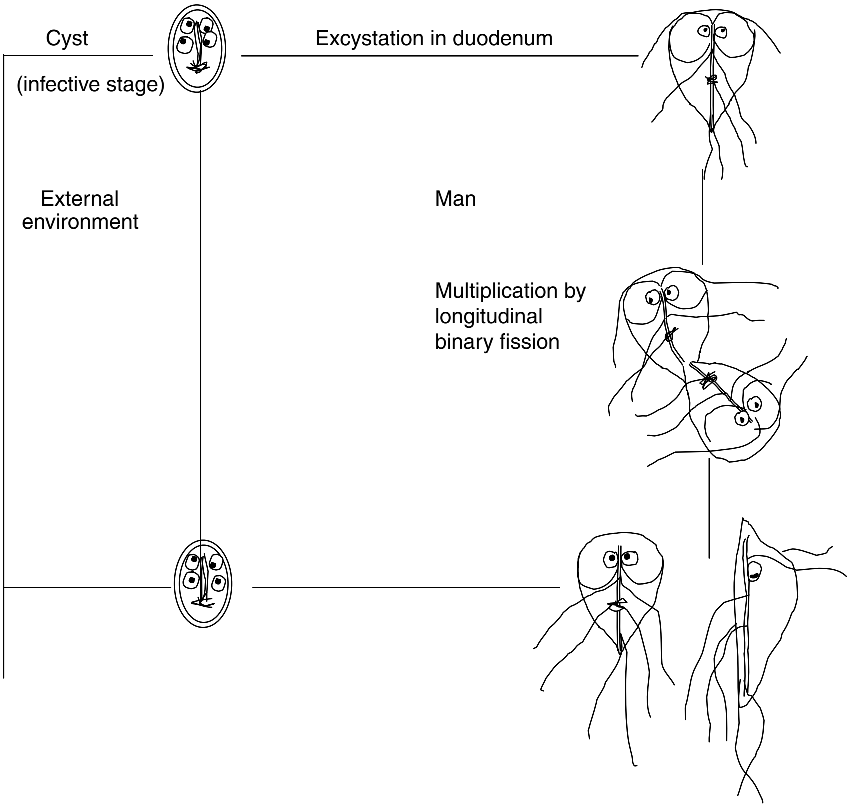


FIGURE 5.9 Life cycle of *Giardia lamblia*.

floats in the fecal stream through the intestine. As it makes this journey, it undergoes a morphologic transformation into an egg-like structure called a cyst. The cyst (about 6–9 nm in diameter × 8–12 μm –1/100 mm in length) has a thick exterior wall that protects the parasite against the harsh elements that it will encounter outside the body. This cyst form of parasite is infectious to other people or animals. Most people become infected either directly (by hand-to-mouth transfer of cysts from the feces of an infected individual) or indirectly (by drinking fecally contaminated water). Less common modes of transmission included ingestion of fecally contaminated food and hand-to-mouth transfer of cysts after touching a fecally contaminated surface. After the cyst is swallowed, the trophozoite is liberated through the action of stomach acid and digestive enzymes and becomes established in the small intestine.

Although infection after ingestion of only one *Giardia* cyst is theoretically possible, the minimum number of cysts shown to infect a human under experimental conditions is 10 (Rendtorff, 1954). Trophozoites divide by binary fission about every 12 h. What this means in practical terms is that if a person swallowed only a single cyst, reproduction at this rate would result in more than 1 million parasites 10 days later, and 1 billion parasites by day 15.

The exact mechanism by which *Giardia* causes illness is not yet well understood, but is not necessarily related to the number of organisms present. Nearly all of the symptoms, however, are related to dysfunction of the gastrointestinal tract. The parasite rarely invades other parts of the body, such as the gall bladder or pancreatic ducts. Intestinal infection does not result in permanent damage.

√ **Note:** *Giardia* has an incubation period of 1–8 weeks.

Data reported by the CDC indicate that *Giardia* is the most frequently identified cause of diarrheal outbreaks associated with drinking water in the United States. The remainder of this section is devoted specifically to waterborne transmissions of *Giardia*. *Giardia* cysts have been detected in 16% of potable water supplies (lakes, reservoirs, rivers, springs, and groundwater) in the United States at an average concentration of 3 cysts/100 L (Rose et al., 1991). Waterborne epidemics of giardiasis are a relatively frequent occurrence. In 1983, for example, *Giardia* was identified as the cause of diarrhea in 68% of waterborne outbreaks in which the causal agent was identified (CDC, 1984). From 1965 to 1982, more than 50 waterborne outbreaks were reported (Craun, 1984). In 1984, about 250,000 people in Pennsylvania were advised to boil drinking water for 6 months because of *Giardia*-contaminated water.

Many of the municipal waterborne outbreaks of *Giardia* have been subjected to intense study to determine their cause. Several general conclusions can be made from data obtained in those studies. Waterborne transmission of *Giardia* in the United States usually occurs in mountainous regions where community drinking water obtained from clear running streams is chlorinated but not filtered before distribution. Although mountain streams appear to be clean, fecal contamination upstream by human residents or visitors as well as by *Giardia*-infected animals, such as beavers, has been well documented. Water obtained from deep wells is an unlikely source of *Giardia* because of the natural filtration of water as it percolates through the soil to reach underground cisterns. Well-waste sources that pose the greatest risk of fecal contamination are poorly constructed or improperly located ones. A few outbreaks have occurred in towns that included filtration in the water treatment process, where the filtration was not effective in removing *Giardia* cysts because of defects in filter construction, poor maintenance of the filter media, or inadequate pretreatment of the water before filtration. Occasional outbreaks have also occurred because of accidental cross connections between water and sewage systems.

From these data, we conclude that two major ingredients are necessary for waterborne outbreak. *Giardia* cysts must be present in untreated source water, and the water purification process must either fail to kill or to remove *Giardia* cysts from the water.

Although beavers are often blamed for contaminating water with *Giardia* cysts, that they are responsible for introducing the parasite into new areas seem unlikely. Far more likely is that they are also victims: *Giardia* cysts may be carried in untreated human sewage discharged into the water by small-town sewage disposal plants, or they originate from cabin toilets that drain directly into streams and rivers. Backpackers, campers, and sports enthusiasts may also deposit *Giardia*-contaminated feces in the environment, which are subsequently washed into streams by rain. In support of this concept is a growing amount of data that indicate a higher *Giardia* infection rate in beavers living downstream from U.S. National Forest campgrounds, compared with a near zero rate of infection in beavers living in more remote areas.

Although beavers may be unwitting victims of the *Giardia* story, they still play an important part in the contamination scheme because they can (and probably do) serve as amplifying hosts. An *amplifying host* is one that is easy to infect, serves as a good habitat for the parasite to reproduce, and in the case of *Giardia*, returns millions of cysts to the water for every one ingested. Beavers are especially important in this regard, because they tend to defecate in or very near the water, which ensures that most of the *Giardia* cysts excreted are returned to the water.

The microbial quality of water resources and the management of the microbially laden wastes generated by the burgeoning animal agriculture industry are critical local, regional, and national problems. Animal wastes from cattle, hogs, sheep, horses, poultry, and other livestock and commercial animals can contain high concentrations of microorganisms, such as *Giardia,* that are pathogenic to humans.

The contribution of other animals to waterborne outbreaks of *Giardia* is less clear. Muskrats (another semiaquatic animal) have been found in several parts of the United States to have high infection rates (30–40%) (Frost et al., 1984). Recent studies have shown that muskrats can be infected with *Giardia* cysts from humans and beavers. Occasional *Giardia* infections have been reported in coyotes, deer, elk, cattle, dogs, and cats (but not in horses and sheep) encountered in mountainous regions of the United States. Naturally occurring *Giardia* infections have not been found in most other wild animals (bear, nutria, rabbit, squirrel, badger, marmot, skunk, ferret, porcupine, mink, raccoon, river otter, bobcat, lynx, moose, and bighorn sheep).

Scientific knowledge about what is required to kill or remove *Giardia* cysts from a contaminated water supply has increased considerably. For example, we know that cysts can survive in cold water (4°C) for at least 2 months, and they are killed instantaneously by boiling water (100°C) (Bingham et al., 1979). We do not know how long the cysts will remain viable at other water temperatures (e.g., at 0°C or in a canteen at 15–20°C), nor do we know how long the parasite will survive on various environment surfaces, e.g., under a pine tree, in the sun, on a diaper-changing table, or in carpets in a day-care center.

The effect of chemical disinfection (for example, chlorination) on the viability of *Giardia* cysts is an even more complex issue. The number of waterborne outbreaks of *Giardia* that have occurred in communities where chlorination was employed as a disinfectant-process demonstrates that the amount of chlorine used routinely for municipal water treatment is not effective against *Giardia* cysts. These observations have been confirmed in the laboratory under experimental conditions (Jarroll et al., 1979, 1980). This does not mean that chlorine does not work at all. It does work under certain favorable conditions. Without getting too technical, gaining some appreciation of the problem can be achieved by understanding a few of the variables that influence the efficacy of chlorine as a disinfectant.

1. *Water pH*— At pH above 7.5, the disinfectant capability of chlorine is greatly reduced.
2. *Water temperature*—The warmer the water, the higher the efficacy. Chlorine does not work in ice-cold water from mountain streams.
3. *Organic content of the water*— Mud, decayed vegetation, or other suspended organic debris in water chemically combines with chlorine, making it unavailable as a disinfectant.
4. *Chlorine contact time*—The longer *Giardia* cysts are exposed to chlorine, more likely the chemical will kill them.

5. *Chlorine concentration*—The higher the chlorine concentration, the more likely chlorine will kill *Giardia* cysts. Most water treatment facilities try to add enough chlorine to give a free (unbound) chlorine residual at the customer tap of 0.5 mg/L of water.

The five variables above are so closely interrelated that improving another can often compensate for an unfavorable occurrence in one. For example, if chlorine efficacy is expected to be low because water is obtained from an icy stream, the chlorine contact time, chlorine concentration, or both could be increased. In the case of *Giardia*-contaminated water, producing safe drinking water with a chlorine concentration of 1 mg/L and contact time as short as 10 min might be possible—if all the other variables were optimal (i.e., pH of 7.0, water temperature of 25°C, and a total organic content of the water close to zero). In contrast, if all of these variables were unfavorable (i.e., pH of 7.9, water temperature of 5°C, and high organic content), chlorine concentrations in excess of 8 mg/L with several hours of contact time may not be consistently effective. Because water conditions and water treatment plant operations (especially those related to water retention time, and therefore, to chlorine contact time) vary considerably in different parts of the United States, neither the USEPA nor the CDC has been able to identify a chlorine concentration that would be safe yet effective against *Giardia* cysts under all water conditions. Therefore, the use of chlorine as a preventive measure against waterborne giardiasis generally has been used under outbreak conditions when the amount of chlorine and contact time have been tailored to fit specific water conditions and the existing operational design of the water utility.

In an outbreak, for example, the local health department and water utility may issue an advisory to boil water, may increase the chlorine residual at the consumer's tap from 0.5 to 1 or 2 mg/L, and if the physical layout and operation of the water treatment facility permit, increase the chlorine contact time. These are emergency procedures intended to reduce the risk of transmission until a filtration device can be installed or repaired or until an alternative source of safe water (for example, a well) can be made operational.

The long-term solution to the problem of municipal waterborne outbreaks of giardiasis involves improvements in and more widespread use of filters in the municipal water treatment process. The sand filters most commonly used in municipal water treatment today cost millions of dollars to install, which makes them unattractive for many small communities. The pore sizes in these filters are not sufficiently small to remove a *Giardia* (6–9 μm × 8–12 μm). For the sand filter to remove *Giardia* cysts from the water effectively, the water must receive some additional treatment before it reaches the filter. The flow of water through the filter bed must also be carefully regulated.

An ideal prefilter treatment for muddy water would include sedimentation (a holding pond where large suspended particles are allowed to settle out by the action of gravity) followed by flocculation or coagulation (the addition of chemicals such as alum or ammonium to cause microscopic particles to clump together). The sand filter easily removes the large particles resulting from the flocculation/coagulation process, including *Giardia* cysts bound to other microparticulates. Chlorine is then added to kill the bacteria and viruses that may escape the filtration process. If the water comes from a relatively clear source, chlorine may be added to the water before it reaches the filter.

The successful operation of a complete waterworks operation is a complex process that requires considerable training. Troubleshooting breakdowns or recognizing the potential problems in the system before they occur often requires the skills of an engineer. Unfortunately, most small water utilities with water treatment facilities that include filtration cannot afford the services of a full-time engineer. Filter operation or maintenance problems in such systems may not be detected until a *Giardia* outbreak is recognized in the community. The bottom line is that although filtration is the best that water treatment technology has to offer for municipal water systems against waterborne giardiasis, it is not infallible. For municipal water filtration facilities to work properly, they must be properly constructed, operated, and maintained.

Whenever possible, persons in the out-of-doors should carry drinking water of known purity with them. When this is not practical, and when water from streams, lakes, ponds, and other outdoor sources must be used, time should be taken to properly disinfect the water before drinking it.

Cryptosporidium

Ernest E. Tyzzer first described the protozoan parasite *Cryptosporidium* in 1907. Tyzzer frequently found a parasite in the gastric glands of laboratory mice. Tyzzer identified the parasite as a sporozoan, but of uncertain taxonomic status; he named it *Cryptosporidium muris*. Later, in 1910, after a more detailed study, he proposed *Cryptosporidium* as a new genus and *C. muris* as the type of species. Amazingly, except for developmental stages, Tyzzer's original description of the life cycle (see Figure 5.10) was later confirmed by electron microscopy. Later, in 1912, Tyzzer described a new species, *Cryptosporidium parvum* (Tyzzer, 1912).

For almost 50 years, Tyzzer's discovery of the genus *Cryptosporidium* (because it appeared to be of no medical or economic importance) remained (like himself) relatively obscure. However, slight rumblings of the genus' importance were felt in the medical community when Slavin wrote about a new species, *Cryptosporidium meleagridis,* associated with illness and death in turkeys (Tyzzer, 1912). Interest remained slight even when *Cryptosporidium* was found to be associated with bovine diarrhea (Panciera et al., 1971).

Not until 1982 did worldwide interest focus in on the study of organisms in the genus *Cryptosporidium*. During this period, the medical community and other interested parties were beginning to attempt a full-scale, frantic effort to find out as much as possible about acquired immune deficiency syndrome (AIDS). The CDC reported that 21 AIDS-infected males from six large cities in the United States had severe protracted diarrhea caused by *Cryptosporidium*.

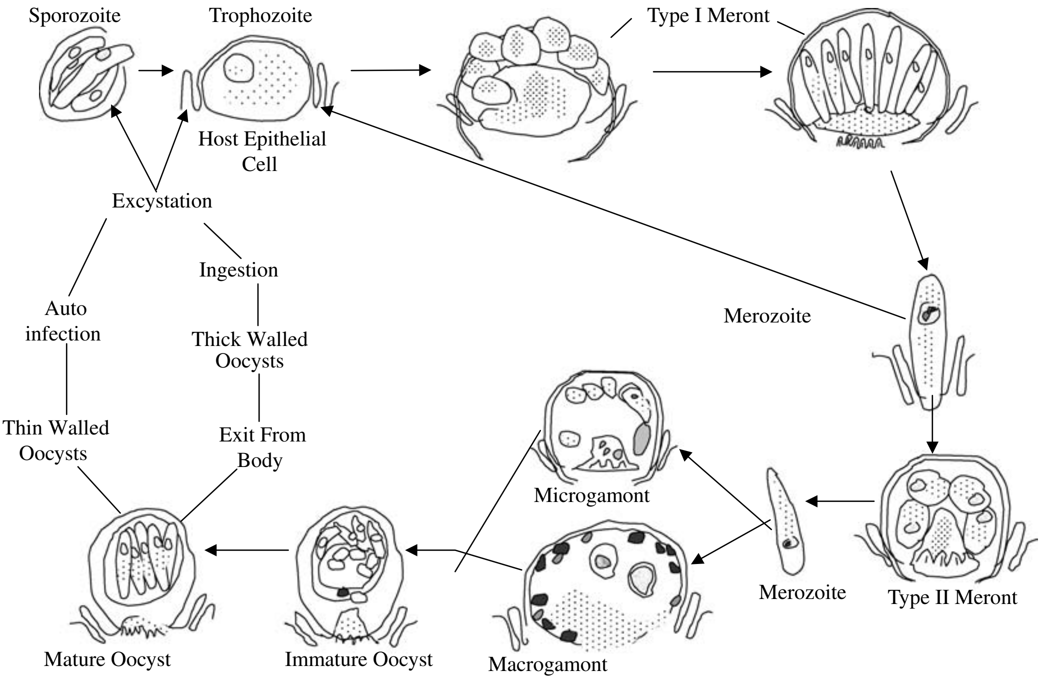


FIGURE 5.10 Life cycle of *Cryptosporidium parvum*.

However, 1993 was when the "bug—the pernicious parasite *Cryptosporidium*—made [itself and] Milwaukee famous" (Mayo Foundation, 1996).

√ **Note:** The *Cryptosporidium* outbreak in Milwaukee caused the deaths of 100 people—the largest episode of waterborne disease in the United States in the 70 years since health officials began tracking such outbreaks.

Today we know that the massive waterborne outbreak in Milwaukee (more than 400,000 persons developed acute and often prolonged diarrhea or other gastrointestinal symptoms) increased interest in *Cryptosporidium* at an exponential level. The Milwaukee incident spurred both public interest and the interest of public health agencies, agricultural agencies and groups, environmental agencies and groups, and suppliers of drinking water. This increase in interest level and concern has spurred on new studies of *Cryptosporidium* with emphasis on developing methods for recovery, detection, prevention, and treatment (Fayer et al., 1997).

The USEPA has become particularly interested in this "new" pathogen. For example, in the reexamination of regulations on water treatment and disinfection, the USEPA issued MCLG and CCL for *Cryptosporidium.* The similarity to *G. lamblia* and the necessity to provide an efficient conventional water treatment capable of eliminating viruses at the same time forced the USEPA to regulate the surface water supplies in particular. The proposed "Enhanced Surface Water Treatment Rule" (ESWTR) included regulations from watershed protection to specialized operation of treatment plants (certification of operators and state overview) and effective chlorination. Protection against *Cryptosporidium* included control of waterborne pathogens such as *Giardia* and viruses (De Zuane, 1997).

THE BASICS OF *CRYPTOSPORIDIUM*

*Cryptosporidium (*crip-toe-spor-ID-ee-um) is one of several single-celled protozoan genera in the phylum Apircomplexa (all referred to as coccidian). *Cryptosporidium* along with other genera in the phylum Apircomplexa develop in the gastrointestinal tract of vertebrates through all of their life cycle—in short, they live in the intestines of animals and people. This microscopic pathogen causes a disease called *cryptosporidiosis* (crip-toe-spor-id-ee-O-sis).

The dormant (inactive) form of *Cryptosporidium* called an oocyst (O-o-sist) is excreted in the feces (stool) of infected humans and animals. The tough-walled oocysts survive under a wide range of environmental conditions.

Several species of *Cryptosporidium* were incorrectly named after the host in which they were found; subsequent studies have invalidated many species. To date eight valid species of *Cryptosporidium* (see Table 5.4) have been named.

Upton reports that *C. muris* infects the gastric glands of laboratory rodents and several other mammalian species, but (even though several texts state otherwise) is not known to infect humans. However, *C. parvum* infects the small intestine of an unusually wide range of mammals, including humans, and is the zoonotic species responsible for human cryptosporidiosis. In most mammals *C. parvum* is predominately a parasite of neonate (newborn) animals. He points out that even though exceptions occur, older animals generally develop poor infections, even when unexposed previously to the parasite. Humans are the one host that can be seriously infected at any time in their lives, and only previous exposure to the parasite results in either full or partial immunity to challenge infections.

Oocysts are present in most surface bodies of water across the United States, many of which supply public drinking water. Oocysts are more prevalent in surface waters when heavy rains increase runoff of wild and domestic animal wastes from the land, or when sewage treatment plants are overloaded or break down.

Only laboratories with specialized capabilities can detect the presence of *Cryptosporidium* oocysts in water. Unfortunately, present sampling and detection methods are unreliable.

TABLE 5.4
Valid Named Species of *Cryptosporidium*

Species	Host
C. baileyi	Chicken
C. felis	Domestic cat
C. meleagridis	Turkey
C. murishouse	House mouse
C. nasorium	Fish
C. parvum	House mouse
C. serpentis	Corn snake
C. wrairi	Guinea pig

Source: Adapted from Fayer, R. et al., *Cryptosporidium and Cryptosporidiosis*, Fayer, R. (ed.), Boca Raton, FL, CRC Press, 1997.

Recovering oocysts trapped on the material used to filter water samples is difficult. Once a sample is obtained, however, determining whether the oocyst is alive or whether it is the species *C. parvum* that can infect humans is easily accomplished by looking at the sample under a microscope.

The number of oocysts detected in raw (untreated) water varies with location, sampling time, and laboratory methods. Water treatment plants remove most, but not always all, oocysts. Low numbers of oocysts are sufficient to cause cryptosporidiosis, but the low numbers of oocysts sometimes present in drinking water are not considered cause for alarm in the public.

Protecting water supplies from *Cryptosporidium* demands multiple barriers. Why? Because *Cryptosporidium* oocysts have tough walls that can withstand many environmental stresses and are resistant to the chemical disinfectants such as chlorine that are traditionally used in municipal drinking water systems.

Physical removal of particles, including oocysts, from water by filtration is an important step in the water treatment process. Typically, water pumped from rivers or lakes into a treatment plant is mixed with coagulants, which help settle out particles suspended in the water. If sand filtration is used, even more particles are removed. Finally, the clarified water is disinfected and piped to customers. Filtration is the only conventional method now in use in the United States for controlling *Cryptosporidium*.

Ozone is a strong disinfectant that kills protozoa if sufficient doses and contact times are used, but ozone leaves no residual for killing microorganisms in the distribution system, as does chlorine. The high costs of new filtration or ozone treatment plants must be weighed against the benefits of additional treatment. Even well-operated water treatment plants cannot ensure that drinking water will be completely free of *Cryptosporidium* oocysts. Water treatment methods alone cannot solve the problem; watershed protection and monitoring of water quality are critical. For example, land use controls such as septic system regulations and best management practices to control runoff can help keep human and animal wastes out of water.

Under the SWTR of 1989, public water systems must filter surface water sources unless water quality and disinfection requirements are met and a watershed control program is maintained. This rule, however, did not address *Cryptosporidium*. The USEPA has now set standards for turbidity (cloudiness) and coliform bacteria (which indicate that pathogens are probably present) in drinking water. Frequent monitoring must occur to provide officials with early warning of potential problems to enable them to take steps to protect public health. Unfortunately, no water quality indicators can reliably predict the occurrence of cryptosporidiosis. More accurate and rapid assays of oocysts will make it possible to notify residents promptly if their water supply is contaminated with *Cryptosporidium* and thus avert outbreaks.

The bottom line: The collaborative efforts of water utilities, government agencies, health care providers, and individuals are needed to prevent outbreaks of cryptosporidiosis.

CRYPTOSPORIDIOSIS

Dennis D. Juranek (1995) of the CDC writes in *Clinical Infectious Diseases:*

> *Cryptosporidium parvum* is an important emerging pathogen in the U.S. and a cause of severe, life-threatening disease in patients with AIDS. No safe and effective form of specific treatment for Cryptosporidiosis has been identified to date. The parasite is transmitted by ingestion of oocysts excreted in the feces of infected humans or animals. The infection can therefore be transmitted from person-to-person, through ingestion of contaminated water (drinking water and water used for recreational purposes) or food, from animal to person, or by contact with fecally contaminated environmental surfaces. Outbreaks associated with all of these modes of transmission have been documented. Patients with human immunodeficiency virus infection should be made more aware of the many ways that *Cryptosporidium* species are transmitted, and they should be given guidance on how to reduce their risk of exposure.

The CDC points out that since the Milwaukee outbreak, concern about the safety of drinking water in the United States has increased, and new attention has been focused on determining and reducing the risk of cryptosporidiosis from community and municipal water supplies.

Cryptosporidiosis is spread by ingesting something that has been contaminated with the stool of an infected person or animal. In this way, people swallow the *Cryptosporidium* parasite. As previously mentioned, a person can become infected by drinking contaminated water or eating raw or undercooked food contaminated with *Cryptosporidium* oocysts; direct contact with the droppings of infected animals or stools of infected humans; or hand-to-mouth transfer of oocysts from surfaces that may have become contaminated with microscopic amounts of stool from an infected person or animal.

The symptoms may appear 2–10 days after infection by the parasite. Although some persons may not have symptoms, others have watery diarrhea, headache, abdominal cramps, nausea, vomiting, and low-grade fever. These symptoms may lead to weight loss and dehydration.

In otherwise healthy persons, these symptoms usually last for 1–2 weeks, at which time the immune system is able to stop the infection. In persons with suppressed immune systems, such as persons who have AIDS or who recently have had an organ or bone marrow transplant, the infection may continue and become life threatening.

Now, no safe and effective cure for cryptosporidiosis exists. People with normal immune systems improve without taking antibiotic or antiparasitic medications. The treatment recommend for this diarrheal illness is to drink plenty of fluids and to get extra rest. Physicians may prescribe medication to slow the diarrhea during recovery.

The best ways to prevent cryptosporidiosis include:

- Avoid water or food that may be contaminated.
- Wash hands after using the toilet and before handling food.
- If you work in a childcare center where you change diapers, be sure to wash your hands thoroughly with plenty of soap and warm water after every diaper change, even if you wear gloves.

During community-wide outbreaks caused by contaminated drinking water, drinking water practitioners should inform the public to boil drinking water for 1 min to kill the *Cryptosporidium* parasite.

Cyclospora

Cyclospora organisms, which until recently were considered blue-green algae, were discovered at the turn of the century. The first human cases of *Cyclospora* infection were reported in the 1970s. In the early 1980s, *Cyclospora* was recognized as pathogen in patients with AIDS. We now know that *Cyclospora* is endemic in many parts of the world, and appears to be an important cause of traveler's diarrhea. *Cyclospora* are two to three times larger than *Cryptosporidium*, but otherwise have similar features. *Cyclospora* diarrheal illness in patients with healthy immune systems can be cured with a week of therapy with trimethoprim-sulfamethoxazole (TMP-SMX).

So, exactly what is *Cyclospora?* In 1998, the CDC described *Cyclospora cayetanesis* as a unicellular parasite previously known as a cyanobacterium-like (blue-green algae-like) or coccidian-like body (CLB). The disease is known as cyclosporiasis. *Cyclospora* infects the small intestine and causes an illness characterized by diarrhea with frequent stools. Other symptoms can include loss of appetite, bloating, gas, stomach cramps, nausea, vomiting, fatigue, muscle ache, and fever. Some individuals infected with *Cyclospora* may not show symptoms. Since the first known cases of illness caused by *Cyclospora* infection were reported in the medical journals in the 1970s, cases have been reported with increased frequency from various countries since the mid-1980s (in part because of the availability of better techniques for detecting the parasite in stool specimens).

Huang et al. detailed what they believe is the first known outbreak of diarrheal illness associated with *Cyclospora* in the United States The outbreak, which occurred in 1990, consisted of 21 cases of illness among physicians and others working at a Chicago hospital. Contaminated tap water from a physicians' dormitory at the hospital was the probable source of the organisms. The tap water probably picked up the organism while in a storage tank at the top of the dormitory after the failure of a water pump (Huang et al., 1995).

The transmission of *Cyclospora* is not a straightforward process. When infected persons excrete the oocyst state of *Cyclospora* in their feces, the oocysts are not infectious and may require from days to weeks to become so (i.e., to sporulate). Therefore, transmission of *Cyclospora* directly from an infected person to someone else is unlikely. However, indirect transmission can occur if an infected person contaminates the environment and oocysts have sufficient time, under appropriate conditions, to become infectious. For example, *Cyclospora* may be transmitted by ingestion of water or food contaminated with oocysts. Outbreaks linked to contaminated water, as well as outbreaks linked to various types of fresh produce, have been reported in recent years (Herwaldt, 1997). How common the various modes of transmission and sources of infection are not yet known, nor is it known whether animals can be infected and serve as sources of infection for humans.

√ **Note:** *Cyclospora* organisms have not yet been grown in tissue cultures or laboratory animal models.

Persons of all ages are at risk for infection. Persons living or traveling in developing countries may be at increased risk; but infection can be acquired worldwide, including in the United States. In some countries of the world, infection appears to be seasonal.

Based on currently available information, avoiding water or food that may be contaminated with stool is the best way to prevent infection. Reinfection can occur.

√ **Note:** De Zuane (1997) points out that pathogenic parasites are not easily removed or eliminated by conventional treatment and disinfection unit processes. This is particularly true for *G. lamblia*, *Cryptosporidium*, and *Cyclospora*. Filtration facilities can be adjusted in depth, prechlorination, filtration rate, and backwashing to become more effective in the removal of cysts. The pretreatment of protected watershed raw water is a major factor in the elimination of pathogenic protozoa.

REFERENCES

Bingham, A.K., Jarroll, E.L., Meyer, E.A., and Radulescu, S., 1979. *Introduction of Giardia Excystation and the Effect of Temperature on Cyst Viability Compared by Eosin-Exclusion and In Vitro Excystation in Waterborne Transmission of Giardiasis*, Jakubowski, J., and Hoff, H.C. (eds.). Washington, DC: United States Environmental Protection Agency, EPA-600/9-79-001, pp. 217–229.

Black, R.E., Dykes, A.C., Anderson, K.E., Wells, J.G., Sinclair, S.P., Gary, G.W., Hatch, M.H., and Gnagarosa, E.J., 1981. Handwashing to Prevent Diarrhea in Day-Care Centers. *Am. J. Epidemiol.*, 113: 445–451.

Brodsky, R.E., Spencer, H.C., and Schultz, M.G., 1974. Giardiasis in American Travelers to the Soviet Union. *J. Infect. Dis.*, 130:319–323.

Cibas, E.S. and Ducatman, B.S., 2003. *Cytology: Diagnostic Principles and Clinical Correlates.* London: Saunders Ltd.

CDC, 1979. *Intestinal Parasite Surveillance, Annual Summary 1978.* Atlanta: Centers for Disease Control.

CDC, 1984. *Water-related Disease Outbreaks Surveillance, Annual Summary 1983.* Atlanta: Centers for Disease Control.

CDC, 1995. *Cryptosporidiosis (Fact Sheet).* Atlanta: Centers for Disease Control.

Davidson, R.A., 1984. Issues in Clinical Parasitology: The Treatment of Giardiasis. *Am. J. Gastroenterol.*, 79:256–261.

De Zuane, J., 1997. *Handbook of Drinking Water Quality.* New York: John Wiley & Sons.

Fayer, R., Speer, C.A., and Dubey, J.P., 1997. The General Biology of *Cryptosporidium.* In *Cryptosporidium and Cryptosporidiosis*, Fayer, R. (ed.). Boca Raton, FL: CRC Press.

Frost, F., Plan, B., and Liechty, B., 1984. Giardia Prevalence in Commercially Trapped Mammals. *J. Environ. Health*, 42:245–249.

Hickman, C.P. et al., 1997. *The Biology of Animals*, 7th ed. New York: William C. Brown/McGraw-Hill.

Huang, P., Weber, J.T., Sosin, D.M. et al., 1995. The First Reported Outbreak of Diarrheal Illness Associated with Cyclospora in the United States. *Ann. Intern. Med.*, 123:401–414.

Jarroll, E.L., Jr., Bingham, A.K., and Meyer, E.A., 1979. Giardia Cyst Destruction: Effectiveness of Six Small-Quantity Water Disinfection Methods. *Am. J. Trop. Med. Hygiene*, 29:8–11.

Jarroll, E.L., Jr., Bingham, A.K., and Meyer, E.A., 1980. Inability of an Iodination Method to Destroy Completely *Giardia* Cysts in Cold Water. *West J. Med.*, 132:567–569.

Jokipii, L. and Jokipii, A.M.M., 1974. Giardiasis in Travelers: A Prospective Study. *J. Infect. Dis.*, 130: 295–299.

Juranek, D.D., 1995. *Cryptosporidium parvum. Clin Infect. Dis.*, 21 (Suppl. 1):S57–S61.

Kemmer, F.N., 1979. *Water: The Universal Solvent*, 2nd ed. Oak Brook, IL: Nalco Chemical Company.

Koren, H., 1991. *Handbook of Environmental Health and Safety: Principles and Practices.* Chelsea, MI: Lewis Publishers.

LeChevallier, M.W., Norton, W.D., and Lee, R.G., 1991. Occurrence of *Giardia* and *Cryptosporidium* spp. in Surface Water Supplies. *Appl. Environ. Microbiol.*, 57(9):2610–2616.

Mayo Foundation, 1996. *The "Bug" That Made Milwaukee Famous.* Washington, DC: Mayo Foundation for Medical Education and Research.

Panciera, R.J., Thomassen, R.W., and Garner, R.M., 1971. Cryptosporidial Infection in a Calf. *Vet. Pathol.*, 8:479.

Pickering, L.K., Woodward, W.E., Dupont, H.L., and Sullivan, P., 1984. Occurrence of *Giardia lamblia* in Children in Day Care Centers. *J. Pediatr.*, 104:522–526.

Rendtorff, R.C., 1954. The Experimental Transmission of Human Intestinal Protozoan Parasites. II. *Giardia lamblia* Cysts Given in Capsules. *Am. J. Hygiene*, 59:209–220.

Rose, J.B., Gerba, C.P., and Jakubowski, W., 1991. Survey of Potable Water Supplies for *Cryptosporidium* and *Giardia. Environ. Sci. Technol.*, 25:1393–1399.

Tyzzer, E.E., 1912. *Cryptosporidium parvum* (sp. nov.), a Coccidium Found in the Small Intestine of the Common Mouse. *Arch. Protistenkd.*, 26:394.

Walsh, J.D. and Warren, K.S., 1979. Selective Primary Health Care: An Interim Strategy for Disease Control in developing countries. *N. Engl. J. Med.*, 301:970–974.

Walsh, J.A., 1981. Estimating the Burden of Illness in the Tropics. In *Tropical and Geographic Medicine*, Warren, K.S., and Mahmoud, A.F. (eds.). New York: McGraw-Hill, pp. 1073–1085.

Weller, P.F., 1985. Intestinal Protozoa: Giardiasis. *Sci. Am. Med.*, 5:37–51.

Wistreich, G.A. and Lechtman, M.D., 1980. *Microbiology*, 3rd ed. New York: Macmillan Publishing Co.

FURTHER READING

Badenock, J., 1990. *Cryptosporidium in Water Supplies.* London: HMSO Publications.

Black-Covilli, L.L., 1992. Basic Environmental Chemistry of Hazardous and Solid Wastes. In *Fundamentals of Environmental Science and Technology*, Knowles, P.C. (ed.). Rockville, MD: Government Institutes, Inc., pp. 13–30.

Craun, G.T., 1979. Waterborne Giardiasis in the United States: A Review. *Am. J. Public Health*, 69:817–819.

Craun, G.F., 1984. Waterborne Outbreaks of Giardiasis—Current Status in Giardia and Giardiasis. In *Giardia and Giardisis: Biology, Pathogenicity, and Epidemiology*, Erlandsen, S.L., and Meyer, E.A. (eds.). New York: Plenum Press, pp. 243–261.

CDC, 1997a. Update: Outbreaks of Cyclosporiasis—United States and Canada. *Morbidity and Mortality Weekly Report*, 46:521–523.

CDC, 1997b. Outbreak of Cyclosporiasis—Northern Virginia–Washington, DC–Baltimore, Maryland, Metropolitan Area. *Morbidity and Mortality Weekly Report*, 46:689–691.

DeDuve, C., 1984. *A Guided Tour of the Living Cell.* New York: Scientific Library, W.H. Freeman Company.

Finean, J.B., 1984. *Membranes and Their Cellular Functions.* Oxford: Blackwell Scientific Publications.

Frank, J. et al., 1995. A Model of Synthesis Based on Cryo-Electron Microscopy of the *E. coli* Ribosome. *Nature*, 376:440–444.

Garrett, R. et al., 2000. *The Ribosome: Structure, Function, Antibiotics, and Cellular Interactions.* Washington, DC: American Society for Microbiology.

Herwaldt, B.L. et al., 1997. An Outbreak in 1996 of Cyclosporiasis Associated with Imported Raspberries. *N. Engl. J. Med.*, 336:1548–1556.

Hoge, C.W. et al., 1995. Placebo-Controlled Trial of Co-trimoxazole for *Cyclospora* Infections among Travelers and Foreign Residents in Nepal. *Lancet*, 345:691–693.

Jarroll, E.L., Bingham, A.K., and Meyer, E.A., 1981. Effect of Chlorine on *Giardia lamblia* Cyst Viability. *Appl. Environ. Microbiol.*, 41:483–487.

Kordon, C., 1993. *The Language of the Cell.* New York: McGraw-Hill.

Marchin, B.L., Fina, L.R., Lambert, J.L., and Fina, G.T., 1983. Effect of Resin Disinfectants—13 and 15 on *Giardia muris* and *Giardia lamblia*. *Appl. Environ. Microbiol.*, 46:965–969.

Martin, S., 1981. *Understanding Cell Structure.* Cambridge, NY: Cambridge University Press.

Murray, A.W., 1993. *The Cell Cycle: An Introduction.* New York: W.H. Freeman.

National Academy of Sciences, 1977. *Drinking Water and Health* (Vol. 1). Washington, DC: The National Research Council, National Academy Press.

National Academy of Sciences, 1982. *Drinking Water and Health* (Vol. 4). Washington, DC: The National Research Council, National Academy Press.

Patterson, D.J., and Hedley, S., 1992. *Free-Living Freshwater Protozoa: A Color Guide.* Boca Raton, FL: CRC Press.

Pickering, L.K., Evans, D.G., Dupont, H.L., Vollet, J.J., III, and Evans, D.J., Jr., 1981. Diarrhea Caused by *Shigella*, Rotavirus, and *Giardia* in Day-Care Centers: Prospective Study. *J. Pediatr.*, 99:51–56.

Prescott, L.M., Harley, J.P., and Klein, D.A., 1993. *Microbiology*, 3rd ed. Dubuque, IA: Wm. C. Brown Company Publishers.

Sealy, D.P. and Schuman, S.H., 1983. Endemic Giardiasis and Day Care. *Pediatrics*, 72:154–158.

Serafini, A., 1993. *The Epic History of Biology.* New York: Plenum.

Singleton, P., 1992. *Introduction to Bacteria*, 2nd ed. New York: Wiley.

Singleton, P., and Sainsbury, D., 1994. *Dictionary of Microbiology and Molecular Biology*, 2nd ed. New York: Wiley.

Slavin, D., 1955. *Cryptosporidium meleagridis* (s. nov.), *J. Comp. Pathol.*, 65: 262.

Spellman, F.R., 1997. *Microbiology for Water/Wastewater Operators.* Lancaster, PA: Technomic Publishing Company.

Spirin, A., 1986. *Ribosome Structure and Protein Biosynthesis.* Menlo Park, CA: Benjamin Cummings.

Tchobanoglous, G. and Schroeder, E.D., 1987. *Water Quality.* Reading, MA: Addison-Wesley Publishing Company.

The Age, 1998. *Water Bugs are Algae, Says Expert.* Sydney, Australia, September 29.

Thomas, L., 1974. *The Lives of a Cell.* New York: Viking Press.

Thomas, L., 1982. *Late Night Thoughts on Listening to Mahler's Ninth Symphony.* New York: Viking Press.

Thomas, L., 1995. *The Life of a Cell: Notes of a Biology Watcher.* New York: Penguin Books.

Tyzzer, E.E., 1907. A Sporozoan Found in the Peptic Glands of the Common Mouse. *Proc. Soc. Exp. Biol. Med.*, 5:12–13.

Upton, S.J., 1997. *Basic Biology of Cryptosporidium*. Manhattan, KS: Kansas State University.

Visvesvara, G.S. et al., 1997. Uniform staining of *Cyclospora* oocysts in fecal smears by a modified safranin technique with microwave heating. *J. Clin. Microbiol.*, 35:730–733.

Weniger, B.D., Blaser, M.J., Gedrose, H., Lippy, E.C., and Juranek, D.D., 1983. An outbreak of waterborne giardiasis associated with heavy water runoff due to warm weather and volcanic ashfall. *Am. J. Public Health*, 78:868–872.

WHO, 1984. *Guidelines for Drinking Water Quality.* (Vol. 1—Recommendation; Vol. 2—Health Criteria and Other Supporting Information). Geneva, Switzerland: World Health Organization.

Running Water. White Oak Canyon Trail, Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

6 Water Ecology

> The subject of man's relationship to his environment is one that has been uppermost in my own thoughts for many years. Contrary to the beliefs that seem often to guide our actions, man does not live apart from the world; he lives in the midst of a complex, dynamic interplay of physical, chemical, and biological forces, and between himself and this environment there are continuing, never-ending interactions.
>
> Unfortunately, there is so much that could be said. I am afraid it is true that, since the beginning of time, man has been a most untidy animal. But in the earlier days this perhaps mattered less. When men were relatively few, their settlements were scattered; their industries undeveloped; but now pollution has become one of the most vital problems of our society …
>
> **—R. Carson (1998)**

A few years ago, my sampling partner and I were preparing to perform benthic macroinvertebrate sampling protocols in a wadeable section in one of the many reaches of the Yellowstone River. It was autumn, windy, and cold. Before joining my partner knee deep in the slow-moving frigid waters, I stood for a moment at the bank and took in the surroundings. Except for a line of gold, the pallet of autumn is austere in Yellowstone. The coniferous forests west of the Mississippi lack the bronzes, the coppers, the peach-tinted yellows, the livid scarlets that set mixed stands of the East aflame. All I could see in that line was the quaking aspen and its gold. This species, showing the closest thing to eastern autumn in the west, is gathered in the narrow, rounded crowns of *Populus tremuloides*. The aspen trunks stood white and antithetical against the darkness of the firs and pines. The shiny pale gold leaves, sensitive to the slightest rumor of wind, agitated and bounced the sun into my eyes. Each tree scintillated, like a heap of gold coins in free fall. The aspens tried desperately, by all their flash and motion, to make up for the area's failure to fill the full spectrum of fall. But I didn't care much … I certainly wasn't disappointed. While it is true that little is comparable to leaf fall in autumn along the Appalachian Trail of my home, it simply didn't matter. Nature's venue with its display of gold against dark green eased the task that was before me. Bone-chilling water and all—it simply didn't matter.

***

Streams are arteries of the Earth, beginning in capillary creeks, brooks, and rivulets. Irrespective of the source, they move in only one direction—downhill—the heavy hand of gravity tugs and drags the stream toward the sea. During its inexorable flow downward, now and then there is an abrupt change in geology. Boulders are mowed down by "slumping" (gravity) from their "in place" points high up on canyon walls.

As the stream flow grinds, chisels, and sculpts the landscape, the effort is increased by the momentum and augmented by turbulence provided by rapids, cataracts, and waterfalls. These falling waters always hypnotize, like fire gazing or wave-watching.

Before emptying into the sea, streams often pause, forming lakes. When one stares into a healthy lake, its phantom blue-green eye stares right back. Only for a moment—relatively speaking, of course—because all lakes are ephemeral, doomed. Eventually, the phantom blue-green eye is close lidded by the moist verdant green of landfill.

For water that escapes the temporary bounds of a lake, most of it evaporates or moves on to the sea.

***

This chapter deals primarily with the interrelationship (the ecology) of biota (life forms) in placid water bodies (lakes) and running water (streams). The bias of this chapter is dictated by the author's experience and interest and by his belief that there is a need for water practitioners and students of water science to have a basic knowledge of water-related ecological processes.

Ecology is important because the environmental challenges we face today include all the same ones that we faced more than 30 years ago at the first Earth Day celebration in 1970. In spite of unflagging efforts of environmental professionals (and others), environmental problems remain. Many large metropolitan areas continue to be plagued by smog, our beaches are periodically polluted by oil spills, and many of our running and standing waters (streams and lakes) still suffer the effects of poorly treated sewage and industrial discharges. However, considerable progress has been made. For example, many of our rivers and lakes that were once unpleasant and unhealthy are now fishable and swimmable.

This is not to say that we are out of the woods yet. The problem with making progress in one area is that new problems are discovered that prove to be even more intractable than those we have already encountered. In restoring our running and standing waters to their original pristine state, this has been found to be the case.

Those interested in the science of freshwater ecology (e.g., water practitioners and students) must understand the effects of environmental stressors, such as toxics, on the microbiological ecosystem in running and standing waters. Moreover, changes in these ecosystems must be measured and monitored.

The science of freshwater ecology is a dynamic discipline; new scientific discoveries are made daily and new regulatory requirements are almost as frequent. Today's emphasis is placed on other aspects of freshwater ecology [e.g., nonpoint source pollution and total maximum daily load (TMDL)]. Finally, in the study of freshwater ecology it is important to remember the axiom: left to her, Mother Nature can perform wonders, but overload her and there might be hell to pay.

SETTING THE STAGE

> We poison the caddis flies in a stream and the salmon runs dwindle and die. We poison the gnats in a lake and the poison travels from link to link of the food chain and soon the birds of the lake margins become victims. We spray our elms and the following springs are silent of robin song, not because we sprayed the robins directly but because the poison traveled, step by step, through the now familiar elm leaf-earthworm-robin cycle. These are matters of record, observable, part of the visible world around us. They reflect the web of life—or death—that scientists know as ecology.
>
> **—R. Carson (1962)**

As Rachel Carson points out, what we do to any part of our environment has an impact upon other parts. There is the interrelationship between the parts that make up our environment. Probably the best way to state this interrelationship is to define ecology. *Ecology* is the science that deals with the specific interactions that exist between organisms and their living and nonliving environment. The word "ecology" is derived from the Greek word *oikos*, meaning home. Therefore, ecology is the study of the relation of an organism or a group of organisms to their environment (their "home").

Charles Darwin explained ecology in a famous passage in *The Origin of Species*—a passage that helped establish the science of ecology. A "web of complex relations" binds all living things in any region, Darwin writes. Adding or subtracting even a single species causes waves of change that race through the web, "onwards in ever-increasing circles of complexity." The simple act of adding cats to an English village would reduce the number of field mice. Killing mice would benefit the bumblebees, whose nest and honeycombs the mice often devour. Increasing the number of bumblebees would benefit the heartsease and red clover, which are fertilized almost exclusively by bumblebees. So adding cats to the village could end by adding flowers. For Darwin, the whole of the Galapagos archipelago argues this fundamental lesson. The volcanoes are much more diverse in their ecology than their biology. The contrast suggests that in the struggle for existence, species are shaped at least as much by the local flora and fauna as by the local soil and climate. "Why else would the plants and animals differ radically among islands that have the same geological nature, the same height, and climate?" (Darwin, 1998).

The environment includes everything important to the organism in its surroundings. The organism's environment can be divided into four parts:

1. Habitat and distribution—its place to live
2. Other organisms—whether friendly or hostile
3. Food
4. Weather—light, moisture, temperature, soil, etc.

There are two major subdivisions of ecology: autecology and synecology. *Autecology* is the study of the individual organism or a species, for example, when a biologist spends his/her entire lifetime studying the ecology of the salmon. It emphasizes life history, adaptations, and behavior. It is the study of communities, ecosystems, and the biosphere. *Synecology*, on the other hand, is the study of groups of organisms associated together as a unit. It deals with the environmental problems caused by humankind. For example, the effects of discharging phosphorus-laden effluent into a stream or lake involve several organisms. The activities of human beings have become a major component of many natural areas. As a result, it is important to realize that the study of ecology must involve people.

KEY DEFINITIONS

Each division of ecology has its own set of terms that are essential for communication between ecologists and those who are studying running and standing water ecological systems. For this reason, along with basic ecological terms, key terms that specifically pertain to this chapter are defined and presented in the following section.

Abiotic factor The nonliving part of the environment composed of sunlight, soil, mineral elements, moisture, temperature, and topography.

Aeration A process whereby water and air or oxygen are mixed.

Bacteria Among the most common microorganisms in water. Bacteria are primitive, single-celled organisms with a variety of shapes and nutritional needs.

Biochemical oxygen demand (BOD) A widely used parameter of organic pollution applied to both wastewater and surface water … involving the measurement of the dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter.

Biotic factor (community) The living part of the environment composed of organisms that share the same area; are mutually sustaining and interdependent; and constantly fixing, utilizing, and dissipating energy.

Biotic index The diversity of species in an ecosystem is often a good indicator of the presence of pollution. The greater the diversity, the lower the degree of pollution. The biotic index is a systematic survey of invertebrate aquatic organism used to correlate with river quality.

Climax community The terminal stage of an ecological succession in an area.

Community In an ecological sense, community includes all the populations occupying a given area.

Competition A critical factor for organisms in any community. Animals and plants must compete successfully in the community to stay alive.

Decomposition The breakdown of complex material into simple substances by chemical or biological processes.

Dissolved oxygen (DO) The amount of oxygen dissolved in a stream is an indication of the degree of health of the stream and its ability to support a balanced aquatic ecosystem.

Ecosystem The community and the nonliving environment functioning together as an ecological system.

Emigration The departure of organisms from one place to take up residence in another area.

Eutrophication The natural aging of a lake or land-locked body of water, which results in organic material being produced in abundance due to a ready supply of nutrients accumulated over the years.

Habitat Ecologists use this term to refer to the place where an organism lives.

Heterotroph Any living organism that obtains energy by consuming organic substances produced by other organisms.

Immigration The movement of organisms into a new area of residence.

Limiting factor A necessary material that is in short supply. Because of the lack of it, an organism cannot reach its full potential.

Niche The role that an organism plays in its natural ecosystem, including its activities, resource use, and interaction with other organisms.

Nonpoint pollution Sources of pollutants in the landscape (e.g., agricultural runoff).

Point source Source of pollutants that involves discharge of pollutants from an identifiable point, such as a smokestack or sewage treatment plant.

Pollution An adverse alteration to the environment by a pollutant.

Population A group of organisms of a single species that inhabit a certain region at a particular time.

Runoff After an organic waste has been applied to a soil, the possibility exists that some of this waste may be transmitted by rainfall, snowmelt, or irrigation runoff into surface waters.

Sewage The liquid wastes from a community. Domestic sewage comes from housing. Industrial sewage is normally from mixed industrial and residential sources.

Succession A process that occurs subsequent to disturbance and involves the progressive replacement of biotic communities with others over time.

Symbiosis A compatible association between dissimilar organisms to their mutual advantage.

Trophic level The feeding position occupied by a given organism in a food chain measured by the number of steps removed from the producers.

LEVELS OF ORGANIZATION

Odum (1983) explains, "The best way to delimit modern ecology is to consider the concept of *levels of organization*." Levels of organization can be simplified as shown in Figure 6.1. In this relationship, organs form an organism; organisms of a particular species form a population; populations occupying a particular area form a community. Communities, interacting with nonliving or abiotic factors, separate in a natural unit to create a stable system known as the *ecosystem* (the major ecological unit); and the part of the Earth in which ecosystem operates in is known as the *biosphere*. Tomera (1989) points out that "every community is influenced by a particular set of abiotic factors." Inorganic substances such as oxygen, carbon dioxide, several other inorganic substances, and some organic substances represent the abiotic part of the ecosystem.

The physical and biological environment in which an organism lives is referred to as its *habitat*. For example, the habitat of two common aquatic insects, the "backswimmer" (*Notonecta*) and the "water boatman" (*Corixa*), is the littoral zone of ponds and lakes (shallow, vegetation-choked areas) (see Figure 6.2) (Odum, 1983).

Within each level of organization of a particular habitat, each organism has a special role. The role the organism plays in the environment is referred to as its *niche*. A niche might be that an

Organs → Organism → Population → Communities → Ecosystem → Biosphere

FIGURE 6.1 Levels of organization.

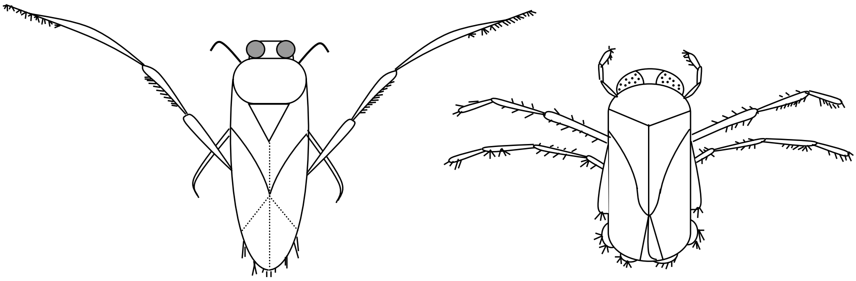


FIGURE 6.2 *Notonecta* (left) and *Corixa* (right). (Adapted from Odum, E.P., *Basic Ecology*, Saunders College Publishing, Philadelphia, 1983, p. 402.)

organism is a predator of or prey for some other organisms. Odum refers to an organism's niche as its "profession" (Odum, 1975). In other words, each organism has a job or role to fulfill in its environment. Although two different species might occupy the same habitat, "niche separation based on food habits" differentiates two species (Odum, 1983). Comparing the niches of the water backswimmer and the water boatman reveals such niche separation. The backswimmer is an active predator, while the water boatman feeds largely on decaying vegetation (McCafferty, 1981).

ECOSYSTEM

Ecosystem denotes an area that includes all organisms therein and their physical environment. The ecosystem is the major ecological unit in nature. Living organisms and their nonliving environment are inseparably interrelated and interact with each other to create a self-regulating and self-maintaining system. To create a self-regulating and self-maintaining system, ecosystems are homeostatic, i.e., they resist any change through natural controls. These natural controls are important in ecology. This is especially the case because natural controls tend to be disrupted by people through their complex activities.

As stated earlier, the ecosystem encompasses both the living and nonliving factors in a particular environment. The living or biotic part of the ecosystem is formed by two components: autotrophic and heterotrophic. The autotrophic (self-nourishing) component does not require food from its environment but can manufacture food from inorganic substances. For example, some autotrophic components (plants) manufacture needed energy through photosynthesis, whereas heterotrophic components depend upon autotrophic components for food.

The nonliving or abiotic part of the ecosystem is formed by three components: inorganic substances, organic compounds (link biotic and abiotic parts), and climate regime. Figure 6.3 is a simplified diagram showing a few of the living and nonliving components of an ecosystem found in a freshwater pond.

An ecosystem is a cyclic mechanism in which biotic and abiotic materials are constantly exchanged through *biogeochemical cycles. Bio* refers to living organisms and *geo* to water, air, rocks, or solids. *Chemical* is concerned with the chemical composition of the Earth. Biogeochemical cycles are driven by energy, directly or indirectly from the sun.

Figure 6.3 depicts an ecosystem where biotic and abiotic materials are constantly exchanged. Producers construct organic substances through photosynthesis and chemosynthesis. Consumers and decomposers use organic matter as their food and convert it into abiotic components; that is, they dissipate energy fixed by producers through food chains. The abiotic part of the pond in Figure 6.3 is formed of inorganic and organic compounds dissolved and in sediments such as carbon, oxygen, nitrogen, sulfur, calcium, hydrogen, and humic acids. Producers such as rooted plants and phytoplanktons represent the biotic part. Fish, crustaceans, and insect larvae make up the consumers. Mayfly nymphs represent detrivores, which feed on organic detritus.

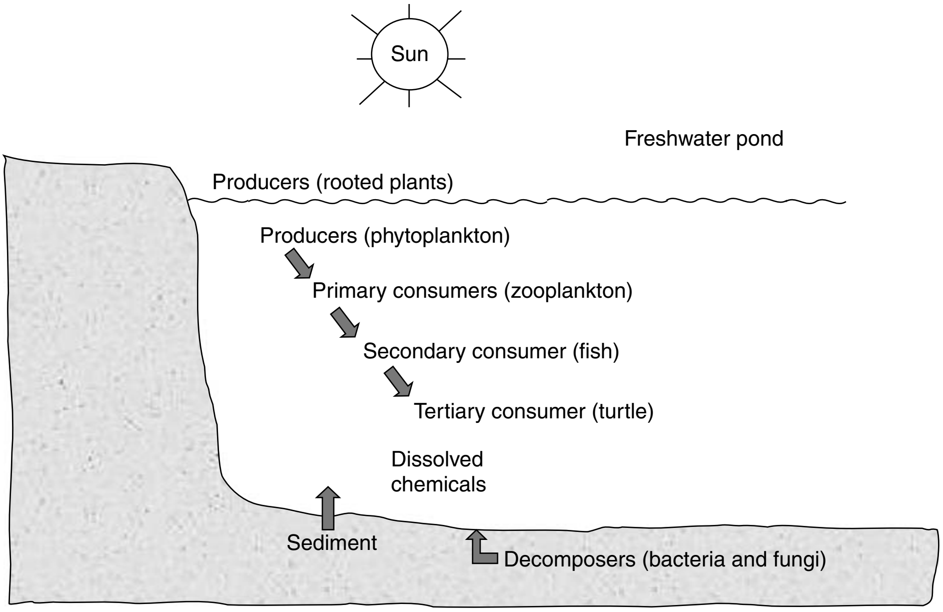


FIGURE 6.3 Major components of a freshwater pond ecosystem.

Decomposers make up the final biotic part. They include aquatic bacteria and fungi, which are distributed throughout the pond.

As stated earlier, an ecosystem is a cyclic mechanism. From a functional viewpoint, an ecosystem can be analyzed in terms of several factors. The factors important in this study include the biogeochemical cycles and energy and food chains.

BIOGEOCHEMICAL CYCLES

Several chemicals are essential to life and follow predictable cycles through nature. In these natural cycles or biogeochemical cycles, the chemicals are converted from one form to another as they progress through the environment. The water/wastewater operator should be aware of those cycles dealing with the nutrients (e.g., carbon, nitrogen, and sulfur) because they have a major impact on the performance of the plant and may require changes in operation at various times of the year to keep them functioning properly; this is especially the case in wastewater treatment. The microbiology of each cycle deals with the biotransformation and subsequent biological removal of these nutrients in wastewater treatment plants.

√ **Note:** Smith (1974) categorizes biogeochemical cycles into two types, the *gaseous* and the *sedimentary*. Gaseous cycles include the carbon and nitrogen cycles. The main sink of nutrients in the gaseous cycle is the atmosphere and the ocean. Sedimentary cycles include the sulfur cycle. The main sink for sedimentary cycles is soil and rocks of the Earth's crust.

CARBON CYCLE

Carbon, which is an essential ingredient of all living things, is the basic building block of the large organic molecules necessary for life. Carbon is cycled into food chains from the atmosphere, as shown in Figure 6.4.

From Figure 6.4 it can be seen that green plants obtain carbon dioxide (CO_2) from the air and through photosynthesis, which is described by Asimov (1989) as the "most important chemical

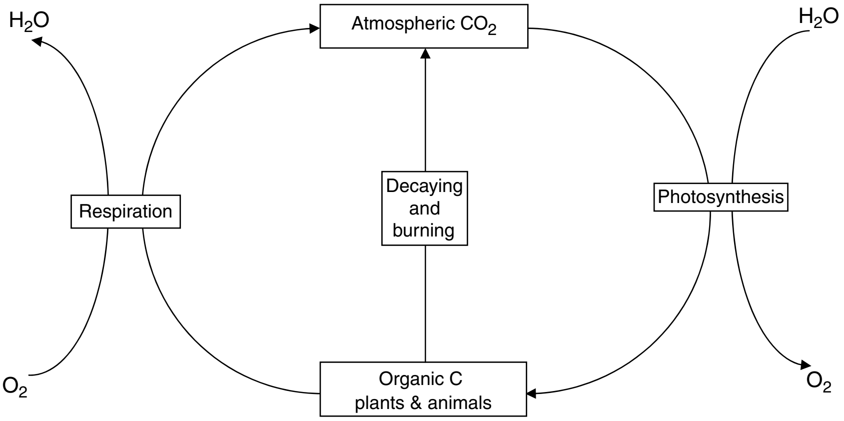


FIGURE 6.4 Carbon cycle.

process on Earth." This process produces the food and oxygen that all organisms live on. Part of the carbon produced remains in living matter; the other part is released as CO_2 in cellular respiration. Miller (1988) points out that the carbon dioxide released by cellular respiration in all living organisms is returned to the atmosphere.

Some carbon is contained in buried, dead animal and plant materials. Much of these buried animal and plant materials were transformed into fossil fuels. Fossil fuels, coal, oil, and natural gas contain large amounts of carbon. When fossil fuels are burned, stored carbon combines with oxygen in the air to form carbon dioxide, which enters the atmosphere.

In the atmosphere, carbon dioxide acts as a beneficial heat screen because it does not allow the radiation of the Earth's heat into space. This balance is important. The problem is that as more carbon dioxide from burning is released into the atmosphere, the balance can be and is being altered. Odum (1983) warns that the recent increase in consumption of fossil fuels "coupled with the decrease in 'removal capacity' of the green belt is beginning to exceed the delicate balance." Massive increases of carbon dioxide into the atmosphere tend to increase the possibility of global warming. The consequences of global warming "would be catastrophic … and the resulting climatic change would be irreversible" (Abrahamson, 1988).

NITROGEN CYCLE

Nitrogen is an essential element for all organisms. In animals, nitrogen is a component of crucial organic molecules such as proteins and DNA and constitutes 1–3% of the dry weight of cells. Our atmosphere contains 78% by volume of nitrogen, yet it is not a common element on the Earth. Although nitrogen is an essential ingredient for plant growth, it is chemically very inactive, and before the vast majority of the biomass can incorporate it, it must be "fixed." Special nitrogen-fixing bacteria found in soil and water fix nitrogen. Thus, microorganisms play a major role in nitrogen cycling in the environment. These microorganisms (bacteria) have the ability to take nitrogen gas from the air and convert it to nitrate. This is called *nitrogen fixation*. Some of these bacteria occur as free-living organisms in the soil. Others live in a *symbiotic relationship* (a close relationship between two organisms of different species, and one where both partners benefit from the association) with plants. An example of a symbiotic relationship, related to nitrogen, can be seen, for example, in the roots of peas. These roots have small swellings along their length. These contain millions of symbiotic bacteria, which have the ability to take nitrogen gas from the atmosphere and convert it to nitrates that can be used by the plant. Then the plant is plowed into the soil after the growing season to improve the nitrogen content. Price (1984) describes the nitrogen cycle as an example "of a largely complete chemical cycle in ecosystems with little leaching out of the system."

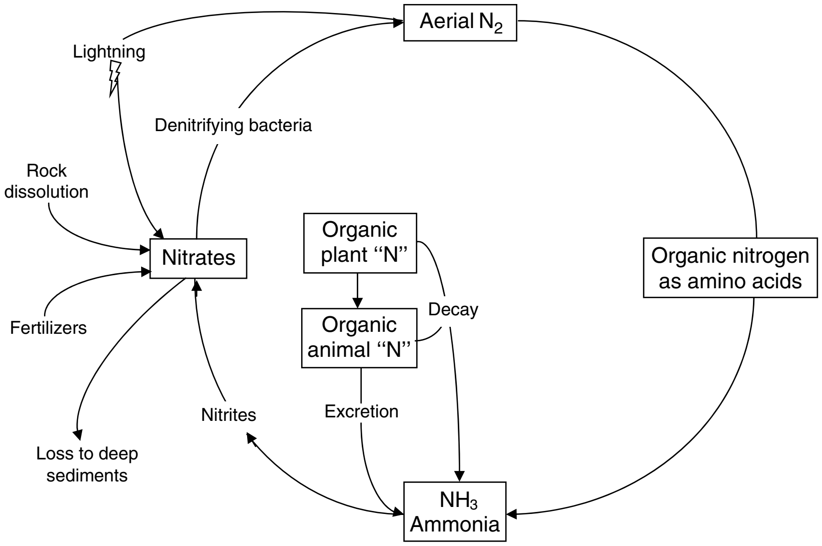


FIGURE 6.5 Nitrogen cycle.

Simply, the nitrogen cycle provides various bridges between the atmospheric reservoirs and the biological communities (see Figure 6.5).

Atmospheric nitrogen is fixed either by natural or industrial means. For example, nitrogen is fixed by lightning or by soil bacteria that convert it to ammonia, then to nitrite, and finally to nitrates, which plants can use. Nitrifying bacteria make nitrogen from animal wastes. Denitrifying bacteria convert nitrates back to nitrogen and release it as a gas.

The logical question is: What does all of this have to do with water? The best way to answer this question is to ask another question. Have you ever swum in a slow-moving stream and had the noxious misfortune to surface right in the middle of an algal bloom? When this happens to you, the first thought that runs through your mind is, "Where is my nose plug?" Why? Because of the horrendous stench, disablement of the olfactory sense is an absolute necessity.

Algal blooms are formed when too much nitrate enters the water supply—as runoff from fertilizers—producing an overabundance of algae. If this runoff containing fertilizer gets into a body of water, algae may grow so profusely that they form a blanket over the surface. This usually happens in summer, when the light levels and warm temperatures favor rapid growth.

Metcalf & Eddy, Inc. (1991) in the third edition of its voluminous and authoritative text, *Wastewater Engineering: Treatment, Disposal, Reuse*, point out that nitrogen is found in wastewater in the form of urea. During wastewater treatment, the urea is transformed into ammonia. Since ammonia exerts a BOD and chlorine demand, high quantities of ammonia in wastewater effluents are undesirable. The process of nitrification is utilized to convert ammonia to nitrates. *Nitrification* is a biological process that involves the addition of oxygen to the wastewater. If further treatment is necessary, another biological process called *denitrification* is used. In this process, nitrate is converted into nitrogen gas, which is lost to the atmosphere, as can be seen in Figure 6.5. From the wastewater operator's point of view, nitrogen and phosphorus are both considered limiting factors for productivity. Phosphorus discharged into streams contributes to pollution. Of the two, nitrogen is harder to control but is found in smaller quantities in wastewater.

SULFUR CYCLE

Sulfur, like nitrogen, is characteristic of organic compounds. The *sulfur cycle* (see Figure 6.6) is both sedimentary and gaseous. Tchobanglous and Schroeder (1985) note that "the principal forms

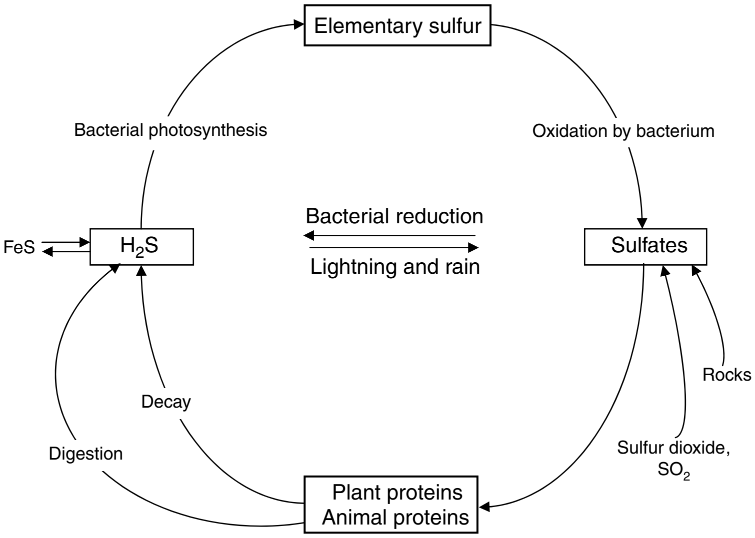


FIGURE 6.6 The sulfur cycle.

of sulfur that are of special significance in water quality management are organic sulfur, hydrogen sulfide, elemental sulfur and sulfate."

Bacteria play a major role in the conversion of sulfur from one form to another. In an anaerobic environment, bacteria break down organic matter, thereby producing hydrogen sulfide with its characteristic rotten-egg odor. A bacterium called *Beggiatoa* converts hydrogen sulfide into elemental sulfur into sulfates. Other sulfates are contributed by the dissolving of rocks and some sulfur dioxide. Sulfur is incorporated by plants into proteins. Organisms then consume some of these plants. Many heterotrophic anaerobic bacteria liberate sulfur from proteins as hydrogen sulfide.

PHOSPHORUS CYCLE

Phosphorus is another element that is common in the structure of living organisms. Of all the elements recycled in the biosphere, phosphorus is the scarcest and therefore the one most limiting in any given ecological system. It is indispensable to life, being intimately involved in energy transfer and in the passage of genetic information in the DNA of all cells.

The ultimate source of phosphorus is rock, from which it is released by weathering, leaching, and mining. Phosphorus occurs as phosphate or other minerals formed in past geological ages. These massive deposits are gradually eroding to provide phosphorus to ecosystems. A large amount of eroded phosphorus ends up in deep sediments in the oceans and lesser amounts in shallow sediments. Part of the phosphorus comes to land when marine animals are brought out. Birds also play a role in the recovery of phosphorus. The great guano deposit, bird excreta, of the Peruvian coast is an example. Man has hastened the rate of loss of phosphorus through mining activities and the subsequent production of fertilizers, which are washed away and lost. Even with the increase in human activities, however, there is no immediate cause for concern, since the known reserves of phosphate are quite large. Figure 6.7 shows the phosphorus cycle.

Phosphorus has become very important in water quality studies because it is often found to be a limiting factor (i.e., limiting plant nutrient). Control of phosphorus compounds that enter surface waters and contribute to growth of algal blooms is of great interest to stream ecologists. Phosphates, upon entering a stream, act as fertilizers, which promote the growth of undesirable algae populations or algal blooms. As the organic matter decays, DO levels decrease, and fish and other aquatic species die.

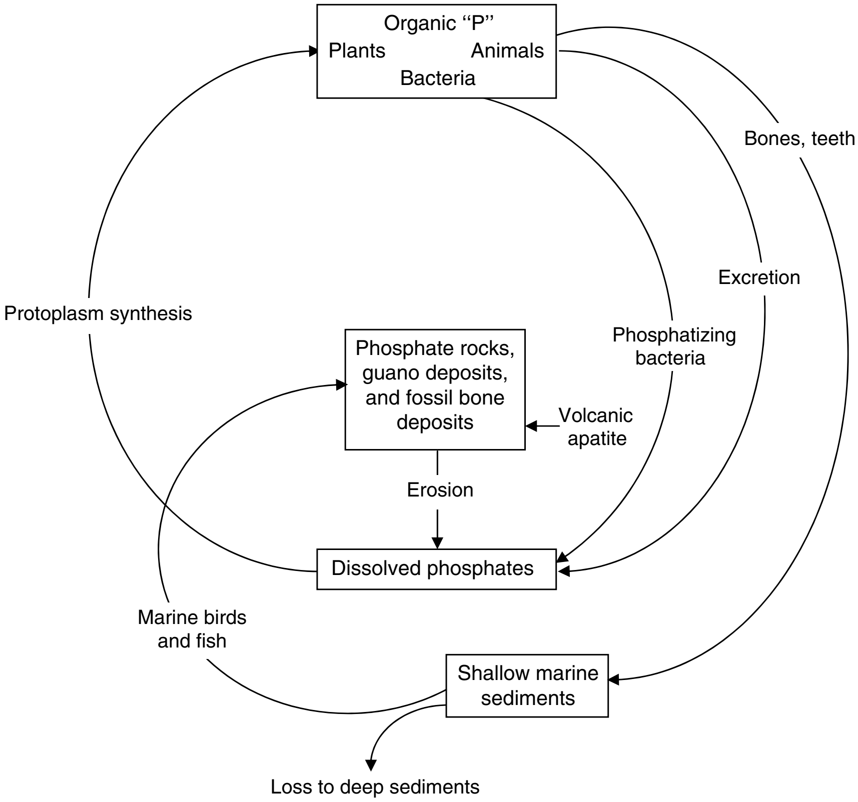


FIGURE 6.7 The phosphorus cycle.

While it is true that phosphorus discharged into streams is a contributing factor to stream pollution (and causes eutrophication), it is also true that phosphorus is not the lone factor. Odum warns against what he calls the one-factor control hypothesis, i.e., the one-problem/one solution syndrome. Odum (1975) points out that environmentalists in the past have focused on one or two items, such as phosphorus contamination, and "have failed to understand that the strategy for pollution control must involve reducing the input of all enriching and toxic materials."

√ **Important Point:** Because of its high reactivity, phosphorus exists in combined form with other elements. Microorganisms produce acids that form soluble phosphate from insoluble phosphorus compounds. The phosphates are utilized by algae and terrestrial green plants, which in turn pass into the bodies of animal consumers. Upon death and decay of organisms, phosphates are released for recycling (*Phosphorus Cycle*, 2007).

ENERGY FLOW IN THE ECOSYSTEM

Simply defined, energy is the ability or capacity to do work. For an ecosystem to exist, it must have energy. All activities of living organisms involve work, which is the expenditure of energy. This means the degradation of a higher state of energy to a lower state. Two laws govern the flow of energy through an ecosystem: *The First and Second Laws of Thermodynamics*.

The first law, sometimes called the *conservation law*, states that energy may not be created or destroyed. The second law states that no energy transformation is 100% efficient. That is, in every energy transformation, some energy is dissipated as heat. The term *entropy* is used as a measure of the nonavailability of energy to a system. Entropy increases with an increase in dissipation.

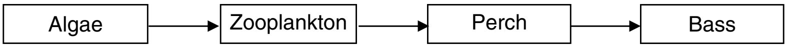


FIGURE 6.8 Aquatic food chain.

Because of entropy, input of energy in any system is higher than the output or work done; thus, the resultant, efficiency, is less than 100%.

The interaction of energy and materials in the ecosystem is important. Earlier, we discussed the biogeochemical nutrient cycles. It is important to remember that it is the flow of energy that drives these cycles. Moreover, it should be noted that energy does not cycle as nutrients do in biogeochemical cycles. For example, when food passes from one organism to another, energy contained in the food is reduced systematically until all the energy in the system is dissipated as heat. Price (1984) refers to this process as "a unidirectional flow of energy through the system, with no possibility for recycling of energy." When water or nutrients are recycled, energy is required. The energy expended in this recycling is not recyclable.

As mentioned, the principal source of energy for any ecosystem is sunlight. Green plants, through the process of photosynthesis, transform the sun's energy into carbohydrates, which are consumed by animals. This transfer of energy, again, is unidirectional—from producers to consumers. Often this transfer of energy to different organisms is called a *food chain*. Figure 6.8 shows a simple aquatic food chain.

All organisms, alive or dead, are potential sources of food for other organisms. All organisms that share the same general type of food in a food chain are said to be at the same *trophic level* (nourishment or feeding level). Since green plants use sunlight to produce food for animals, they are called the *producers*, or the first trophic level. The herbivores, which eat plants directly, are called the *primary consumers*, or the second trophic level. The carnivores are flesh-eating consumers; they include several trophic levels from the third on up. At each transfer, a large amount of energy (about 80–90%) is lost as heat and wastes. Thus, nature normally limits food chains to four or five links. In aquatic ecosystems, however, food chains are commonly longer than those on land. The aquatic food chain is longer because several predatory fish may be feeding on the plant consumers. Even so, the built-in inefficiency of the energy transfer process prevents development of extremely long food chains.

Only a few simple food chains are found in nature. Most of them are interlocked. This interlocking of food chains forms a *food web*. Most ecosystems support a complex food web. A food web involves animals that do not feed on one trophic level. For example, humans feed on both plants and animals. An organism in a food web may occupy one or more trophic levels. Trophic level is determined by an organism's role in its particular community, not by its species. Food chains and webs help explain how energy moves through an ecosystem.

An important trophic level of the food web consists of the *decomposers*. The decomposers feed on dead plants or animals and play an important role in recycling nutrients in the ecosystem. Simply stated, there is no waste in ecosystems. All organisms, dead or alive, are potential sources of food for other organisms. An example of an aquatic food web is shown in Figure 6.9.

FOOD CHAIN EFFICIENCY

Earlier it was pointed out that energy from the sun is captured (via photosynthesis) by green plants and used to make food. Most of this energy is used to carry on the plant's life activities. The rest of the energy is passed on as food to the next level of the food chain.

Nature limits the amount of energy that is accessible to organisms within each food chain. Not all food energy is transferred from one trophic level to the next. Only about 10% (the 10%-rule) of the amount of energy is actually transferred through a food chain. For example, if we apply the 10%-rule to the diatoms–copepods–minnows–medium fish–large fish food chain shown in Figure 6.10, we can predict that 1000 g of diatoms produce 100 g of copepods, which will produce

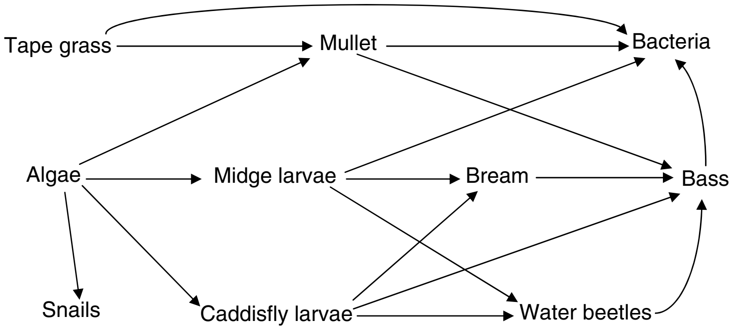


FIGURE 6.9 Aquatic food web.

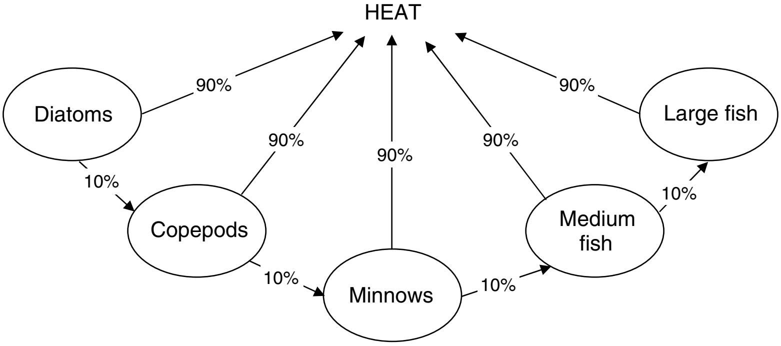


FIGURE 6.10 Simple food chain.

10 g of minnows, which will produce 1 g of medium fish, which, in turn, will produce 0.1 g of large fish. Thus, only about 10% of the chemical energy available at each trophic level is transferred and stored in a usable form at the next level. The other 90% is lost to the environment as low-quality heat in accordance with the second law of thermodynamics.

ECOLOGICAL PYRAMIDS

In the food chain, from the producer to the final consumer, it is clear that a particular community in nature often consists of several small organisms associated with a smaller and smaller number of larger organisms. A grassy field, for example, has a larger number of grasses and other small plants, a smaller number of herbivores like rabbits, and an even smaller number of carnivores like fox. The practical significance of this is that we must have several more producers than consumers.

This pound-for-pound relationship, where it takes more producers than consumers, can be demonstrated graphically by building an *ecological pyramid*. In an ecological pyramid, separate levels represent the number of organisms at various trophic levels in a food chain or bars placed one above the other with a base formed by producers and the apex formed by the final consumer. The pyramid shape is formed due to a great amount of energy loss at each trophic level. The same is true if the corresponding biomass or energy substitutes numbers. Ecologists generally use three types of ecological pyramids: *pyramids of number, biomass,* and *energy*. Obviously, there will be differences among them. Some generalizations:

1. Energy pyramids must always be larger at the base than at the top (because of the Second Law of Thermodynamics and has to do with dissipation of energy as it moves from one trophic level to another).

2. Likewise, biomass pyramids (in which biomass is used as an indicator of production) are usually pyramid shaped. This is particularly true of terrestrial systems and aquatic ones dominated by large plants (marshes), in which consumption by heterotrophs is low and organic matter accumulates with time.

   However, biomass pyramids can sometimes be inverted. This is common in aquatic ecosystems, in which the primary producers are microscopic planktonic organisms that multiply very rapidly, have very short life spans, and are heavily grazed by herbivores. At any single point in time, the amount of biomass in primary producers is less than that in larger, long-lived animals that consume primary producers.
3. Numbers pyramids can have various shapes (and not be pyramids at all) depending on the sizes of the organisms that make up the trophic levels. In forests, the primary producers are large trees and the herbivore level usually consists of insects, so the base of the pyramid is smaller than the herbivore level above it. In grasslands, the number of primary producers (grasses) is much larger than that of the herbivores above (large grazing animals) (Ecosystems Topics, 2000).

PRODUCTIVITY

As mentioned, the flow of energy through an ecosystem starts with the fixation of sunlight by plants through photosynthesis. In evaluating an ecosystem, the measurement of photosynthesis is important. Ecosystems may be classified into highly productive or less productive. Therefore, the study of ecosystems must involve some measure of the productivity of that ecosystem.

Primary production is the rate at which the ecosystem's primary producers capture and store a given amount of energy in a specified time interval. In simpler terms, primary productivity is a measure of the rate at which photosynthesis occurs. Four successive steps in the production process are:

1. *Gross primary productivity*—The total rate of photosynthesis in an ecosystem during a specified interval
2. *Net primary productivity*—The rate of energy storage in plant tissues in excess of the rate of aerobic respiration by primary producers
3. *Net community productivity*—The rate of storage of organic matter not used
4. *Secondary productivity*—The rate of energy storage at consumer levels

When attempting to comprehend the significance of the term *productivity* as it relates to ecosystems, it is wise to consider an example. Consider the productivity of an agricultural ecosystem such as a wheat field. Often its productivity is expressed as the number of bushels produced per acre. This is an example of the harvest method for measuring productivity. For a natural ecosystem, several one-square-meter plots are marked off, and the entire area is harvested and weighed to give an estimate of productivity as grams of biomass per square meter per given time interval. From this method, a measure of net primary production (net yield) can be measured.

Productivity, both in the natural and cultured ecosystem, may vary considerably, not only between types of ecosystems, but also within the same ecosystem. Several factors influence year-to-year productivity within an ecosystem. Such factors as temperature, availability of nutrients, fire, animal grazing, and human cultivation activities are directly or indirectly related to the productivity of a particular ecosystem.

Productivity can be measured in several different ways in the aquatic ecosystem. For example, the production of oxygen may be used to determine productivity. Oxygen content may be measured in several ways. One way is to measure it in the water every few hours for a period of 24 h. During daylight, when photosynthesis is occurring, the oxygen concentration should rise. At night the oxygen level should drop. The oxygen level can be measured by using a simple x–y graph. The oxygen level can be plotted on the y-axis with time plotted on the x-axis, as shown in Figure 6.11.

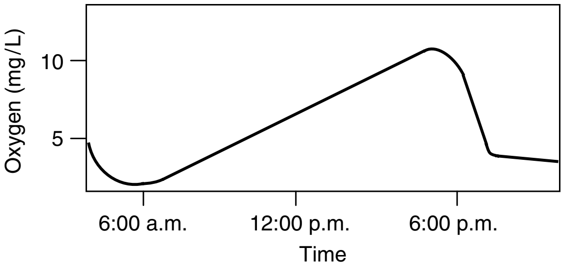


FIGURE 6.11 The diurnal oxygen curve for an aquatic ecosystem.

Another method of measuring oxygen production in aquatic ecosystems is to use light and dark bottles. BOD bottles (300 mL) are filled with water to a particular height. One of the bottles is tested for the initial DO, and then the other two bottles (one clear, one dark) are suspended in the water at the depth from which they were taken. After a 12-h period, the bottles are collected and the DO values for each bottle are recorded. Once the oxygen production is known, the productivity in terms of grams per meter per day can be calculated.

Pollution can have a profound impact upon an aquatic ecosystem's productivity.

POPULATION ECOLOGY

Charles Darwin (1809–1882) made theoretical potential rate of increase in population an integral part of his theory of evolution. He stated:

> The elephant is a slow breeder.
> *The elephant is reckoned to be the slowest breeder of all known animals, and I have taken some pains to estimate its probable minimum rate of natural increase; it will be safest to assume that it begins breeding when 30 years old, and goes on breeding till 90 years old, bringing forth 6 young in the interval, and surviving till 100 years old; if this be so, after a period of 740–750 years there would be nearly 19 million elephants alive descended from the first pair.*
> And the elephant is a slow breeder.

Webster's Third New International Dictionary defines *population* as "the total number or amount of things especially within a given area; the organisms inhabiting a particular area or biotype; and a group of interbreeding biotypes that represents the level of organization at which speciation begins."

The term *population* is interpreted differently in various sciences. For example, in human demography a population is a set of humans in a given area. In genetics, a population is a group of interbreeding individuals of the same species, which is isolated from other groups. In population ecology, a population is an interbreeding group of organisms of the same species, inhabiting the same area at a particular time.

If we wanted to study the organisms in a slow-moving stream or stream pond, we would have two options. We could study each fish, aquatic plant, crustacean, and insect one by one. In that case, we would be studying individuals. It would be easier to do this if the subject were, say, trout, but it would be difficult to separate and study each aquatic plant.

The second option would be to study all of the trout, all of the insects of each specific kind, and all of a certain aquatic plant type in the stream or pond at the time of the study. When ecologists study a group of the same kind of individuals in a given location at a given time, they are investigating a population. When attempting to determine the population of a particular species, it is important to remember that time is a factor. Whether it is at various times during the day, during the different seasons, or from year to year, time is important because populations change.

Population density, the number of organisms per unit of area or volume, may change dramatically. For example, if a dam were closed off in a river midway through salmon spawning season, with no provision allowed for fish movement upstream (a fish ladder), it would drastically decrease the density of spawning salmon upstream. Along with the swift and sometimes unpredictable consequences of change, it can be difficult to draw exact boundaries between various populations. Density is the characteristic of populations that has always been of greatest interest to man. Are there enough deer to hunt? Are there too many pests?

The population density or level of a species depends on *natality, mortality, immigration,* and *emigration*. Changes in population density are the result of both births and deaths. The birth rate of a population is called *natality* and the death rate *mortality*. In aquatic populations, two factors other than natality and mortality can affect density. For example, in a run of returning salmon to their spawning grounds, the density could vary as more salmon migrate in or as others leave the run for their own spawning grounds. The arrival of new salmon to a population from other places is termed *immigration* (ingress). The departure of salmon from a population is called *emigration* (egress). Thus, natality and immigration increase population density, whereas mortality and emigration decrease it. The net increase in population is the difference between these two sets of factors.

The distribution of a population is the area in which that population can be found. Each organism occupies only those areas that can provide for its requirements, resulting in an irregular distribution. How a particular population is distributed within a given area has considerable influence on density. As shown in Figure 6.12, organisms in nature may be distributed in three ways.

In a random distribution, there is an equal probability of an organism occupying any point in space, and "each individual is independent of the others" (Smith, 1974).

In a regular or uniform distribution, in turn, organisms are spaced more evenly; they are not distributed by chance. Animals compete with one another and effectively defend a specific territory, excluding other individuals of the same species. Here, the competition between individuals can be quite severe and antagonistic to the point where the spacing generated is quite even.

The most common distribution is the contagious or clumped distribution where organisms are found in groups; this may reflect the heterogeneity of the habitat.

Organisms that exhibit a contagious or clumped distribution may develop social hierarchies to live together more effectively. Animals within the same species have evolved many symbolic aggressive displays that carry meanings that are not only mutually understood but also prevent injury or death within the same species.

√ **Important Point:** Distribution is usually mapped for species of plants and animals. For example, bird guides contain distribution maps showing where each species of bird lives and reproduces.

The size of animal populations is constantly changing due to natality, mortality, emigration, and immigration. As mentioned, the population size will increase if the natality and immigration rates are high, whereas it will decrease if the mortality and emigration rates are high. Each population has an upper limit on size, often called the *carrying capacity*. Carrying capacity is the optimum number of species' individuals that can survive in a specific area over time. Stated differently,

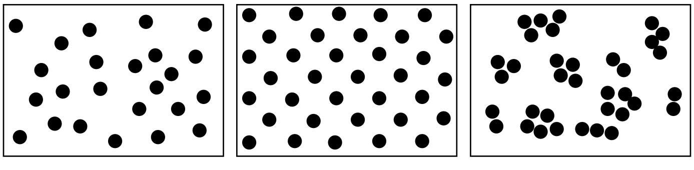


FIGURE 6.12 Basic patterns of distribution. (Adapted from Odum, E.P., *Fundamentals of Ecology*, Saunders College Publishing, Philadelphia, 1971, p. 205.)

the carrying capacity is the maximum number of species that can be supported in a bioregion. A pond may be able to support only a dozen frogs depending on the food resources for the frogs in the pond. If there were 30 frogs in the same pond, at least half of them would probably die because the pond environment would not have enough food for them to live. Carrying capacity is based on the quantity of food supplies, the physical space available, the degree of predation, and several other environmental factors (environmental resistance).

The carrying capacity is of two types: ultimate and environmental. *Ultimate carrying capacity* is the theoretical maximum density, that is, it is the maximum number of individuals of a species in a place that can support itself without rendering the place uninhabitable. The *environmental carrying capacity* is the actual maximum population density that a species maintains in an area. Ultimate carrying capacity is always higher than environmental carrying capacity. Ecologists have concluded that a major factor that affects population stability or persistence is *species diversity*. Species diversity is a measure of the number of species and their relative abundance.

If the stress on an ecosystem is small, the ecosystem can usually adapt quite easily. Moreover, even when severe stress occurs, ecosystems have a way of adapting. Severe environmental change to an ecosystem can result from such natural occurrences as fires, earthquakes, and floods, and from people-induced changes such as land clearing, surface mining, and pollution. One of the most important applications of species diversity is in the evaluation of pollution. Stress of any kind will reduce the species diversity of an ecosystem to a significant degree. In the case of domestic sewage pollution, for example, the stress is caused by a lack of DO for aquatic organisms.

Ecosystems can and do change. For example, if a fire devastates a forest, it will grow back, eventually, because of *ecological succession*. Ecological succession is the observed process of change (a normal occurrence in nature) in the species structure of an ecological community over time. Succession usually occurs in an orderly, predictable manner. It involves the entire system. The science of ecology has developed to such a point that ecologists are now able to predict several years in advance what will occur in a given ecosystem. For example, scientists know that if a burned-out forest region receives light, water, nutrients, and an influx or immigration of animals and seeds, it will eventually develop into another forest through a sequence of steps or stages. Ecologists recognize two types of ecological succession: primary and secondary. The particular type that takes place depends on the condition at a particular site at the beginning of the process. *Primary succession*, sometimes called *bare-rock succession*, occurs on surfaces such as hardened volcanic lava, bare rock, and sand dunes, where no soil exists, and where nothing has ever grown before (see Figure 6.13). Obviously, to grow, plants need soil. Thus, soil must form on the bare rock before succession can begin. Usually this soil formation process results from weathering. Atmospheric exposure—weathering, wind, rain, and frost—forms tiny cracks and holes in rock surfaces. Water collects in the rock fissures and slowly dissolves the minerals out of the rock's surface. A pioneer soil layer is formed from the dissolved minerals and supports such plants as lichens. Lichens gradually cover the rock surface and secrete carbonic acid, which dissolves additional minerals from the rock. Eventually, mosses replace the lichens. Organisms called *decomposers* move in and feed on dead lichen and moss. A few small animals such as mites and spiders arrive next. The result is what is known as a *pioneer community*. The pioneer community is defined as the first successful integration of plants, animals, and decomposers into a bare-rock community.

After several years, the pioneer community builds up enough organic matter in its soil to be able to support rooted plants like herbs and shrubs. Eventually, the pioneer community is crowded out and is replaced by a different environment. This, in turn, works to thicken the upper soil layers. The progression continues through several other stages until a mature or climax ecosystem is developed, several decades later. In bare-rock succession, each stage in the complex succession pattern dooms the stage that existed before it. *Secondary succession* is the most common type of succession. Secondary succession occurs in an area where the natural vegetation has been removed or destroyed but the soil is not destroyed. For example, succession that occurs in abandoned farm fields, known as *old-field succession*, illustrates secondary succession. An example of secondary

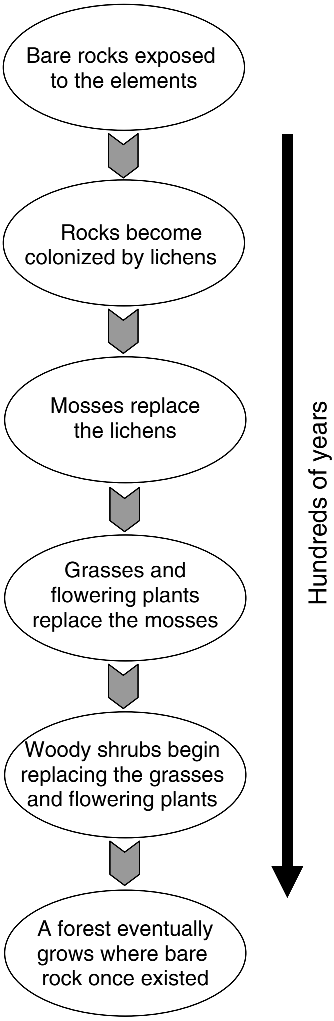


FIGURE 6.13 Bare-rock succession. (Adapted from Tomera, A.N., *Understanding Basic Ecological Concepts,* J. Weston Walch, Portland, ME, 1989, p. 67.)

succession can be seen in the Piedmont region of North Carolina. Early settlers of the area cleared away the native oak-hickory forests and cultivated the land. In the ensuing years, the soil became depleted of nutrients, reducing the soil's fertility. As a result, farming ceased in the region a few generations later, and the fields were abandoned. Some 150–200 years after abandonment, the climax oak-hickory forest was restored.

In a stream ecosystem, growth is enhanced by biotic and abiotic factors. These factors include:

- Ability to produce offspring
- Ability to adapt to new environments
- Ability to migrate to new territories
- Ability to compete with species for food and space to live
- Ability to blend into the environment so as not to be eaten
- Ability to find food
- Ability to defend itself from enemies
- Favorable light

- Favorable temperature
- Favorable DO content
- Sufficient water level

The biotic and abiotic factors in an aquatic ecosystem that reduce growth include:

- Predators
- Disease
- Parasites
- Pollution
- Competition for space and food
- Unfavorable stream conditions (i.e., low water levels)
- Lack of food

With regard to stability in a freshwater ecosystem, the higher the species diversity, the greater the inertia and resilience of the ecosystem. At the same time, when the species diversity is high within a stream ecosystem, a population within the stream can be out of control because of an imbalance between growth and reduction factors, with the ecosystem still remaining stable at the same time. With regard to instability in a freshwater ecosystem, recall that imbalance occurs when growth and reduction factors are out of balance. For example, when sewage is accidentally dumped into a stream, the stream ecosystem, via the natural self-purification process, responds and returns to normal. This process is described as follows:

- Raw sewage is dumped into the stream.
- It decreases the oxygen available as the detritus food chain breaks down the sewage.
- Some fish die at the pollution site and downstream.
- Sewage is broken down and washes out to the sea and is finally broken down in the ocean.
- The oxygen levels return to normal.
- Fish populations that were deleted are restored as fish about the spill reproduce and the young occupy the real estate formerly occupied by the dead fish.
- Populations return to "normal."

A shift in balance in a stream's ecosystem (or in any ecosystem) similar to the one just described is a common occurrence. In this particular case, the stream responded (on its own) to the imbalance the sewage caused and through the self-purification process returned to normal. Recall that succession is the method by which an ecosystem either forms itself or heals itself. Thus, we can say that a type of succession has occurred in the polluted stream described above, because, in the end, it healed itself. More importantly, this healing process is a good thing; otherwise, there would have been few streams left on Earth suitable for much more than the dumping of garbage.

In summary, through research and observation, ecologists have found that the succession patterns in different ecosystems usually display common characteristics. First, succession brings about changes in the plant and animal members present. Second, organic matter increases from stage to stage. Finally, as each stage progresses, there is a tendency toward greater stability or persistence. Remember, succession is usually predictable. This is the case unless humans interfere.

STREAM GENESIS AND STRUCTURE

Consider the following:

Early in spring on a snow and ice-covered high alpine meadow, the time and place, the water cycle continues. The cycle's main component, water, has been held in reserve—literally frozen, for the long dark winter months, but with longer, warmer spring days, the sun is higher, more direct, and of longer duration, and the frozen masses of water respond to the increased warmth. The melt begins with a single drop, then two, then increasingly more. As the snow and ice melts, the drops join a chorus that continues unending; they fall from their ice-bound lip to the bare rock and soil terrain below.

The terrain the snow-melt strikes is not like glacial till, the unconsolidated, heterogeneous mixture of clay, sand, gravel, and boulders, dug-out, ground-out, and exposed by the force of a huge, slow, and inexorably moving glacier. Instead, this soil and rock ground is exposed to the falling drops of snow-melt because of a combination of wind and the tiny, enduring force exerted by drops of water as over season after season they collide with the thin soil cover, exposing the intimate bones of the Earth.

Gradually, the single drops increase to a small rush—they join to form a splashing, rebounding, helter-skelter cascade, many separate rivulets that trickle, then run their way down the face of the granite mountain. At an indented ledge halfway down the mountain slope, a pool forms whose beauty, clarity, iciness, and pure sweet taste provide the visitor with an incomprehensible, incomparable gift—a blessing from the Earth.

The mountain pool fills slowly, tranquil under the blue sky, reflecting the pines, snow, and sky around and above it, an open invitation to lie down and drink, and to peer into that glass-clear, deep phantom blue-green eye, so clear that it seems possible to reach down over 50 feet and touch the very bowels of the mountain. The pool has no transition from shallow margin to depth; it is simply deep and pure. As the pool fills with more melt water, we wish to freeze time, to hold this place and this pool in its perfect state forever, it is such a rarity to us in our modern world. However, this cannot be—Mother Nature calls, prodding, urging—and for a brief instant, the water laps in the breeze against the outermost edge of the ridge, then a trickle flows over the rim. The giant hand of gravity reaches out and tips the overflowing melt onward and it continues the downward journey, following the path of least resistance to its next destination, several thousand feet below.

When the liquid overflow, still high in altitude but its rock-strewn bed bent downward, toward the sea, meets the angled, broken rocks below, it bounces, bursts, and mists its way against steep, V-shaped walls that form a small valley, carved out over time by water and the forces of the Earth.

Within the valley confines, the melt water has grown from drops to rivulets to a small mass of flowing water. It flows through what is at first a narrow opening, gaining strength, speed, and power as the V-shaped valley widens to form a U shape. The journey continues as the water mass picks up speed and tumbles over massive boulders, and then slows again.

At a larger but shallower pool, waters from higher elevations have joined the main body—from the hillsides, crevices, springs, rills, and mountain creeks. At the influent poolsides, all appears peaceful, quiet, and restful, but not far away, at the effluent end of the pool, gravity takes control again. The overflow is flung over the jagged lip, and cascades downward several hundred feet, where the waterfall again brings its load to a violent, mist-filled meeting.

The water separates and joins repeatedly, forming a deep, furious, wild stream that calms gradually as it continues to flow over lands less steep. The waters widen into pools overhung by vegetation, surrounded by tall trees. The pure, crystalline waters have become progressively discolored on their downward journey, stained brown-black with humic acid, and literally filled with suspended sediments; the once-pure stream is now muddy.

The mass divides and flows in different directions, over different landscapes. Small streams divert and flow into open country. Different soils work to retain or speed the waters, and in some places, the waters spread out into shallow swamps, bogs, marshes, fens, or mires. Other streams pause long enough to fill deep depressions in the land and form lakes. For a time, the water remains and pauses in its journey to the sea. However, this is only a short-term pause, because lakes are only a short-term resting place in the water cycle. The lake water will eventually move on, by evaporation or seepage into groundwater. Other portions of the water mass stay with the main flow, and the speed of flow changes to form a river, which braids its way through the landscape, heading for the sea. As it changes speed and slows, the river bottom changes from rock and stone to silt and clay.

Plants begin to grow, stems thicken, and leaves broaden. The river is now full of life and the nutrients needed to sustain life. However, the river courses onward, its destiny met when the flowing rich mass slows and finally spills into the sea.

*****

Freshwater systems are divided into two broad categories: running waters (lotic systems) and standing waters (lentic systems). In this text, the concentration is on lotic systems (although many of the principles described here apply to other freshwater surface bodies as well), which are known by common names. Some examples include seeps, springs, brooks, branches, creeks, streams, and rivers. Again, because it is the best term (in the author's view) to use in freshwater ecology, it is the stream that is the concern here. Although there is no standard scientific definition of a stream, it is usually distinguished subjectively as follows: A *stream* is a water body of intermediate size that can be waded from one side to the other.

Physical processes involved in the formation of a stream are important to its ecology because stream channel and flow characteristics directly influence the functioning of the stream's ecosystem and the biota found therein. Thus, in this section, we discuss the pathways of water flow contributing to stream flow, namely, precipitation inputs as they contribute to the flow. Moreover, stream flow discharge, transport of material, characteristics of stream channels, stream profile, sinuosity, the floodplain, pool-riffle sequences, and depositional features—all of which directly or indirectly impact the ecology of the stream—are discussed.

WATER FLOW IN A STREAM

Most elementary students learn early in their education process that water on the Earth flows downhill—from land to the sea. However, they may or may not be told that water flows downhill toward the sea by various routes.

At this time, the "route" (or pathway) that we are primarily concerned with is the surface water route taken by surface water runoff. Surface runoff is dependent on various factors. For example, climate, vegetation, topography, geology, soil characteristics, and land-use determine how much surface runoff occurs compared with other pathways.

The primary source (input) of water to total surface runoff, of course, is precipitation. This is the case even though a substantial portion of all precipitation input returns directly to the atmosphere by evapotranspiration. *Evapotranspiration* is a combination process, as the name suggests, whereby water in plant tissue and in the soil evaporates and transpires to water vapor in the atmosphere.

Probably it is easier to understand precipitation's input to surface water runoff by looking closer at this precipitation input.

We stated that a substantial portion of the precipitation input returns directly to the atmosphere by evapotranspiration. It is also important to point out that when precipitation occurs, some rainwater is intercepted by vegetation where it evaporates, never reaching the ground or being absorbed by plants.

A large portion of the rainwater that reaches the surface of the ground in lakes and streams also evaporates directly back to the atmosphere.

Although plants display a special adaptation to minimize transpiration, they still lose water to the atmosphere during the exchange of gases necessary for photosynthesis.

Notwithstanding the large percentage of precipitation that evaporates, rain- or melt-water that reaches the ground surface follows several pathways in reaching a stream channel or groundwater.

Soil can absorb rainfall to its *infiltration capacity* (i.e., to its maximum rate). During a rain event, this capacity decreases. Any rainfall in excess of infiltration capacity accumulates on the surface. When this surface water exceeds the depression storage capacity of the surface, it moves as an irregular sheet of overland flow. In arid areas, overland flow is likely because of the low permeability of the soil. Overland flow is also likely when the surface is frozen and/or when human activities have rendered the land surface less permeable. In humid areas, where infiltration capacities are high, overland flow is rare.

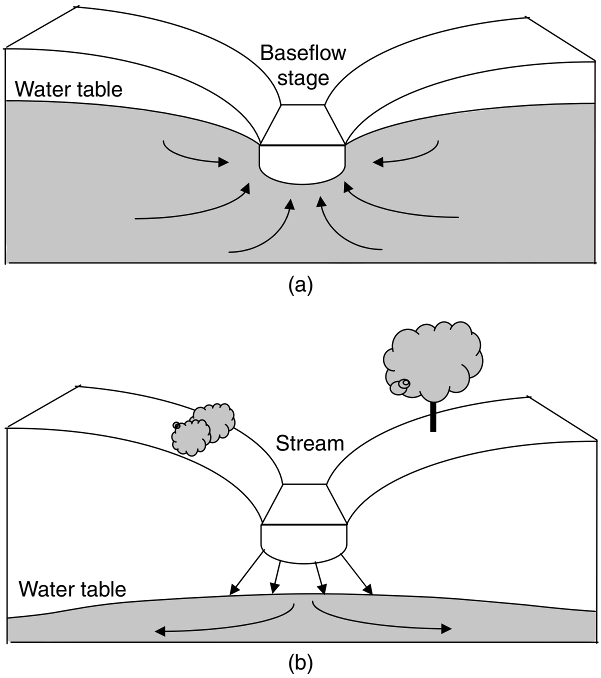


FIGURE 6.14 (a) Cross-section of a gaining stream. (b) Cross-section of a losing stream.

In rain events where the infiltration capacity of the soil is not exceeded, rain penetrates the soil and eventually reaches the groundwater, from which it discharges to the stream slowly and over a long period. This phenomenon helps explain why stream flow through a dry weather region remains constant; the flow is continuously augmented by groundwater. This type of stream is known as a *perennial stream*, as opposed to an *intermittent* one, because the flow continues during periods of no rainfall.

When a stream courses through a humid region, it is fed water via the water table, which slopes toward the stream channel. Discharge from the water table into the stream accounts for flow during periods without precipitation and explains why this flow increases, even without tributary input, as one proceeds downstream. Such streams are called *gaining* or *effluent*, as opposed to *losing* or *influent streams* that lose water into the ground (see Figure 6.14). The same stream can shift between gaining and losing conditions along its course because of changes in underlying strata and local climate.

STREAM WATER DISCHARGE

The current velocity (speed) of water (driven by gravitational energy) in a channel varies considerably within a stream's cross-section owing to friction with the bottom and sides, with sediment, and the atmosphere, and to sinuosity (bending or curving) and obstructions. Highest velocities, obviously, are found where friction is least, generally at or near the surface and near the center of the channel. In deeper streams, current velocity is greatest just below the surface due to the friction with the atmosphere; in shallower streams, current velocity is greatest at the surface due to friction with the bed. Velocity decreases as a function of depth, approaching zero at the substrate surface.

TRANSPORT OF MATERIAL

Water flowing in a channel may exhibit *laminar flow* (parallel layers of water shear over one another vertically) or *turbulent flow* (complex mixing). In streams, laminar flow is uncommon, except at boundaries where flow is very low and in groundwater. Thus, the flow in streams generally is turbulent. Turbulence exerts a shearing force that causes particles to move along the streambed by pushing, rolling, and skipping referred to as *bed load*. This same shear causes turbulent eddies that entrain particles in suspension (called the *suspended* load—particles size under 0.06 mm).

Entrainment is the incorporation of particles when stream velocity exceeds the *entraining velocity* for a particular particle size. The entrained particles in suspension (suspended load) also include fine sediment, primarily clays, silts, and fine sands that require only low velocities and minor turbulence to remain in suspension. These are referred to as *wash* load (under 0.002 mm). Thus, the suspended load includes the wash load and coarser materials (at lower flows). Together, the suspended load and bed load constitutes the *solid load*. It is important to note that in bedrock streams the bed load will be a lower fraction than in alluvial streams where channels are composed of easily transported material.

A substantial amount of material is also transported as the *dissolved load*. Solutes are generally derived from chemical weathering of bedrock and soils, and their contribution is greatest in subsurface flows, and in regions of limestone geology.

The relative amount of material transported as solute rather than solid load depends on basin characteristics, lithology (i.e., the physical character of rock), and hydrologic pathways. In areas of very high runoff, the contribution of solutes approaches or exceeds sediment load, whereas in dry regions, sediments make up as much as 90% of the total load.

Deposition occurs when *stream competence* (i.e., the largest particle that can be moved as bedload, and the critical erosion—competent—velocity is the lowest velocity at which a particle resting on the streambed will move) falls below a given velocity. Simply stated, the size of the particle that can be eroded and transported is a function of the current velocity.

Sand particles are the most easily eroded. The greater the mass of larger particles (e.g., coarse gravel), the higher the initial current velocities must be for movement. However, smaller particles (silts and clays) require even greater initial velocities because of their cohesiveness and because they present smaller, streamlined surfaces to the flow. Once in transport, particles will continue in motion at somewhat slower velocities than initially required to initiate movement, and will settle at still lower velocities.

Particle movement is determined by size, flow conditions, and mode of entrainment. Particles over 0.02 mm (medium-coarse sand size) tend to move by rolling or sliding along the channel bed as *traction load*. When sand particles fall out of the flow, they move by *saltation* or repeated bouncing. Particles under 0.06 mm (silt) move as suspended load, and particles under 0.002 (clay), as wash load. Unless the supply of sediments deplete, the concentration and amount of transported solids would increase. However, discharge is usually too low, throughout most of the year, to scrape or scour, shape channels, or move significant quantities of sediment in all but sand-bed streams, which can experience change more rapidly. During extreme events, the greatest scour occurs and the amount of material removed increases dramatically.

Sediment inflow into streams can both be increased and decreased because of human activities. For example, poor agricultural practices and deforestation greatly increase erosion. Fabricated structures such as dams and channel diversions can, on the other hand, greatly reduce sediment inflow.

CHARACTERISTICS OF STREAM CHANNELS

Flowing waters (rivers and streams) determine their own channels, and these channels exhibit relationships attesting to the operation of physical laws—laws that are not, as yet, fully understood. We could say that a stream is an unconscious artist; it is a shaper, molder, transformer, and sculptor of landscapes. The development of stream channels and entire drainage networks, and the existence of various regular patterns in the shape of channels, indicate that streams are in a state of dynamic equilibrium between erosion (sediment loading) and deposition (sediment deposit), and governed by common hydraulic processes. However, because channel geometry is four dimensional with a long profile, cross-section, depth and slope profile, and because these mutually adjust over a time scale as short as years and as long as centuries or more, cause-and-effect relationships are difficult to establish. Other variables that are presumed to interact as the stream achieves its graded state include width and depth, velocity, size of sediment load, bed roughness, and the degree of braiding (sinuosity).

STREAM PROFILES

Mainly because of gravity, most streams exhibit a downstream decrease in gradient along their length. Beginning at the headwaters, the steep gradient lessens as one proceeds downstream, resulting in a concave longitudinal profile. Though diverse geography provides almost unlimited variation, a lengthy stream that originates in a mountainous area typically comes into existence as a series of springs and rivulets; these coalesce into a fast-flowing, turbulent mountain stream, and the addition of tributaries results in a large and smoothly flowing river that winds through the lowlands to the sea.

When studying a stream system of any length, it becomes readily apparent (almost from the start) that what we are studying is a body of flowing water that varies considerably from place to place along its length. For example, a common variable—the results of which can be readily seen—is whenever discharge increases, causing corresponding changes in the stream's width, depth, and velocity. In addition to physical changes that occur from location to location along a stream's course, there are a legion of biological variables that correlate with the stream size and distance downstream. The most apparent and striking changes are in steepness of slope and in the transition from a shallow stream with large boulders and a stony substrate to a deep stream with a sandy substrate.

The particle size of bed material at various locations is also variable along the stream's course. The particle size usually shifts from an abundance of coarser material upstream to mainly finer material in downstream areas.

SINUOSITY

Unless forced by man in the form of heavily regulated and channelized streams, straight channels are uncommon. Stream flow creates distinctive landforms composed of straight (usually in appearance only), meandering, and braided channels, channel networks, and flood plains. Simply put: flowing water will follow a sinuous course. The most commonly used measure is the *sinuosity index* (SI). Sinuosity equals 1 in straight channels and more than 1 in sinuous channels.

Meandering is the natural tendency for alluvial channels and is usually defined as an arbitrarily extreme level of sinuosity, typically a SI greater than 1.5. Many variables affect the degree of sinuosity.

Even in many natural channel sections of a stream course that appear straight, meandering occurs in the line of maximum water or channel depth (known as the *thalweg*). Keep in mind that a stream has to meander, that is how they renew themselves. By meandering, they wash plants and soil from the land into their waters, and these serve as nutrients for the plants in the rivers. If rivers are not allowed to meander, if they are *channelized*, the amount of life they can support will gradually decrease. That means less fish, ultimately—and less bald eagles, herons, and other fishing birds (Cave, 2000).

Meander flow follows predictable pattern and causes regular regions of erosion and deposition (see Figure 6.15). The streamlines of maximum velocity and the deepest part of the channel lie close to the outer side of each bend and cross over near the point of inflection between the banks (see Figure 6.15). A huge elevation of water at the outside of a bend causes a helical flow of water towards the opposite bank. In addition, a separation of surface flow causes a back eddy. The result is zones of erosion and deposition, and this explains why point bars develop in a downstream direction in depositional zones.

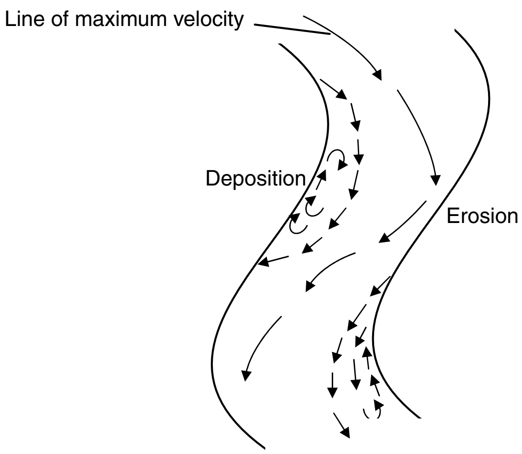


FIGURE 6.15 A meandering reach.

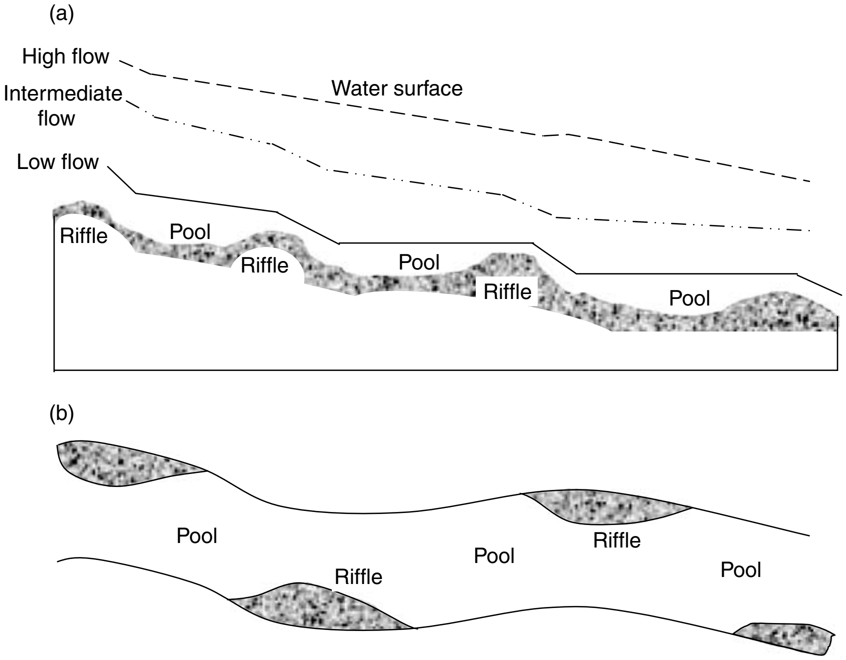


FIGURE 6.16 (a) Longitudinal profile of a riffle-pool sequence. (b) Plain view of riffle-pool sequence.

BARS, RIFFLES, AND POOLS

Implicit in the morphology and formation of meanders are *bars*, *riffles*, and *pools*. Bars develop by deposition in slower, less competent flow on either side of the sinuous mainstream. Onward moving water, depleted of bed load, regains competence and shears a pool in the meander—reloading the stream for the next bar. Alternating bars migrate to form riffles (see Figure 6.16).

As stream flow continues along its course, a pool-riffle sequence is formed. The riffle is a mound or hillock and the pool is a depression.

THE FLOODPLAIN

A stream channel influences the shape of the valley floor through which it courses. The self-formed, self-adjusted flat area near the stream is the *flood plain*, which loosely describes the valley floor prone to periodic inundation during over-bank discharges. What is not commonly known is that valley flooding is a regular and natural behavior of the stream.

A stream's aquatic community has several unique characteristics. The aquatic community operates under the same ecologic principles as terrestrial ecosystems, but the physical structure of the community is more isolated and exhibits limiting factors that are very different than the limiting factors of a terrestrial ecosystem. Certain materials and conditions are necessary for the growth and reproduction of organisms. If, for instance, a farmer plants wheat in a field containing too little nitrogen, it will stop growing when it has used up the available nitrogen, even if the wheat's requirements for oxygen, water, potassium, and other nutrients are met. In this particular case, nitrogen is said to be the limiting factor. A *limiting factor* is a condition or a substance (the resource in shortest supply), which limits the presence and success of an organism or a group of organisms in an area. Even the smallest mountain stream provides an astonishing number of different places, or *habitats*, for aquatic organisms to live. If it is a rocky stream, every rock of the substrate provides several different habitats. On the side facing upriver: organisms with special adaptations, that are very good at clinging to rocks, do well here. On the side that faces downriver, a certain degree of shelter is provided from the current but it still allows organisms to hunt for food. The top of a rock, if it contacts air, is a good place for organisms that cannot breathe underwater and need to surface now and then. Underneath the rock is a popular place for organisms that hide to prevent predation. Normal stream life can be compared to that of a "balanced aquarium" (ASTM, 1969). That is, nature continuously strives to provide clean, healthy, normal streams. This is accomplished by maintaining the stream's flora and fauna in a balanced state. Nature balances stream life by maintaining both the number and the type of species present in any one part of the stream. Such balance ensures that there is never an overabundance of one species compared to another. Nature structures the stream environment so that both plant and animal life is dependent upon the existence of others within the stream.

As mentioned, lotic (washed) habitats are characterized by continuous running waters or current flow. These running water bodies have typically three zones: riffle, run, and pool. The riffle zone contains faster flowing, well-oxygenated water, with coarse sediments. In the riffle zone, the velocity of the current is high enough to keep the bottom clear of silt and sludge, thus providing a firm bottom for organisms. This zone contains specialized organisms, which are adapted to live in running water. For example, organisms adapted to live in fast streams or rapids (trout) have streamlined bodies that aid in their respiration and in obtaining food (Smith, 1974). Stream organisms that live under rocks to avoid the strong current have flat or streamlined bodies. Others have hooks or suckers to cling or attach to a firm substrate to avoid the washing-away effect of the strong current.

The run zone (or intermediate zone) is the slow-moving, relatively shallow part of the stream with moderately low velocities and little or no surface turbulence.

The pool zone of the stream is usually a deeper water region where velocity of water is reduced and silt and other settling solids provide a soft bottom (more homogeneous sediments) that is unfavorable for sensitive bottom-dwellers. Decomposition of some of these solids causes a lower amount of DO. Some stream organisms spend some of their time in the rapids part of the stream and others in the pool zone. For example, trout typically spend about the same amount of time in the rapid zone pursuing food as they do in the pool zone pursuing shelter.

Organisms are sometimes classified based on their mode of life.

1. *Benthos* (mud dwellers)—The term originates from the Greek word for bottom and broadly includes aquatic organisms living on the bottom or on submerged vegetation. They live under and on rocks and in the sediments. A shallow sandy bottom has sponges, snails, earthworms, and some insects. A deep, muddy bottom will support clams, crayfish,

and nymphs of damselflies, dragonflies, and mayflies. A firm, shallow, rocky bottom has nymphs of mayflies, stoneflies, and larvae of water beetles.

2. *Periphytons* or *aufwuchs*—The first term usually refers to microfloral growth upon substrata (i.e., benthic-attached algae). The second term, *aufwuchs* (pronounce: OWF-vooks; German, "growth upon"), refers to the fuzzy, sort of furry-looking, slimy green coating that attach or cling to stems and leaves of rooted plants or other objects projecting above the bottom without penetrating the surface. It consists not only of algae like Chlorophyta, but also diatoms, protozoans, bacteria, and fungi.
3. *Planktons* (drifters)—They are small, mostly microscopic plants and animals that are suspended in the water column; movement depends on water currents. They mostly float in the direction of the current. There are two types of planktons. The first type, phytoplanktons, is assemblages of small plants (algae) and has limited locomotion abilities; they are subject to movement and distribution by water movements. The second type, zooplankton, are animals that are suspended in water and have limited means of locomotion. Examples of zooplanktons include crustaceans, protozoans, and rotifers.
4. *Nektons* or *pelagic organisms* (capable of living in open waters)—They are distinct from other planktons in that they are capable of swimming independently of turbulence. They are swimmers that can navigate against the current. Examples of nektons include fish, snakes, diving beetles, newts, turtles, birds, and large crayfish.
5. *Neustons*—They are organisms that float or rest on the surface of the water (never break water tension). Some varieties can spread out their legs so that the surface tension of the water is not broken; for example, water striders (see Figure 6.17).
6. *Madricoles*—Organisms that live on rock faces in waterfalls or seepages.

In a stream, the rocky substrate is the home for many organisms. Thus, we need to know something about the particles that make up the substrate. Namely, we need to know how to measure the particles so that we can classify them by size.

Substrate particles are measured with a metric ruler, in centimeters. As rocks can be long and narrow, we measure them twice: first the width, then the length. By adding the width to the length and dividing by two, we obtain the average size of the rock.

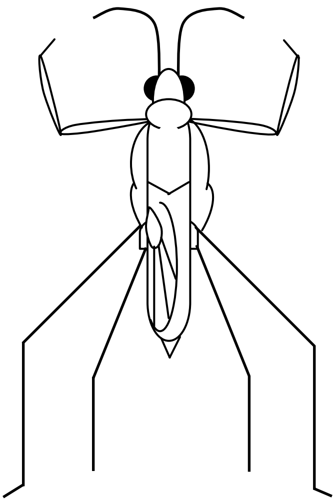


FIGURE 6.17 Water strider. (Adapted from American Public Health Association, *Standard Methods*, 15th ed., American Public Health Association, Washington, DC, 1981.)

It is important to randomly select the rocks we wish to measure. Otherwise, we would tend to select larger rocks, or more colorful rocks, or those with unusual shapes. Instead, we should just reach down and collect those rocks in front of us and within easy reach. Then measure each rock. Upon completion of measurement, each rock should be classified. Ecologists have developed a standard scale (Wentworth scale) for size categories of substrate rock and other mineral materials, along with the different sizes:

Boulder	>256 mm
Cobble	64–256 mm
Pebble	16–64 mm
Gravel	2–16 mm
Sand	0.0625–2 mm
Silt	0.0039–0.0625 mm
Clay	<0.0039 mm

Organisms that live in, on, or under rocks or small spaces occupy what is known as a *microhabitat*. Some organisms make their own microhabitats: many of the caddisflies build a case about themselves and use it for their shelter.

Rocks are not the only physical features of streams where aquatic organisms can be found. For example, fallen logs and branches (commonly referred to as large woody debris) provide an excellent place for some aquatic organisms to burrow into and provide surfaces for others to attach themselves, as they might to a rock. They also create areas where small detritus such as leaf litter can pile up underwater. These piles of leaf litter are excellent shelters for many organisms, including large, fiercely predaceous larvae of dobsonflies.

Another important aquatic organism habitat is found in the matter, or drift, that floats along down stream. Drift is important because it is the main source of food for many fish. It may include insects such as mayflies (Ephemeroptera), some true flies (Diptera), some stoneflies (Plecoptera), and caddisflies (Trichoptera). In addition, dead or dying insects and other small organisms and terrestrial insects that fall from the trees, leaves, and other matter are common components of drift. Among the crustaceans, amphipods (small crustaceans) and isopods (small crustaceans including sow bugs and gribbles) also have been reported in the drift.

ADAPTATIONS TO STREAM CURRENT

Current in streams is the outstanding feature of streams and the major factor limiting the distribution of organisms. The current is determined by the steepness of the bottom gradient, the roughness of the streambed, and the depth and width of the streambed. The current in streams has promoted many special adaptations by stream organisms. Odum (1971) lists these adaptations as follows (see Figure 6.18):

1. *Attachment to a firm substrate*—Attachment is to stones, logs, leaves, and other underwater objects such as discarded tires, bottles, pipes, etc. Organisms in this group are primarily composed of the primary producer plants and animals, such as green algae, diatoms, aquatic mosses, caddisfly larvae, and freshwater sponges.
2. *The use of hooks and suckers*—These organisms have the unusual ability to remain attached and withstand even the strongest rapids. Two Diptera larvae, *Simulium* and *Blepharocera*, are examples of organisms with hooks and suckers.
3. *A sticky undersurface*—Snails and flatworms are examples of organisms that are able to use their sticky undersurfaces to adhere to underwater surfaces.
4. *Flattened and streamlined bodies*—All macroconsumers have streamlined bodies, i.e., the body is broad in front and tapers posteriorly to offer minimum resistance to the current.

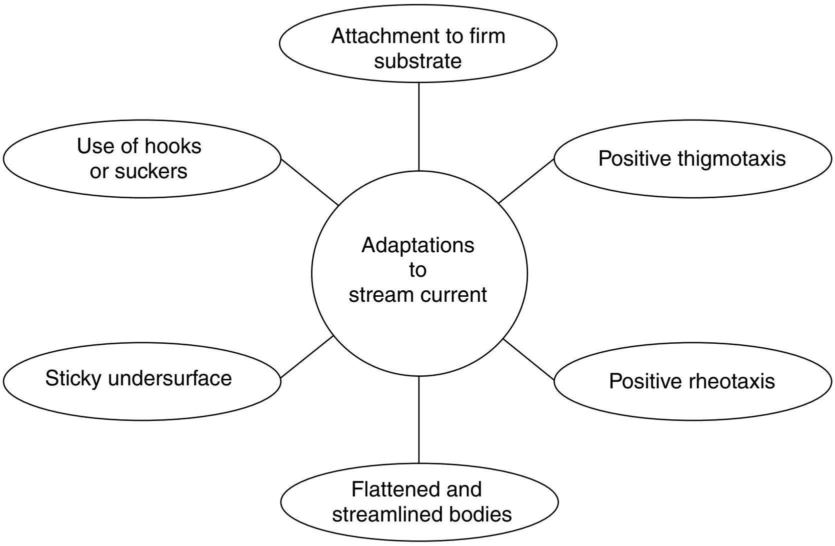


FIGURE 6.18 Adaptations to stream current.

All nektons such as fish, amphibians, and insect larvae exhibit this adaptation. Some organisms have flattened bodies, which enable them to stay under rocks and in narrow places. Examples are water penny, a beetle larva, mayfly, and stone fly nymphs.

5. *Positive rheotaxis (rheo: current; taxis: arrangement)*—An inherent behavioral trait of stream animals (especially those capable of swimming) is to orient themselves upstream and swim against the current.
6. *Positive thigmotaxis (thigmo: touch, contact)*—Another inherent behavior pattern for many stream animals is to cling close to a surface or keep the body in close contact with the surface. This is the reason that stonefly nymphs (when removed from one environment and placed into another) will attempt to cling to just about anything, including each other.

It would take an entire text to describe the great number of adaptations made by aquatic organisms to their surroundings in streams. For our purposes, instead, we cover those special adaptations that are germane to this discussion. The important thing to remember is that there are several basic ways for an aquatic organism to adapt to its environment.

Types of Adaptive Changes

Adaptive changes are classed as genotypic, phenotypic, behavioral, or ontogenic.

1. *Genotypic changes*—Tend to be great enough to separate closely related animals into species, such as mutations or recombination of genes. A salmonid is an example that has evolved a subterminal mouth (i.e., below the snout) to eat from the benthos.
2. *Phenotypic changes*—These are the changes that an organism might make during its lifetime to better utilize its environment (e.g., a fish that changes sex from female to male because of an absence of males).
3. *Behavioral changes*—These changes have little to do with body structure or type: a fish might spend more time under an overhang to hide from predators.
4. *Ontogenetic change*—This change takes place as an organism grows and matures (e.g., a coho salmon that inhabits streams when young, and migrates to the sea when older, changing its body chemistry to allow it to tolerate saltwater).

Specific Adaptations

Specific adaptations observed in aquatic organisms include mouths, shape, color, aestivation, and schooling.

1. *Mouths*—Aquatic organisms such as fish change mouth shape (morphology) depending on the food they eat. The arrangement of the jawbones and even other head bones, the length and width of gill rakers, the number, shape, and location of teeth, and barbels all change to allow the fish to eat just about anything found in a stream.
2. *Shape*—Changes to allow fish to do different things in the water. Some organisms have body shapes that push them down in the water, against the substrate, and allow them to hold their place even against strong currents (e.g., chubs, catfish, dace, and sculpins). Other organisms, especially predators, have evolved an arrangement and shape of fins that allows them to lurk without moving and they lunge suddenly to catch their prey (e.g., bass, perch, pike, trout, and sunfish).
3. *Color*—May change within hours, to camouflage, or within days, or may be genetically predetermined. Fish tend to turn dark in clear water, and pale in muddy water.
4. *Aestivation*—Helps fishes survive in arid desert climates, where streams may dry up from time to time. Aestivation refers to the ability of some fishes to burrow into the mud and wait out the dry period.
5. *Schooling*—Serves as protection for many fish, particularly those that are subject to predation.

BENTHIC LIFE: AN OVERVIEW

The benthic habitat is found in the streambed, or benthos. As mentioned, the streambed consists of various physical and organic materials where erosion and deposition are continuous characteristics. Erosion and deposition may occur simultaneously or alternately at different locations in the same streambed. Where channels are exceptionally deep and taper slowly to meet the relatively flattened streambed, habitats may form on the slopes of the channel. These habitats are referred to as littoral habitats. Shallow channels may dry up periodically in accordance with weather changes. The streambed is then exposed to open air and may take on the characteristics of a wetland.

Silt and organic materials settle and accumulate in the streambed of slowly flowing streams. These materials decay and become the primary food resource for the invertebrates inhabiting the streambed. Productivity in this habitat depends upon the breakdown of these organic materials by herbivores. Bottom-dwelling organisms do not use all the organic materials; a substantial amount becomes part of the streambed in the form of peat.

In faster moving streams, organic materials do not accumulate so easily. Primary production occurs in a different type of habitat found in the riffle regions where there are shoals and rocky regions for organisms to adhere to. Therefore, plants that can root themselves into the streambed dominate these regions. By plants, we are referring mostly to forms of algae, often microscopic and filamentous, that can cover rocks and debris that have settled into the streambed during summer months.

√ **Note:** If you have ever stepped into a stream, the green, slippery slime on the rocks in the streambed is representative of this type of algae.

Although filamentous algae seem well anchored, strong currents can easily lift it from the streambed and carry it downstream where it becomes a food resource for low-level consumers. One factor that greatly influences the productivity of a stream is the width of the channel; a direct relationship exists between stream width and richness of bottom-dwelling organisms. Bottom-dwelling organisms are very important to the ecosystem as they provide food for other, larger benthic organisms through consuming detritus.

BENTHIC PLANTS AND ANIMALS

Vegetation is not common in the streambed of slow-moving streams; however, they may anchor themselves along the banks. Alga (mainly green and blue-green) and common types of water moss attach themselves to rocks in fast-moving streams. Mosses and liverworts often climb up the sides of the channel onto the banks as well. Some plants similar to the reeds of wetlands with long stems and narrow leaves are able to maintain roots and withstand the current.

Aquatic insects and invertebrates dominate slow-moving streams. Most aquatic insects such as the blackfly, caddisfly, and stonefly are in their larval and nymph forms. Adult water beetles and waterbugs are also abundant. Insect larvae and nymphs provide the primary food source for many fish species, including American eel and brown bullhead catfish. Representatives of crustaceans, rotifers, and nematodes (flat worms) are sometimes present. Abundance of leeches, worms, and mollusks (especially freshwater mussels) varies with stream conditions, but generally favors low phosphate conditions. Larger animals found in slow-moving streams and rivers include newts, tadpoles, and frogs. As mentioned, the important characteristic of all life in streams is adaptability to withstand currents.

BENTHIC MACROINVERTEBRATES

The emphasis on aquatic insect studies, which has expanded exponentially in the last three decades, has been largely ecological. Freshwater macroinvertebrates are ubiquitous; even polluted waters contain some representative of this diverse and ecologically important group of organisms.

Benthic macroinvertebrates are aquatic organisms without backbones that spend at least a part of their life cycle on the stream bottom. Examples include aquatic insects—such as stoneflies, mayflies, caddisflies, midges, and beetles—as well as crayfish, worms, clams, and snails. Most hatch from eggs and mature from larvae to adults. The majority of the insects spends their larval phase on the river bottom and after a few weeks to several years emerges as winged adults. The aquatic beetles, true bugs, and other groups remain in the water as adults. Macroinvertebrates typically collected from the stream substrate are either aquatic larvae or adults.

In practice, stream ecologists observe indicator organisms and their responses (*biomonitoring*) to determine the quality of the stream environment. There are a number of methods for determining water quality based on biological characteristics. A wide variety of indicator organisms (biotic groups) are used for biomonitoring. The most commonly used include algae, bacteria, fish, and macroinvertebrates.

Notwithstanding their popularity, in this text, we use benthic macroinvertebrates for a number of other reasons. Simply, they offer a number of advantages:

1. They are ubiquitous, so they are affected by perturbations in many different habitats.
2. They are species rich, so the large number of species produces a range of responses.
3. They are sedentary, so they stay put, which allows determination of the spatial extent of a perturbation.
4. They are long-lived, which allows temporal changes in abundance and age structure to be followed.
5. They integrate conditions temporally, so like any biotic group, they provide evidence of conditions over long periods.

In addition, benthic macroinvertebrates are preferred as bioindicators because they are easily collected and handled by samplers; they require no special culture protocols. They are visible to the naked eye and samplers easily distinguish their characteristics. They have a variety of fascinating adaptations to stream life. Certain benthic macroinvertebrates have very special tolerances and thus are excellent specific indicators of water quality. Useful benthic macroinvertebrate data are easy to collect without expensive equipment. The data obtained by macroinvertebrate sampling can serve to indicate the need for additional data collection, possibly including water analysis and fish sampling.

In short, we base the focus of this discussion on benthic macroinvertebrates (with regard to water quality in streams and lakes) simply because some cannot survive in polluted water while others can survive or even thrive in polluted water. In a healthy stream, the benthic community includes a variety of pollution-sensitive macroinvertebrates. In an unhealthy stream or lake, there may be only a few types of nonsensitive macroinvertebrates present. Thus, the presence or absence of certain benthic macroinvertebrates is an excellent indicator of water quality.

It may also be difficult to identify stream or lake pollution with water analysis, which can only provide information for the time of sampling (a snapshot of time). Even the presence of fish may not provide information about a polluted stream because fish can move away to avoid polluted water and then return when conditions improve. Most benthic macroinvertebrates cannot move to avoid pollution. A macroinvertebrate sample may provide information about pollution that is not present at the time of sample collection.

Before anyone is able to use benthic macroinvertebrates to gauge water quality in a stream (or for any other reason), they must be familiar with the macroinvertebrates that are commonly used as bioindicators. Samplers need to be aware of basic insect structures before they can classify the macroinvertebrates they collect. Structures, which need to be stressed, include head, eyes (compound and simple), antennae, mouth (no emphasis on parts), segments, thorax, legs and leg parts, gills, and abdomen. Samplers also need to be familiar with insect metamorphosis—both complete and incomplete—as most of the macroinvertebrates collected are larval or nymph stages.

√ **Note:** Information on basic insect structures is beyond the scope of this text. Thus, we highly recommend the standard guide to aquatic insects of North America (Merritt and Cummins, 1996).

IDENTIFICATION OF BENTHIC MACROINVERTEBRATES

Before identifying and describing the key benthic macroinvertebrates significant to water/wastewater operators, it is important first to provide foundational information. We characterize benthic macroinvertebrates using two important descriptive classifications: trophic groups and mode of existence. In addition, we discuss their relationship in the food web, meaning what or whom they eat.

1. *Trophic groups*—Of the trophic groups (i.e., feeding groups) that Merritt and Cummins have identified for aquatic insects, only five are likely to be found in a stream using typical collection and sorting methods (Merrit and Cummins, 1996):
    a. *Shredders*—These have strong, sharp mouthparts that allow them to shred and chew coarse organic material such as leaves, algae, and rooted aquatic plants. These organisms play an important role in breaking down leaves or larger pieces of organic material to a size that can be used by other macroinvertebrates. Shredders include certain stonefly and caddisfly larvae, sowbugs, scuds, and others.
    b. *Collectors*—These gather the very finest suspended matter in the water. To do this, they often sieve the water through rows of tiny hairs. These sieves of hairs may be displayed in fans on their heads (blackfly larvae) or on their forelegs (some mayflies). Some caddisflies and midges spin nets and catch their food in them as the water flows through.
    c. *Scrapers*—These scrape the algae and diatoms off surfaces of rocks and debris, using their mouthparts. Many of these organisms are flattened to hold onto surfaces while feeding. Scrapers include water pennies, limpets and snails, netwinged midge larvae, certain mayfly larvae, and others.

   - d. *Piercers*—These herbivores pierce plant tissues or cells and suck the fluids out. Some caddisflies do this.
   - e. *Predators*—Predators eat other living creatures. Some of these are *engulfers*, that is, they eat their prey completely or in parts. This is very common in stoneflies and dragonflies, as well as caddisflies. Others are *piercers*, which are like the herbivorous piercers except that they eat live animal tissues.

2. *Mode of Existence (habit, locomotion, attachment, concealment)*:
   - a. *Skaters*—Adapted for "skating" on the surface where they feed as scavengers on organisms trapped in the surface film (e.g., water striders).
   - b. *Planktonic*—Inhabiting the open-water limnetic zone of standing waters (lentic; lakes, bogs, ponds). Representatives may float and swim about in the open water, but usually exhibit a diurnal vertical migration pattern (e.g., phantom midges) or float at the surface to obtain oxygen and food, diving when alarmed (e.g., mosquitoes).
   - c. *Divers*—Adapted for swimming by "rowing" with the hind legs in lentic habitats and lotic pools. Representatives come to the surface to obtain oxygen, dive and swim when feeding or alarmed; may cling to or crawl on submerged objects such as vascular plants (e.g., water boatmen; predaceous diving beetle).
   - d. *Swimmers*—Adapted for "fishlike" swimming in lotic or lentic habitats. Individuals usually cling to submerged objects, such as rocks (lotic riffles) or vascular plants (lentic), between short bursts of swimming (e.g., mayflies).
   - e. *Clingers*—Representatives have behavioral (e.g., fixed retreat construction) and morphological (e.g., long, curved tarsal claws, dorsoventral flattening, and ventral gills arranged as a sucker) adaptations for attachment to surfaces in stream riffles and wave-swept rocky littoral zones of lakes (e.g., mayflies and caddisflies).
   - f. *Sprawlers*—Inhabiting the surface of floating leaves of vascular hydrophytes or fine sediments, usually with modifications for staying on top of the substrate and maintaining the respiratory surfaces free of silt (e.g., mayflies, dobsonflies, and damselflies).
   - g. *Climbers*—Adapted for living on vascular hydrophytes or detrital debris (e.g., overhanging branches, roots and vegetation along streams, and submerged brush in lakes) with modifications for moving vertically on stem-type surfaces (e.g., dragonflies and damselflies).
   - h. *Burrowers*—Inhabiting the fine sediments of streams (pools) and lakes. Some construct discrete burrows, which may have sand grain tubes extending above the surface of the substrate or the individuals, may ingest their way through the sediments (e.g., mayflies and midges).

MACROINVERTEBRATES AND THE FOOD WEB

In a stream or lake, there are two possible sources of primary energy: (1) photosynthesis by algae, mosses, and higher aquatic plants and (2) imported organic matter from streamside/lakeside vegetation (e.g., leaves and other parts of vegetation). Simply put, a portion of the food that is eaten grows right in the stream or lake, such as algae, diatoms, nymphs and larvae, and fish. A food that originates from within the stream is called autochthonous.

Most food in a stream comes from outside the stream. This is especially the case in small, heavily wooded streams, where there is normally insufficient light to support instream photosynthesis, so energy pathways are supported largely by imported energy. Leaves provide a large portion of this imported energy. Worms drown in floods and are washed in. Leafhoppers and caterpillars fall from trees. Adult mayflies and other insects mate above the stream, lay their eggs in it, and then die in it. All of this food from outside the stream is called allochthonous.

UNITS OF ORGANIZATION

Macroinvertebrates, like all other organisms, are classified and named. Macroinvertebrates are classified and named using a *taxonomic hierarchy*. The taxonomic hierarchy for the caddisfly (a macroinvertebrate insect commonly found in streams) is shown below.

Kingdom:	Animalia (animals)
Phylum:	Arthropoda ("jointed legs")
Class:	Insecta (insect)
Order:	Trichoptera (caddisfly)
Family:	Hydropsychidae (net-spinning caddis)
Genus species:	*Hydropsyche morosa*

INSECT MACROINVERTEBRATES

As mentioned, the macroinvertebrates are the best-studied and most diverse animals in streams; therefore, we devote our discussion to the various macroinvertebrate groups.

While it is true that noninsect macroinvertebrates, such as Oligochaeta (worms), Hirudinea (leeches), and Acari (water mites), are frequently encountered groups in lotic environments, the insects are among the most conspicuous inhabitants of streams. In most cases, it is the larval stages of these insects that are aquatic, whereas the adults are terrestrial. Typically, the larval stage is extended, while the adult lifespan is short.

The most important insects groups in streams are Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Diptera (true flies), Coleoptera (beetles), Hemiptera (bugs), Megaloptera (alderflies and dobsonflies), and Odonata (dragonflies and damselflies). The identification of these different orders is usually easy and there are many keys and specialized references (Merritt and Cummins, 1996) available to help with the identification up to species. In contrast, specialist taxonomists can often diagnose only some genera and species, particularly in Diptera.

As mentioned, insect macroinvertebrates are ubiquitous in streams and are often represented by many species. Although the numbers refer to aquatic species, a majority is to be found in streams. Lotic insects are found among many different orders and brief accounts of their biology are presented in the following sections.

(1) MAYFLIES (ORDER: EPHEMEROPTERA)

Streams and rivers are generally inhabited by many species of mayflies (common names: mays, mayfly, upwings, duns, dippers, and spinners) and, in fact, most species are restricted to streams. For the experienced freshwater ecologist who looks upon a mayfly nymph, recognition is obtained through trained observation: abdomen with leaf-like or feather-like gills, legs with a single tarsal claw, generally (but not always) with three cerci (three "tails," two cerci, and between them usually a terminal filament; see Figure 6.19). The experienced ecologist knows that mayflies are hemimetabolous insects (i.e., where larvae or nymphs resemble wingless adults) that go through many postembryonic molts, often in the range between 20 and 30. For some species, body length increases about 15% for each instar (i.e., time between each molt). During instars the nymph is very vulnerable to its principal animal, bird fish, amphibian, and insect predators such as diving beetles, frogs, salamanders, swifts, phoebes, and dragon fly nymphs and adults.

Mayfly nymphs are mainly grazers or collector-gatherers feeding on algae and fine detritus, although a few genera are predatory. Some members filter particles from the water using hair-fringed legs or maxillary palps. Shredders are rare among mayflies. In general, mayfly nymphs tend to live mostly in unpolluted streams, where with densities of up to 10,000/m^2, they contribute substantially to secondary producers.

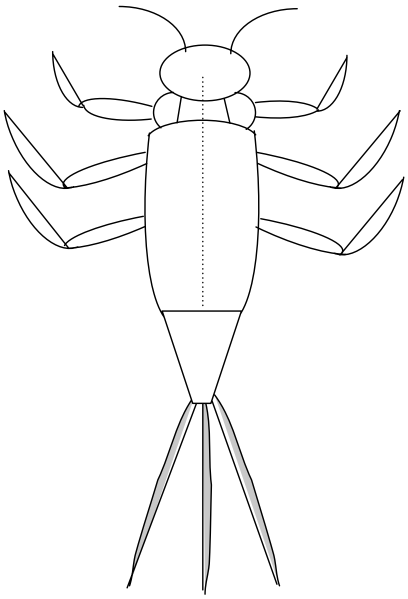


FIGURE 6.19 Mayfly (Order: Emphemeroptera).

Adult mayflies resemble nymphs, but usually possess two pair of long, lacy wings folded upright; adults usually have only two cerci. The adult lifespan is short, ranging from a few hours to a few days, rarely up to 2 weeks, and the adults do not feed. Mayflies are unique among insects in having two winged stages: the subimago (fully-winged but not adults) and the imago (sexually mature). The emergence of adults tends to be synchronous, thus ensuring the survival of enough adults to continue the species.

(2) STONEFLIES (ORDER: PLECOPTERA)

Although many freshwater ecologists would maintain that the stonefly is a well-studied group of insects, this is not exactly the case. Despite their importance, less than 5–10% of stonefly species are well known with respect to life history, trophic interactions, growth, development, spatial distribution, and nymphal behavior.

Our knowledge of stoneflies is not extensive, but enough is known to provide an accurate characterization of these aquatic insects. We know, for example, that stonefly larvae are characteristic inhabitants of cool, clean streams (i.e., most nymphs occur under stones in well-aerated streams). While they are sensitive to organic pollution, or more precisely to low oxygen concentrations accompanying organic breakdown processes, stoneflies seem rather tolerant to acidic conditions. Lack of extensive gills at least partly explains their relative intolerance of low oxygen levels.

Stoneflies are drab-colored (tan, brown, gold, and black), small- to medium-sized (1/6–2¼ in. [4–60 mm]), rather flattened insects. Females deposit eggs on top of the water where they drift down to the bottom. Stoneflies have long, slender, many-segmented antennae and two long narrow antenna-like structures (cerci) on the tip of the abdomen (see Figure 6.20). The cerci may be long or short. At rest, the wings are held flat over the abdomen, giving a "square-shouldered" look compared to the roof-like position of most caddisflies and the vertical position of mayflies. Stoneflies have two pair of wings. The hind wings are slightly shorter than the forewings and much wider, with a large anal lobe that is folded fanwise when the wings are at rest. This fanlike folding of the wings gives the order its name: pleco (folded or plaited) and -ptera (wings). The aquatic nymphs are generally very similar to mayfly nymphs except that they have only two cerci at the tip of the abdomen.

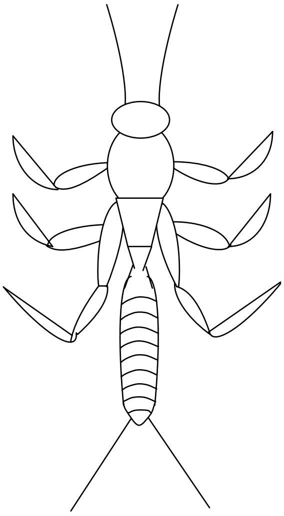


FIGURE 6.20 Stonefly (Order: Plecoptera).

The stoneflies have chewing mouthparts; some are carnivorous, others feed on algae, bacteria, and vegetable debris. They may be found anywhere in a nonpolluted stream where food is available. Many adults, however, do not feed and have reduced or vestigial mouthparts.

Stoneflies have a specific niche in high-quality streams (mostly found in the swift flow of stream riffles) where they are very important as a fish food source at specific times of the year (winter to spring, especially) and of the day. They complement other important food sources, such as caddisflies, mayflies, and midges.

(3) CADDISFLIES (ORDER: TRICHOPTERA)

Trichoptera (Greek: *trichos*, a hair; *ptera*, wing) is one of the most diverse insect orders living in the stream environment, and caddisflies have nearly a worldwide distribution (the exception: Antarctica). Caddisflies may be categorized broadly into free-living (roving and net spinning) and case-building species.

Caddisflies are described as medium-sized insects with bristle-like and often long antennae. They have membranous hairy wings (explains the Latin name "Trichos"), which are held tent-like over the body when at rest; most are weak fliers. They have greatly reduced mouthparts and five tarsi. The larvae are mostly caterpillar or worm-like and have a strongly sclerotized (hardened) head with very short antennae and biting mouthparts. Color can vary from yellow or brown, but is usually green. They have well-developed legs with a single tarsi. The abdomen is usually 10-segmented; in case-bearing species the first segment bears three papillae, one dorsally and the other two laterally, which help hold the insect centrally in its case, allowing a good flow of water to pass the cuticle and gills; the last or anal segment bears a pair of grappling hooks.

In addition to being aquatic insects, caddisflies are superb architects. Most caddisfly larvae (see Figure 6.21) live in self-designed, self-built houses, called *cases*. They spin out silk, and either live in silk nets or use the silk to stick together bits of whatever is lying on the stream bottom (sand, twigs, small stones, crushed shells, rolled leaves, and bark pieces). These houses are so specialized that you can usually identify a caddisfly larva to genus if you can see its house (case). With nearly 1,400 species of caddisfly species in North America (north of Mexico), this is a good thing!

Caddisflies are closely related to butterflies and moths (Order: Lepidoptera). They live in most stream habitats, and that is why they are so diverse (i.e., have so many species). Each species has special adaptations that allow it to live in the environment in which it is found.

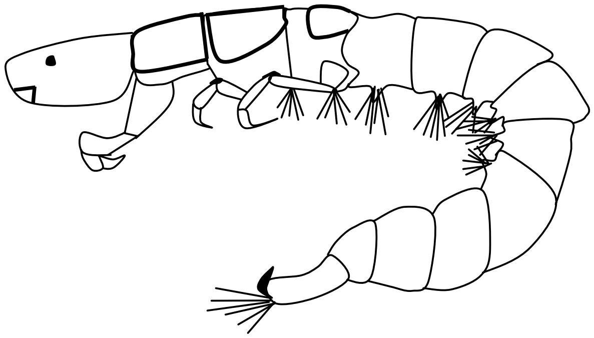


FIGURE 6.21 Caddis larvae, *Hydropsyche* spp.

Mostly herbivorous, most caddisflies feed on decaying plant tissue, small bits of plant material, and algae. Some species build nets that they use to catch drifting food. Their favorite algae are diatoms, which they scrape off rocks. Some of them, though, are predaceous.

Caddisfly larvae can take a year or two to change into adults. They then change into *pupae* (the inactive stage in the metamorphosis of many insects, following the larval stage and preceding the adult form) while still inside their cases for their metamorphosis. It is interesting to note that caddisflies, unlike stoneflies and mayflies, go through a "complete" metamorphosis.

Caddisflies remain as pupae for 2–3 weeks, then emerge as adults. When they leave their pupae, splitting their case, they must swim to the surface of the water to escape it. The winged adults fly during evenings and nights, and some are known to feed on plant nectar. Most of them will live less than a month: like many other winged stream insects, their adult lives are brief compared to the time they spend in the water as larvae.

Caddisflies are sometimes grouped by the kinds of cases they make into five main groups: free-living forms that do not make cases, saddle-case makers, purse-case makers, net-spinners and retreat-makers, and tube-case makers.

As mentioned, caddisflies demonstrate their "architectural" talents in the cases they design and make. For example, a caddisfly might make a perfect, four-sided box case of bits of leaves and bark or tiny bits of twigs. It may make a clumsy dome of large pebbles. Others make rounded tubes out of twigs or very small pebbles. In our experience in gathering caddisflies, we have come to appreciate not only their architectural ability but also their flare in the selection of construction materials. For example, we have found many caddisfly cases constructed of silk, emitted through an opening at the tip of the labium, used together with bits of ordinary rock mixed with sparkling quartz and red garnet, green peridot, and bright fool's gold.

Besides the protection their cases provide them, it also provides another advantage. The cases actually help caddisflies breathe. They move their bodies up and down, back and forth inside their cases, and this creates a current that brings them fresh oxygen. The less oxygen there is in the water, the faster they have to move. It has been seen that caddisflies inside their cases get more oxygen than those that are outside of their cases—and this is why stream ecologists think that caddisflies can often be found even in still waters, where dissolved oxygen is low, in contrast to stoneflies and mayflies.

(4) TRUE FLIES (ORDER: DIPTERA)

True or two- (*Di-*) winged (*ptera*) flies not only include the flies that we are most familiar with, like fruitflies and houseflies, but also midges (see Figure 6.22), mosquitoes, craneflies (see Figure 6.23), and others. Houseflies and fruitflies live only on land, and we do not concern ourselves with them. Some, however, spend nearly their whole lives in water; they contribute to the ecology of streams.

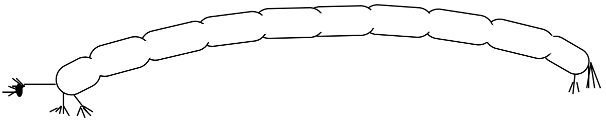


FIGURE 6.22 Midge larvae.

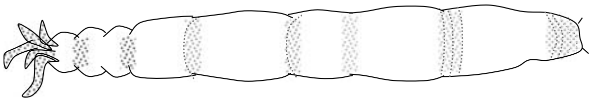


FIGURE 6.23 Cranefly larvae.

True flies are in the order Diptera, and are one of the most diverse orders of the class Insecta, with about 120,000 species worldwide. Dipteran larvae occur almost everywhere except Antarctica and deserts where there is no running water. Females deposit a gelatinous mass of eggs on the water surface or attach it to submerged vegetation. They may live in a variety of places within a stream: buried in sediments, attached to rocks, beneath stones, in saturated wood or moss, or in silken tubes, attached to the stream bottom. Some even live below the stream bottom.

True fly larvae may eat almost anything, depending on their species. Those with brushes on their heads use them to strain food out of the water that passes through. Others may eat algae, detritus, plants, and even other fly larvae.

The longest part of the true fly's life cycle, like that of mayflies, stoneflies, and caddisflies, is the larval stage. It may remain an underwater larva anywhere from a few hours to 5 years. The colder the environment, the longer it takes to mature. It pupates and emerges, then, and becomes a winged adult. The adult may live 4 months—or it may only live for a few days. While reproducing, it will often eat plant nectar for the energy it needs to make its eggs. Mating sometimes takes place in aerial swarms. The eggs are deposited back in the stream; some females will crawl along the stream bottom, losing their wings, to search for the perfect place to put their eggs. Once they lay them, they die.

Diptera serve an important role in cleaning water and breaking down decaying material, and they are a vital food source (i.e., they play pivotal roles in the processing of food energy) for many of the animals living in and around streams. However, the true flies most familiar to us are the midges, mosquitoes, and the craneflies because they are pests. Some midge flies and mosquitoes bite; the cranefly, however, which looks like a giant mosquito, does not bite.

Like mayflies, stoneflies, and caddisflies, true flies are mostly in the larval form. Like caddisflies, you can also find their pupae, because they are holometabolous insects (i.e., go through complete metamorphosis). Most of them are free-living; that is, they can travel around. Although none of the true fly larvae has the six, jointed legs we see on the other insects in the stream, they sometimes have strange little almost-legs—prolegs—that help them move around.

Others may move somewhat like worms do, and some—the ones who live in waterfalls and rapids—have a row of six suction discs that they use to move much like a caterpillar does. Many use silk pads and hooks at the ends of their abdomens to hold them fast to smooth rock surfaces.

(5) BEETLES (ORDER: COLEOPTERA)

According to Hutchinson (1981), of the one million and more species of insect described, at least one third are beetles, making Coleoptera not only the largest order of insects but also the most diverse order of living organisms. Although they are the most speciose order of terrestrial insects, surprisingly their diversity is not so apparent in running waters. Coleoptera belongs to the infraclass Neoptera, division Endpterygota. Members of this order have an anterior pair of wings (the *elytra*) that are hard and leathery and not used in flight; the membranous hindwings, which are used for flight, are concealed under the elytra when the organisms are at rest. Only 10% of the 350,000 described species of beetles are aquatic.

Beetles are holometabolous (i.e., they complete metamorphosis). Eggs of aquatic coleopterans hatch in 1 or 2 weeks, with diapause (i.e., no suspension of development) occurring rarely. Larvae undergo from three to eight molts. The pupal phase of all coleopterans is technically terrestrial, making this life stage of beetles the only one that has not successfully invaded the aquatic habitat. A few species have diapausing prepupae, but most complete transformation to adults in 2–3 weeks. Terrestrial adults of aquatic beetles are typically short-lived and sometimes nonfeeding, like those of the other orders of aquatic insects. The larvae of Coleoptera are morphologically and behaviorally different from the adults, and their diversity is high.

Aquatic species occur in two major suborders, the Adephaga and the Polyphaga. Both larvae and adults of the six beetle families are aquatic. Dytiscidae (predaceous diving beetles), Elmidae (riffle beetles), Gyrinidae (whirligig beetles), Halipidae (crawling water beetles), Hydrophilidae (water scavenger beetles), and Noteridae (burrowing water beetles). Five families—Chrysomelidae (leaf beetles), Limnichidae (marsh-loving beetles), Psephenidae (water pennies), Ptilodactylidae (toe-winged beetles), and scirtidae (marsh beetles)—have aquatic larvae and terrestrial adults, as do most of the other orders of aquatic insects; adult limnichids, however, readily submerge when disturbed. Three families have species that are terrestrial as larvae and aquatic as adults: Curculionidae (weevils), Dryopidae (long-toed water beetles), and Hydraenidae (moss beetles), a highly unusual combination among insects.

√ **Note:** Because they provide a greater understanding of the condition of a freshwater body (i.e., they are useful indicators of water quality), the focus of discussion here is on the riffle beetle, water penny, and whirligig beetle.

Riffle beetle larvae (most commonly found in running waters, hence the name riffle beetle) are up to 3/4 in. long (see Figure 6.24). Their bodies are not only long, but also hard, stiff, and segmented; they resemble small torpedoes and are usually grayish in color. They have six long segmented legs on the upper middle section of body; the back end has two tiny hooks and short hairs. Larvae may take 3 years to mature before they leave the water to form a pupa; adults return to the stream.

Riffle beetle adults are considered better indicators of water quality than larvae because they have been subjected to water quality conditions over a longer period. They walk very slowly under the water (on stream bottom), and do not swim on the surface. They have small oval-shaped bodies (see Figure 6.25) and are typically about 1/4 in. in length.

Both adults and larvae of most species feed on fine detritus with associated microorganisms that are scraped from the substrate. Others may be xylophagous, that is, wood eating (e.g., *Lara*, Elmidae). Predators do not seem to include riffle beetles in their diet, except perhaps for eggs, which are sometimes attacked by flatworms.

The adult *water penny* is inconspicuous; it resembles circular encrustations on rocks and is often found clinging tightly in a sucker-like fashion to the undersides of submerged rocks, where they feed on attached algae. The body is broad, slightly oval and flat in shape, ranging from 4–6 mm (1/4 in.) in length. The body is covered with segmented plates and looks like a tiny round leaf

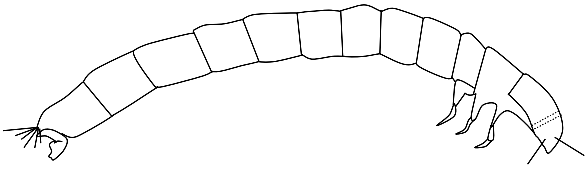


FIGURE 6.24 Riffle beetle larvae.

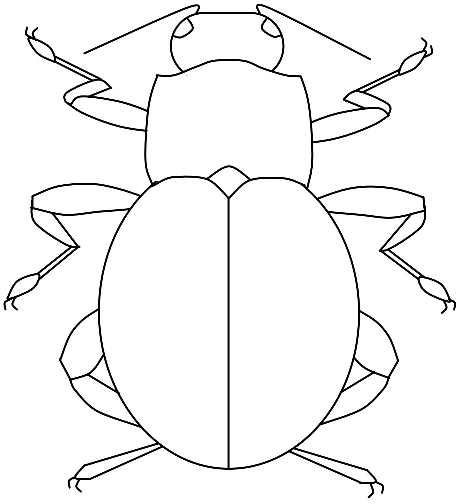


FIGURE 6.25 Riffle beetle adult.

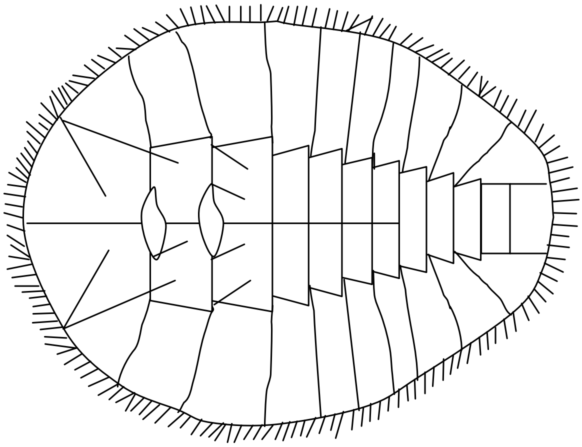


FIGURE 6.26 Water penny larva.

(see Figure 6.26). It has six tiny jointed legs (underneath). The color ranges from light brown to green to almost black.

There are 14 water penny species in the United States. They live predominately in clean, fast-moving streams. Adult females crawl into water and deposit eggs on the underside of stones. Aquatic larvae live 1 year or more (they are aquatic); adults (they are terrestrial) live on land for only a few days. They scrape algae and plants from surfaces.

Whirligig beetles are common inhabitants of streams and are usually found on the surface of quiet pools. The body has pincher-like mouthparts. They have six segmented legs on the middle of the body; the legs end in tiny claws. Many filaments extend from the sides of the abdomen. They have four hooks at the end of the body and no tail.

√ **Note:** When disturbed, whirligig beetles swim erratically or dive while emitting defensive secretions.

As larvae (see Figure 6.27), whirligig beetles are benthic predators, whereas the adults live on the water surface, attacking dead and living organisms trapped in the surface film. They occur on

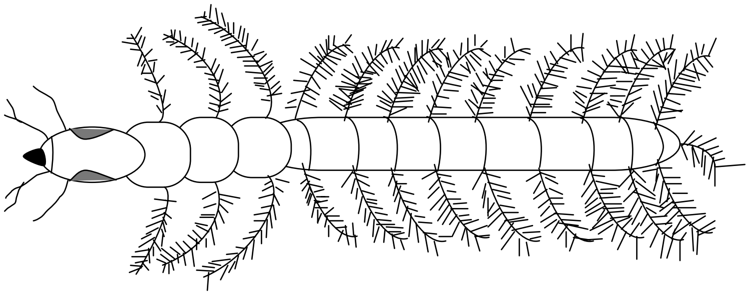


FIGURE 6.27 Whirligig beetle larvae.

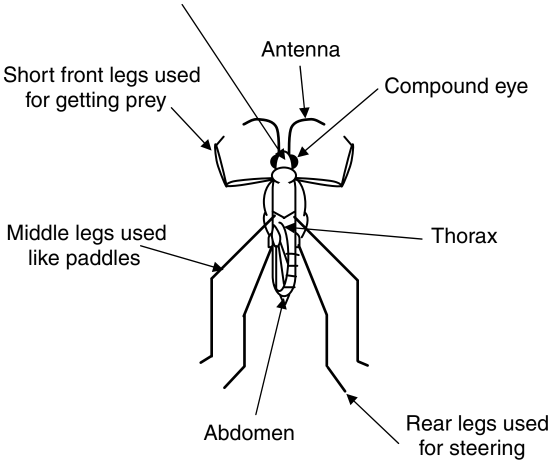


FIGURE 6.28 Water strider.

the surface in aggregations of up to thousands of individuals. Unlike the mating swarms of mayflies, these aggregations serve primarily to confuse predators. Whirligig beetles have other interesting defensive adaptations. For example, the Johnston's organ at the base of the antennae enables them to echolocate using surface wave signals; their compound eyes are divided into two pairs, one above and one below the water surface, enabling them to detect both aerial and aquatic predators; and they produce noxious chemicals that are highly effective for deterring predatory fish.

(6) WATER STRIDER ("JESUS BUGS"; ORDER: HEMIPTERA)

It is fascinating to sit on a log at the edge of a stream pool and watch the drama that unfolds among small water animals. Among the star performers in small streams are the water bugs. These are aquatic members of that large group of insects called the "true bugs," most of which live on land. Moreover, unlike many other types of water insects, they do not have gills but get their oxygen directly from the air.

Most conspicuous and commonly known are the water striders or water skaters. These ride the top of the water, with only their feet making dimples in the surface film. Like all insects, the water striders have a three-part body (head, thorax and abdomen), six jointed legs, and two antennae. It has a long, dark, narrow body (see Figure 6.28). The underside of the body is covered with water-repellent hair. Some water striders have wings; others do not. Most water striders are over 0.2 in. (5 mm) long.

Water striders eat small insects that fall on the water's surface and larvae. Water striders are very sensitive to motion and vibrations on the water's surface. They use this ability to locate prey.

They push their mouths into the prey, paralyze it, and suck the insect dry. Predators of the water strider, such as birds, fish, water beetles, backswimmers, dragonflies, and spiders, take advantage of the fact that water striders cannot detect motion above or below the water's surface.

(7) ALDERFLIES AND DOBSONFLIES (ORDER: MEGALOPTERA)

Larvae of all species of Megaloptera ("large wing") are aquatic and attain the largest size of all aquatic insects. Megaloptera is a medium-sized order with less than 5000 species worldwide. Most species are terrestrial; in North America 64 aquatic species occur.

In running waters, alderflies (Family: Sialidae) and dobsonflies (Family: Corydalidae; sometimes called hellgrammites or toe biters) are particularly important. They are voracious predators, having large mandibles with sharp teeth.

Alderfly brownish-colored larvae possess a single tail filament with distinct hairs. The body is thick-skinned with six to eight filaments on each side of the abdomen; gills are located near the base of each filament. Mature body size is 0.5–1.25 in. (see Figure 6.29). Larvae are aggressive predators, feeding on other adult aquatic macroinvertebrates (they swallow their prey without chewing); as secondary consumers, other larger predators eat them. Female alderflies deposit eggs on vegetation that overhangs water, and the larvae hatch and fall directly into water (i.e., into quiet but moving water). Adult alderflies are dark with long wings folded back over the body; they only live a few days.

Dobsonfly larvae are extremely ugly (thus, they are rather easy to identify) and can be rather large, anywhere from 25 to 90 mm (1–3 in.) in length. The body is stout, with eight pairs of appendages on the abdomen. Brush-like gills at the base of each appendage look like "hairy armpits" (see Figure 6.30). The elongated body has spiracles (spines) and three pair of walking legs near the upper body and one pair of hooked legs at the rear. The head bears four segmented antennae, small compound eyes, and strong mouth parts (large chewing pinchers). Coloration varies from yellowish to brown, gray and black, often mottled. Dobsonfly larvae, commonly known as hellgrammites, are usually found along stream banks under and between stones. As indicated by the mouthparts, they are predators and feed on all kinds of aquatic organisms. They are an important food source for larger game fish.

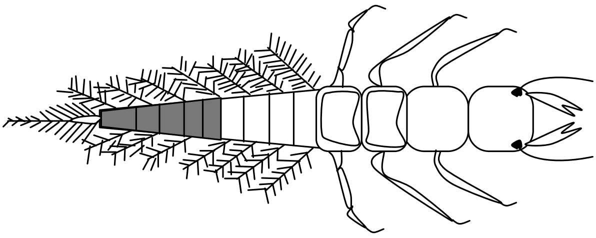


FIGURE 6.29 Alderfly larvae.

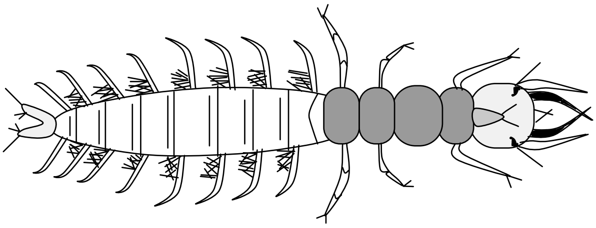


FIGURE 6.30 Dobsonfly larvae.

(8) DRAGONFLIES AND DAMSELFLIES (ORDER: ODONATA)

The Odonata (dragonflies, suborder Anisoptera; and damselflies, suborder Zygoptera) is a small order of conspicuous, hemimetabolous insects (lack a pupal stage) of about 5000 named species and 23 families worldwide. *Odonata* is a Greek word meaning "toothed one." It refers to the serrated teeth located on the insect's chewing mouthparts (mandibles).

Characteristics of dragonfly and damselfly larvae include:

- Large eyes
- Three pair of long segmented legs on the upper middle section (thorax) of the body
- Large scoop-like lower lip that covers the bottom of the mouth
- No gills on the sides or underneath the abdomen

√ **Note:** Dragonflies and damselflies are unable to fold their four elongated wings back over the abdomen when at rest.

Dragonflies and damselflies are medium to large insects with two pair of long, equal-sized wings. The body is long and slender, with short antennae. Immature stages are aquatic and development occurs in three stages (egg, nymph, and adult).

Dragonflies are also known as darning needles.

Note: Myths about dragonflies warned children to keep quiet or else the dragonfly's "darning needles" would sew the children's mouths shut.

At the nymphal stage dragonflies are grotesque creatures, robust, and stoutly elongated. They do not have long "tails" (see Figure 6.31). They are commonly gray, greenish, or brown to black in color. They are medium to large aquatic insects size ranging from 15 to 45 mm; the legs are short and used for perching. They are often found on submerged vegetation and at the bottom of streams in the shallows. They are rarely found in polluted waters. Food consists of other aquatic insects, annelids, small crustacea, and mollusks. Transformation occurs when the nymph crawls out of the water, usually onto vegetation. There it splits its skin and emerges prepared for flight. The adult dragonfly is a strong flier, capable of great speed (>60 mph) and maneuverability (fly backward, stop on a dime, zip 20 ft straight up, and slip sideways in the blink of an eye!). When at rest the wings remain open and out to the sides of the body. A dragonfly's freely movable head has large, hemispherical eyes (nearly 30,000 facets each), which the insect uses to locate prey with its excellent vision. Dragonflies eat small insects, mainly mosquitoes (large numbers of mosquitoes), while in flight. Depending on the species, dragonflies lay hundreds of eggs by dropping them into the water and

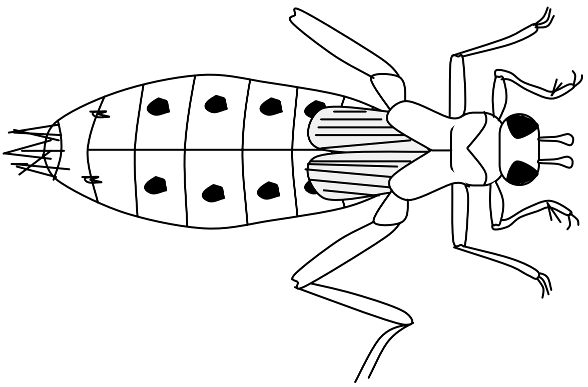


FIGURE 6.31 Dragonfly nymph.

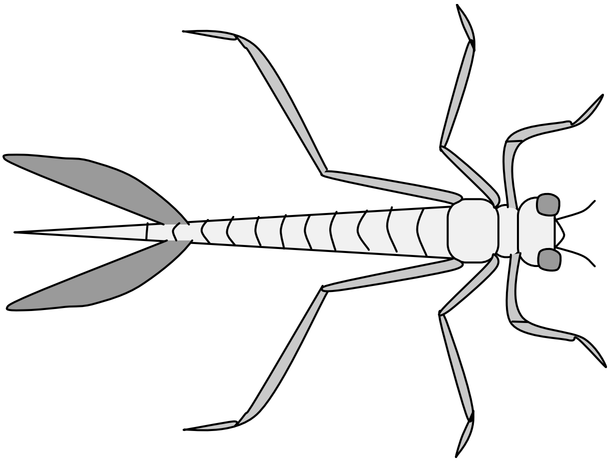


FIGURE 6.32 Damselfly.

leaving them to hatch or by inserting eggs singly into a slit in the stem of a submerged plant. The incomplete metamorphosis (egg, nymph, mature nymph, and adult) can take 2–3 years. Nymphs are often covered by algal growth.

√ **Note:** Adult dragonflies are sometimes called "mosquito hawks" because they eat such a large number of mosquitoes that they catch while they are flying.

Damselflies are smaller and more slender than dragonflies. They have three long, oar-shaped feathery tails, which are actually gills, and long slender legs (see Figure 6.32). They are gray, greenish, or brown to black in color. Their habits are similar to those of dragonfly nymphs, and they emerge from the water as adults in the same manner. The adult damselflies are slow and seem uncertain in flight. Wings are commonly black or clear, and their bodies are often brilliantly colored. When at rest, they perch on vegetation with their wings closed upright. Damselflies mature in 1–4 years. Adults live for a few weeks or months. Unlike the dragonflies, adult damselflies rest with their wings held vertically over their backs. They are predaceous and mostly feed on live insect larvae.

√ **Note:** Relatives of the dragonflies and damselflies are some of the most ancient of the flying insects. Fossils have been found of giant dragonflies with wingspans up to 720 mm that lived long before the dinosaurs!

NONINSECT MACROINVERTEBRATES

√ **Note:** Noninsect macroinvertebrates are important to any discussion of stream and freshwater ecology because many of them are used as bioindicators of stream quality.

Three frequently encountered groups in running water systems are Oligochaeta (worms), Hirudinea (leeches), and Gastropoda (lung-breathing snails). They are by no means restricted to running water conditions and the great majority of them occupy slow-flowing marginal habitats where the sedimentation of fine organic materials takes place.

(1) OLIGOCHAETA (FAMILY TUIFICIDAE, GENUS *Tubifex*)

Tubifex worms (commonly known as sludge worms) are unique because of the fact that they build tubes. Sometimes there are as many as 8000 individuals/m^2. They attach themselves within the tube and wave their posterior end in the water to circulate the water and make more oxygen available to their body surface. These worms are commonly red because their blood contains hemoglobin. Tubifex worms may be very abundant in situations when other macroinvertebrates are absent; they can survive in very low oxygen levels and can live with no oxygen at all for short periods. They are commonly found in polluted streams, and they feed on sewage or detritus.

(2) HIRUDINEA (LEECHES)

There are many different families of leeches, but all have common characteristics. They are soft-bodied, worm-like creatures that are flattened when extended. Their bodies are dull in color, ranging from black to brown and reddish to yellow, often with a brilliant pattern of stripes or diamonds on the upper body. Their size varies within species but generally ranges from 5 mm to 45 cm when extended. Leeches are very good swimmers, but they typically move in an inchworm fashion. They are carnivorous and feed on other organisms ranging from snails to warm-blooded animals. Leeches are found in warm protected shallows under rocks and other debris.

(3) GASTROPODA (LUNG-BREATHING SNAIL)

Lung-breathing snails (pulmonates) may be found in streams that are clean. However, their dominance may indicate low DO levels. These snails are different from *right-handed snails* because they do not breathe under water by use of gills but instead have a lung-like sac called a pulmonary cavity, which they fill with air at the surface of the water. When the snail takes in air from the surface, it makes a clicking sound. The air taken in can enable the snail to breathe under water for long periods, sometimes hours.

Lung-breathing snails have two characteristics that help us identify them. First, they have no operculum or hard cover over the opening to the body cavity. Second, snails are either "right-handed" or "left-handed"; the lung-breathing snails are "left-handed." We can tell the difference by holding the shell so that its tip is upward and the opening toward us. If the opening is to the "left" of the axis of the shell, the snail is termed *sinistral*—that is, it is left-handed. If the opening is to the "right" of the axis of the shell, the snail is termed *dextral*—that is, it is right-handed, and it breathes with gills. Snails are animals of the substrate and are often found creeping along all types of submerged surfaces in water from 10 cm to 2 m deep.

Before the Industrial Revolution of the 1800s, metropolitan areas were small and sparsely populated. Thus, river and stream systems within or close to early communities received insignificant quantities of discarded waste. Early on, these river and stream systems were able to compensate for the small amount of wastes they received; when wounded (polluted), nature has a way of fighting back. In the case of rivers and streams, nature provides their flowing waters with the ability to restore themselves through their own self-purification process. It was only when humans gathered in great numbers to form great cities that the stream systems were not always able to recover from having received great quantities of refuse and other wastes. What exactly is it that man does to rivers and streams? Man upsets the delicate balance between pollution and the purification process, unbalancing the aquarium.

REFERENCES

Abrahamson, D.E. (ed.), 1988. *The Challenge of Global Warming*. Washington, DC: Island Press.

American Public Health Association, 1981. *Standard Methods*, 15th ed. Washington, DC: American Public Health Association.

Asimov, L., 1989. *How Did We Find Out About Photosynthesis?* New York: Walker & Company.

ASTM, 1969. *Man on Water*. Philadelphia: American Society for Testing and Materials.

Carson, R., 1962. *Silent Spring*. New York: Houghton Mifflin.

Carson, R., 1998. Preface, in *Lost Woods: The Discovered Writing of Rachel Carson*, Linda, L. (ed.). Boston: Beacon Press.

Darwin, C., 1998. In *The Origin of Species*, Suriano, G. (ed.). New York: Gramercy.

Ecosystems Topics, 2000. http://www.so.gmu.edu/Irockwoo/ECCSTSTEMS%20TOPICS.htm. Accessed December 2006.

Hutchinson, G.E., 1981. Thoughts on Aquatic Insects. *Bioscience*, 31:495–500.

McCafferty, P.W., 1981. *Aquatic Entomology.* Boston: Jones and Bartlett.

Merrit, R.W. and Cummins, K.W., 1996. *An Introduction to the Aquatic Insects of North America*, 3rd ed. Dubuque, IA: Kendall/Hunt Publishing.

Metcalf & Eddy, Inc., 1991. *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd ed. New York: McGraw-Hill.

Miller, G.T., 1988. *Environmental Science: An Introduction*. Belmont, CA: Wadsworth Publishing Company.

Odum, E.P., 1971. *Fundamentals of Ecology.* Philadelphia: Saunders College Publishing.

Odum, E.P., 1975. *Ecology: The Link Between the Natural and the Social Sciences.* New York: Holt, Rinehart and Winston.

Odum, E.P., 1983. *Basic Ecology.* Philadelphia: Saunders College Publishing.

Price, P.W., 1984. *Insect Ecology.* New York: John Wiley & Sons.

Smith, R.L., 1974. *Ecology and Field Biology.* New York: Harper & Row.

Tchobanglous, G. and Schroeder, E.D., 1985. *Water Quality.* Reading, MA: Addison-Wesley Publishing Company.

Tomera, A.N., 1989. *Understanding Basic Ecological Concepts.* Portland, ME: J. Weston Walch.

FURTHER READING

Britannica.com., 2007. *Phosphorus Cycle.*

Lichatowich, J., 1999. *Salmon Without Rivers: A History of the Pacific Salmon Crisis.* Washington, DC: Island Press.

Watson, L., 1988. *The Water Planet: A Celebration of the Wonders of Water.* New York: Harper & Row.

Running Waters. White Oak Canyon Trail. Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

7 Water Pollution

> This country's waterways have been transformed by **omission**. Without beavers, water makes its way too quickly to the sea; without prairie dogs, water runs over the surface instead of sinking into the aquifer; without bison, there are no ground-water-recharge ponds in the grasslands and the riparian zone is trampled; without alligators, the edge between the water and land is simplified. Without forests, the water runs unfiltered to the waterways, and there is less deadwood in the channel, reducing stream productivity. Without floodplains and meanders, the water moves more swiftly, and silt carried in the water is more likely to be swept to sea.
>
> The beaver, the prairie dog, the bison, and the alligator have been scarce for so long that we have forgotten how plentiful they once were. Beaver populations are controlled, because they flood fields and forests, while wetlands acreage decrease annually. Prairie dogs are poisoned, because they compete with cattle for grass, while the grasslands grow more barren year by year. Buffalo are generally seen as photogenic anachronisms, and alligators are too reptilian to be very welcome. But all of these animals once shaped the land in ways that improve water quality.
>
> **—A. Outwater (1996, pp. 175–176)**

Is water contamination really a problem—a serious problem? In answer to the first part of the question, we can say it depends upon where your water comes from. As to the second part of the question, we refer you to a book (or the film based upon the book) that describes a case of toxic contamination—one you might be familiar with—*A Civil Action*, written by Jonathan Harr. The book and film portray the legal repercussions connected with polluted water supplies in Woburn, Massachusetts. Two wells became polluted with industrial solvents, in all apparent likelihood causing 24 of the town's children, who lived in neighborhoods supplied by those wells, to contract leukemia and die.

Many who have read the book or have seen the movie may get the mistaken notion that Woburn, a toxic "hot spot," is a rare occurrence. Nothing could be farther from the truth. Toxic "hot spots" abound. Most striking are areas of cancer clusters—a short list includes:

- Woburn, where about two dozen children were stricken with leukemia over 12 years, a rate several times the national average for a community of its size.
- Storrs, Connecticut, where wells polluted by a landfill were suspected of sickening and killing residents in nearby homes.
- Bellingham, Washington, where pesticide-contaminated drinking water was thought to be linked to a sixfold increase in childhood cancers.

As *USA Today* (1999) points out, these are only a few examples of an underlying pathology that threatens many other communities. Meanwhile, cancer is now the primary cause of childhood death.

Water contamination is a problem—a very serious problem. In this chapter, a wide range of water contaminants and the contaminant sources—and their impact on drinking water supplies from both surface water and groundwater sources—are discussed. In addition, the point is made that when it comes to fresh water pollution, Nature is not defenseless in mitigating the situation. The point is made that Nature through its self-purification process in running water systems is able to fight back against pollution—to a point, at least.

SOURCES OF CONTAMINANTS

If we were to list all the sources of contaminants and the contaminants themselves (the ones that can and do foul our water supply systems), along with a brief description of each contaminant, we

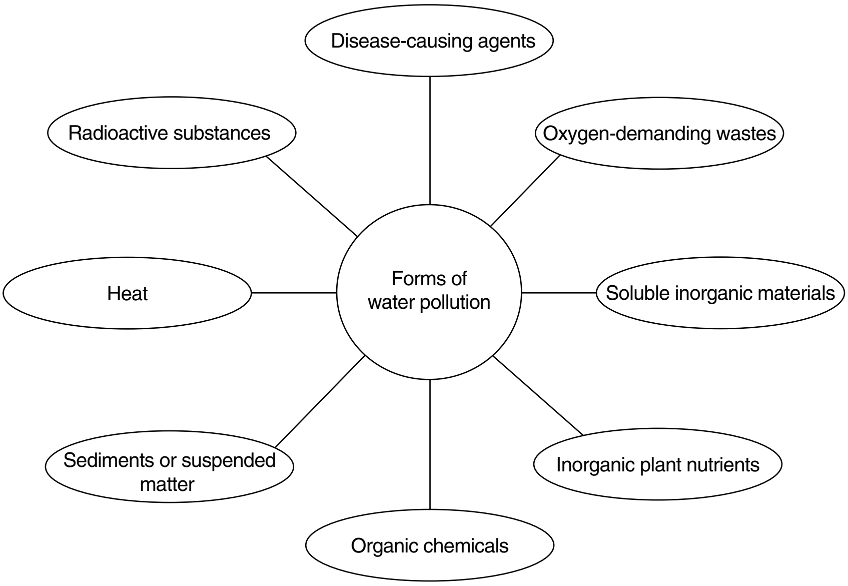


FIGURE 7.1 Biological, chemical, and physical forms of water pollution.

could easily fill a book—probably several volumes. To give you some idea of the magnitude of the problem, Figure 7.1 is provided along with a condensed list of selected sources and contaminants (a "short list").

√ **Important Point:** Keep in mind that when we specify "water pollutants" we are in most cases speaking about pollutants that somehow get into the water (by whatever means) from the interactions of the other two environmental media: air and soil. Probably the best example of this is the acid rain phenomenon—pollutants originally emitted only into the atmosphere land on Earth and affect both soil and water. Consider that 69% of the anthropogenic (human-generated) lead and 73% of the mercury in Lake Superior reach it by atmospheric deposition (Hill, 1997).

1. *Subsurface percolation*—Hydrocarbons, metals, nitrates, phosphates, microorganisms, and cleaning agents (TCE).
2. *Injection wells*—Hydrocarbons, metals, nonmetals, organics, organic and inorganic acids, microorganisms, and radionuclides.
3. *Land application*—Nitrogen, phosphorous, heavy metals, hydrocarbons, microorganisms, and radionuclides.
4. *Landfills*—Organics, inorganics, microorganisms, and radionuclides.
5. *Open dumps*—Organics, inorganics, and microorganisms.
6. *Residential (local) disposal*—Organic chemicals, metals, nonmetal inorganics, inorganic acids, and microorganisms.
7. *Surface impoundments*—Organic chemicals, metals, nonmetal inorganics, inorganic acids, microorganisms, and radionuclides.
8. *Waste tailings*—Arsenic, sulfuric acid, copper, selenium, molybdenum, uranium, thorium, radium, lead, manganese, and vanadium.
9. *Waste piles*—Arsenic, sulfuric acid, copper, selenium, molybdenum, uranium, thorium, radium, lead, manganese, and vanadium.

10. *Materials stockpiles*
    - *Coal pile*—Aluminum, iron, calcium, manganese, sulfur, and traces of arsenic, cadmium, mercury, lead, zinc, uranium, and copper.
    - *Other materials piles*—Metals/nonmetals and microorganisms.
11. *Graveyards*—Metals, nonmetals, and microorganisms.
12. *Animal burial*—Contamination is site-specific—depending on disposal practices, surface and subsurface, hydrology, proximity of the site to water sources, type and amount of disposed material, and cause of death.
13. *Above ground storage tanks*—Organics, metal/nonmetal inorganics, inorganic acids, microorganisms, and radionuclides.
14. *Underground storage tanks*—Organics, metal, inorganic acids, microorganisms, and radionuclides.
15. *Containers*—Organics, metal/nonmetal inorganics, inorganic acids, microorganisms, and radionuclides.
16. *Open burning and detonating sites*—Inorganics, including heavy metals; organics, including TNT.
17. *Radioactive disposal sites*—Radioactive cesium, plutonium, strontium, cobalt, radium, thorium, and uranium.
18. *Pipelines*—Organics, metals, inorganic acids, and microorganisms.
19. *Material transport and transfer operations*—Organics, metals, inorganic acids, microorganisms, and radionuclides.
20. *Irrigation practices*—Fertilizers, pesticides, naturally occurring contamination and sediments.
21. *Pesticide applications*—1200–1400 active ingredients. Contamination already detected: alachlor, aldicarb, atrazine, bromacil, carbofuran, cyanazine, DBCP, DCPA, 1,2-dichloropropane, dyfonate, EDB, metolachlor, metribyzen, oxalyl, siazine, and 1,2,3-trichloropropane. The extent of groundwater contamination cannot be determined with current data.
22. *Animal feeding operations*—Nitrogen, bacteria, viruses, and phosphates.
23. *De-icing salts applications*—Chromate, phosphate, ferric ferocyanide, Na-ferrocyan, and chlorine.
24. *Urban runoff*—Suspended solids and toxic substances, especially heavy metals and hydrocarbons, bacteria, nutrients, and petroleum residues.
25. *Percolation of atmospheric pollutants*—Sulfur and nitrogen compounds, asbestos, and heavy metals.
26. *Mining and mine drainage*
    - *Coal*—Acids, toxic inorganics (heavy metals), and nutrients.
    - *Phosphate*—Radium, uranium, and fluorides.
    - *Metallic ores*—Sulfuric acid, lead, cadmium, arsenic, sulfur, and cyan.
27. *Production wells*
    - *Oil*—1.2 million abandoned production wells.
    - *Irrigation*—Farms.
    - *All*—Potential to contaminate: installation, operation, and plugging techniques.
28. *Construction excavation*—Pesticides, diesel fuel, oil, salt, and variety of others.

√ **Note:** Before discussing specific water pollutants, it is important to examine several terms important to the understanding of water pollution. One of these is *point source*. The USEPA defines a *point source* as “any single identifiable source of pollution from which pollutants are discharged, e.g., a pipe, ditch, ship, or factory smokestack.” For example, the outlet pipes of an industrial facility or a municipal wastewater treatment plant are point sources. In contrast, *nonpoint sources* are widely dispersed sources and are a major cause of stream pollution. An example of a nonpoint source (NPS) of pollution is rainwater carrying topsoil and chemical contaminants into a river or stream. Some of the major sources of nonpoint pollution include water runoff from farming, urban areas, forestry, and construction activities. The word *runoff* signals a NPS that originated on land. Runoff may carry a variety of toxic substances and nutrients, as well as bacteria and viruses with it. NPSs now comprise the largest source of water pollution, contributing approximately 65% of the contamination in quality-impaired streams and lakes.

RADIONUCLIDES

When radioactive elements decay, they emit alpha, beta, or gamma radiations caused by transformation of the nuclei to lower energy states. In drinking water, radioactivity can be from natural or artificial radionuclides (the radioactive metals and minerals that cause contamination). These radioactive substances in water are of two types: radioactive minerals and radioactive gas. The USEPA reports that some 50 million Americans face increased cancer risk because of radioactive contamination of their drinking water.

Because of their occurrence in drinking water and their effects on human health, the natural radionuclides of chief concern are radium-226, radium-228, radon-222, and uranium. The source of some of these naturally occurring radioactive minerals is typically associated with certain regions of the country where mining is active or was active in the past. Mining activities expose rock strata, most of which contains some amount of radioactive ore. Uranium mining, for example, produces runoff. Another source of natural radioactive contamination occurs when underground streams flow through various rockbed and geologic formations containing radioactive materials. Other natural occurring sources where radioactive minerals may enter water supplies are smelters and coal-fired electrical generating plants. Sources of man-made radioactive minerals in water are nuclear power plants, nuclear weapons facilities, radioactive materials disposal sites, and mooring sites for nuclear-powered ships. Hospitals also contribute radioactive pollution when they dump low-level radioactive wastes into sewers. Some of these radioactive wastes eventually find their way into water supply systems.

While radioactive minerals such as uranium and radium in water may present a health hazard in these particular areas, a far more dangerous threat exists in the form of radon. *Radon* is a colorless, odorless gas created by (or as a by-product of) the natural decay of minerals in the soil. Normally present in all water in minute amounts, radon is especially concentrated in water that has passed through rock strata of granite, uranium, or shale.

Radon enters homes from the soil beneath the house, through cracks in the foundation, through crawl spaces and unfinished basements, and in tainted water, and is considered the second leading cause of lung cancer in the United States (about 20,000 cases each year), after cigarette smoking. Contrary to popular belief, radon is not a threat from surface water (lake, river, or aboveground reservoir), because radon dissipates rapidly when water is exposed to air. Even if the water source is groundwater, radon is still not a threat if the water is exposed to air (aerated) or if it is processed through an open tank during treatment. Studies show that where high concentrations of radon occur within the air in a house, most of the radon comes through the foundation and from the water; however, radon in the tap water, showers, baths, and cooking (with hot water) will cause high concentrations of radon in the air.

Note, however, that radon is a threat from groundwater taken directly from an underground source—either a private well or from a public water supply and where treatment of the water does not include exposure to air. Because radon in water evaporates quickly into air, the primary danger is from inhaling it from the air in a house, not from drinking it.

THE CHEMICAL COCKTAIL

Previously, we referred to a glass of water filled to the brim from the household tap. When we hold such a full glass (though we usually do not hold it; instead, we fill the glass and drink the water, and that is that), if we were to inspect the contents, a few possibilities might present themselves. The contents might appear cloudy or colored (making us think that the water is not fit to drink). The contents might look fine, but carry the prevalent odor of chlorine. Most often, when we take the time to look at water drawn from the tap, it simply looks like water and we drink it or use it to cook with, or whatever.

The fact is, typically a glass of treated water is a chemical cocktail (Kay, 1996). While water utilities in communities seek to protect the public health by treating raw water with certain chemicals, what they are in essence doing is providing us a drinking water product that is a mixture of various treatment chemicals and their by-products. For example, the water treatment facility typically adds chlorine to disinfect; chlorine can produce contaminants. Another concoction is formed when ammonia is added to disinfect. Alum and polymers are added to the water to settle out various contaminants. The water distribution system and appurtenances also need to be protected to prevent pipe corrosion or soften water, so the water treatment facility adds caustic soda, ferric chloride, and lime, which in turn work to increase the aluminum, sulfates, and salts in the water. Thus, when we hold that glass of water before us, and we perceive what appears to be a full glass of crystal clear, refreshing water—what we really see is a concoction of many chemicals mixed with water, forming the chemical cocktail.

The most common chemical additives used in water treatment are chlorine, fluorides, and flocculants. Because we have already discussed fluorides, our discussion in the following sections is on the by-products of chlorine and flocculant additives.

BY-PRODUCTS OF CHLORINE

To lessen the potential impact of that water cocktail, the biggest challenge today is to make sure the old standby—chlorine—will not produce as many new contaminants as it destroys. At the present time, weighing the balance of the argument, arguing against chlorine and the chlorination process is difficult. Since 1908, chlorine has been used in the United States to kill off microorganisms that spread cholera, typhoid fever, and other waterborne diseases. However, in the 1970s, scientists discovered that while chlorine does not seem to cause cancer in lab animals, it can—in the water treatment process—create a whole list of by-products that do. The by-products of chlorine—organic hydrocarbons called *trihalomethanes* (usually discussed as total trihalomethanes or TTHMs)—present the biggest health concern.

The USEPA classifies three of these trihalomethanes by-products—chloroform, bromoform, and bromodichloromethane—as probable human carcinogens. The fourth, dibromochloromethane, is classified as a possible human carcinogen.

The USEPA set the first trihalomethane limits in 1979. Most water companies met these standards initially, but the standards were tightened after the 1996 Safe Drinking Water Act (SDWA) Amendments. The USEPA is continuously studying the need to regulate other cancer-causing contaminants, including haloacetic acids (HAAs) also produced by chlorination.

Most people concerned with protecting public health applaud the USEPA's efforts in regulating water additives and disinfection by-products. However, some of those in the water treatment and supply business express concern. A common concern often heard from water utilities having a tough time balancing the use of chlorine without going over the regulated limits revolves around the necessity of meeting regulatory requirements by lowering chlorine amounts to meet by-products standards, and at the same time ensuring that all the pathogenic microorganisms are killed off. Many make the strong argument that while no proven case exists that disinfection by-products cause cancer in humans, many cases—a whole history of cases—show that if we do not chlorinate water, people get sick and sometimes die from waterborne diseases.

Because chlorine and chlorination are now prompting regulatory pressure and compliance with new, demanding regulations, many water treatment facilities are looking for options. Choosing alternative disinfection chemical processes is feeding a growing business enterprise. One alternative that is currently being given widespread consideration in the United States is ozonation, which uses ozone gas to kill microorganisms. Ozonation is Europe's favorite method, and it does not produce trihalomethanes. But the USEPA does not yet recommend wholesale switchover to ozone to replace chlorine or chlorination systems (sodium hypochlorite or calcium hypochlorite vice elemental chlorine). The USEPA points out that ozone also has problems: (1) it does not produce a residual disinfectant in the water distribution system; (2) it is much more expensive; and (3) in salty water, it can produce another carcinogen, bromate.

At the present time, drinking water practitioners (in the real world) are attempting to fine-tune water treatment. It all boils down to a delicate balancing act. Drinking water professionals do not want to cut back disinfection—if anything, they would prefer to strengthen it.

The compound question is: "How do we bring into parity the microbial risks versus the chemical risks? How do you reduce them both to an acceptable level?" The answer?—No one is quite sure how to do this. The problem really revolves around the enigma associated with a "we don't know what we don't know" scenario.

The disinfection by-products problem stems from the fact that most U.S. water systems produce the unwanted by-products when the chlorine reacts with decayed organics such as vegetation and other carbon-containing materials in water. Communities that take drinking water from lakes and rivers have a tougher time keeping the chlorine by-products out of the tap than those that use clean groundwater.

In some communities, when a lot of debris is in the reservoir, the water utility switches to alternate sources—for example, wells. In other facilities, chlorine is combined with ammonia in a disinfection method called *chloramination*. This method is not as potent as pure chlorination, but it stops the production of unwanted trihalomethanes.

In communities where rains wash leaves, trees, and grasses into the local water source (lake or river), hot summer days trigger algae blooms, upping the organic matter that can produce trihalomethanes. Spring runoff in many communities acerbates the problem. With increased runoff comes agricultural waste, pesticides, and quantities of growth falling into the water that must be dealt with.

Nature's conditions in summer diminish some precursors for trihalomethanes—the bromides in salty water.

The irony is that under such conditions nothing unusual is visible in the drinking water. However, cloudy water from silt (dissolved organics from decayed plants) is enough to create trihalomethanes.

With the advent of the new century, most cities will strain out (filter) the organics from their water supplies before chlorinating to prevent the formation of trihalomethanes and HAAs.

In other communities, the move is already on to switch from chlorine to ozone and other disinfectant methods. The National Resources Defense Council states that probably in 15–20 years, most U.S. systems will catch up with Europe and use ozone to kill resistant microbes like *Cryptosporidium*. Note that when this method is employed, the finishing touch is usually accomplished by filtering through granulated activated carbon, which increases the cost slightly (estimated at about $100 or more per year per hookup) that customers must pay.

TOTAL TRIHALOMETHANE

TTHMs (USEPA, 1998) are a by-product of chlorinating water that contains natural organics. A USEPA survey discovered that trihalomethanes are present in virtually all chlorinated water supplies. Many years ago, the USEPA required large towns and cites to reduce TTHM levels in potable water. However, recent changes in national drinking water quality standards now require that water treatment systems of smaller towns begin to reduce TTHM. It is important to note that TTHMs do not pose a high health risk compared to waterborne diseases, but they are among the most important water quality issues to be addressed in the U.S. water supply.

A major challenge for drinking water practitioners is how to balance the risks from microbial pathogens and disinfection by-products. Providing protection from these microbial pathogens while simultaneously ensuring decreasing health risks to the population from disinfection by-products (DBPs) is important. The SDWA Amendments, signed by the president in August 1996, required the USEPA to develop rules to achieve these goals. The new Stage 1 Disinfectant and DBP Rule and Interim Enhanced Surface Water Treatment Rule are the first of a set of rules under the amendments.

PUBLIC HEALTH CONCERNS

Most Americans drink tap water that meets all existing health standards all the time. These new rules will further strengthen existing drinking water standards and thus increase protection for many water systems.

The USEPA's Science Advisory Board concluded in 1990 that exposure to microbial contaminants such as bacteria, viruses, and protozoa (e.g., *Giardia lamblia* and *Cryptosporidium*) was likely the greatest remaining health risk management challenge for drinking water suppliers. Acute health effects from exposure to microbial pathogens is documented, and associated illness can range from mild to moderate cases lasting only a few days, to more severe infections that can last several weeks and that may result in death for those with weakened immune systems.

While disinfectants are effective in controlling many microorganisms, they react with natural organic and inorganic matter in source water and distribution systems to form potential DBPs. Many of these DBPs have been shown to cause cancer and reproductive and developmental effects in laboratory animals. More than 200 million people consume water that has been disinfected. Because of the large population exposed, health risks associated with DBPs, even if small, need to be taken seriously.

EXISTING REGULATIONS

Microbial contaminants—The SWTR, promulgated in 1989, applies to all public water systems using surface water sources or groundwater sources under the direct influence of surface water. It establishes maximum contaminant level goals (MCLGs) for viruses, bacteria, and *G. lamblia*. It also includes treatment technique requirements for filtered and unfiltered systems specifically designed to protect against the adverse health effects of exposure to these microbial pathogens. The total coliform rule, revised in 1989, applies to all public water systems (PWSs) and establishes a maximum contaminant level (MCL) for total coliforms.

Disinfection by-products—In 1979, the USEPA set an interim MCL for total trihalomethanes of 0.10 mg/L as an annual average. This applies to any community water system serving at least 10,000 people that adds a disinfectant to the drinking water during any part of the treatment process.

INFORMATION COLLECTION RULE

To support the M-DBP rulemaking process, the *Information Collection Rule* establishes monitoring and data reporting requirements for large PWSs serving at least 100,000 people. This rule is intended to provide the USEPA with information on the occurrence in drinking water of microbial pathogens and DBPs. The USEPA is collecting engineering data on how PWSs currently control such contaminants as part of the Information Collection Rule.

GROUNDWATER RULE

The USEPA developed a groundwater rule that specifies the appropriate use of disinfection, and equally importantly, addresses other components of groundwater systems to ensure public health protection. More than 158,000 public or community systems serve almost 89 million people through groundwater systems. A total of 99% (157,000) of groundwater systems serve fewer than 10,000 people. However, systems serving more than 10,000 people serve 55%—more than 60 million—of all people who get their drinking water from public groundwater systems.

Filter Backwash Recycling

The 1996 SDWA Amendments require that the USEPA set a standard on recycling filter backwash within the treatment process of public water systems. The regulation applies to all public water systems, regardless of size.

Opportunities for Public Involvement

The USEPA encourages public input into regulation development. Public meetings and opportunities for public comment on M-DBP rules are announced in the Federal Register. The USEPA's Office of Groundwater and Drinking Water also provides this information for the M-DBP rule and other programs in its online *Calendar of Events* (www.epa.gov).

Flocculants

In addition to chlorine and sometimes fluoride, water treatment plants often add several other chemicals, including flocculants, to improve the efficiency of the treatment process—and they all add to the cocktail mix. *Flocculants* are chemical substances added to water to make particles clump together, which improves the effectiveness of filtration. Some of the most common flocculants are polyelectrolytes (polymers)—chemicals with constituents that cause cancer and birth defects and are banned for use by several countries. Although the USEPA classifies them as "probable human carcinogens," it still allows their continued use. Acrylamide and epichlorohydrin are two flocculants used in the United States that are known to be associated with probable cancer risk (Lewis, 1996).

GROUNDWATER CONTAMINATION

Note that groundwater under the direct influence of surface water comes under the same monitoring regulations as does surface water (i.e., all water open to the atmosphere and subject to surface runoff. The legal definition of *groundwater under the direct influence of surface water* is any water beneath the surface of the ground with (1) significant occurrence of insects or microorganisms, algae, or large diameter pathogens such as *G. lamblia* or (2) significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH, which closely correlate to climatological or surface water conditions. Direct influence must be determined for individual sources in accordance with criteria established by the state. The state determines for individual sources in accordance with criteria established by the state, and that determination may be based on site-specific measurements of water quality and documentation of well-construction characteristics and geology with field evaluation.

Generally, most groundwater supplies in the United States are of good quality and produce essential quantities. The full magnitude of groundwater contamination in the United States is, however, not fully documented, and federal, state, and local efforts continue to assess and address the problems (Rail, 1985).

Groundwater supplies about 25% of the fresh water used for all purposes in the United States, including irrigation, industrial uses, and drinking water (about 50% of the U.S. population relies on groundwater for drinking water). John Chilton (1998) points out that the groundwater aquifers beneath or close to Mexico City provide the areas with more than 3.2 billion L/day. As groundwater pumping increases to meet water demand, it can exceed the aquifers' rates of replenishment, and in many urban aquifers, water levels show long-term decline. With excessive extraction comes a variety of other undesirable effects, including:

- Increased pumping costs
- Changes in hydraulic pressure and underground flow directions (in coastal areas, this results in seawater intrusion)
- Saline water drawn up from deeper geological formations
- Poor-quality water from polluted shallow aquifers leaking downward

Severe depletion of groundwater resources is often compounded by a serious deterioration in its quality. Thus, without a doubt, the contamination of a groundwater supply should be a concern of those drinking water practitioners responsible for supplying a community with potable water provided by groundwater.

Despite our strong reliance on groundwater, groundwater has for many years been one of the most neglected and ignored natural resources. Groundwater has been ignored because it is less visible than other environmental resources, for example, rivers or lakes. What the public cannot see or observe, the public doesn't worry about—or even think about. However, recent publicity about events concerning groundwater contamination is making the public more aware of the problem, and the regulators have also taken notice.

Are natural contaminants a threat to human health—harbingers of serious groundwater pollution events? No, not really. The main problem with respect to serious groundwater pollution has been human activities. When we (all of us) improperly dispose of wastes, or spill hazardous substances onto/into the ground, we threaten groundwater, and in turn, the threat passes on to public health.

UNDERGROUND STORAGE TANKS

If we looked at a map of the United States marked with the exact location of every underground storage tank (UST) shown (we wish such a map existed!), with the exception of isolated areas, most of us would be surprised at the large number of tanks buried underground. With so many buried tanks it should come as no surprise that structural failures arising from a wide variety of causes have occurred over the years. Subsequent leaking has become a huge source of contamination that affects the quality of local groundwaters.

√ **Note:** A UST is any tank, including any underground piping connected to the tank that has at least 10% of its volume below ground (USEPA, 1987).

The fact is that leakage of petroleum and its products from USTs occurs more often than we generally realize. This widespread problem has been a major concern and priority in the United States for well over a decade. In 1987, the USEPA promulgated regulations for many of the nation's USTs, and much progress has been made in mitigating this problem to date.

When a UST leak or past leak is discovered, the contaminants released to the soil and thus to groundwater, for the average person, would seem rather straightforward to identify: fuel oil, diesel, and gasoline. However, even though true that these are the most common contaminants released from leaking USTs, others also present problems. For example, in the following section, we discuss one such contaminant, a by-product of gasoline—one that is not well known—to help illustrate the magnitude of leaking USTs.

MTBE

In December 1997, the USEPA issued a drinking water advisory titled *Consumer Acceptability Advice and Health Effects Analysis on Methyl Tertiary-Butyl Ether (MTBE).* The purpose of the advisory was to provide guidance to communities exposed to drinking water contaminated with MTBE.

√ **Note:** A USEPA Advisory is usually initiated to provide information and guidance to individuals or agencies concerned with potential risk from drinking water contaminants for which no national regulations currently exist. Advisories are not mandatory standards for action, and are used only for guidance. They are not legally enforceable, and are subject to revision as new information becomes available. The USEPA's Health Advisory program is recognized in the SDWA Amendments of 1996, which state in section 102(b)(1)(F):

> The Administrator may publish health advisories (which are not regulations) or take other appropriate actions for contaminants not subject to any national primary drinking water regulation.

As its title indicates, this advisory includes consumer acceptability advice as "appropriate" under this statutory provision, as well as a health effects analysis.

What Is MTBE?

MTBE is a volatile, organic chemical. Since the late 1970s, MTBE has been used as an octane enhancer in gasoline. Because it promotes more complete burning of gasoline (thereby reducing carbon monoxide and ozone levels) it is commonly used as a gasoline additive in localities that do not meet the national ambient air quality standards.

In the Clean Air Act of 1990, Congress mandated the use of reformulated gasoline (RFG) in areas of the country with the worst ozone or smog problems. RFG must meet certain technical specifications set forth in the Act, including a specific oxygen content. Ethanol and MTBE are the primary oxygenates used to meet the oxygen content requirement. MTBE is used in about 84% of RFG supplies. Currently, 32 areas in a total of 18 states are participating in the RFG program, and RFG accounts for about 30% of gasoline nationwide.

Studies identify significant air quality and public health benefits that directly result from the use of fuels oxygenated with MTBE, ethanol, or other chemicals. The refiners' 1995/96 fuel data submitted to the USEPA indicate that the national emissions benefits exceeded those required. The 1996 Air Quality Trends Report shows that toxic air pollutants declined significantly between 1994 and 1995. Early analysis indicates this progress may be attributable to the use of RFG. Starting in the year 2000, required emission reductions are substantially greater, at about 27% for volatile organic compounds, 22% for toxic air pollutants, and 7% for nitrogen oxides.

√ **Note:** When gasoline that has been oxygenated with MTBE comes in contact with water, large amounts of MTBE dissolve. At 25°C, the water solubility of MTBE is about 5000 mg/L for a gasoline, that is, 10% MTBE by weight. In contrast, for a nonoxygenated gasoline, the total hydrocarbon solubility in water is typically about 120 mg/L. MTBE sorbs only weakly to soil and aquifer material; therefore, sorption will not significantly retard MTBE's transport by groundwater. In addition, the compound generally resists degradation in groundwater (Squillace et al., 1998).

Why Is MTBE a Drinking Water Concern?

A limited number of instances of significant contamination of drinking water with MTBE have occurred because of leaks from underground and aboveground petroleum storage tank systems and pipelines. Owing to its small molecular size and solubility in water, MTBE moves rapidly into groundwater, faster than do other constituents of gasoline. Public and private wells have been contaminated in this manner. Nonpoint sources (such as recreational watercraft) are most likely to be the cause of small amounts of contamination in a large number of shallow aquifers and surface waters. Air deposition through precipitation of industrial or vehicular emissions may also contribute to surface water contamination. The extent of any potential for build-up in the environment from such deposition is uncertain.

Is MTBE in Drinking Water Harmful?

Based on the limited sampling data currently available, most concentrations at which MTBE has been found in drinking water sources are unlikely to cause adverse health effects. However, the USEPA is continuing to evaluate the available information and is doing additional research to seek more definitive estimates of potential risks to humans from drinking water.

There are not data on the effects on humans of drinking MTBE-contaminated water. In laboratory tests on animals, cancer and noncancer effects occur at high levels of exposure. These tests were conducted by inhalation exposure or by introducing the chemical in oil directly to the stomach. The tests support a concern for potential human hazard. Because the animals were not exposed through drinking water, significant uncertainties exist concerning the degree of risk associated with human exposure to low concentrations typically found in drinking water.

How Can People Be Protected?

MTBE has a very unpleasant taste and odor, and these properties make contaminated drinking water unacceptable to the public. The advisory recommends control levels for taste and odor acceptability that will also protect against potential health effects.

Studies conducted on the concentrations of MTBE in drinking water determined the level at which individuals can detect the odor or taste of the chemical. Humans vary widely in the concentrations they are able to detect. Some who are sensitive can detect very low concentrations. Others do not taste or smell the chemical, even at much higher concentrations. The presence or absence of other natural or water treatment chemicals sometimes masks or reveals the taste or odor effects.

Studies to date have not been extensive enough to completely describe the extent of this variability, or to establish a population response threshold. Nevertheless, we conclude from the available studies that keeping concentrations in the range of 20–40 μg/L of water or below will likely avert unpleasant taste and odor effects, recognizing that some people may detect the chemical below this.

Concentrations in the range of 20–40 μg/L are about 20,000 to 100,000 (or more) times lower than the range of exposure levels in which cancer or noncancer effects were observed in rodent tests. This margin of exposure lies within the range of margins of exposure typically provided to protect against cancer effects by the National Primary Drinking Water Standards under the Federal Safe Drinking Water Act—a margin greater than such standards typically provided to protect against noncancer effects. Protection of the water source from unpleasant taste and odor as recommended also safeguards consumers from potential health effects.

The USEPA also notes that occurrences of groundwater contamination observed at or above this 20–40 μg/L taste and odor threshold—that is, contamination at levels that may create consumer acceptability problems for water supplies—have, to date, resulted from leaks in petroleum storage tanks or pipelines, not from other sources.

Recommendations for State or Public Water Suppliers

Public water systems that conduct routine monitoring for volatile organic chemicals can test for MTBE at little additional cost, and some states are already moving in this direction.

Public water systems detecting MTBE in their source water at problematic concentrations can remove MTBE from water using the same conventional treatment techniques that are used to clean up other contaminants originating from gasoline releases—for example, air stripping and granular activated carbon (GAC). However, because MTBE is more soluble in water and more resistant to biodegradation than other chemical constituents in gasoline, air stripping and GAC treatment requires additional optimization, and must often be used together to effectively remove MTBE from water. The costs of removing MTBE are higher than when treating for gasoline releases that do not contain MTBE. Oxidation of MTBE using UV/peroxide/ozone treatment may also be feasible, but typically has higher capital and operating costs than air stripping and GAC.

The bottom line: Because MTBE has been found in sources of drinking water many states are phasing out the sale of gasoline with MTBE.

√ **Note:** Of the 60 volatile organic compounds (VOCs) analyzed in samples of shallow ambient groundwater collected from eight urban areas during 1993–1994 as part of the U.S. Geological Survey's Nation Water Quality Assessment program, MTBE was the second most frequently detected compound (after trichloromethane [chloroform]) (Squillace et al., 1998).

INDUSTRIAL WASTES

Since industrial waste represents a significant source of groundwater contamination, water practitioners and others expend an increasing amount of time in abating or mitigating pollution events that damage groundwater supplies.

Groundwater contamination from industrial wastes usually begins with the practice of disposing of industrial chemical wastes in surface impoundments, for example, unlined landfills or lagoons. Fortunately, these practices, for the most part, are part of our past. Today, we know better. For example, we now know that what is most expedient or least expensive does not work for industrial waste disposal practices. We have found through actual experience that in the long run the opposite has been proven true—for society as a whole (with respect to health hazards and the costs of cleanup activities) to ensure clean or unpolluted groundwater supplies is very expensive—and utterly necessary.

SEPTIC TANKS

Septage from septic tanks is a biodegradable waste capable of affecting the environment through water and air pollution. The potential environmental problems associated with the use of septic tanks are magnified when you consider that subsurface sewage disposal systems (septic tanks) are used by almost one-third of the U.S. population.

Briefly, a septic tank and leaching field system traps and stores solids while the liquid effluent from the tank flows into a leaching or absorption field, where it slowly seeps into the soil and degrades naturally.

The problem with subsurface sewage disposal systems, such as septic tanks, is that most of the billions of gallons of sewage that enter the ground each year are not properly treated. Because of faulty construction or lack of maintenance, not all of these systems work properly.

Experience has shown that septic disposal systems are frequently sources of fecal bacteria and virus contamination of water supplies taken from private wells. Many septic tank owners dispose of detergents, nitrates, chlorides and solvents in their septic systems, or use solvents to treat their sewage waste. A septic tank cleaning fluid that is commonly used contains organic solvents (trichlorethylene or TCE)—potential human carcinogens that in turn pollute the groundwater in areas served by septic systems.

LANDFILLS

Humans have been disposing of waste by burying it in the ground since time immemorial. In the past, this practice was largely uncontrolled, and the disposal sites (i.e., garbage dumps) were places where municipal solid wastes were simply dumped on and into the ground without much thought or concern. Even in this modern age, landfills have been used to dispose of trash and waste products at controlled locations that are then sealed and buried under earth. Now such practices are increasingly seen as a less-than-satisfactory disposal method, because of the long-term environmental impact of waste materials in the ground and groundwater.

Unfortunately, many of the older (and even some of the newer) sites were located in low-lying areas with high groundwater tables. *Leachate* (see page of liquid through the waste), high in BOD, chloride, organics, heavy metals, nitrate, and other contaminants, has little difficulty reaching the groundwater in such disposal sites. In the United States, literally thousands of inactive or abandoned dumps like this exist.

AGRICULTURE

Fertilizers and pesticides are the two most significant groundwater contaminants that result from agricultural activities. The impact of agricultural practices wherein fertilizers and pesticides are normally used is dependent upon local soil conditions. If, for example, the soil is sandy, nitrates from fertilizers are easily carried through the porous soil into the groundwater, contaminating private wells.

Pesticide contamination of groundwater is a subject of national importance because groundwater is used for drinking water by about 50% of the nation's population. This especially concerns people living in the agricultural areas where pesticides are most often used, as about 95% of that population relies upon groundwater for drinking water. Before the mid-1970s, the common thought was that soil acted as a protective filter, one that stopped pesticides from reaching groundwater. Studies have now shown that this is not the case. Pesticides can reach water-bearing aquifers below ground from applications onto crop fields, seepage of contaminated surface water, accidental spills and leaks, improper disposal, and even through injection of waste material into wells.

Pesticides are mostly modern chemicals. Many hundreds of these compounds are used, and extensive tests and studies of their effect on humans have not been completed. That leads us to ask, "Just how concerned we should be about their presence in our drinking water?" Certainly, treating pesticides as potentially dangerous, and thus handling them with care would be wise. We can say they pose a potential danger if they are consumed in large quantities, but as any experienced scientist knows, you cannot draw factual conclusions unless scientific tests have been done. Some pesticides have had a designated MCL in drinking water set by the USEPA, but many have not. Another serious point to consider is the potential effect of combining more than one pesticide in drinking water, which might be different than the effects of each individual pesticide alone. This is another situation where we don't have sufficient scientific data to draw reliable conclusions—in other words, again, we don't know what we don't know.

SALTWATER INTRUSION

In many coastal cites and towns as well as in island locations, the intrusion of salty seawater presents a serious water-quality problem. Because fresh water is lighter than saltwater (the specific gravity of seawater is about 1.025), it will usually float above a layer of saltwater. When an aquifer in a coastal area is pumped, the original equilibrium is disturbed and saltwater replaces the fresh water (Viessman and Hammer, 1998). The problem is compounded by increasing population, urbanization, and industrialization, which increase use of groundwater supplies. In such areas, while groundwater is heavily drawn upon, the quantity of natural groundwater recharge is decreased because of the construction of roads, tarmac, and parking lots, which prevent rainwater from infiltrating, decreasing the groundwater table elevation.

In coastal areas, the natural interface between the fresh groundwater flowing from upland areas and the saline water from the sea is constantly under attack by human activities. Since seawater is approximately 2.5 times more dense than freshwater, a high pressure head of seawater occurs (in relation to freshwater), which results in a significant rise in the seawater boundary. Potable water wells close to this rise in sea level may have to be abandoned because of saltwater intrusion.

OTHER SOURCES OF GROUNDWATER CONTAMINATION

To this point, we have discussed only a few of the many sources of groundwater contamination. For example, we have not discussed mining and petroleum activities that lead to contamination of groundwater or contamination caused by activities in urban areas. Both of these are important sources. Urban activities (including spreading salt on roads to keep them ice free during winter) eventually contribute to contamination of groundwater supplies. Underground injection wells used to dispose of hazardous materials can lead to groundwater contamination. As we have discussed, USTs are also significant contributors to groundwater pollution.

Other sources of groundwater contamination include these items:

- Waste tailings
- Residential disposal
- Urban runoff
- Hog wastes
- Biosolids
- Land-applied wastewater
- Graveyards
- Deicing salts
- Surface impoundments
- Waste piles
- Animal feeding operations
- Natural leaching
- Animal burial
- Mine drainage
- Pipelines
- Open dumps
- Open burning
- Atmospheric pollutants

Raw sewage is not listed, because for the most part, raw sewage is no longer routinely dumped into our nation's wells or into our soil. Sewage treatment plants effectively treat wastewater so that it can be safely discharged to local water bodies. In fact, the amount of pollution being discharged from these plants has been cut by more than one third during the past 20 years, even as the number of people served has doubled.

Yet in some areas, raw sewage spills still occur, sometimes because an underground sewer line is blocked, broken, or too small, or because periods of heavy rainfall overload the capacity of the sewer line or sewage treatment plant so that overflows into city streets or streams occur. Some of this sewage finds its way to groundwater supplies.

The best way to prevent groundwater pollution is to stop it from occurring in the first place. Unfortunately, a perception held by many is that natural purification of chemically contaminated ground can take place on its own—without the aid of human intervention. To a degree this is true—however, natural purification functions on its own time, not on human time. Natural purification could take decades and perhaps centuries. The alternative? Remediation. But remediation and mitigation do not come cheap. When groundwater is contaminated, the cleanup efforts are sometimes much too expensive to be practical.

The USEPA has established the groundwater guardian program. The program is a voluntary way to improve drinking water safety. Established and managed by a nonprofit organization in the Midwest and strongly promoted by the USEPA, this program focuses on communities that rely on groundwater for their drinking water. It provides special recognition and technical assistance to help communities protect their groundwater from contamination. Since their inception in 1994, groundwater guardian programs have been established in nearly 100 communities in 31 states (USEPA, 1996).

SELF-PURIFICATION OF STREAMS

Hercules, that great mythical giant and arguably the globe's first environmental engineer, pointed out that the solution to stream pollution is dilution—that is, dilution is the solution. In reality, today's humans depend on various human-made water treatment processes to restore water to potable and palatable condition. However, it should be pointed out that Nature, as Hercules pointed out, is not defenseless in its fight against water pollution. For example, when a river or stream is contaminated, natural processes (including dilution) immediately kick in to restore the water body and its contents back to its natural state. If the level of contamination is not excessive, the stream or river can restore itself to normal conditions in a relatively short period. In this section, Nature's ability to purify and restore typical river systems to normal conditions is discussed.

In terms of practical usefulness the waste assimilation capacity of streams as a water resource has its basis in the complex phenomenon termed stream self-purification. This is a dynamic phenomenon reflecting hydrologic and biologic variations, and the interrelations are not yet fully understood in precise terms. However, this does not preclude applying what is known. Sufficient knowledge is available to permit quantitative definition of resultant stream conditions under expected ranges of variation to serve as practical guides in decisions dealing with water resource use, development, and management (Velz, 1970).

BALANCING THE "AQUARIUM"

An outdoor excursion to the local stream can be a relaxing and enjoyable undertaking. In contrast, when you arrive at the local stream, spread your blanket on the stream bank, and then look out upon the stream's flowing mass and discover a parade of waste and discarded rubble bobbing along the stream's course and cluttering the adjacent shoreline and downstream areas, any feeling of relaxation or enjoyment is quickly extinguished. Further, the sickening sensation the observer feels is not lessened, but worsens as he scrutinizes the putrid flow more closely. He recognizes the rainbow-colored shimmer of an oil slick, interrupted here and there by dead fish and floating refuse, and the slimy fungal growth that prevails. At the same time, the observer's sense of smell is alerted to the noxious conditions. Along with the fouled water and the stench of rot-filled air, the observer notices the ultimate insult and tragedy: The signs warn, "DANGER—NO SWIMMING or FISHING." The observer soon realizes that the stream before him is not a stream at all; it is little more than an unsightly drainage ditch. The observer has discovered what ecologists have known and warned about for years, that is, contrary to popular belief, rivers and streams do not have an infinite capacity for pollution.

Before the early 1970s, disgusting occurrences such as the one just described were common along the rivers and streams near main metropolitan areas throughout most of the United States. Many aquatic habitats were fouled during the past because of industrialization. However, our streams and rivers were not always in such deplorable condition.

Before the Industrial Revolution of the 1800s, metropolitan areas were small and sparsely populated. Thus, river and stream systems in or next to early communities received insignificant quantities of discarded waste. Early on, these river and stream systems were able to compensate for the small amount of wastes they received; when wounded (polluted), Nature has a way of fighting back. In the case of rivers and streams, Nature provides flowing waters with the ability to restore themselves through a self-purification process. It was only when humans gathered in great numbers to form great cities that the stream systems were not always able to recover from having received great quantities of refuse and other wastes.

What exactly is it that man does to rivers and streams? As stated earlier, Halsam points out that man's actions are determined by his expediency. In addition, what most people do not realize is that we have the same amount of water as we did millions of years ago, and through the water cycle, we continually reuse that same water—water that was used by the ancient Romans and Greeks is the same water we are using today. Increased demand has put enormous stress on our water supply. Man is the cause of this stress. Thus, what man does to rivers and streams is to upset the delicate balance between pollution and the purification process. That is, we tend to unbalance the aquarium.

As mentioned, with the advent of industrialization, local rivers and streams became deplorable cesspools that worsened with time. During the Industrial Revolution, the removal of horse manure and garbage from city streets became a pressing concern. For example, Moran et al. (1986) point out that "none too frequently, garbage collectors cleaned the streets and dumped the refuse into the nearest river." Halsam (1990) reports that as late as 1887, river keepers gained were employed full time to remove a constant flow of dead animals from a river in London. Moreover, the prevailing attitude of that day was "I don't want it anymore, throw it into the river."

As pointed out, as of the early 1970s any threat to the quality of water destined for use for drinking and recreation has quickly angered those affected. Fortunately, since the 1970s we have moved to correct the stream pollution problem. Through scientific study and incorporation of wastewater treatment technology, we have started to restore streams to their natural condition.

Fortunately, we are aided in this effort to restore a stream's natural water quality by the stream itself through the phenomenon of self-purification.

A balance of biological organisms is normal for all streams. Clean, healthy streams have certain characteristics in common. For example, as mentioned, one property of streams is their ability to dispose of small amounts of pollution. However, if streams receive unusually large amounts of waste, the stream life will change and attempt to stabilize such pollutants; that is, the biota will attempt to balance the aquarium. However, if stream biota are not capable of self-purifying, then the stream may become a lifeless body.

√ **Important Point:** The self-purification process discussed here relates to the purification of organic matter only.

SOURCES OF STREAM POLLUTION

Sources of stream pollution are normally classified as point or nonpoint sources. A point source is a source that discharges effluents, such as wastewater from sewage treatment and industrial plants. Simply put, a point source is usually easily identified as "end of the pipe" pollution; that is, it emanates from a concentrated source or sources. In addition to organic pollution received from the effluents of sewage treatment plants, other sources of organic pollution include runoffs and dissolution of minerals throughout an area that are not from one or more concentrated sources.

Nonconcentrated sources are known as nonpoint sources (see Figure 7.2). NPS pollution, unlike pollution from industrial and sewage treatment plants, comes from many diffuse sources. NPS pollution is caused by rainfall or snowmelt moving over and through the ground. As the runoff moves, it picks up and carries away natural and man-made pollutants, finally depositing them into streams, lakes, wetlands, rivers, coastal waters, and even our underground sources of drinking water. These pollutants include:

- Excess fertilizers, herbicides, and insecticides from agricultural lands and residential areas
- Oil, grease, and toxic chemicals from urban runoff and energy production
- Sediment from improperly managed construction sites, crop and forest lands, and eroding streambanks
- Salt from irrigation practices and acid drainage from abandoned mines
- Bacteria and nutrients from livestock, pet wastes, and faulty septic systems

Atmospheric deposition and hydromodification are also sources of NPS pollution (USEPA, 1994).

As mentioned, specific examples of nonpoint sources include runoff from agricultural fields and also cleared forest areas, construction sites, and roadways. Of particular interest to environmentalists in recent years has been agricultural effluents. A case in point, for example, is farm silage effluent, which has been estimated to be more than 200 times as potent (in terms of BOD) as treated sewage (USEPA, 1994).

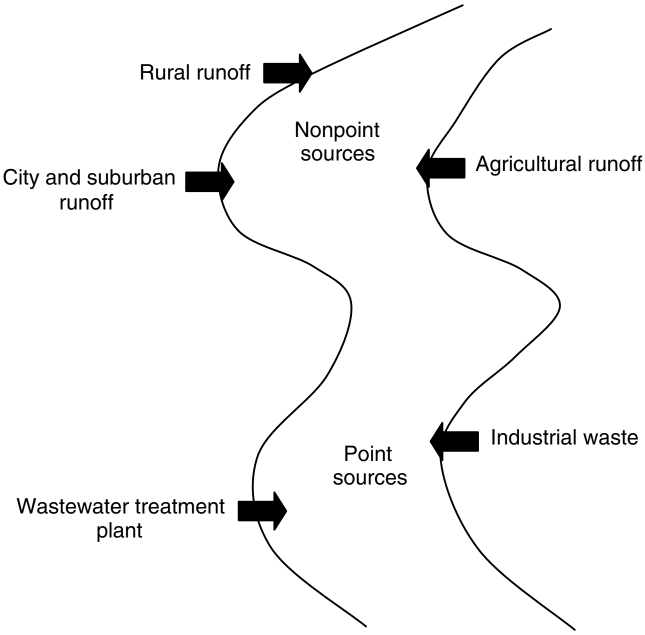


FIGURE 7.2 Point and nonpoint sources of pollution.

Nutrients are organic and inorganic substances that provide food for microorganisms such as bacteria, fungi, and algae. Nutrients are supplemented by the discharge of sewage. The bacteria, fungi, and algae are consumed by the higher trophic levels in the community. Each stream, due to a limited amount of dissolved oxygen (DO), has a limited capacity for aerobic decomposition of organic matter without becoming anaerobic. If the organic load received is above that capacity, the stream becomes unfit for normal aquatic life and it is not able to support organisms sensitive to oxygen depletion (Mason, 1991).

Effluent from a sewage treatment plant is most commonly disposed of in a nearby waterway. At the point of entry of the discharge, there is a sharp decline in the concentration of DO in the stream. This phenomenon is known as the oxygen sag. Unfortunately (for the organisms that normally occupy a clean, healthy stream), when the DO is decreased, there is a concurrent massive increase in BOD as microorganisms utilize the DO as they break down the organic matter. When the organic matter is depleted, the microbial population and BOD decline, while the DO concentration increases, assisted by stream flow (in the form of turbulence) and by the photosynthesis of aquatic plants. This self-purification process is very efficient, and the stream will suffer no permanent damage as long as the quantity of waste is not too high. Obviously, an understanding of this self-purification process is important to prevent overloading the stream ecosystem.

As urban and industrial centers continue to grow, waste disposal problems also grow. Because wastes have increased in volume and are much more concentrated than earlier, natural waterways must have help in the purification process. This help is provided by wastewater treatment plants. A wastewater treatment plant functions to reduce the organic loading that raw sewage would impose on discharge into streams. Wastewater treatment plants utilize three stages of treatment: primary, secondary, and tertiary treatment. In breaking down the wastes, a secondary wastewater treatment plant uses the same type of self-purification process found in any stream ecosystem. Small bacteria and protozoans (one-celled organisms) begin breaking down the organic material. Aquatic insects and rotifers are then able to continue the purification process. Eventually, the stream will recover and show little or no effects of the sewage discharge. Again, this phenomenon is known as natural stream purification (Spellman and Whiting, 1999).

REFERENCES

Chilton, J., 1988. *Dry or Drowning*? London: Banson.

Halsam, S.M., 1990. *River Pollution: An Ecological Perspective*. New York: Belhaven Press.

Hill, M.K., 1997. *Understanding Environmental Pollution*. Cambridge, UK: Cambridge University Press.

Kay, J., 1996. Chemicals Used to Cleanse Water Can Also Cause Problems. *San Francisco Examiner*, October 3.

Lewis, S.A., 1996. *The Sierra Club Guide to Safe Drinking Water.* San Francisco: The Sierra Book Club.

Mason, C.F., 1990. Biological Aspects of Freshwater Pollution. In *Pollution: Causes, Effects, and Control*, Harrison, R.M. (ed.). Cambridge, UK: The Royal Society of Chemistry.

Outwater, A., 1996. *Water: A Natural History*. New York: Basic Books.

Rail, C.D., 1985. Groundwater Monitoring Within an Aquifer—A Protocol. *J. Environ. Health*, 48(3): 128–132.

Spellman, F.R., and Whiting, N.E., 1999. *Water Pollution Control Technology*. Rockville, MD: Government Institutes.

Squillace, P.J., Pankow, J.F., Korte, N.E., and Zogorski, J.S., 1998. Environmental Behavior and Fate of Methyl Tertiary-Butyl Ether. In *Water Online*, www.wateronline.com, November 4.

USA Today, 1999. Pollution is Top Environmental Concern. August 29.

USEPA, 1987. *Proposed Regulations for Underground Storage Tanks: What's in the Pipeline?* Washington, DC: Office of Underground Storage Tanks.

USEPA, 1994. *What Is Nonpoint Source Pollution?* Washington, DC: United States Environmental Protection Agency, EPA-F-94-005.

USEPA, 1996. *Targeting High Priority Problems*. epamail.epa.gov.

USEPA, 1998. *Drinking Water Priority Rulemaking: Microbial and Disinfection By-Products Rules.* Washington, DC: United States Environmental Protection Agency, EPA 815-F-95-0014.

Velz, F.J., 1970. *Applied Stream Sanitation*. New York: Wiley-Interscience.

Viessman, W., Jr. and Hammer, M.J., 1998. *Water Supply and Pollution Control*, 6th ed. Menlo Park, CA: Addison-Wesley.

FURTHER READING

Smith, R.L., 1974. *Ecology and Field Biology*. New York: Harper & Row.

Running Water. White Oak Canyon Trail. Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

8 Environmental Biomonitoring, Sampling, and Testing

> During another visit to the New England Medical Center, three months after Robbie's first complaints of bone pain, doctors noted that his spleen was enlarged and that he had a decreased white-blood-cell count with a high percentage of immature cells—blasts—in the peripheral blood. A bone marrow aspiration was performed. The bone marrow confirmed what the doctors had begun to suspect: Robbie had acute lymphatic leukemia.
>
> **—J. Harr (1995)**

In January, we take our nets to a no-name stream in the foothills of the Blue Ridge Mountains of Virginia to do a special kind of benthic macroinvertebrate monitoring—looking for "winter stoneflies." Winter stoneflies have an unusual life cycle. Soon after hatching in early spring, the larvae bury themselves in the streambed. They spend the summer lying dormant in the mud, thereby avoiding problems like overheated streams, low oxygen concentrations, fluctuating flows, and heavy predation. In late November, they emerge, grow quickly for a couple of months, and then lay their eggs in January.

January monitoring of winter stoneflies helps in interpreting the results of spring and fall macroinvertebrate surveys. In spring and fall, a thorough benthic survey is conducted, based on Protocol II of the USEPA's Rapid Bioassessment Protocols for Use in Streams and Rivers. Some sites on various rural streams have poor diversity and sensitive families. Is the lack of macroinvertebrate diversity because of specific warm-weather conditions, high water temperature, low oxygen, or fluctuating flows, or is some toxic contamination present? In the January screening, if winter stoneflies are plentiful, seasonal conditions were probably to blame for the earlier results; if winter stoneflies are absent, the site probably suffers from toxic contamination (based on our rural location, probably emanating from nonpoint sources) that is present year-round.

Although different genera of winter stoneflies are found in our region (southwestern Virginia), *Allocapnia* is sought because it is present even in the smallest streams (Spellman and Drinan, 2001).

√ **Note:** Much of the information presented in this chapter is taken from Spellman (2003).

WHAT IS BIOMONITORING?

The life in and physical characteristics of a stream ecosystem provide insight into the historical and current status of its quality. The assessment of a water body ecosystem based on organisms living in it is called *biomonitoring.* The assessment of the system based on its physical characteristics is called a *habitat assessment.* Biomonitoring and habitat assessments are two tools that stream ecologists use to assess the water quality of a stream.

Biological monitoring, as mentioned, involves the use of organisms to assess environmental condition. Biological observation is more representative as it reveals cumulative effects as opposed to chemical observation, which is representative only at the actual time of sampling. The presence of benthic macroinvertebrates (bottom-dwelling fauna) is monitored; as mentioned, these are the larger-than-microscopic organisms such as aquatic insects, insect larvae, and crustaceans, which are generally ubiquitous in freshwater and live in the bottom portions of a waterway for part of their life cycle. They are ideal for use in biomonitoring because besides being ubiquitous they are also relatively sedentary and long-lived. The overall community is holistically reflective of conditions in its environment. They provide a cross-section of the situation as some species are extremely sensitive to pollution while others are more tolerant. However, like toxicity testing, biomonitoring does not tell you why animals are present or absent. As mentioned, benthic macroinvertebrates are excellent indicators for several reasons:

1. Biological communities reflect overall ecological integrity (i.e., chemical, physical, and biological integrity). Therefore, biosurvey results directly assess the status of a water body relative to the primary goal of the Clean Water Act (CWA).
2. Biological communities integrate the effects of different stressors and thus provide a broad measure of their aggregate impact.
3. Because they are ubiquitous, communities integrate the stressors over time and provide an ecological measure of fluctuating environmental conditions.
4. Routine monitoring of biological communities can be relatively inexpensive because they are easy to collect and identify.
5. The status of biological comminutes is of direct interest to the public as a measure of a particular environment.
6. Where criteria for specific ambient impacts do not exist (e.g., nonpoint-sources that degrade habitats), biological communities may be the only practical means of evaluation.
7. They can be used to assess nonchemical impacts to the aquatic habitat, such as by thermal pollution, excessive sediment loading (siltation), or eutrophication.

Benthic macroinvertebrates act as continuous monitors of the water they live in. Unlike chemical monitoring, which provides information about water quality at the time of measurement (a snapshot), biological monitoring can provide information about past and episodic pollution (a videotape). This concept is analogous to miners who took canaries into deep mines with them to test for air quality. If the canary died, the miners knew the air was bad and they had to leave the mine. Biomonitoring a water body ecosystem uses the same theoretical approach. Aquatic macroinvertebrates are subject to pollutants in the water body. Consequently, the health of the organisms reflects the quality of the water they live in. If the pollution levels reach a critical concentration, certain organisms will migrate away, fail to reproduce, or die, eventually leading to the disappearance of those species at the polluted site. Normally, these organisms will return if conditions improve in the system (Bly and Smith, 1994).

Biomonitoring (and the related term, bioassessment) surveys are conducted before and after an anticipated impact to determine the effect of the activity on the water body habitat. Moreover, surveys are performed periodically to monitor water body habitats and watch for unanticipated impacts. Finally, biomonitoring surveys are designed to reference conditions or to set biocriteria (serve as monitoring thresholds to signal future impacts, regulatory actions, etc.) for determining that an impact has occurred (Camann, 1996).

Biological monitoring cannot replace chemical monitoring, toxicity testing, and other standard environmental measurements. Each of these tools provides the analyst with specific information available only through its respective methodology.

√ **Note:** The primary justification for bioassessment and monitoring is that degradation of water body habitats affects the biota using those habitats, and, therefore, the living organisms themselves provide the most direct means of assessing real environmental impacts.

BIOTIC INDEX (STREAMS)

Certain common aquatic organisms, by indicating the extent of oxygenation of a stream, may be regarded as indicators of the intensity of pollution from organic waste. The responses of aquatic organisms in water bodies to large quantities of organic wastes are well documented. They occur in a predictable cyclical manner. For example, upstream from the discharge point, a stream can support a wide variety of algae, fish, and other organisms, but in the section of the water body where oxygen levels are low (below 5 ppm), only a few types of worms survive. As stream flow courses downstream, oxygen levels recover, and those species that can tolerate low rates of oxygen (such as gar, catfish, and carp) begin to appear. In a stream, eventually, at some further point downstream, a clean water zone reestablishes itself, and a more diverse and desirable community of organisms returns.

During this characteristic pattern of alternating levels of dissolved oxygen (DO) (in response to the dumping of large amounts of biodegradable organic material), a stream, as stated above, goes through a cycle called an *oxygen sag curve*. Its state can be determined using the biotic index as an indicator of oxygen content.

The biotic index is a systematic survey of macroinvertebrates organisms. Because the diversity of species in a stream is often a good indicator of the presence of pollution, the biotic index can be used to correlate with stream quality. Observation of types of species present or missing is used as an indicator of stream pollution. The biotic index, used in the determination of the types, species, and numbers of biological organisms present in a stream, is commonly used as an auxiliary to BOD determination in determining stream pollution.

The biotic index is based on two principles:

1. A large dumping of organic waste into a stream tends to restrict the variety of organisms at a certain point in the stream.
2. As the degree of pollution in a stream increases, key organisms tend to disappear in a predictable order. The disappearance of particular organisms tends to indicate the water quality of the stream.

There are several different forms of the biotic index. In Great Britain, for example, the Trent Biotic Index (TBI), the Chandler score, the Biological Monitoring Working Party (BMWP) score, and the Lincoln Quality Index (LQI) are widely used. Most of the forms use a biotic index that ranges from 0 to 10. The most polluted stream, which, therefore, contains the smallest variety of organisms, is at the lowest end of the scale (0); the clean streams are at the highest end (10). A stream with a biotic index of greater than 5 will support game fish, whereas a stream with a biotic index of less than 4 will not.

As mentioned, because they are easy to sample, macroinvertebrates have predominated in biological monitoring. In addition, macroinvertebrates can be easily identified using identification keys that are portable and easily used in field settings. Present knowledge of macroinvertebrate tolerances and response to stream pollution is well documented. In the United States, for example, the Environmental Protection Agency (EPA) required states to incorporate a narrative biological criteria into its water quality standards by 1993. The National Park Service (NPS) has collected macroinvertebrate samples from American streams since 1984. Through its sampling effort, the NPS has been able to derive quantitative biological standards (Huff, 1993).

Macroinvertebrates are a diverse group. They demonstrate tolerances that vary between species. Thus, discrete differences tend to show up, containing both tolerant and sensitive indicators.

The biotic index provides a valuable measure of pollution. This is especially the case for species that are very sensitive to lack of oxygen. An example of an organism that is commonly used in biological monitoring is the stonefly. Stonefly larvae live underwater and survive best in cool, well-aerated, unpolluted waters with clean gravel bottoms. When stream water quality deteriorates due to organic pollution, these larvae cannot survive. The degradation of stonefly larvae has an exponential effect upon other insects and fish that feed off the larvae; when the larvae disappears, so in turn do many insects and fish (O'Toole, 1986).

Table 8.1 shows a modified version of the BMWP biotic index. Considering that the BMWP biotic index indicates ideal stream conditions, it takes into account the sensitivities of different macroinvertebrate species, which are represented by diverse populations and are excellent indicators of

TABLE 8.1
BMWP Score System (modified for illustrative purposes)

Families	Common-Name Examples	Score
Heptageniidae	Mayflies	10
Leuctridae	Stoneflies	
Aeshnidae	Dragonflies	8
Polycentropidae	Caddisflies	7
Hydrometridae	Water Strider	
Gyrinidae	Whirligig beetle	5
Chironomidae	Mosquitoes	2
Oligochaeta	Worms	1

pollution. These aquatic macroinvertebrates are organisms that are large enough to be seen by the unaided eye. Moreover, most aquatic macroinvertebrates species live for at least a year, and they are sensitive to stream water quality on both short- and long-term bases. For example, mayflies, stoneflies, and caddisflies are aquatic macroinvertebrates that are considered clean-water organisms; they are generally the first to disappear from a stream if water quality declines and are, therefore, given a high score. On the other hand, tubificid worms (which are tolerant to pollution) are given a low score.

In Table 8.1, a score from 1 to 10 is given for each family present. A site score is calculated by adding the individual family scores. The site score or total score is then divided by the number of families recorded to derive the Average Score Per Taxon (ASPT). High ASPT scores are the result of taxa such as stoneflies, mayflies, and caddisflies being present in the stream. A low ASPT score is obtained from streams that are heavily polluted and dominated by tubificid worms and other pollution-tolerant organisms.

From Table 8.1, it can be seen that those organisms having high scores, especially mayflies and stoneflies, are the most sensitive, and others, such as dragonflies and caddisflies, are very sensitive to any pollution (deoxygenation) of their aquatic environment.

BENTHIC MACROINVERTEBRATE BIOTIC INDEX

The Benthic Macroinvertebrate Biotic Index employs the use of certain benthic macroinvertebrates to determine (to gauge) the water quality (relative health) of a water body (stream or river).

In this discussion, benthic macroinvertebrates are classified into three groups based on their sensitivity to pollution. The number of taxa in each of these groups are tallied and assigned a score. The scores are then summed to yield a total score that can be used as an estimate of the quality of the water body life.

Metrics within the Benthic Macroinvertebrates

A sample index of macroinvertebrates and sensitivity to pollution is listed in Table 8.2.

In summary, it can be said that unpolluted streams normally support a wide variety of macroinvertebrates and other aquatic organisms with relatively few of any one kind. Any significant change in the normal population usually indicates pollution.

BIOLOGICAL SAMPLING (STREAMS)

When planning a biological sampling outing, it is important to determine the precise objectives. One important consideration is to determine whether sampling will be accomplished at a single point or at isolated points. Additionally, the frequency of sampling must be determined. That is,

TABLE 8.2
Sample Index of Macroinvertebrates

Group One (Sensitive to Pollution)	Group Two (Somewhat Sensitive to Pollution)	Group Three (Tolerant of Pollution)
Stonefly larva	Alderfly larva	Aquatic worm
Caddisfly larva	Damselfly larva	Midgefly larva
Water penny larva	Cranefly larva	Blackfly larva
Riffle beetle (adult)	Beetle (adult)	Leech
Mayfly larva	Dragonfly larva	Snails
Gilled snail	Sowbugs	

will sampling be accomplished at hourly, daily, weekly, monthly, or even longer intervals? Whatever sampling frequency of sampling is chosen, the entire process will probably continue over a protracted period (i.e., preparing for biological sampling in the field might take several months from the initial planning stages to the time when actual sampling occurs). An experienced freshwater ecologist should be centrally involved in all aspects of planning.

The USEPA (2000a) points out that the following issues should be considered in planning the sampling program:

1. Availability of reference conditions for the chosen area
2. Appropriate dates to sample in each season
3. Appropriate sampling gear
4. Availability of laboratory facilities
5. Sample storage
6. Data management
7. Appropriate taxonomic keys, metrics, or measurement for macroinvertebrate analysis
8. Habitat assessment consistency
9. A USGS topographical map
10. Familiarity with safety procedures

Once the initial objectives (issues) have been determined and the plan devised, then the sampler can move to other important aspects of the sampling procedure. Along with the items just mentioned, it is imperative that the sampler understand what biological sampling is all about.

Biological sampling allows for rapid and general water-quality classification. Rapid classification is possible because quick and easy crosschecking between stream biota and a standard stream biotic index is possible. Biological sampling is typically used for general water-quality classification in the field because sophisticated laboratory apparatus is usually not available. Additionally, stream communities often show a great deal of variation in basic water-quality parameters such as DO, BOD, suspended solids, and coliform bacteria. This occurrence can be observed in eutrophic lakes that may vary from oxygen saturation to less than 0.5 mg/L in a single day, and the concentration of suspended solids may double immediately after a heavy rain. Moreover, the sampling method chosen must take into account the differences in the habits and habitats of the aquatic organisms. Tchobanoglous and Schroeder (1985) explain, “Sampling is one of the most basic and important aspects of water-quality management.”

The first step toward accurate measurement of a stream’s water quality is to make sure that the sampling targets those organisms (i.e., macroinvertebrates) that are most likely to provide the information that is being sought. Second, it is essential that representative samples be collected. Laboratory analysis is meaningless if the sample collected is not representative of the aquatic environment being analyzed. As a rule, samples should be taken at many locations, as often as possible. If, for example, you are studying the effects of sewage discharge into a stream, you should first take at least six samples upstream of the discharge, six samples at the discharge, and at least six samples at several points below the discharge for 2–3 days (the six-six sampling rule). If these samples show wide variability, then the number of samples should be increased. On the other hand, if the initial samples exhibit little variation, then a reduction in the number of samples may be appropriate (Kittrell, 1969).

When planning the biological sampling protocol (using biotic indices as the standards) remember that when the sampling is to be conducted in a stream, findings are based on the presence or absence of certain organisms. Thus, the absence of these organisms must be a function of pollution and not of some other ecological problem. The preferred (favored in this text) aquatic group for biological monitoring in streams is the macroinvertebrates, which are usually retained by 30-mesh sieves (pond nets).

SAMPLING STATIONS

After determining the number of samples to be taken, sampling stations (locations) must be determined. Several factors determine where the sampling stations should be set up. These factors include stream habitat types, the position of the wastewater effluent outfalls, the stream characteristics, stream developments (dams, bridges, navigation locks, and other man-made structures), the self-purification characteristics of the stream, and the nature of the objectives of the study (Velz, 1970).

The stream habitat types used in this discussion are those that are macroinvertebrate assemblage in stream ecosystems. Some combination of these habitats would be sampled in a multi-habitat approach to benthic sampling (Barbour et al., 1997):

1. *Cobble (hard substrate)*—Cobble is prevalent in the riffles (and runs), which are a common feature throughout most mountain and piedmont streams. In many high-gradient streams, this habitat type will be dominant. However, riffles are not a common feature of most coastal or other low-gradient streams. Sample shallow areas with coarse substrates (mixed gravel, cobble, or larger) by holding the bottom of the dip net against the substrate and dislodging organisms by kicking (this is where the "designated kicker," your sampling partner, comes into play) the substrate for 0.5 m upstream of the net.
2. *Snags*—Snags and other woody debris that have been submerged for a relatively long period (not recent deadfall) provides excellent colonization habitat. Sample submerged woody debris by jabbing into medium-sized snag material (sticks and branches). The snag habitat may be kicked first to help dislodge organisms, but only after placing the net downstream of the snag. Accumulated woody material in pool areas is considered snag habitat. Large logs should be avoided because they are generally difficult to sample adequately.
3. *Vegetated banks*—When lower banks are submerged and have roots and emergent plants associated with them, they are sampled in a fashion similar to snags. Submerged areas of undercut banks are good habitats to sample. Sample banks with protruding roots and plants by jabbing into the habitat. Bank habitat can be kicked first to help dislodge organisms, but only after placing the net downstream.
4. *Submerged macrophytes*—Submerged macrophytes are seasonal in their occurrence and may not be a common feature of many streams, particularly those that are high gradient. Sample aquatic plants that are rooted on the bottom of the stream in deep water by drawing the net through the vegetation from the bottom to the surface of the water (maximum of 0.5 m each jab). In shallow water, sample by bumping or jabbing the net along the bottom in the rooted area, avoiding sediments where possible.

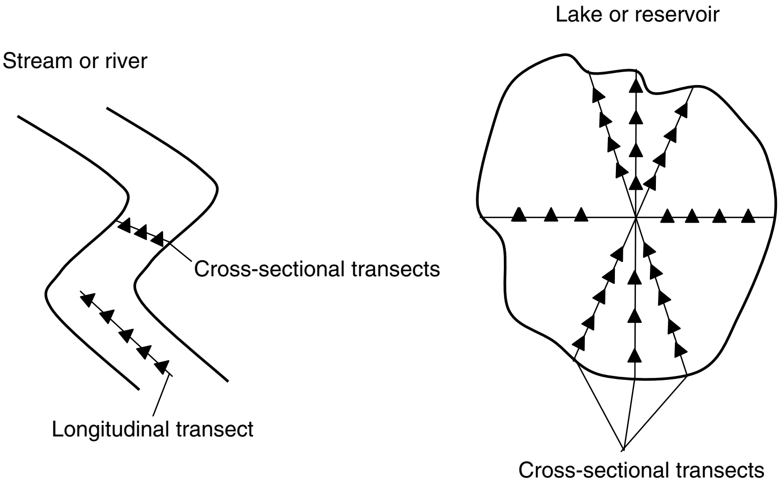


FIGURE 8.1 Transect sampling.

5. *Sand (and other fine sediment)*—Usually the least productive macroinvertebrate habitat in streams, this habitat may be the most prevalent in some streams. Sample banks of unvegetated or soft soil by bumping the net along the surface of the substrate rather than dragging the net through the soft substrate; this reduces the amount of debris in the sample.

In a biological sampling program (i.e., based on our experience), the most common sampling methods are the transect and the grid. Transect sampling involves taking samples along a straight line either at uniform or at random intervals (see Figure 8.1). The transect involves the cross section of a lake or stream or the longitudinal section of a river or stream. The transect sampling method allows for a more complete analysis by including variations in habitat.

In grid sampling, an imaginary grid system is placed over the study area. The grids may be numbered, and random numbers are generated to determine which grids should be sampled (see Figure 8.2). This type of sampling method allows for quantitative analysis because the grids are all of a certain size. For example, to sample a stream for benthic macroinvertebrates, grids that are 0.25 m (squared) may be used. Then, the weight or number of benthic macroinvertebrates per square meter can be determined.

Random sampling requires that each possible sampling location have an equal chance of being selected. After numbering all sampling locations, a computer, calculator, or a random numbers table is used to collect a series of random numbers. An illustration of how to put the random numbers to work is provided in the following example. Given a pond that has 300 grid units, find eight random sampling locations using the following sequence of random numbers taken from a standard random numbers table: 101, 209, 007, 018, 099, 100, 017, 069, 096, 033, 041, 011. The first eight numbers of the sequence for sample collection will depend on the type of sample.

SAMPLE COLLECTION*

After establishing the sampling methodology and the sampling locations, the frequency of sampling must be determined. The more samples collected, the more reliable the data will be. A frequency of once a week or once a month will be adequate for most aquatic studies. Usually, the sampling period covers an entire year so that yearly variations may be included. The details of sample collection will

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*The following procedures are suggested by USEPA, 2000b.

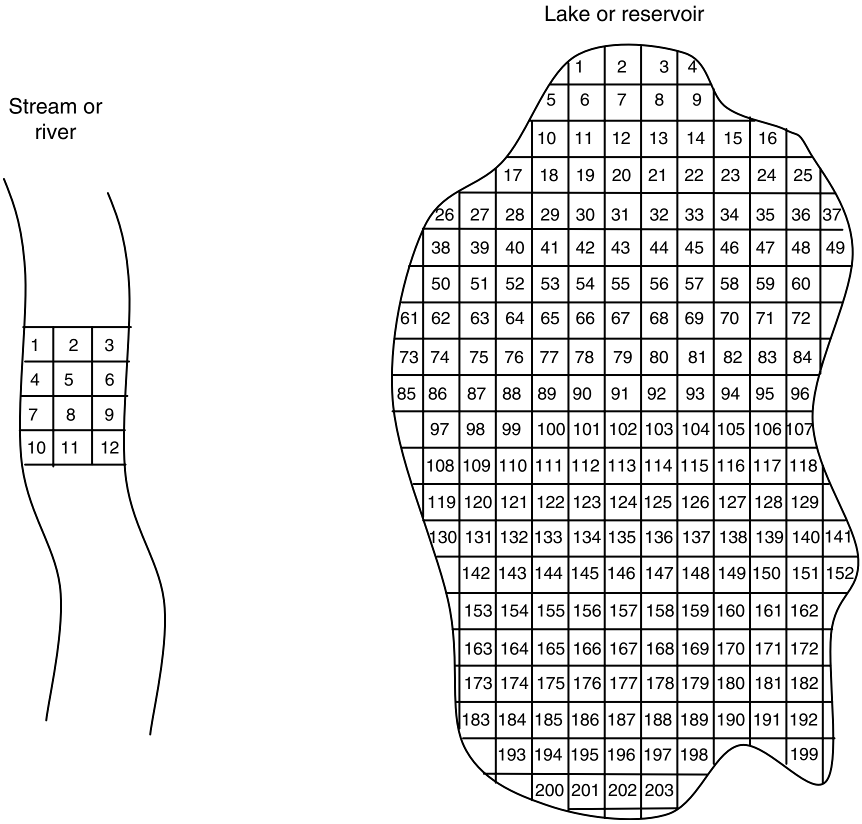


FIGURE 8.2 Grid Sampling.

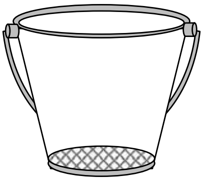
depend on the type of problem that is being solved and will vary with each study. When a sample is collected, it must be carefully identified with the following information:

- Location—Name of the water body and place of study; longitude and latitude.
- Date and time.
- Site—Point of sampling (sampling location).
- Name of collector.
- Weather—Temperature, precipitation, humidity, wind, etc.
- Miscellaneous—Any other important information, such as observations.
- Field notebook—On each sampling day, notes on field conditions should be written. For example, miscellaneous notes and weather conditions can be entered. Additionally, notes that describe the condition of the water are also helpful (color, turbidity, odor, algae, etc.). All unusual findings and conditions should also be entered.

MACROINVERTEBRATE SAMPLING EQUIPMENT

In addition to the appropriate sampling equipment described earlier, assemble the following equipment.

- Jars (two, at least quart size), plastic, wide-mouth with tight cap; one should be empty and the other filled about two thirds with 70% ethyl alcohol
- Hand lens, magnifying glass, or field microscope



Most professional biological monitoring programs employ sieve buckets as a holding container for composited samples. These buckets have a mesh bottom that allows water to drain out while the organisms and debris remain. This material can then be easily transferred to the alcohol-filled jars. However, sieve buckets can be expensive. Many volunteer programs employ alternative equipment, such as the two regular buckets described in this section. Regardless of the equipment, the process for compositing and transferring the sample is basically the same. The decision is one of cost and convenience.

FIGURE 8.3 Sieve bucket.

- Fine-point forceps
- Heavy-duty rubber gloves
- Plastic sugar scoop or ice-cream scoop
- Kink net (rocky-bottom stream) or dip net (muddy-bottom stream)
- Buckets (two; see Figure 8.3)
- String or twine (50 yards); tape measure
- Stakes (four)
- Orange (a stick, an apple, or a fish float may also be used in place of an orange) to measure velocity
- Reference maps indicating general information pertinent to the sampling area, including the surrounding roadways, as well as a hand-drawn station map
- Station ID tags
- Spray water bottle
- Pencils (at least two)

MACROINVERTEBRATE SAMPLING: ROCKY-BOTTOM STREAMS

Rocky-bottom streams are defined as those with bottoms made up of gravel, cobbles, and boulders in any combination. They usually have definite riffle areas. As mentioned, riffle areas are fairly well oxygenated and, therefore, are prime habitats for benthic macroinvertebrates. In these streams, we use the rocky-bottom sampling method described below.

Rocky-Bottom Sampling Method

The following method of macroinvertebrate sampling is used in streams that have riffles and gravel/cobble substrates. Three samples are to be collected at each site, and a composite sample is obtained (i.e., one large total sample).

Step 1—A site should have already been located on a map, with its latitude and longitude indicated.

1. Samples will be taken in three different spots within a 100-yard stream site.

   These spots may be three separate riffles; one large riffle with different current velocities, or, if no riffles are present, three run areas with gravel or cobble substrate. Combinations are also possible (if, for example, your site has only one small riffle and several run areas). Mark off the 100-yard stream site. If possible, it should begin at least 50 yards upstream of any human-made modification of the channel, such as a bridge, dam, or pipeline crossing. Avoid walking in the stream, because this might dislodge macroinvertebrates and later sampling results.

2. Sketch the 100-yard sampling area. Indicate the location of the three sampling spots on the sketch. Mark the most downstream site as Site 1, the middle site as Site 2, and the upstream site as Site 3.

Step 2—Get into place.

1. Always approach sampling locations from the downstream end and sample the site farthest downstream first (Site 1). This prevents biasing of the second and third collections with dislodged sediment of macroinvertebrates. Always use a clean kick-seine, relatively free of mud and debris from previous uses. Fill a bucket about one third full with stream water, and fill your spray bottle.
2. Select a 3 × 3 ft riffle area for sampling at Site 1. One member of the team, the net holder, should position the net at the downstream end of this sampling area. Hold the net handles at a 45° angle to the water's surface. Be sure that the bottom of the net fits tightly against the streambed so that no macroinvertebrates escape under the net. You may use rocks from the sampling area to anchor the net against the stream bottom. Do not allow any water to flow over the net.

Step 3—Dislodge the macroinvertebrates.

1. Pick up any large rocks in the 3 × 3 ft sampling area and rub them thoroughly over the partially filled bucket so that any macroinvertebrates clinging to the rocks will be dislodged into the bucket. Then place each cleaned rock outside of the sampling area. After the sampling is completed, rocks can be returned to the stretch of stream they came from.
2. The member of the team designated as the "kicker" should thoroughly stir up the sampling areas with his feet, starting at the upstream edge of the 3 × 3 ft sampling area and working downstream, moving toward the net. All dislodged organisms will be carried by the stream flow into the net. Be sure to disturb the first few inches of stream sediment to dislodge burrowing organisms. As a guide, disturb the sampling area for about 3 min, or until the area is thoroughly worked over.
3. Any large rocks used to anchor the net should be thoroughly rubbed into the bucket as above.

Step 4—Remove the net.

1. Next, remove the net without allowing any of the organisms it contains to wash away. While the net holder grabs the top of the net handles, the kicker grabs the bottom of the net handles and the net's bottom edge. Remove the net from the stream with a forward scooping motion.
2. Roll the kick net into a cylinder shape and place it vertically in the partially filled bucket. Pour or spray water down the net to flush its contents into the bucket. If necessary, pick debris and organisms from the net by hand. Release back into the stream any fish, amphibians, or reptiles caught in the net.

Step 5—Collect the second and third samples.

1. Once all the organisms have been removed from the net, repeat the steps above at Sites 2 and 3. Put the samples from all three sites into the same bucket. Combining the debris and organisms from all three sites into the same bucket is called *compositing.*

√ **Note:** If your bucket is nearly full of water after you have washed the net clean, let the debris and organisms settle to the bottom. Then cup the net over the bucket and pour the water through the net into a second bucket. Inspect the water in the second bucket to be sure no organisms came through.

Step 6—Preserve the sample.

1. After collecting and compositing all three samples, it is time to preserve them. All team members should leave the stream and return to a relatively flat section of the stream bank with their equipment. The next step will be to remove large pieces of debris (leaves, twigs, and rocks) from the sample. Carefully remove the debris one piece at a time. While holding the material over the bucket, use the forceps, spray bottle, and your hands to pick, rub, and rinse the leaves, twigs, and rocks to remove any attached organisms. Use a magnifying lens and forceps to find and remove small organisms clinging to the debris. When satisfied that the material is clean, discard it back into the stream.
2. The water will have to be drained before transferring material to the jar. This process will require two team members. Place the kick net over the second bucket, which has not yet been used and should be completely empty. One team member should push the center of the net into bucket no. 2, creating a small indentation or depression. Then hold the sides of the net closely over the mouth of the bucket. The second person can now carefully pour the remaining contents of bucket no. 1 onto a small area of the net to drain the water and concentrate the organisms. Use care when pouring so that organisms are not lost over the side of the net (see Figure 8.4).

   Use the spray bottle, forceps, sugar scoop, and gloved hands to remove all material from bucket no. 1 onto the net. When you are satisfied that bucket no. 1 is empty, use your hands and the sugar scoop to transfer the material from the net into the empty jar.

   Bucket no. 2 captures the water and any organisms that might have fallen through the netting during pouring. As a final check, repeat the process above, but this time pour bucket no. 2 over the net into bucket no. 1. Transfer any organisms on the net into the jar.

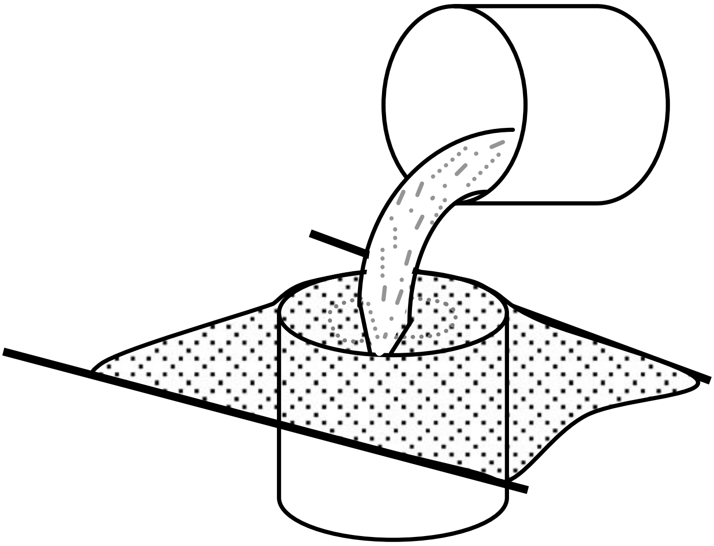


FIGURE 8.4 Pouring sample water through the net.

3. Fill the jar (so that all material is submerged) with the alcohol from the second jar. Put the lid tightly back onto the jar and gently turn the jar upside down two or three times to distribute the alcohol and remove air bubbles.
4. Complete the sampling station ID tag. Be sure to use a pencil, not a pen, because the ink will run in the alcohol! The tag includes your station number, the stream, and location (e.g., upstream from a road crossing), date, time, and the names of the members of the collecting team. Place the ID tag into the sample container, writing side facing out, so that identification can be seen clearly.

Rocky-Bottom Habitat Assessment

The habitat assessment (including measuring general characteristics and local land use) for a rocky-bottom stream is conducted in a 100-yard section of the stream that includes the riffles from which organisms were collected.

Step 1—Delineate the habitat assessment boundaries.

1. Begin by identifying the most downstream riffle that was sampled for macroinvertebrates. Using tape measure or twine, mark off a 100-yard section extending 25 yards below the downstream riffle and about 75 yards upstream.
2. Complete the identifying information of the field data sheet for the habitat assessment site. On the stream sketch, be as detailed as possible, and be sure to note which riffles were sampled.

Step 2—Describe the general characteristics and local land use on the field sheet.

1. For safety reasons as well as to protect the stream habitat, it is best to estimate the following characteristics rather than actually wading into the stream to measure them.
   A. Water appearance can be a physical indicator of water pollution.
      1. Clear—Colorless, transparent
      2. Milky—Cloudy-white or gray, not transparent; might be natural or due to pollution
      3. Foamy—Might be natural or due to pollution, generally detergents or nutrients (foam that is several inches high and does not brush apart easily is generally due to pollution)
      4. Turbid—Cloudy brown due to suspended silt or organic material
      5. Dark brown—Might indicate that acids are being released into the stream due to decaying plants
      6. Oily sheen—Multicolored reflection might indicate oil floating in the stream, although some sheens are natural
      7. Orange—Might indicate acid drainage
      8. Green—Might indicate that excess nutrients are being released into the stream
   B. Water odor can be a physical indicator of water pollution.
      1. None or natural smell
      2. Sewage—Might indicate the release of human waste material
      3. Chlorine—Might indicate that a sewage treatment plant is over-chlorinating its effluent
      4. Fishy—Might indicate the presence of excessive algal growth or dead fish
      5. Rotten eggs—Might indicate sewage pollution (the presence of a natural gas)
   C. Water temperature can be particularly important for determining whether the stream is suitable as habitat for some species of fish and macroinvertebrates that have distinct temperature requirements. Temperature also has a direct effect on the amount

of DO available to aquatic organisms. Measure temperature by submerging a thermometer for at least 2 min in a typical stream run. Repeat once again and average the results.

D. The width of the stream channel can be determined by estimating the width of the streambed that is covered by water from bank to bank. If it varies widely along the stream, estimate an average width.

E. Local land use refers to the part of the watershed within one-quarter mile upstream of and adjacent to the site. Note which land uses are present, as well as which ones seem to be having a negative impact on the stream. Base observations on what can be seen, what was passed on the way to the stream, and, if possible, what is noticed when leaving the stream.

Step 3—Conduct the habitat assessment.

1. The following information describes the parameters that will be evaluated for rocky-bottom habitats. Use these definitions when completing the habitat assessment field data sheet. The first two parameters should be assessed directly at the riffle(s) or run(s) that were used for the macroinvertebrate sampling. The last eight parameters should be assessed in the entire 100-yard section of the stream.

   A. Attachment sites for macroinvertebrates are essentially the amount of living space or hard substrates (rocks, snags) available for adequate insects and snails. Many insects begin their life underwater in streams and need to attach themselves to rocks, logs, branches, or other submerged substrates. The greater the variety and number of available living spaces or attachment sites, the greater the variety of insects in the stream. Optimally, cobble should predominate and boulders and gravel should be common. The availability of suitable living spaces for macroinvertebrates decreases as cobble becomes less abundant and boulders, gravel, or bedrock become more prevalent.

   B. Embeddedness refers to the extent to which rocks (gravel, cobble, and boulders) are surrounded by, covered, or sunken into the silt, sand, or mud of the stream bottom. Generally, as rocks become embedded, fewer living spaces are available to macroinvertebrates and fish for shelter, spawning, and egg incubation.

√ **Note:** To estimate the percent of embeddedness, observe the amount of silt or finer sediments overlaying and surrounding the rocks. If kicking does not dislodge the rocks or cobbles, they might be greatly embedded.

   C. Shelter for fish includes the relative quantity and variety of natural structures in stream, such as fallen trees, logs, and branches; cobble and large rock; and undercut banks that are available to fish for hiding, sleeping, or feeding. A wide variety of submerged structures in the stream provide fish with many living spaces; the more living spaces in a stream, the more types of fish the stream can support.

   D. Channel alteration is a measure of large-scale changes in the shape of the stream channel. Many streams in urban and agricultural areas have been straightened, deepened (e.g., dredged), or diverted into concrete channels, often for flood control purposes. Such streams have far fewer natural habitats than do naturally meandering streams for fish, macroinvertebrates, and plants. Channel alteration occurs when the stream runs through a concrete channel, when artificial embankments, riprap, and other forms of artificial bank stabilization or structures are present; when the stream is very straight for significant distances; when dams, bridges, and flow-altering structures such as combined sewer overflow (CSO) are present; when the stream is of uniform depth due to dredging; and when other such changes have occurred. Signs that indicate the occurrence of dredging include straightened, deepened, and otherwise uniform stream channels, as well as the removal of streamside vegetation to provide dredging equipment access to the stream.

E. Sediment deposition is a measure of the amount of sediment that has been deposited in the stream channel and the changes to the stream bottom that have occurred as a result of the deposition. High levels of sediment deposition create an unstable and continually changing environment that is unsuitable for many aquatic organisms.

 Sediments are naturally deposited in areas where the stream flow is reduced, such as in pools and bends, or where flow is obstructed. These deposits can lead to the formation of islands, shoals, or point bars (sediments that build up in the stream, usually at the beginning of a meander), or can result in the complete filling of pools. To determine whether these sediment deposits are new, look for vegetation growing on them: new sediments will not yet have been colonized by vegetation.

F. Stream velocity and depth combinations are important for the maintenance of healthy aquatic communities. Fast water increases the amount of DO in the water; keeps pools from being filled with sediment; and helps food items like leaves, twigs, and algae move more quickly through the aquatic system. Slow water provides spawning areas for fish and shelters macroinvertebrates that might be washed downstream in higher stream velocities. Similarly, shallow water tends to be more easily aerated (i.e., it holds more oxygen), but deeper water stays cooler longer. Thus, the best stream habitat includes all of the following velocity/depth combinations and can maintain a wide variety of organisms:

 slow (<1 ft/sec), shallow (<1.5 ft)
 slow, deep
 fast, deep
 fast, shallow

 Measure stream velocity by marking off a 10-ft section of stream run and measuring the time it takes an orange, stick, or other floating biodegradable objects to float the 10 ft. Repeat five times in the same 10-ft section and determine the average time. Divide the distance (10 ft) by the average time (seconds) to determine the velocity in feet per second.

 Measure the stream depth by using a stick of known length and taking readings at various points within your stream site, including riffles, runs, and pools. Compare velocity and depth at various points within the 100-yard site to see how many of the combinations are present.

G. Channel flow status is the percent of the existing channel that is filled with water. The flow status changes as the channel enlarges or as flow decreases because of dams and other obstructions, diversions for irrigation, or drought. When water does not cover much of the streambed, the living area for aquatic organisms is limited.

√ **Note:** For the following parameters, evaluate the conditions of the left and right stream banks separately. Define the "left" and "right" banks by standing at the downstream end of the study stretch and look upstream. Each bank is evaluated on a scale of 0–10.

H. Bank vegetation protection measures the amount of the stream bank that is covered by natural (i.e., growing wild and not obviously planted) vegetation. The root system of plants growing on stream banks helps hold soil in place, reducing erosion. Vegetation on banks provides shade for fish and macroinvertebrates and serves as a food source by dropping leaves and other organic matter into the stream. Ideally, a variety of vegetation should be present, including trees, shrubs, and grasses. Vegetation disruption can occur when the grasses and plants on the stream banks are mowed or grazed, or when the trees and shrubs are cut back or cleared.

I. Condition of banks measures the erosion potential and whether the stream banks are eroded. Steep banks are more likely to collapse and suffer from erosion than are gently sloping banks and are, therefore, considered to have erosion potential. Signs of erosion include crumbling, unvegetated banks, exposed tree roots, and exposed soil.

J. The *riparian vegetative zone* is defined as the width of natural vegetation from the edge of the stream bank. The riparian vegetative zone is a buffer zone to pollutants entering a stream from runoff. It also controls erosion and provides stream habitat and nutrient input into the stream.

√ **Note:** A wide, relatively undisturbed riparian vegetative zone reflects a healthy stream system; narrow, far less useful riparian zones occur when roads, parking lots, fields, lawns, and other artificially cultivated areas, bare soil, rock, or buildings are near the stream bank. The presence of "old fields" (i.e., previously developed agricultural fields allowed to revert to natural conditions) should rate higher than fields in continuous or periodic use. In arid areas, the riparian vegetative zone can be measured by observing the width of the area dominated by riparian or water-loving plants, such as willows, marsh grasses, and cottonwood trees.

MACROINVERTEBRATE SAMPLING: MUDDY-BOTTOM STREAMS

In muddy-bottom streams, as in rocky-bottom streams, the goal is to sample the most productive habitat available and look for the widest variety of organisms. The most productive habitat is the one that harbors a diverse population of pollution-sensitive macroinvertebrates. Samples should be collected using a D-frame net (see Figure 8.5) to jab at the habitat and scoop up the organisms that are dislodged. The idea is to collect a total sample that consists of 20 jabs taken from a variety of habitats.

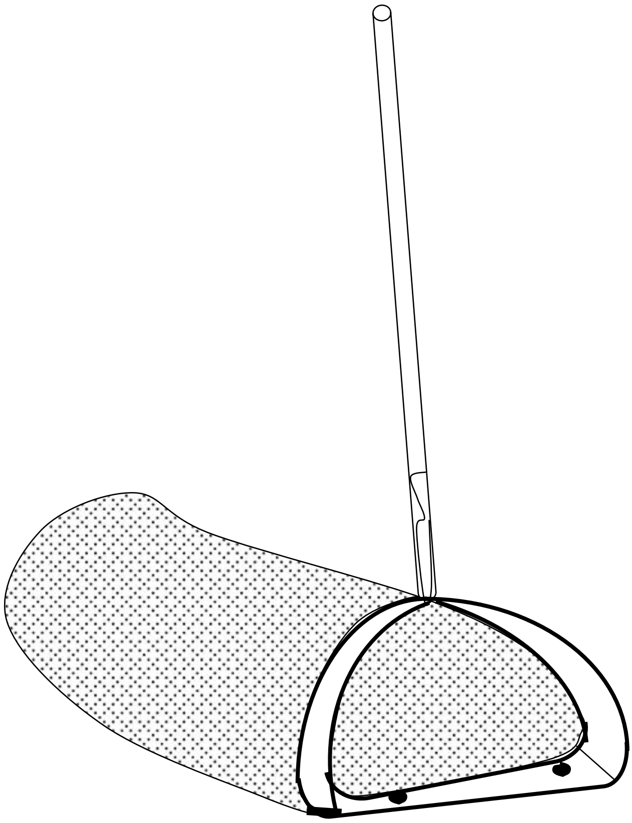


FIGURE 8.5 D-frame aquatic net.

Muddy-Bottom Sampling Method

Use the following method of macroinvertebrate sampling in streams that have muddy-bottom substrates.

Step 1—Determine which habitats are present.

> Muddy-bottom streams usually have four habitats: vegetated banks margins, snags and logs, aquatic vegetation beds and decaying organic matter, and silt/sand/gravel substrate. It is generally best to concentrate sampling efforts on the most productive habitat available, yet to sample other principal habitats if they are present. This ensures that you will secure as wide a variety of organisms as possible. Not all habitats are present in all streams or are present in significant amounts. If the sampling areas have not been preselected, determine which of the following habitats are present.

√ **Note:** Avoid standing in the stream while making habitat determinations.

A. Vegetated bank margins consist of overhanging bank vegetation and submerged root mats attached to banks. The bank margins may also contain submerged, decomposing leaf packs trapped in root wads or lining the streambanks. This is generally a highly productive habitat in a muddy stream, and it is often the most abundant type of habitat.

B. Snags and logs consist of submerged wood, primarily dead trees, logs, branches, roots, cypress knees, and leaf packs lodged between rocks or logs. This is also a very productive muddy-bottom stream habitat.

C. Aquatic vegetation beds and decaying organic matter consist of beds of submerged, green/leafy plants that are attached to the stream bottom. This habitat can be as productive as vegetated bank margins and snags and logs.

D. Silt/sand/gravel substrate includes sandy, silty, or muddy stream bottoms, rocks along the stream bottom, or wetted gravel bars. This habitat may also contain algae-covered rocks (Aufwuchs). This is the least productive of the four muddy-bottom stream habitats and it is always present in one form or another (e.g., silt, sand, mud, or gravel might predominate).

Step 2—Determine how many times to jab into each habitat type.

1. The sampler's goal is to jab 20 times. The D-frame net (see Figure 8.5) is 1 ft wide, and a jab should be approximately 1 ft in length. Thus, 20 jabs equal 20 ft^2 of combined habitat.
   A. If all four habitats are present in plentiful amounts, jab the vegetated banks 10 times and divide the remaining 10 jabs among the remaining three habitats.
   B. If three habitats are present in plentiful amounts, and one is absent, jab the silt/sand/gravel substrate, the least productive habitat, five times and divide the remaining 15 jabs between the other two productive habitats.
   C. If only two habitats are preset in plentiful amounts, the silt/sand/gravel substrate will most likely be one of those habitats. Jab the silt/sand/gravel substrate five times and the more productive habitat 15 times.
   D. If some habitats are plentiful and others are sparse, sample the sparse habitats to the extent possible, even if you can take only one or two jabs. Take the remaining jabs from the plentiful habitat(s). This rule also applies if you cannot reach a habitat because of unsafe stream conditions. Jab 20 times.

√ **Note:** Because the sampler might need to make an educated guess to decide how many jabs to take in each habitat type, it is critical that the sampler note, on the field data sheet, how many jabs were taken in each habitat. This information can be used to help characterize the findings.

Step 3—Get into place.

1. Outside and downstream of the first sampling location (first habitat), rinse the dip net and check to make sure it does not contain any macroinvertebrates or debris from the last time it was used. Fill a bucket approximately one-third with clean stream water. Also, fill the spray bottle with clean stream water. This bottle will be used to wash the net between jabs and after sampling is completed.

√ **Note:** This method of sampling requires only one person to disturb the stream habitats. While one person is sampling, a second person should stand outside the sampling area, holding the bucket and spray bottle. After every few jabs, the sampler should hand the net to the second person, who can then rinse the contents of the net into the bucket.

Step 4—Dislodge the macroinvertebrates.

1. Approach the first sample site from downstream, and sample while walking upstream. Sample in the four habitat types as follows:
    A. Sample vegetated bank margins by jabbing vigorously, with an upward motion, brushing the net against vegetation and roots along the bank. The entire jab motion should occur underwater.
    B. To sample snags and logs, hold the net with one hand under the section of submerged wood being sampled. With the other hand (which should be gloved), rub about 1 ft^2 of area on the snag or log. Scoop organisms, bark, twigs, or other organic matter dislodged into the net. Each combination of log rubbing and net scooping is one jab.
    C. To sample aquatic vegetation beds, jab vigorously, with an upward motion, against or through the plant bed. The entire jab motion should occur underwater.
    D. To sample a silt/sand/gravel substrate, place the net with one edge against the stream bottom and push it forward about a foot (in an upstream direction) to dislodge the first few inches of silt, sand, gravel, or rocks. To avoid gathering a net full of mud, periodically sweep the mesh bottom of the net back and forth in the water, making sure that water does not run over the top of the net. This will allow fine silt to rinse out of the net. When 20 jabs have been completed, rinse the net thoroughly in the bucket. If necessary, pick any clinging organisms from the net by hand, and put them in the bucket.

Step 5—Preserve the sample.

1. Look through the material in the bucket, and immediately return any fish, amphibians, or reptiles to the stream. Carefully remove large pieces of debris (leaves, twigs, and rocks) from the sample. While holding the material over the bucket, use the forceps, spray bottle, and your hands to pick, rub, and rinse the leaves, twigs, and rocks to remove any attached organisms. Use the magnifying lens and forceps to find and remove small organisms clinging to the debris. When satisfied that the material is clean, discard it back into the stream.
2. Drain the water before transferring material to the jar. This process will require two people. One person should place the net into the second bucket, like a sieve (this bucket, which has not yet been used, should be completely empty) and hold it securely. The second person can now carefully pour the remaining contents of bucket no. 1 onto the center of the net to drain the water and concentrate the organisms. Use care when pouring so that organisms are not lost over the side of the net. Use the spray bottle, forceps, sugar scoop, and gloved hands to remove all the material from bucket no. 1 onto the net. When satisfied that bucket no. 1 is empty, use your hands and the sugar scoop to transfer all the material from the net into the empty jar. The contents of the net can also be emptied directly into the jar by turning the net inside out into the jar. Bucket no. 2 captures the water and any

Station ID tag

Station no. ____

Stream ____

Location ____

Date/Time ____

Team members: ____

____

____

FIGURE 8.6 Station ID tag.

organisms that might have fallen through the netting. As a final check, repeat the process above, but this time, pour bucket no. 2 over the net into bucket no. 1. Transfer any organisms on the net into the jar.

3. Fill the jar (so that all material is submerged) with alcohol. Put the lid tightly back onto the jar and gently turn the jar upside down two or three times to distribute the alcohol and remove air bubbles.
4. Complete the sampling station ID tag (see Figure 8.6). Be sure to use a pencil, not a pen, because the ink will run in the alcohol. The tag should include your station number, the stream, and location (e.g., upstream from a road crossing), date, time, and the names of the members of the collecting crew. Place the ID tag into the sample container, writing side facing out, so that identification can be seen clearly.

√ **Note:** To prevent samples from being mixed up, samplers should place the ID tag inside the sample jar.

Muddy-Bottom Stream Habitat Assessment

The muddy-bottom stream habitat assessment (which includes measuring general characteristics and local land use) is conducted in a 100-yard section of the stream that includes the habitat areas from which organisms were collected.

√ **Note:** Reference was made previously, and is made in the following sections, about a field data sheet (habitat assessment field data sheet). Assume that the sampling team is using either the standard forms provided by the USEPA, the USGS, state water control authorities, or generic forms put together by the sampling team. The source of the form and exact type of form are not important. Some type of data recording field sheet should be employed to record pertinent data.

Step 1—Delineate the habitat assessment boundaries.

1. Begin by identifying the most downstream point that was sampled for macroinvertebrates. Using your tape measure or twine, mark off a 100-yard section extending 25 yards below the downstream sampling point and about 75 yards upstream.

2. Complete the identifying information on the field data sheet for the habitat assessment site. On the stream sketch, be as detailed as possible, and be sure to note which habitats were sampled.

Step 2—Record general characteristics and local land use on the data field sheet.

1. For safety reasons as well as to protect the stream habitat, it is best to estimate these characteristics rather than to actually wade into the stream to measure them. For instructions on completing these sections of the field data sheet, see the rocky-bottom habitat assessment instructions.

Step 3—Conduct the habitat assessment.

2. The following information describes the parameters to be evaluated for muddy-bottom habitats. Use these definitions when completing the habitat assessment field data sheet.
   A. Shelter for fish and attachment sites for macroinvertebrates are essentially the amount of living space and shelter (rocks, snags, and undercut banks) available for fish, insects, and snails. Many insects attach themselves to rocks, logs, branches, or other submerged substrates. Fish can hide or feed in these areas. The greater the variety and number of available shelter sites or attachment sites, the greater the variety of fish and insects in the stream.

√ **Note:** Many of the attachment sites result from debris falling into the stream from the surrounding vegetation. When debris first falls into the water, it is termed *new fall*, and it has not yet been "broken down" by microbes (conditioned) for macroinvertebrate colonization. Leaf material or debris that is conditioned is called *old fall*. Leaves that have been in the stream for some time lose their color, turn brown or dull yellow, become soft and supple with age, and might be slimy to touch. Woody debris becomes blackened or dark in color; smooth bark becomes coarse and partially disintegrated, creating holes and crevices. It might also be slimy to touch.

   B. Poor substrate characterization evaluates the type and condition of bottom substrates found in pools. Pools with firmer sediment types (e.g., gravel, sand) and rooted aquatic plants support a wider variety of organisms than do pools with substrates dominated by mud or bedrock and no plants. In addition, a pool with one uniform substrate type will support far fewer types of organisms than will a pool with a wide variety of substrate types.
   C. Pool variability rates the overall mixture of pool types found in the stream according to size and depth. The four basic types of pools are large-shallow, large-deep, small-shallow, and small-deep. A stream with many pool types will support a wide variety of aquatic species. Rivers with low sinuosity (few bends) and monotonous pool characteristics do not have sufficient quantities and types of habitats to support a diverse aquatic community.
   D. Channel alteration (see Rocky-Bottom Habitat Assessment, Step 3, 1-D).
   E. Sediment deposition (see Rocky-Bottom Habitat Assessment, Step 3, 1-E).
   F. Channel sinuosity evaluates the sinuosity or meandering of the stream. Streams that meander provide a variety of habitats (such as pools and runs) and stream velocities and reduce the energy from current surges during storm events. Straight stream segments are characterized by even stream depth and unvarying velocity, and they are prone to flooding. To evaluate this parameter, imagine how much longer the stream would be if it were straightened out.
   G. Channel flow status (see Rocky-Bottom Habitat Assessment, Step 3, 1-G).
   H. Bank vegetative protection (see Rocky-Bottom Habitat Assessment, Step 3, 1-H).

I. Condition of banks (see Rocky-Bottom Habitat Assessment, Step 3, 1-I).
J. The riparian vegetative zone width (see Rocky-Bottom Habitat Assessment, Step 3, 1-J).

√ **Note:** Whenever stream sampling is to be conducted, it is a good idea to have a reference collection on hand. A reference collection is a sample of locally found macroinvertebrates that have been identified, labeled, and preserved in alcohol. The program advisor, along with a professional biologist/entomologist, should assemble the reference collection, properly identify all samples, preserve them in vials, and label them. This collection may then be used as a training tool and, in the field, as an aid in macroinvertebrate identification.

POST-SAMPLING ROUTINE

After completing the stream characterization and habitat assessment, make sure that all of the field data sheets have been completed properly and that the information is legible. Be sure to include the site's identifying name and the sampling date on each sheet. This information will function as a quality control element.

Before leaving the stream location, make sure that all sampling equipment/devices have been collected and rinsed properly. Double-check that sample jars are tightly closed and properly identified. All samples, field sheets, and equipment should be returned to the team leader at this point. Keep a copy of the field data sheet(s) for comparison with future monitoring trips and for personal records.

The next step is to prepare for the macroinvertebrate laboratory work. This step includes all the work needed to set up a laboratory for processing samples into subsamples and identifying macroinvertebrates to the family level. A professional biologist/entomologist/freshwater ecologist or the professional advisor should supervise the identification procedure.

√ **Note:** The actual laboratory procedures after the sampling and collecting phase are beyond the scope of this text.

SAMPLING DEVICES

In addition to the sampling equipment mention previously, depending on stream conditions, it may be desirable to employ the use of other sampling devices. Additional sampling devices commonly used, and discussed in the following sections, include DO and temperature monitors, sampling nets (including the D-frame aquatic net), sediment samplers (dredges), plankton samplers, and Secchi disks.

Dissolved Oxygen and Temperature Monitor

√ **Note:** The methods described in this section are approved by the USEPA (1998) with detailed coverage available.

As mentioned, the DO content of a stream sample can provide the investigator with vital information, as DO content reflects the stream's ability to maintain aquatic life.

The Winkler DO with Azide Modification Method

The Winkler DO with azide modification method is commonly used to measure the DO content. The Winkler method is best suited for clean waters. The Winkler method can be used in the field but is better suited for laboratory work where better accuracy may be achieved. The Winkler method adds a divalent manganese solution followed by a strong alkali to a 300-mL BOD bottle of stream water sample. Any DO rapidly oxidizes an equivalent amount of divalent manganese to basic hydroxides of higher balance states. When the solution is acidified in the presence of iodide, oxidized manganese again reverts to the divalent state, and iodine, equivalent to the original DO content of the sample, is liberated. The amount of iodine is then determined by titration with a standard solution, usually thiosulfate.

Fortunately for the field biologist, this is the age of miniaturized electronic circuit components and devices; thus, it is not too difficult to obtain portable electronic measuring devices for DO and temperature that are of quality construction and have better than moderate accuracy. These modern electronic devices are usually suitable for laboratory and field use. The device may be subjected to severe abuse in the field; therefore, the instrument must be durable, accurate, and easy to use. Several quality DO monitors are available commercially.

When using a DO monitor, it is important to calibrate (standardize) the meter prior to use. Calibration procedures can be found in Standard Methods (latest edition) or in the manufacturer's instructions for the meter to be used. Meter calibration usually is accomplished by determining the air temperature, the DO at saturation for that temperature, and then adjusting the meter so that it reads the saturation value. After calibration, the monitor is ready for use. As mentioned, all recorded measurements, including water temperatures and DO readings, should be entered in a field notebook.

Sampling Nets

A variety of sampling nets are available for use in the field. The two-person seine net shown in Figure 8.7 is 20 ft long × 4 ft deep with 1/8-in. mesh and is utilized to collect a variety of organisms. Two people, each holding one end and then walking upstream, use it. Small organisms are easily collected by this method.

Dip nets are used to collect organisms in shallow streams. The Surber sampler (collects macroinvertebrates stirred up from the bottom; see Figure 8.8) can be used to obtain a quantitative sample (number of organisms/square feet). It is designed for sampling riffle areas in steams and rivers up to a depth of about 450 mm (18 in.). It consists of two folding stainless steel frames set at right angles to each other. The frame is placed on the bottom, with the net extending downstream. Using your

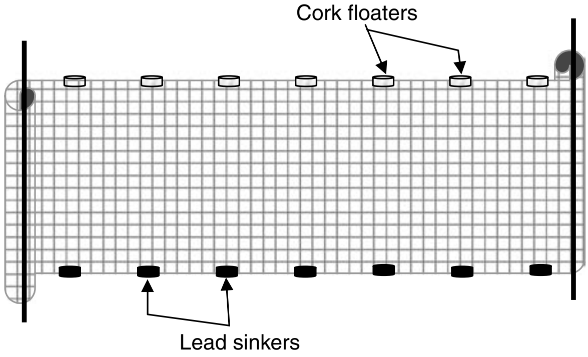


FIGURE 8.7 Two-person seine net.

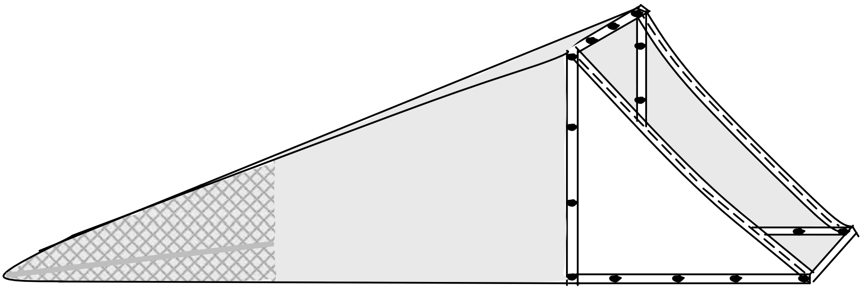


FIGURE 8.8 Surber sampler.

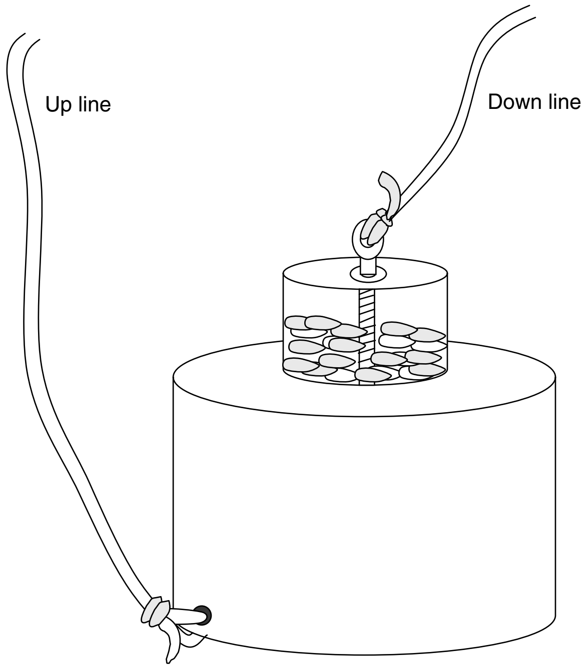


FIGURE 8.9 Homemade dredge.

hand or a rake, all sediment enclosed by the frame is dislodged. All organisms are caught in the net and transferred to another vessel for counting.

The D-frame aquatic dip net (see Figure 8.5) is ideal for sweeping over vegetation or for use in shallow streams.

Sediment Samplers (Dredges)

A sediment sampler or dredge is designed to obtain a sample of the bottom material the organisms in a slow-moving stream. The simple "homemade" dredge shown in Figure 8.9 works well in water too deep to sample effectively with handheld tools. The homemade dredge is fashioned from a no. 3 coffee can and a smaller can (see Figure 8.9) with a tight-fitting plastic lid (a peanut can works well).

To use the homemade dredge, first invert it under water so the can fills with water and no air is trapped. Then lower the dredge as quickly as possible with the down line. The idea is to bury the open end of the coffee can in the bottom. Then, quickly pull the up line to bring the can to the surface with a minimum loss of material. Dump the contents into a sieve or observation pan to sort. This method works best in bottoms composed of sediment, mud, sand, and small gravel.

By using the bottom sampling dredge, a number of different analyses can be made. Because the bottom sediments represent a good area in which macroinvertebrates and benthic algae can be found, the communities of organisms living on or in the bottom can be easily studied quantitatively and qualitatively. A chemical analysis of the bottom sediment can be conducted to determine what chemicals are available to organisms living in the bottom habitat.

Plankton Sampler

Note: More detailed information on plankton sampling can be found in Robert B. Annis Water Resources Institute (2000).

Plankton (meaning "to drift") are distributed through the stream and, in particular, in pool areas. They are found at all depths and consist of plant (phytoplankton) and animal (zooplankton) forms. Plankton show a distribution pattern that can be associated with the time of day and seasons.

There are three fundamental sizes of plankton: nannoplankton, microplankton, and macroplankton. The smallest are nannoplankton that range in size from 5 to 60 μm (millionth of a meter). Because of their small size, most nannoplankton will pass through the pores of a standard sampling net. Special fine mesh nets can be used to capture the larger nannoplankton.

Most planktonic organisms fall into the microplankton or net plankton category. The sizes range from the largest nannoplankton to about 2 mm (thousandths of a meter). Nets of various sizes and shapes are used to collect microplankton. The nets collect the organism by filtering water through fine meshed cloth. The plankton nets on the vessels are used to collect microplankton.

The largest-size plankton is called macroplankton. They are visible to the naked eye. The largest can be several meters long.

The plankton net or sampler (see Figure 8.10) is a device that makes it possible to collect phytoplankton and zooplankton samples. For quantitative comparisons of different samples, some nets have a flow meter used to determine the amount of water passing through the collecting net.

The plankton net or sampler provides a mean of obtaining samples of plankton from various depths so that distribution patterns can be studied. Considering the depth of the water column that is sampled can make quantitative determinations. The net can be towed to sample plankton at a single depth (horizontal tow) or lowered into the water to sample the water column (vertical tow). Another possibility is oblique tows where the net is lowered to a predetermined depth and raised at a constant rate as the vessel moves forward.

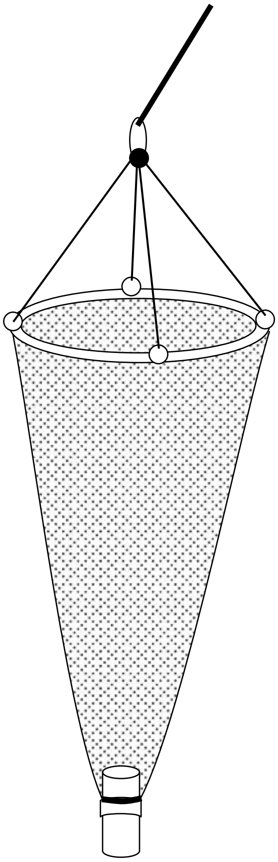


FIGURE 8.10 Plankton net.

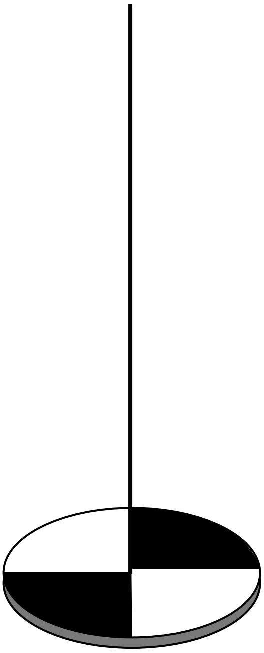


FIGURE 8.11 Secchi disk.

After towing and removal from the stream, the sides of the net are rinsed to dislodge the collected plankton. If a quantitative sample is desired, a certain quantity of water is collected. If the plankton density is low, then the sample may be concentrated using a low-speed centrifuge or some other filtering device. A definite volume of the sample is studied under the compound microscope for counting and identification of plankton.

Secchi Disk

A Secchi disk (Figure 8.11) is often used to determine water turbidity or the degree of visibility in a stream. The Secchi disk originated with Father Pietro Secchi, an astrophysicist and scientific advisor to the Pope, who was requested to measure transparency in the Mediterranean Sea by the head of the Papal Navy. In April 1865, Secchi used some white disks to measure the clarity of water in the Mediterranean. Various sizes of disks have been used since that time, but the most frequently used disk is an 8-in.-diameter metal disk painted in alternate black and white quadrants.

The disk shown in Figure 8.11 is 20 cm in diameter; it is lowered into the stream using the calibrated line. To use the Secchi disk properly, it should be lowered into the stream water until it is no longer visible. At the point where it is no longer visible, a measurement of the depth is taken. This depth is called the Secchi disk transparency light extinction coefficient. The best results are usually obtained after early morning and before late afternoon.

Miscellaneous Sampling Equipment

Several other sampling tools/devices are available for use in sampling a stream. For example, consider the standard sand-mud sieve. Generally made of heavy-duty galvanized 1/8-in. mesh screen supported by a water-sealed 24 × 15 × 3 in. wood frame, this device is useful for collecting burrowing organisms found in soft bottom sediments. Moreover, no stream sampling kit would be complete without a collecting tray, collecting jars of assorted sizes, heavy-duty plastic bags, small pipets, large 2-oz pipets, fine mesh straining net, and black china marking pencil. In addition, depending upon the quantity of material to be sampled, it is prudent to include several 3- and 5-gal collection buckets in the stream sampling field kit.

THE BOTTOM LINE ON BIOLOGICAL SAMPLING

This discussion has stressed the practice of biological monitoring, employing the use of biotic indices as key measuring tools. We emphasized biotic indices not only for their simplicity of use, but also for the relative accuracy they provide, although their development and use can sometimes be derailed. The failure of a monitoring protocol to assess environmental condition accurately or to protect running waters usually stems from conceptual, sampling, or analytical pitfalls. Biotic indices can be combined with other tools for measuring the condition of ecological systems in ways that enhance or hinder their effectiveness. The point is, like any other tool, they can be misused. However, that biotic indices can be, and are, misused does not mean that the indices' approach itself is useless.

To ensure that the biotic indices approach is not useless, it is important for the practicing freshwater ecologist and water sampler to remember a few key guidelines:

1. Sampling everything is not the goal. As Botkin (1990), Pimm (1991), Huston (1994), and Hillborn and Mangel (1997) note, biological systems are complex and unstable in space and time, and samplers often feel compelled to study all components of this variation. Complex sampling programs proliferate. However, every study need not explore everything. Freshwater samplers and monitors should avoid the temptation to sample all the unique habitats and phenomena that make freshwater monitoring so interesting. Concentration should be placed on the central components of a clearly defined research agenda (a sampling/monitoring protocol)—detecting and measuring the influences of human activities on the water body's ecological system.
2. With regard to the influence of human activities on the water body's ecological system, we must see protecting biological condition as a central responsibility of water resource management. One thing is certain: until biological monitoring is seen as essential to track attainment of that goal and biological criteria as enforceable standards mandated by the Clean Water Act, life in the nation's freshwater systems will continue to decline.

Biomonitoring is only one of several tools available to the water practitioner. Regardless of the tool employed, all results depend upon proper biomonitoring techniques. Biological monitoring must be designed to obtain accurate results—present approaches need to be strengthened. In addition, "the way it's always been done" must be reexamined and efforts must be undertaken to do what works to keep freshwater systems alive. We can afford nothing less.

WATER QUALITY MONITORING (DRINKING WATER)

When we speak of water quality monitoring, we refer to monitoring practice based on three criteria:

1. To ensure to the greatest extent possible that the water is not a danger to public health
2. To ensure that the water provided at the tap is as aesthetically pleasing as possible
3. To ensure compliance with applicable regulations

To meet these goals, all public systems must monitor water quality to some extent. The degree of monitoring employed is dependent on local needs and requirements, and on the type of water system; small water systems using good-quality water from deep wells may only need to provide occasional monitoring, but systems using surface water sources must test water quality frequently (AWWA, 1995).

TABLE 8.3
Total Residual Chlorine (TRC) mg/L

0.06	Toxic to striped bass larvae
0.31	Toxic to white perch larvae
0.5–1.0	Typical drinking water residual
1.0–3.0	Recommended for swimming pools

Source: From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators*, Vol. 1, CRC Press, Boca Raton, FL, 1999.

Drinking water must be monitored to provide adequate control of the entire water drawing/treatment/conveyance system. Adequate control is defined as monitoring employed to assess the present level of water quality so action can be taken to maintain the required level (whatever that might be).

We define water quality monitoring as the sampling and analysis of water constituents and conditions. When we monitor, we collect data. As a monitoring program is developed, deciding the reasons for collecting the information is important. The reasons are defined by establishing a set of objectives that includes a description of who will collect the information.

It may come as a surprise to know that today the majority of people collecting data are not water practitioners; instead, many are volunteers. These volunteers have a stake in their local stream, lake, or other water body, and in many cases are proving they can successfully carry out a water quality-monitoring program.

IS THE WATER GOOD OR BAD?*

To answer the question "Is the water good or bad?," we must consider two factors. First, we return to the basic principles of water quality monitoring—sampling and analyzing water constituents and conditions. These constituents include:

1. Introduced pollutants, such as pesticides, metals, and oil
2. Constituents found naturally in water that can nevertheless be affected by human sources, such as DO, bacteria, and nutrients

The magnitude of their effects is influenced by properties such as pH and temperature. For example, temperature influences the quantity of DO that water is able to contain, and pH affects the toxicity of ammonia.

The second factor to be considered is that the only valid way to answer this question is to conduct tests that must be compared to some form of water quality standards. If simply assigning a good and bad value to each test factor were possible, the meters and measuring devices in water quality test kits would be much easier to make. Instead of fine graduations, they could simply have a good and a bad zone.

Water quality—the difference between good and bad water—must be interpreted according to the intended use of the water. For example, the perfect balance of water chemistry that assures a sparkling clear, sanitary swimming pool would not be acceptable as drinking water and would be a deadly environment for many biota. Consider Table 8.3.

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* Much of the information in the following sections is based on USEPA's 2.841B97003 *Volunteer Stream Monitoring: A Methods Manual*, 2000b, and on our personal experience.

TABLE 8.4
Fecal Coliform Bacteria per 100 mL of Water

Desirable	Permissible	Type of Water Use
0	0	Potable and well water (for drinking)
<200	<1000	Primary contact water (for swimming)
<1000	<5000	Secondary contact water (boating and fishing)

Source: From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators*, Vol. 1, CRC Press, Boca Raton, FL, 1999.

In another example, widely different levels of fecal coliform bacteria are considered acceptable, depending on the intended use of the water.

State and local water quality practitioners as well as volunteers have been monitoring water quality conditions for many years. In fact, until the past decade or so (until biological monitoring protocols were developed and began to take hold), water quality monitoring was generally considered the primary way of identifying water pollution problems. Today, professional water quality practitioners and volunteer program coordinators alike are moving toward approaches that combine chemical, physical, and biological monitoring methods to achieve the best picture of water quality conditions.

Water quality monitoring can be used for many purposes:

1. To identify whether waters are meeting designated uses—All states have established specific criteria (limits on pollutants) identifying what concentrations of chemical pollutants are allowable in their waters. When chemical pollutants exceed maximum or minimum allowable concentrations, waters may no longer be able to support the beneficial uses—such as fishing, swimming, and drinking—for which they have been designated (see Table 8.4). Designated or intended uses and the specific criteria that protect them (along with antidegradation statements that say waters should not be allowed to deteriorate below existing or anticipated uses) together form water quality standards. State water quality professionals assess water quality by comparing the concentrations of chemical pollutants found in streams to the criteria in the state's standards, and so judge whether streams are meeting their designated uses.

   Water quality monitoring, however, might be inadequate for determining whether aquatic life needs are being met in a stream. While some constituents (such as DO and temperate) are important in maintaining healthy fish and aquatic insect populations, other factors (such as the physical structure of the stream and the condition of the habitat) play an equal or greater role. Biological monitoring methods are generally better suited for determining whether aquatic life is supported.
2. To identify specific pollutants and sources of pollution—Water quality monitoring helps link sources of pollution to water body quality problems because it identifies specific problem pollutants. Since certain activities tend to generate certain pollutants (bacteria and nutrients are more likely to come from an animal feedlot than an automotive repair shop), a tentative link to what would warrant further investigation or monitoring can be formed.
3. To determine trends—Chemical constituents that are properly monitored (i.e., using consistent time of day and on a regular basis using consistent methods) can be analyzed for trends over time.
4. To screen for impairment—Finding excessive levels of one or more chemical constituents can serve as an early warning "screen" for potential pollution problems.

STATE WATER QUALITY STANDARDS PROGRAMS

Each state has a program to set standards for the protection of each body of water within its boundaries. Standards for each body of water are developed that:

1. Depend on the water's designated use
2. Are based on the USEPA's national water quality criteria and other scientific research into the effects of specific pollutants on different types of aquatic life and on human health
3. May include limits based on the biological diversity of the body of water (the presence of food and prey species)

State water quality standards set limits on pollutants and establish water quality levels that must be maintained for each type of water body, based on its designated use.

Resources for this type of information include:

1. USEPA Water Quality Criteria Program
2. U.S. Fish and Wildlife Service Habitat Suitability Index Models (for specific species of local interest)

Monitoring test results can be plotted against these standards to provide a focused, relevant, and required assessment of water quality.

DESIGNING A WATER QUALITY MONITORING PROGRAM

The first step in designing a water quality monitoring program is to determine the purpose for the monitoring. This aids in selection of parameters to monitor. This decision should be based on factors, which include:

1. Types of water quality problems and pollution sources that will likely be encountered (see Table 8.5)
2. Cost of available monitoring equipment

TABLE 8.5
Water Quality Problems and Pollution Sources

Source	Common Associated Chemical Pollutants
Cropland	Turbidity, phosphorus, nitrates, temperature, and total solids
Forestry harvest	Turbidity, temperature, total solids
Grazing land	Fecal bacteria, turbidity, phosphorus
Industrial discharge	Temperature, conductivity, total solids, toxics, pH
Mining	pH, alkalinity, total dissolved solids
Septic systems	Fecal bacteria (i.e., *Escherichia coli, Enterococcus*), nitrates, DO/BOD, conductivity, temperature
Sewage Treatment	DO and BOD, turbidity, conductivity, phosphorus, nitrates, fecal bacteria, temperature, total solids, pH
Construction	Turbidity, temperature, DO and BDO, total solids, toxics
Urban runoff	Turbidity, phosphorus, nitrates, temperature, conductivity, DO and BOD

Source: From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators*, Vol. 1, CRC Press, Boca Raton, FL, 1999.

3. Precision and accuracy of available monitoring equipment
4. Capabilities of monitors

Note: We discuss the parameters most commonly monitored by drinking water practitioners in streams (i.e., we assume, for illustration and discussion purposes, that our water source is a surface water stream) in detail in this section. They include DO, BOD, temperature, pH, turbidity, total orthophosphate, nitrates, total solids, conductivity, total alkalinity, fecal bacteria, apparent color, odor, and hardness. When monitoring water supplies under the Safe Drinking Water Act (SDWA) or the National Pollutant Discharge Elimination System (NPDES), utilities must follow test procedures approved by the USEPA for these purposes. Additional testing requirements under these and other federal programs are published as amendments in the Federal Register.

Except when monitoring discharges for specific compliance purposes, a large number of approximate measurements can provide more useful information than one or two accurate analyses. Because water quality and chemistry continually change, periodic, representative measurements and observations that indicate the range of water quality is necessary, rather than testing the quality at any single moment. The more complex a water system, the more the time required to observe, understand, and draw conclusions regarding the cause and effect of changes in the particular system.

GENERAL PREPARATION AND SAMPLING CONSIDERATIONS[*]

Sampling devices should be corrosion resistant, easily cleaned, and capable of collecting desired samples safely and in accordance with test requirements. Whenever possible, assign a sampling device to each sampling point. Sampling equipment must be cleaned on a regular schedule to avoid contamination.

√ **Note:** Some tests require special equipment to ensure the sample is representative. DO and fecal bacteria sampling require special equipment and procedures to prevent collection of nonrepresentative samples.

Reused sample containers and glassware must be cleaned and rinsed before the first sampling run and after each run by following Method A or Method B described below. The most suitable method depends on the parameter being measured.

Method A: General Preparation of Sampling Containers

Use the following method when preparing all sample containers and glassware for monitoring conductivity, total solids, turbidity, pH, and total alkalinity. Wearing latex gloves:

1. Wash each sample bottle or piece of glassware with a brush and phosphate-free detergent.
2. Rinse three times with cold tap water.
3. Rinse three times with distilled or deionized water.

Method B: Acid Wash Procedures

Use this method when preparing all sample containers and glassware for monitoring nitrates and phosphorus. Wearing latex gloves:

1. Wash each sample bottle or piece of glassware with a brush and phosphate-free detergent.
2. Rinse three times with cold tap water.
3. Rinse with 10% hydrochloric acid.
4. Rinse three times with deionized water.

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[*] The sections that follow detail specific equipment considerations and analytical procedures for each of the most common water quality parameters.

Sample Types

Two types of samples are commonly used for water quality monitoring: grab samples and composite samples. The type of sample used depends on the specific test, the reason the sample is being colleted, and the applicable regulatory requirements.

Grab samples are taken all at once, at a specific time and place. They are representative only of the conditions at the time of collection.

Grab samples must be used to determine pH, total residual chlorine (TRC), DO, and fecal coliform concentrations. Grab samples may also be used for any test, which does not specifically prohibit their use.

√ **Note:** Before collecting samples for any test procedure, it is best to review the sampling requirements of the test.

Composite samples consist of a series of individual grab samples collected over a specified period in proportion to the flow. The individual grab samples are mixed together in proportion to the flow rate at the time the sample was collected to form the composite sample. This type of sample is taken to determine average conditions in a large volume of water whose properties vary significantly over the course of a day.

Collecting Samples from a Stream

In general, sample away from the stream bank in the main current. Never sample stagnant water. The outside curve of the stream is often a good place to sample, because the main current tends to hug this bank. In shallow stretches, carefully wade into the center current to collect the sample.

A boat is required for deep sites. Try to maneuver the boat into the center of the main current to collect the water sample.

When collecting a water sample for analysis in the field or at the lab, follow the steps below.

Whirl-pak® Bags

To collect water sampling using Whirl-pak bags, use the following procedures:

1. Label the bag with the site number, date, and time.
2. Tear off the top of the bag along the perforation above the wire tab just before sampling. Avoid touching the inside of the bag. If you accidentally touch the inside of the bag, use another one.
3. Wading—Try to disturb as little bottom sediment as possible. In any case, be careful not to collect water that contains bottom sediment. Stand facing upstream. Collect the water samples in front of you.
   Boat—Carefully reach over the side and collect the water sample on the upstream side of the boat.
4. Hold the two white pull-tabs in each hand and lower the bag into the water on your upstream side with the opening facing upstream. Open the bag midway, between the surface and the bottom by pulling the white pull-tabs. The bag should begin to fill with water. You may need to "scoop" water into the bag by drawing it through the water upstream and away from you. Fill the bag no more than three quarters full!
5. Lift the bag out of the water. Pour out excess water. Pull on the wire tabs to close the bag. Continue holding the wire tabs and flip the bag over at least four to five times to quickly seal the bag. Do not try to squeeze the air out of the top of the bag. Fold the ends of the bag, being careful not to puncture the bag. Twist them together, forming a loop.
6. Fill in the bag number or site number on the appropriate field data sheet. This is important. It is the only way the lab specialist will know which bag goes with which site.

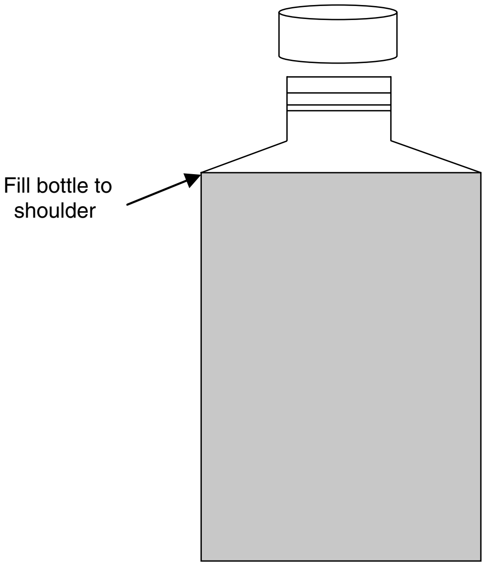

FIGURE 8.12 Sampling bottle. Filling to shoulder assures collecting enough sample. Do not overfill.

7. If samples are to be analyzed in a lab, place the sample in the cooler with ice or cold packs. Take all samples to the lab.

Screw-Cap Bottles

To collect water samples using screw-cap bottles, use the following procedures (see Figure 8.12).

1. Label the bottle with the site number, date, and time.
2. Remove the cap from the bottle just before sampling. Avoid touching the inside of the bottle or the cap. If you accidentally touch the inside of the bottle, use another one.
3. Wading—Try to disturb as little bottom sediment as possible. In any case, be careful not to collect water that has sediment from bottom disturbance. Stand facing upstream. Collect the water sample on your upstream side, in front of you. You may also tape your bottle to an extension pole to sample from deeper water.

   Boat—Carefully reach over the side and collect the water sample on the upstream side of the boat.
4. Hold the bottle near its base and plunge it (opening downward) below the water surface. If you are using an extension pole, remove the cap, turn the bottle upside down, and plunge it into the water, facing upstream. Collect a water sample 8–12 in. beneath the surface, or midway between the surface and the bottom if the stream reach is shallow.
5. Turn your bottle underwater into the current and away from you. In slow-moving stream reaches, push the bottle underneath the surface and away from you in the upstream direction.
6. Leave a 1-in. air space (except for DO and BOD samples). Do not fill the bottle completely (so that the sample can be shaken just before analysis). Recap the bottle carefully, remembering not to touch the inside.
7. Fill in the bottle number or site number on the appropriate field data sheet. This is important because it tells the lab specialist which bottle goes with which site.
8. If the samples are to be analyzed in the lab, place them in the cooler for transport to the lab.

TABLE 8.6
Recommended Sample Storage and Preservation Techniques

Test Factor	Container Type Recommended/Regulatory	Preservation	Max. Storage Time
Alkalinity	P, G	Refrigerate	24 h/14 days
BOD	P, G	Refrigerate	6 h/48 h
Conductivity	P, G	Refrigerate	28 days/28 days
Hardness	P, G	Lower pH to <2	6 months/6 months
Nitrate	P, G	Analyze ASAP	48 h/48 h
Nitrite	P, G	Analyze ASAP	none/48 h
Odor	G	Analyze ASAP	6 h/NR
Oxygen, dissolved			
Electrode	G	Immediately analyze	0.5 h/stat
Winkler	G	"Fix" immediately	8 h/8 h
pH	P, G	Immediately analyze	2 h/stat
Phosphate	G(A)	Filter immediately, refrigerate	48 h/NR
Salinity	G, wax seal	Immediately analyze or use wax seal	6 months/NR
Temperature	P, G	Immediately analyze	stat/stat
Turbidity	P, G	Analyze same day or store in dark up to 24 h, refrigerate	24 h/ 48 h

Note: P = plastic; G = glass; N/R = no result.

Source: From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators*, Vol. 1, CRC Press, Boca Raton, FL, 1999.

SAMPLE PRESERVATION AND STORAGE

Samples can change very rapidly. However, no single preservation method will serve for all samples and constituents. If analysis must be delayed, follow the instructions for sample preservation and storage listed in *Standard Methods*, or those specified by the laboratory that will eventually process the samples (see Table 8.6). In general, handle the sample in a way that prevents changes from biological activity, physical alterations, or chemical reactions. Cool the sample to reduce biological and chemical reactions. Store in darkness to suspend photosynthesis. Fill the sample container completely to prevent the loss of dissolved gases. Metal cations such as iron and lead and suspended particles may adsorb onto container surfaces during storage.

STANDARDIZATION OF METHODS

References used for sampling and testing must correspond to those listed in the most current federal regulation. For the majority of tests, to compare the results of either different water quality monitors or the same monitors over the course of time requires some form of standardization of the methods. The American Public Health Association (APHA) recognized this requirement when in 1899 the association appointed a committee to draw up standard procedures for the analysis of water. The report (published in 1905) constituted the first edition of what is now known as *Standard Methods for the Examination of Water and Wastewater* or *Standard Methods*. This book is now in its 20th edition and serves as the primary reference for water testing methods, and as the basis for most EPA-approved methods.

TEST METHODS (WATER)[*]

Descriptions of general methods to help you understand how each works in specific test kits follow. Always use the specific instructions included with the equipment and individual test kits.

Most water analyses are conducted either by titrimetric analyses or colorimetric analyses. Both methods are easy to use and provide accurate results.

Titrimetric Methods

Titrimetric analyses are based on adding a solution of known strength (the titrant, which must have an exact known concentration) to a specific volume of a treated sample in the presence of an indicator. The indicator produces a color change indicating the reaction is complete. Titrants are generally added by a Titrator (microburette) or a precise glass pipette.

Colorimetric

Colorimetric standards are prepared as a series of solutions with increasing known concentrations of the constituent to be analyzed. Two basic types of colorimetric tests are commonly used:

1. The pH is a measure of the concentration of hydrogen ions (the acidity of a solution) determined by the reaction of an indicator that varies in color, depending on the hydrogen ion levels in the water.
2. Tests that determine a concentration of an element or compound are based on Beer's Law. Simply, this law states that the higher the concentration of a substance, the darker the color produced in the test reaction, and therefore the more light absorbed. Assuming a constant view path, the absorption increases exponentially with concentration.

Visual Methods

The Octet Comparator uses standards that are mounted in a plastic comparator block. It employs eight permanent translucent color standards and built-in filters to eliminate optical distortion. The sample is compared using either of the two viewing windows. Two devices that can be used with the comparator are the B-color reader, which neutralizes color or turbidity in water samples, and view path, which intensifies faint colors of low concentrations for easy distinction.

Electronic Methods

Although the human eye is capable of differentiating color intensity, interpretation is quite subjective. Electronic colorimeters consist of a light source that passes through a sample and is measured on a photodetector with an analog or digital readout.

Besides electronic colorimeters, specific electronic instruments are manufactured for lab and field determination of many water quality factors, including pH, total dissolved solids and conductivity, DO, temperature, and turbidity.

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[*] The material presented in this section is based on personal experience and adaptations from *Standard Methods*, the Federal Register, and *The Monitor's Handbook*, LaMotte Company, Chestertown, MD, 1992.

TABLE 8.7
Maximum DO Concentrations vs. Temperature Variations

Temperature°C	DO (mg/L)	Temperature°C	DO (mg/L)
0	14.60	23	8.56
1	14.19	24	8.40
2	13.81	25	8.24
3	13.44	26	8.09
4	13.09	27	7.95
5	12.75	28	7.81
6	12.43	29	7.67
7	12.12	30	7.54
8	11.83	31	7.41
9	11.55	32	7.28
10	11.27	33	7.16
11	11.01	34	7.05
12	10.76	35	6.93
13	10.52	36	6.82
14	10.29	37	6.71
15	10.07	38	6.61
16	9.85	39	6.51
17	9.65	40	6.41
18	9.45	41	6.31
19	9.26	42	6.22
20	9.07	43	6.13
21	8.90	44	6.04
22	8.72	45	5.95

Source: From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators*, Vol. 1, CRC Press, Boca Raton, FL, 1999.

Dissolved Oxygen Testing*

A stream system used as a source of water produces and consumes oxygen. It gains oxygen from the atmosphere and from plants because of photosynthesis. Because of the running water's churning, it dissolves more oxygen than does still water, such as in a reservoir behind a dam. Respiration by aquatic animals, decomposition, and various chemical reactions consume oxygen.

Oxygen is actually poorly soluble in water. Its solubility is related to pressure and temperature. In water supply systems, DO in raw water is considered the necessary element to support life of many aquatic organisms. From the drinking water practitioner's point of view, DO is an important indicator of the water treatment process, and an important factor in corrosivity.

Oxygen is measured in its dissolved form as DO. If more oxygen is consumed than produced, DO levels decline and some sensitive animals may move away, weaken, or die.

DO levels fluctuate over a 24-h period and seasonally. They vary with water temperature and altitude. Cold water holds more oxygen than warm water (see Table 8.7), and water holds less oxygen at higher altitudes. Thermal discharges (such as water used to cool machinery in a manufacturing plant or a power plant) raise the temperature of water and lower its oxygen content. Aquatic

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* Much of the information in this section is from USEPA Test Methods for *Escherichia coli* and Enterococci in Water by the Membrane Filter Procedure (Method no. 1103.1), EPA 600/4-85-076, 1985, and USEPA Bacteriological Ambient Water Quality Criteria for Marine and Fresh Recreational Waters, EPA 440/5-84-002, Cincinnati, OH, Environmental Protection Agency, Office of Research and Development, 1986.

animals are most vulnerable to lowered DO levels in the early morning on hot summer days when stream flows are low, water temperatures are high, and aquatic plants have not been producing oxygen since sunset.

Sampling and Equipment Considerations

In contrast to lakes, where DO levels are most likely to vary vertically in the water column, changes in DO in rivers and streams move horizontally along the course of the waterway. This is especially true in smaller, shallower streams. In larger, deeper rivers, some vertical stratification of DO might occur. The DO levels in and below riffle areas, waterfalls, or dam spillways are typically higher than those in pools and slower-moving stretches. If you wanted to measure the effect of a dam, sampling for DO behind the dam, immediately below the spillway, and upstream of the dam would be important. Because DO levels are critical to fish, a good place to sample is in the pools that fish tend to favor, or in the spawning areas they use.

An hourly time profile of DO levels at a sampling site is a valuable set of data, because it shows the change in DO levels from the low point (just before sunrise) to the high point (sometime near midday). However, this might not be practical for a volunteer monitoring program. Note the time of your DO sampling to help judge when in the daily cycle the data were collected.

DO is measured either in milligrams per liter (mg/L) or "percent saturation." Milligrams per liter are the amount of oxygen in a liter of water. Percent saturation is the amount of oxygen in a liter of water relative to the total amount of oxygen that the water can hold at that temperature.

DO samples are collected using a special BOD bottle: a glass bottle with a "turtleneck" and a ground stopper. You can fill the bottle directly in the stream if the stream can be waded in or boated in, or you can use a sampler dropped from a bridge or boat into water deep enough to submerse it. Samplers can be made or purchased.

Dissolved Oxygen Test Methods

DO is measured primarily either by using some variation of the Winkler method, or by using a meter and probe.

Winkler Method (Azide Modification)

The Winkler method (azide modification) involves filling a sample bottle completely with water (no air is left to bias the test). The DO is then "fixed" using a series of reagents that form a titrated acid compound. Titration involves the drop-by-drop addition of a reagent that neutralizes the acid compound, causing a change in the color of the solution. The point at which the color changes is the "endpoint" and is equivalent to the amount of oxygen dissolved in the sample. The sample is usually fixed and titrated in the field at the sample site.

The azide modification method is best suited for relatively clean waters; otherwise, substances such as color, organics, suspended solids, sulfide, chlorine, and ferrous and ferric iron can interfere with test results. If fresh azide is used, nitrite will not interfere with the test.

In testing, iodine is released in proportion to the amount of DO present in the sample. By using sodium thiosulfate with starch as the indicator, the sample can be titrated to determine the amount of DO present.

Chemicals used include

1. Manganese sulfate solution
2. Alkaline azide–iodide solution
3. Sulfuric acid—concentrated
4. Starch indicator
5. Sodium thiosulfate solution 0.025 N, or phenylarsine solution 0.025 N, or potassium biniodate solution 0.025 N
6. Distilled or deionized water

Equipment used includes:

1. Buret, graduated to 0.1 mL
2. Buret stand
3. 300-mL BOD bottles
4. 500-mL Erlenmeyer flasks
5. 1.0-mL pipets with elongated tips
6. Pipet bulb
7. 250-mL graduated cylinder
8. Laboratory-grade water rinse bottle
9. Magnetic stirrer and stir bars (optional)

Procedure:

1. Collect sample in a 300-mL BOD bottle.
2. Add 1 mL of manganous sulfate solution to the surface of the liquid.
3. Add 1 mL of alkaline–iodide–azide solution to the surface of the liquid.
4. Stopper bottle and mix by inverting the bottle.
5. Allow the floc to settle halfway in the bottle, remix, and allow to settle again.
6. Add 1 mL of concentrated sulfuric acid to the surface of the liquid.
7. Restopper bottle, rinse the top with laboratory-grade water, and mix until precipitate is dissolved.
8. The liquid in the bottle should appear clear and have an amber color.
9. Measure 201 mL from the BOD bottle into an Erlenmeyer flask.
10. Titrate with 0.025 N PAO or thiosulfate to a pale yellow color, and note the amount of titrant.
11. Add 1 mL of starch indicator solution.
12. Titrate until the blue color first disappears.
13. Record total amount of titrant.

Calculation:

To calculate the DO concentration when the modified Winkler titration method is used:

$$\text{DO, mg/L} = \frac{(\text{Buret}_{\text{Final}}, \text{mL} - \text{Buret}_{\text{Start}}, \text{mL}) \times \text{N} \times 8000)}{\text{Sample Volume, mL}} \tag{8.1}$$

√ **Note:** Using a 200-mL sample and a 0.025 N (N = Normality of the solution used to titrate the sample) titrant reduces this calculation to

$$\text{DO, mg / L} = \text{mL Tirant Used}$$

EXAMPLE 8.1

Problem:

The operator titrates a 200-mL DO sample. The buret reading at the start of the titration was 0.0 mL. At the end of the titration, the buret read 7.1 mL. The concentration of the titrating solution was 0.025 N. What is the DO concentration in mg/L?

Solution:

$$\text{DO, mg/L} = \frac{(7.1\text{ mL} - 0.0\text{ mL}) \times 0.025 \times 8000}{200\text{ mL}} = 7.1\text{ mL}$$

DO field kits using the Winkler method are relatively inexpensive, especially compared to a meter and probe. Field kits run between $35 and $200, and each kit comes with enough reagents to run 50–100 DO tests. Replacement reagents are inexpensive, and you can buy them already measured out for each test in plastic pillows.

You can also purchase the reagents in larger quantities in bottles, and measure them out with a volumetric scoop. The pillows' advantage is that they have a longer shelf life and are much less prone to contamination or spillage. Buying larger quantities in bottles has the advantage of considerably lower cost per test.

The major factor in the expense for the kits is the method of titration used—eyedropper, syringe-type titrator. Eyedropper and syringe-type titration is less precise than digital titration, because a larger drop of titrant is allowed to pass through the dropper opening, and on a micro-scale, the drop size (and thus volume of titrant) can vary from drop to drop. A digital titrator or a burette (a long glass tube with a tapered tip like a pipette) permits much more precision and uniformity for the titrant it allows to pass.

If a high degree of accuracy and precision in DO results are required, a digital titrator should be used. A kit that uses an eyedropper-type or syringe-type titrator is suitable for most other purposes. The lower cost of this type of DO field kit might be attractive if several teams of samplers and testers at multiple sites at the same time are relied on.

Meter and Probe

A DO meter is an electronic device that converts signals from a probe placed in the water into units of DO in milligrams per liter. Most meters and probes also measure temperature. The probe is filled with a salt solution and has a selectively permeable membrane that allows DO to pass from the stream water into the salt solution. The DO that has diffused into the salt solution changes the electric potential of the salt solution, and this change is sent by an electric cable to the meter, which converts the signal to milligrams per liter on a scale that the user can read.

Methodology

If samples are to be collected for analysis in the laboratory, a special APHA sampler or the equivalent must be used. This is the case because, if the sample is exposed or mixed with air during collection, test results can change dramatically. Therefore, the sampling device must allow collection of a sample that is not mixed with atmospheric air and allows for at least 3X bottle overflow (see Figure 8.12).

Again, because the DO level in a sample can change quickly, only grab samples should be used for DO testing. Samples must be tested immediately (within 15 min) after collection.

√ **Note:** Samples collected for analysis using the modified Winkler titration method may be preserved for up to 8 h by adding 0.7 mL of concentrated sulfuric acid or by adding all the chemicals required by the procedure. Samples collected from the aeration tank of the activated sludge process must be preserved using a solution of copper sulfate–sulfamic acid to inhibit biological activity.

The disadvantage of using the DO oxygen meter method is that the meter can be used to determine DO concentration directly (see Figure 8.13). In the field, a direct reading can be obtained using a probe (see Figure 8.14) or by collection of samples for testing in the laboratory using a laboratory probe (see Figure 8.15).

√ **Note:** The field probe can be used for laboratory work by placing a stirrer in the bottom of the sample bottle, but the laboratory probe should never be used in any situation where the entire probe might be submerged.

The probe used in the determination of DO consists of two electrodes, a membrane, and a membrane filling solution. Oxygen passes through the membrane into the filling solution and causes a change in the electrical current passing between the two electrodes. The change is measured and displayed as the concentration of DO. To be accurate, the probe membrane must be in proper operating condition, and the meter must be calibrated before use.

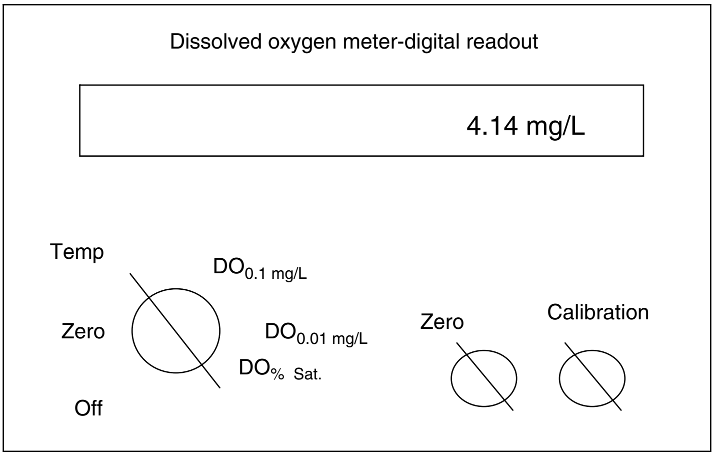

FIGURE 8.13 Dissolved oxygen meter.

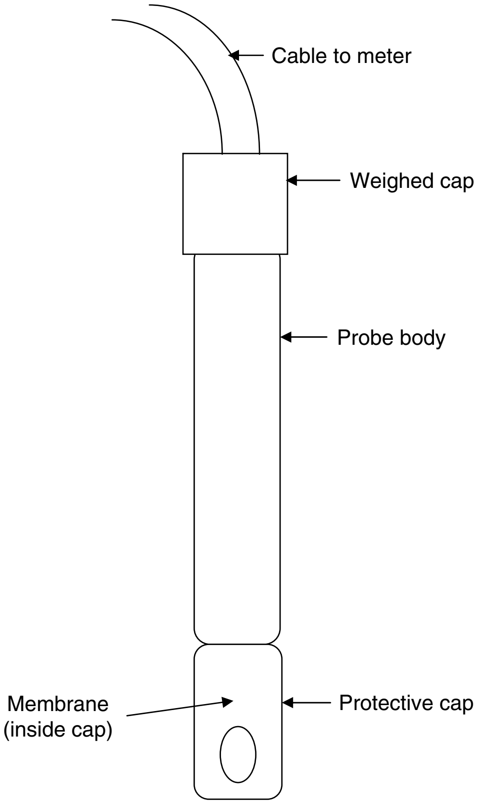

FIGURE 8.14 Dissolved oxygen-field probe.

The only chemical used in the DO meter method during normal operation is the electrode filling solution. However, in the Winkler DO method, chemicals are required for meter calibration.

Calibration prior to use is important. Both the meter and the probe must be calibrated to ensure accurate results. The frequency of calibration is dependent on the frequency of use. For example, if the meter is used once a day, then calibration should be performed before use. There are three

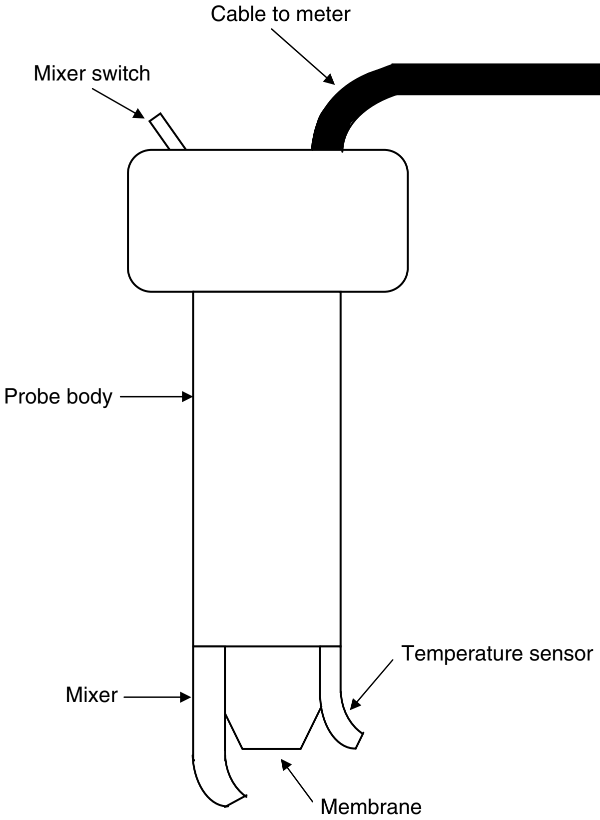

FIGURE 8.15 Dissolved oxygen-lab probe.

methods available for calibration: saturated water, saturated air, and the Winkler method. It is important to note that if the Winkler method is not used for routine calibration method, periodic checks using this method are recommended.

Procedure

It is important to keep in mind that the meter and probe supplier's operating procedures should always be followed. Normally, the manufacturer's recommended procedure will include the following generalized steps:

1. Turn the DO meter on, and allow 15 min for it to warm up.
2. Turn the meter switch to zero, and adjust as needed.
3. Calibrate the meter using the saturated air, saturated water, or Winkler azide procedure for calibration.
4. Collect the sample in a 300-mL bottle, or place the field electrode directly in the stream.
5. Place the laboratory electrode in a BOD bottle without trapping air against the membrane, and turn on the stirrer.
6. Turn the meter switch to temperature setting, and measure temperature.
7. Turn the meter switch to DO mode, and allow 10 s for the meter reading to stabilize.
8. Read the DO mg/L from meter, and record the results.

No calculation is necessary using this method because results are read directly from the meter.

DO meters are expensive compared to field kits that use the titration method. Meter/probe combinations run between $500 and $1200, including a long cable to connect the probe to the meter.

The advantage of a meter/probe is that DO and temperature can be quickly read at any point where the probe is inserted into the stream. DO levels can be measured at a certain point on a continuous basis. The results are read directly as milligrams per liter, unlike the titration methods, in which the final titration result might have to be converted by an equation to milligrams per liter.

DO meters are more fragile than field kits, and repairs to a damaged meter can be costly. The meter/probe must be carefully maintained, and must be calibrated before each sample run, and if many tests are done, between sampling. Because of the expense, a small water/wastewater facility might only have one meter/probe, which means that only one team of samplers can sample DO, and they must test all the sites. With field kits, on the other hand, several teams can sample simultaneously.

Biochemical Oxygen Demand Testing

As mentioned, BOD measures the amount of oxygen consumed by microorganisms in decomposing organic matter in stream water. BOD also measures the chemical oxidation of inorganic matter (the extraction of oxygen from water via chemical reaction). A test is used to measure the amount of oxygen consumed by these organisms during a specified period of time (usually 5 days at 20°C). The rate of oxygen consumption in a stream is affected by a number of variables: temperature, pH, the presence of certain kinds of microorganisms, and the type of organic and inorganic material in the water.

BOD directly affects the amount of DO in water bodies. The greater the BOD, the more rapidly oxygen is depleted in the water body, leaving less oxygen available for higher forms of aquatic life. The consequences of high BOD are the same as those for low DO: aquatic organisms become stressed, suffocate, and die. Most river waters used as water supplies have a BOD less than 7 mg/L; therefore, dilution is not necessary.

Sources of BOD include leaves and wood debris; dead plants and animals; animal manure; effluents from pulp and paper mills, wastewater treatment plants, feedlots, and food-processing plants; failing septic systems; and urban stormwater runoff.

√ **Note:** To evaluate raw water's potential for use as a drinking water supply, it is usually sampled, analyzed, and tested for BOD when turbid, polluted water is the only source available.

Sampling Considerations

BOD is affected by the same factors that affect DO. Aeration of stream water—by rapids and waterfalls, for example—will accelerate the decomposition of organic and inorganic material. Therefore, BOD levels at a sampling site with slower, deeper waters might be higher for a given column of organic and inorganic material than the levels for a similar site in high aerated waters.

Chlorine can also affect BOD measurement by inhibiting or killing the microorganisms that decompose the organic and inorganic matter in a sample. If sampling in chlorinated waters (such as those below the effluent from a sewage treatment plant), neutralizing the chlorine with sodium thiosulfate is necessary (see *Standard Methods*).

BOD measurement requires taking two samples at each site. One is tested immediately for DO, and the second is incubated in the dark at 20°C for 5 days, and then tested for the DO remaining. The difference in oxygen levels between the first test and the second test [in milligrams per liter (mg/L)] is the amount of BOD. This represents the amount of oxygen consumed by microorganisms and used to break down the organic matter present in the sample bottle during the incubation period. Because of the 5-day incubation, the tests are conducted in a laboratory.

Sometimes by the end of the 5-day incubation period, the DO level is zero. This is especially true for rivers and streams with a lot of organic pollution. Since knowing when the zero point was reached is not possible, determining the BOD level is also impossible. In this case, diluting the original sample by a factor that results in a final DO level of at least 2 mg/L is necessary. Special dilution water should be used for the dilutions (see *Standard Methods*).

Some experimentation is needed to determine the appropriate dilution factor for a particular sampling site. The result is the difference in DO between the first measurement and the second, after multiplying the second result by the dilution factor. *Standard Methods* prescribes all phases of procedures and calculations for BOD determination. A BOD test is not required for monitoring water supplies.

BOD Sampling, Analysis, and Testing

The approved BOD sampling and analysis procedure measures the DO depletion (biological oxidation of organic matter in the sample) over a 5-day period under controlled conditions (20°C in the dark). The test is performed using a specified incubation time and temperature. Test results are used to determine plant loadings, plant efficiency, and compliance with NPDES effluent limitations. The duration of the test (5 days) makes it difficult to use the data effectively for process control.

The standard BOD test does not differentiate between oxygen used to oxidize organic matter and that used to oxidize organic and ammonia nitrogen to more stable forms. Because many biological treatment plants now control treatment processes to achieve oxidation of the nitrogen compounds, there is a possibility that BOD test results for plant effluent and some process samples may produce BOD test results based on both carbon and nitrogen oxidation. To avoid this situation, a nitrification inhibitor can be added. When this is done, the test results are known as carbonaceous BOD (CBOD). A second uninhibited BOD should also be run whenever CBOD is determined.

When taking a BOD sample, no special sampling container is required. Either a grab or composite sample can be used. BOD_5 samples can be preserved by refrigeration at or below 4°C (not frozen)—composite samples must be refrigerated during collection. Maximum holding time for preserved samples is 48 h.

Using the incubation approved test method, a sample is mixed in several different concentrations (dilutions) with dilution water. The dilution water contains nutrients and materials to provide optimum environment. Chemicals used include dissolved oxygen, ferric chloride, magnesium sulfate, calcium chloride, phosphate buffer, and ammonium chloride.

√ **Note:** Remember, all chemicals can be dangerous if not used properly and in accordance with the recommended procedures. Review appropriate sections of the individual chemical materials safety data sheet (MSDS) to determine proper methods for handling and for safety precautions that should be taken.

Sometimes it is necessary to add (seed) healthy organisms to the sample. The DO of the dilution and the dilution water is determined. If seed material is used, a series of dilutions of seed material must also be prepared. The dilutions and dilution blanks are incubated in the dark for 5 days at 20°C ± 1°C. At the end of 5 days, the DO of each dilution and the dilution blanks are determined.

For the test results to be valid, certain criteria must be achieved. These test criteria are listed as follows:

1. Dilution water blank DO change must be $\leq$0.2 mg/L.
2. Initial DO must be $>$7.0 mg/L but $\leq$9.0 mg/L (or saturation at 20°C and test elevation).
3. Sample dilution DO depletion must be $\geq$2.0 mg/L.
4. Sample dilution residual DO must be $\geq$1.0 mg/L.
5. Sample dilution initial DO must be $\geq$7.0 mg/L.
6. Seed correction should be $\geq$0.6 but $\leq$1.0 mg/L.

The BOD_5 test procedure consists of 10 steps (for unchlorinated water) as shown in Table 8.8.

√ **Note:** BOD_5 is calculated individually for all sample dilutions that meet the criteria. Reported result is the average of the BOD_5 of each valid sample dilution.

TABLE 8.8
BOD$_5$ Test Procedure

1.	Fill two bottles with BOD dilution water; insert stoppers.
2.	Place sample in two BOD bottles; fill with dilution water; insert stoppers.
3.	Test for DO.
4.	Incubate for 5 days.
5.	Test for DO.
6.	Add 1 mL of $MnSO_4$ below surface.
7.	Add 1 mL of alkaline KI below surface.
8.	Add 1 mL of H_2SO_4.
9.	Transfer 203 mL to a flask.
10.	Titrate with PAO or thiosulfate.

BOD$_5$ Calculation (Unseeded)

Unlike the direct reading instrument used in the DO analysis, BOD results require calculation. There are several criteria used in selecting which BOD$_5$ dilutions should be used for calculating test results. Consult a laboratory testing reference manual (such as *Standard Methods*) for this information.

At present, there are two basic calculations for BOD$_5$. The first is used for samples that have not been seeded. The second must be used whenever BOD$_5$ samples are seeded. In this section, we illustrate the calculation procedure for unseeded samples.

$$\text{BOD}_5\text{(Unseeded)} = \frac{(\text{DO}_{\text{start}}, \text{mg/L} - \text{DO}_{\text{final}}, \text{mg/L}) \times 300 \text{ mL}}{\text{Sample Volume, mL}} \tag{8.2}$$

Example 8.2

Problem:

The BOD$_5$ test is completed. Bottle 1 of the test had a DO of 7.1 mg/L at the start of the test. After 5 days, bottle 1 had a DO of 2.9 mg/L. Bottle 1 contained 120 mg/L of sample.

Solution:

$$\text{BOD}_5\text{ (Unseeded)} = \frac{(7.1 \text{ mg/L} - 2.9 \text{ mg/L}) \times 300 \text{ mL}}{120 \text{ mL}} = 10.5 \text{ mg/L}$$

BOD$_5$ Calculation (Seeded)

If the BOD$_5$ sample has been exposed to conditions that could reduce the number of healthy, active organisms, the sample must be seeded with organisms. Seeding requires the use of a correction factor to remove the BOD$_5$ contribution of the seed material.

$$\text{Seed Correction} = \frac{\text{Seed Material BOD}_5 \times \text{Seed in Dilution, mL}}{300 \text{ mL}} \tag{8.3}$$

$$\text{BOD}_5\text{ (Seeded)} = \frac{[(\text{DO}_{\text{start}}, \text{mg/L} - \text{DO}_{\text{final}}, \text{mg/L}) - \text{Seed Corr.}] \times 300}{\text{Sample Volume, mL}} \tag{8.4}$$

Example 8.3

Problem:

Using the data provided below, determine the BOD_5:

BOD_5 of Seed Material		**90 mg/L**
Dilution no. 1	mL of seed material	3 mL
	mL of sample	100 mL
	Start DO	7.6 mg/L
	Final DO	2.7 mg/L

$$\text{Seed Correction} = \frac{90\ \text{mg/L} \times 3\ \text{mL}}{300\ \text{mL}} = 0.90\ \text{mg/L}$$

$$\text{BOD}_5\text{(Seeded)} = \frac{[(7.6\ \text{mg/L} - 2.7\ \text{mg/L}) - 0.90] \times 300}{100\ \text{mL}} = 12\ \text{mg/L}$$

Temperature Measurement

As mentioned, an ideal water supply should have, at all times, an almost constant temperature or one with minimum variation. Knowing the temperature of the water supply is important because the rates of biological and chemical processes depend on it.

Temperature affects the oxygen content of the water (oxygen levels become lower as temperature increases); the rate of photosynthesis by aquatic plants; the metabolic rates of aquatic organisms; and the sensitivity of organisms to toxic wastes, parasites, and diseases.

Causes of temperature change include weather, removal of shading streambank vegetation, impoundments (a body of water confined by a barrier, such as a dam), and discharge of cooling water, urban stormwater, and groundwater inflows to the stream.

Sampling and Equipment Considerations

Temperature, for example, in a stream, varies with width and depth, and the temperature of well-sunned portions of a stream can be significantly higher than the shaded portion of the water on a sunny day. In a small stream, the temperature will be relatively constant as long as the stream is uniformly in sun or shade. In a large stream, temperature can vary considerably with width and depth, regardless of shade. If safe to do so, temperature measurements should be collected at varying depths and across the surface of the stream to obtain vertical and horizontal temperature profiles. This can be done at each site at least once to determine the necessity of collecting a profile during each sampling visit. Temperature should be measured at the same place every time.

Temperature is measured in the stream with a thermometer or a meter. Alcohol-filled thermometers are preferred over mercury-filled ones ones because they are less hazardous if broken. Armored thermometers for field use can withstand more abuse than unprotected glass thermometers and are worth the additional expense. Meters for other tests [such as pH (acidity) or DO] also measure temperature and can be used instead of a thermometer.

Hardness Measurement

As mentioned, hardness refers primarily to the amount of calcium and magnesium in water. Calcium and magnesium enter water mainly by the leaching of rocks. Calcium is an important component of aquatic plant cell walls and the shells and bones of many aquatic organisms. Magnesium is an essential nutrient for plants and is a component of the chlorophyll molecule.

Hardness test kits express test results in ppm of $CaCO_3$, but these results can be converted directly to calcium or magnesium concentrations:

$$\text{Calcium Hardness as ppm CaCO}_3 \times 0.40 = \text{ppm Ca} \tag{8.5}$$

$$\text{Magnesium Hardness as ppm CaCO}_3 \times 0.24 = \text{ppm Mg} \tag{8.6}$$

√ **Note:** Because of reduced contact with soil minerals and increased contact with rain, surface raw water is usually softer than groundwater.

As a rule, when hardness is greater than 150 mg/L, softening treatment may be required for public water systems. Hardness determination via testing is required to ensure efficiency of treatment.

Measuring Hardness[*]

In the hardness test, the sample must be carefully measured, and then a buffer is added to the sample to correct the pH for the test and an indicator is added to signal the titration end point.

The indicator reagent is normally blue in a sample of pure water, but if calcium or magnesium ions are present in the sample, the indicator combines with them to form a red-colored complex. The titrant in this test is EDTA (ethylenediaminetetraacetic acid, used with its salts in the titration method), a "chelant" which actually "pulls" the calcium and magnesium ions away from a red-colored complex. The EDTA is added dropwise to the sample until all the calcium and magnesium ions have been "chelated" away from the complex and the indicator returns to its normal blue color. The amount of EDTA required to cause the color change is a direct indication of the amount of calcium and magnesium ions in the sample.

Some hardness kits include an additional indicator that is specific for calcium. This type of kit will provide three readings: total hardness, calcium hardness, and magnesium hardness. For interference, precision, and accuracy, consult the latest edition of *Standard Methods.*

pH Measurement

pH is defined as the negative log of the hydrogen ion concentration of the solution. This is a measure of the ionized hydrogen in solution. Simply, it is the relative acidity or basicity of the solution. The chemical and physical properties, and the reactivity of almost every component in water is dependent upon pH. It relates to corrosivity, contaminant solubility, and the water's conductance, and has a secondary MCL range set at 6.5–8.5.

Analytical and Equipment Considerations

The pH can be analyzed in the field or in the lab. If analyzed in the lab, it must be measured within 2 hours of the sample collection, because the pH will change as the carbon dioxide from the air dissolves in the water, bringing the pH toward 7.

If your program requires a high degree of accuracy and precision in pH results, the pH should be measured with a laboratory quality pH meter and electrode. Meters of this quality range cost from around $250–$1000. Color comparators and pH "pocket pals" are suitable for most other purposes. The cost of either of these is in the $50 range. The lower cost of the alternatives might be attractive if multiple samplers are used to sample several sites at the same time.

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[*] Keep in mind that when measuring calcium hardness, the concentration of calcium is routinely measured separately from total hardness. Its concentration in waters can range from zero to several thousand mg/L, as $CaCO_3$. Likewise, when measuring magnesium hardness, magnesium is routinely determined by subtracting calcium hardness from total harness. There is usually less magnesium than calcium in natural water. Lime dosage for water softening operation is partly based on the concentration of magnesium hardness in the water.

pH Meters

A pH meter measures the electric potential (millivolts) across an electrode when immersed in water. This electric potential is a function of the hydrogen ion activity in the sample; therefore, pH meters can display results in either millivolts (mV) or pH units.

A pH meter consists of a potentiometer, which measures the electric potential where it meets the water sample; a reference electrode, which provides a constant electric potential; and a temperature compensating device, which adjusts the readings according to the temperature of the sample (since pH varies with temperature). The reference and glass electrodes are frequently combined into a single probe called a combination electrode.

A wide variety of meters are available, but the most important part of the pH meter is the electrode. Thus, purchasing a good, reliable electrode and following the manufacturer's instructions for proper maintenance is important. Infrequently used or improperly maintained electrodes are subject to corrosion, which makes them highly inaccurate.

pH Pocket Pals and Color Comparators

pH pocket pals are electronic handheld pens that are dipped in the water, providing a digital readout of the pH. They can be calibrated to only one pH buffer. (Lab meters, on the other hand, can be calibrated to two or more buffer solutions and thus are more accurate over a wide range of pH measurements.)

Color comparators involve adding a reagent to the sample that colors the sample water. The intensity of the color is proportional to the pH of the sample, which is then matched against a standard color chart. The color chart equates particular colors to associated pH values, which can be determined by matching the colors from the chart to the color of the sample.

For instructions on how to collect and analyze samples, refer to *Standard Methods*.

Turbidity Measurement

As previously described, turbidity is a measure of water clarity—how much the material suspended in water decreases the passage of light through the water. Turbidity consists of suspended particles in the water and may be caused by a number of materials, organic and inorganic. These particles are typically in the size range of 0.004 mm (clay) to 1.0 mm (sand). The occurrence of turbid source waters may be permanent or temporary. It can affect the color of the water.

Higher turbidity increases water temperatures because suspended particles absorb more heat. This in turn reduces the concentration of DO because warm water holds less DO than cold. Higher turbidity also reduces the amount of light penetrating the water, which reduces photosynthesis and the production of DO. Suspended materials can clog fish gills, reducing resistance to disease in fish, lowering growth rates, and affecting egg and larval development. As the particles settle, they can blanket the stream bottom (especially in slower waters) and smother fish eggs and benthic macroinvertebrates.

Turbidity also affects treatment plant operations. For example, turbidity hinders disinfection by shielding microbes, some of them pathogens, from the disinfectant. Obviously, this is the most significant aspect of turbidity monitoring; the test for it is an indication of the effectiveness of filtration of water supplies. It is important to note that turbidity removal is the principal reason for chemical addition, settling, coagulation, and filtration in potable water treatment. Sources of turbidity include:

1. Soil erosion
2. Waste discharge
3. Urban runoff
4. Eroding stream banks
5. Large numbers of bottom feeders (such as carp), which stir up bottom sediments
6. Excessive algal growth

Sampling and Equipment Considerations

Turbidity can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activity, discharges, and other sources. Turbidity often increases sharply during rainfall, especially in developed watersheds, which typically have relatively high proportions of impervious surfaces. The flow of stormwater runoff from impervious surfaces rapidly increases stream velocity, which increases the erosion rates of streambanks and channels. Turbidity can also rise sharply during dry weather if earth-disturbing activities occur in or near a stream without erosion control practices in place.

Regular monitoring of turbidity can help detect trends that might indicate increasing erosion in developing watersheds. However, turbidity is closely related to stream flow and velocity and should be correlated with these factors. Comparisons of the change in turbidity over time, therefore, should be made at the same point at the same flow.

Keep in mind that turbidity is not a measurement of the amount of suspended solids present or the rate of sedimentation of a stream because it measures only the amount of light that is scattered by suspended particles. Measurement of total solids is a more direct measurement of the amount of material suspended and dissolved in water.

Turbidity is generally measured by using a turbidity meter or tubidimeter. The turbidimeter is a modern nephelometer. [Originally, it was a box containing a light bulb, which directed light at a sample. The amount of light scattered at right angles by the turbidity particles was measured as a measure of the turbidity in the sample, and registered as Nephelometric Turbidity Units (NTU).] The tubidimeter uses a photoelectric cell to register the scattered light on an analog or digital scale, and the instrument is calibrated with permanent turbidity standards composed of the colloidal substance, formazin. Meters can measure turbidity over a wide range—from 0 to 1000 NTUs. A clear mountain stream might have a turbidity of around 1 NTU, whereas a large river like the Mississippi might have a dry-weather turbidity of 10 NTUs. Because these values can jump into hundreds of NTUs during runoff events, the turbidity meter to be used should be reliable over the range in which you will be working. Meters of this quality cost about $800. Many meters in this price range are designed for field or lab use.

An operator may also take samples to a lab for analysis. Another approach, discussed previously, is to measure transparency (an integrated measure of light scattering and absorption) instead of turbidity. Water clarity/transparency can be measured using a Secchi disk or transparency tube. The Secchi disk can only be used in deep, slow-moving rivers; the transparency tube (a comparatively new development) is gaining acceptance in and around the country, but is not yet in wide use.

Using a Secchi Disk

A Secchi disk is a black and white disk that is lowered by hand into the water to the depth at which it vanishes from sight (see Figure 8.11). The distance to vanishing is then recorded—the clearer the water, the greater the distance. Secchi disks are simple to use and inexpensive. For river monitoring they have limited use, however, because in most cases the river bottom will be visible and the disk will not reach a vanishing point. Deeper, slower-moving rivers are the most appropriate places for Secchi disk measurement, although the current might require that the disk be extra-weighted so it does not sway and make measurement difficult. Secchi disks cost about $50; they can also be homemade.

The line attached to the Secchi disk must be marked in waterproof ink according to units designated by the sampling program. Many programs require samplers to measure to the nearest 1/10 meter. Meter intervals can be tagged (e.g., with duct tape) for ease of use.

To measure water clarity with a Secchi disk:

1. Check to make sure that the Secchi disk is securely attached to the measured line.
2. Lean over the side of the boat and lower the Secchi disk into the water, keeping your back to the sun to block glare.

3. Lower the disk until it disappears from view. Lower it one third of a meter and then slowly raise the disk until it just reappears. Move the disk up and down until you find the exact vanishing point.
4. Attach a clothespin to the line at the point where the line enters the water. Record the measurement on your data sheet. Repeating the measurement provides you with a quality control check.

The key to consistent results is to train samplers to follow standard sampling procedures, and if possible, have the same individual take the reading at the same site throughout the season.

Transparency Tube

Pioneered by Australia's Department of Conservation, the transparency tube is a clear, narrow plastic tube marked in units with a dark pattern painted on the bottom. Water is poured into the tube until the pattern painted on the bottom disappears. Some U.S. volunteer monitoring programs [e.g., the Tennessee Valley Authority (TWA) Clean Water Initiative and the Minnesota Pollution Control Agency (MPCA)] are testing the transparency tube in streams and rivers. MPCA uses tubes marked in centimeters, and has found tube readings to relate fairly well to lab measurements of turbidity and total suspended solids, although it does not recommend the transparency tube for applications in highly colored waters or where precise and accurate measurement is required.

The TVA and MPCA recommend the following sampling considerations:

1. Collect the sample in a bottle or bucket in mid-stream and at mid-depth if possible. Avoid stagnant water and sample as far from the shoreline as is safe. Avoid collecting sediment from the bottom of the stream.
2. Face upstream as you fill the bottle or bucket.
3. Take readings in open but shaded conditions. Avoid direct sunlight by turning your back to the sun.
4. Carefully stir or swish the water in the bucket or bottle until it is homogeneous, taking care not to produce air bubbles (these scatter light and affect the measurement). Then pour the water slowly in the tube while looking down the tube. Measure the depth of the water column in the tube at the point where the symbol just disappears.

Orthophosphate Measurement

Earlier we discussed the nutrients phosphorus and nitrogen. Both phosphorus and nitrogen are essential nutrients for plants and animals that make up the aquatic food web. Because phosphorus is the nutrient in short supply in most freshwater systems, even a modest increase in phosphorus can (under the right conditions) set off a whole chain of undesirable events in a stream, including accelerated plant growth, algae blooms, low DO, and the death of certain fish, invertebrates, and other aquatic animals.

Phosphorus comes from many sources, both natural and human. These include soil and rocks, wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic systems, runoff from animal manure storage areas, disturbed land areas, drained wetlands, water treatment, and commercial cleaning preparations.

Forms of Phosphorus

Phosphorus has a complicated story. Pure "elemental" phosphorus (P) is rare. In nature, phosphorus usually exists as part of a phosphate molecule (PO_4). Phosphorus in aquatic systems occurs as organic phosphate and inorganic phosphate. Organic phosphate consists of a phosphate molecule associated with a carbon-based molecule, as in plant or animal tissue. Phosphate that is not associated with organic material is inorganic, the form required by plants. Animals can use either organic or inorganic phosphate.

Both organic and inorganic phosphate can either be dissolved in the water or suspended (attached to particles in the water column).

The Phosphorus Cycle

Phosphorus cycles through the environment, changing form as it does so. Aquatic plants take in dissolved inorganic phosphorus, as it becomes part of their tissues. Animals get the organic phosphorus they need by eating either aquatic plants, other animals, or decomposing plant and animal material.

In water bodies, as plants and animals excrete wastes or die, the organic phosphorus they contain sinks to the bottom, where bacterial decomposition converts it back to inorganic phosphorus, both dissolved and attached to particles. This inorganic phosphorus gets back into the water column when animals, human activity, interactions, or water currents stir up the bottom. Then plants take it up and the cycle begins again.

In a stream system, the phosphorus cycle tends to move phosphorus downstream as the current carries decomposing plant and animal tissue and dissolved phosphorus. It becomes stationary only when it is taken up by plants or is bound to particles that settle in the bottoms of ponds.

In the field of water quality chemistry, phosphorus is described by several terms. Some of these terms are chemistry based (they refer to chemically based compounds), and others are method based (they describe what is measured by a particular method).

The term *orthophosphate* is a chemistry-based term that refers to the phosphate molecule all by itself. More specifically, orthophosphate is the simple phosphate, or reactive phosphate, i.e., Na_3PO_4, sodium phosphate (tribasic), NaH_2PO_4, and sodium phosphate (monobasic). Orthophosphate is the only form of phosphate that can be directly tested for in the laboratory, and is the form that bacteria use directly for metabolic processes. *Reactive phosphorus* is a corresponding method-based term that describes what is actually being measured when the test for orthophosphate is being performed. Because the lab procedure is not quite perfect, mostly orthophosphate is obtained along with a small fraction of some other forms.

More complex inorganic phosphate compounds are referred to as condensed phosphates or polyphosphates. The method-based term for these forms in acid hydrolyzable.

Testing Phosphorus

Testing phosphorus is challenging because it involves measuring very low concentrations, down to 0.01 mg/L or even lower. Even such very low concentrations of phosphorus can have a dramatic impact on streams. Less sensitive methods should be used only to identify serious problem areas.

While many tests for phosphorus exist, only four are likely to be performed by most samplers:

1. The total orthophosphate test is largely a measure of orthophosphate. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate. The USEPA-approved method for measuring is known as the *ascorbic acid method*. Briefly, a reagent (either liquid or powder) containing ascorbic acid and ammonium molybdate reacts with orthophosphate in the sample to form a blue compound. The intensity of the blue color is directly proportional to the amount of orthophosphate in the water.
2. The total phosphate test measures all the forms of phosphorus in the sample (orthophosphate, condensed phosphate, and organic phosphate) by first “digesting” (heating and acidifying) the sample to convert all the other forms to orthophosphate, then the orthophosphate is measured by the ascorbic acid method. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate.
3. The dissolved phosphorus test measures that fraction of the total phosphorus that is in solution in the water (as opposed to being attached to suspended particles). It is determined by first filtering the sample, then analyzing the filtered sample for total phosphorus.
4. Insoluble phosphorus is calculated by subtracting the dissolved phosphorus result from the total phosphorus result.

All these tests have one thing in common—they all depend on measuring orthophosphate. The total orthophosphate test measures the orthophosphate that is already present in the sample. The others measure that which is already present and that which is formed when the other forms of phosphorus are converted to orthophosphate by digestion.

Monitoring phosphorus involves two basic steps:

1. Collecting a water sample
2. Analyzing it in the field or lab for one of the types of phosphorus described above

Sampling and Equipment Considerations

Sample containers made of either some form of plastic or Pyrex® glass are acceptable to the USEPA. Because phosphorus molecules have a tendency to "absorb" (attach) to the inside surface of sample containers, if containers are to be reused, they must be acid-washed to remove absorbed phosphorus. The container must be able to withstand repeated contact with hydrochloric acid. Plastic containers, either high-density polyethylene or polypropylene, might be preferable to glass from a practical standpoint because they are better able to withstand breakage. Some programs use disposable, sterile, plastic Whirl-pak bags. The size of the container depends on the sample amount needed for the phosphorus analysis method chosen, and the amount needed for other analyses to be performed.

All containers that will hold water samples or come into contact with reagents used in the orthophosphate test must be dedicated. They should not be used for other tests, to eliminate the possibility that reagents containing phosphorus will contaminate the labware. All labware should be acid-washed.

The only form of phosphorus this text recommends for field analysis is total orthophosphate, which uses the ascorbic acid method on an untreated sample. Analysis of any of the other forms requires adding potentially hazardous reagents, heating the sample to boiling, and requires too much time and too much equipment to be practical. In addition, analysis for other forms of phosphorus is prone to errors and inaccuracies in field situations. Pretreatment and analysis for these other forms should be handled in a laboratory.

Ascorbic Acid Method for Determining Orthophosphate

In the ascorbic acid method, a combined liquid or prepackaged powder reagent consisting of sulfuric acid, potassium antimonyl tartrate, ammonium molybdate, and ascorbic acid (or comparable compounds) is added to either 50 or 25 mL of the water sample. This colors the sample blue in direct proportion to the amount of orthophosphate in the sample. Absorbence or transmittance is then measured after 10 min, but before 30 min, using a color comparator with a scale in milligrams per liter that increases with the increase in color hue, or an electronic meter that measures the amount of light absorbed or transmitted at a wavelength of 700–880 nm (again, depending on the manufacturer's directions).

A color comparator may be useful for identifying heavily polluted sites with high concentrations (>0.1 mg/L). However, matching the color of a treated sample to a comparator can be very subjective, especially at low concentrations, and lead to variable results.

A field spectrophotometer or colorimeter with a 2.5-cm light path and an infrared photocell (set for a wavelength of 700–880 nm) is recommended for accurate determination of low concentrations (between 0.2 and 0.02 mg/L). Use of a meter requires that a prepared known standard concentration be analyzed ahead of time to convert the absorbence readings of a stream sample to milligrams per liter, or that the meter reads directly in milligrams per liter.

For information on how to prepare standard concentrations and on how to collect and analyze samples, refer to *Standard Methods* and USEPA, 1991 (Method 365.2).

Nitrates Measurement

As mentioned, nitrates are a form of nitrogen found in several different forms in terrestrial and aquatic ecosystems. These forms of nitrogen include ammonia (NH_3), nitrates (NO_3), and nitrites

(NO_2). Nitrates are essential plant nutrients, but excess amounts can cause significant water quality problems. Together with phosphorus, nitrates in excess amounts can accelerate eutrophication, causing dramatic increases in aquatic plant growth and changes in the types of plants and animals that live in the stream. This, in turn, affects DO, temperature, and other indicators. Excess nitrates can cause hypoxia (low levels of DO) and can become toxic to warm-blooded animals at higher concentrations (10 mg/L or higher) under certain conditions. The natural level of ammonia or nitrate in surface water is typically low (<1 mg/L); in the effluent of wastewater treatment plants, it can range up to 30 mg/L. Conventional potable water treatment plants cannot remove nitrate. High concentrations must be prevented by controlling the input at the source.

Sources of nitrates include wastewater treatment plants, runoff from fertilized lawns and cropland, failing on-site septic systems, runoff from animal manure storage areas, and industrial discharges that contain corrosion inhibitors.

Sampling and Equipment Considerations

Nitrates from land sources end up in rivers and streams more quickly than other nutrients like phosphorus, because they dissolve in water more readily than phosphorus, which has an attraction for soil particles. As a result, nitrates serve as a better indicator of the possibility of a source of sewage or manure pollution during dry weather.

Water that is polluted with nitrogen-rich organic matter might show low nitrates. Decomposition of the organic matter lowers the DO level, which in turn slows the rate at which ammonia is oxidized to nitrite and then to nitrates. Under such circumstances, monitoring for nitrites or ammonia (considerably more toxic to aquatic life than nitrate) might be also necessary. (See *Standard Methods* sections 4500-NH3 and 4500-NH2 for appropriate nitrite methods.)

Water samples to be tested for nitrate should be collected in glass or polyethylene containers that have been prepared by using Method B (described previously).

Two methods are typically used for nitrate testing: the cadmium reduction method and the nitrate electrode. The more commonly used cadmium reduction method produces a color reaction measured either by comparison to a color wheel or by use of a spectrophotometer. A few programs also use a nitrate electrode, which can measure in the range of 0–100 mg/L of nitrate. A newer colorimetric immunoassay technique for nitrate screening is also available now.

Cadmium Reduction Method

In the cadmium reduction method, nitrate is reduced to nitrite by passing the sample through a column packed with activated cadmium. The sample is then measured quantitatively for nitrite.

More specifically, the cadmium reduction method is a colorimetric method that involves contact of the nitrate in the sample with cadmium particles, which cause nitrates to be converted to nitrites. The nitrites then react with another reagent to form a red color, in proportional intensity to the original amount of nitrate. The color is measured either by comparison to a color wheel with a scale in milligrams per liter that increases with the increase in color hue, or by use of an electronic spectrophotometer that measures the amount of light absorbed by the treated sample at a 543-nm wavelength. The absorbence value converts to the equivalent concentration of nitrate against a standard curve. Methods for making standard solutions and standard curves are presented in *Standard Methods*.

The sampling/monitoring supervisor before each sampling run should create this curve. The curve is developed by making a set of standard concentrations of nitrate, making them react, developing the corresponding color, and then plotting the absorbence value for each concentration against the concentration. A standard curve could also be generated for the color wheel. Use of the color wheel is appropriate only if nitrate concentrations are greater than 1 mg/L. For concentrations below 1 mg/L, use a spectrophotometer. Matching the color of a treated sample at low concentrations to a color wheel (or cubes) can be very subjective and can lead to variable results. Color comparators can, however, be effectively used to identify sites with high nitrates.

This method requires that the samples being treated are clear. If a sample is turbid, filter it through a 0.45-µm filter. Be sure to test to ensure that the filter is nitrate-free. If copper, iron, or other metals are present in concentrations above several milligrams per liter, the reaction with the cadmium will slow down and the reaction time must be increased.

The reagents used for this method are often prepackaged for different ranges, depending on the expected concentration of nitrate in the stream. For example, Hack provides reagents for the following ranges: low (0–0.40 mg/L), medium (0–15 mg/L), and high (0–30 mg/L). Determining the appropriate range for the stream being monitored is important.

Nitrate Electrode Method

A nitrate electrode (used with a meter) is similar in function to a DO meter. It consists of a probe with a sensor that measures nitrate activity in the water; this activity affects the electric potential of a solution in the probe. This change is then transmitted to the meter, which converts the electric signal to a scale that is read in millivolts; then the millivolts are converted to milligram per liter of nitrate by plotting them against a standard curve. The accuracy of the electrode can be affected by high concentrations of chloride or bicarbonate ions in the sample water. Fluctuating pH levels can also affect the meter reading.

Nitrate electrodes and meters are expensive compared to field kits that employ the cadmium reduction method. (The expense is comparable, however, if a spectrophotometer is used rather than a color wheel.) Meter/probe combinations run between $700 and $1200, including a long cable to connect the probe to the meter. If the program has a pH meter that displays readings in millivolts, it can be used with a nitrate probe and no separate nitrate meter is needed. Results are read directly as milligrams per liter.

Although nitrate electrodes and spectrophotometers can be used in the field, they have certain disadvantages. These devices are more fragile than the color comparators and are therefore more at risk of breaking in the field. They must be carefully maintained and must be calibrated before each sample run, and if many tests are being run, between samplings. This means that samples are best tested in the lab. Note that samples to be tested with a nitrate electrode should be at room temperature, whereas color comparators can be used in the field with samples at any temperature.

Solids Measurement

Solids in water are defined as any matter that remains as residue upon evaporation and drying at 103°C. They are separated into two classes: suspended solids and dissolved solids.

$$\text{Total Solids} \quad = \quad \underset{\text{(nonfilterable residue)}}{\text{Suspended Solids}} \quad + \quad \underset{\text{(filterable residue)}}{\text{Dissolved Solids}}$$

As shown above, total solids are dissolved solids plus suspended and settleable solids in water. In natural freshwater bodies, dissolved solids consist of calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ions—particles that will pass through a filter with pores of around 2 μm (0.002 cm) in size. Suspended solids include silt and clay particles, plankton, algae, fine organic debris, and other particulate matter. These are particles that will not pass through a 2-μm filter.

The concentration of total dissolved solids affects the water balance in the cells of aquatic organisms. An organism placed in water with very low level of solids (distilled water, for example) swells because water tends to move into its cells, which have a higher concentration of solids. An organism placed in water with a high concentration of solids shrinks somewhat because the water in its cells tends to move out. This in turn affects the organism's ability to maintain the proper cell density, making it difficult to keep its position in the water column. It might float up or sink down to a depth to which it is not adapted, and it might not survive.

Higher concentrations of suspended solids can serve as carriers of toxics, which readily cling to suspended particles. This is particularly a concern where pesticides are being used on irrigated crops. Where solids are high, pesticide concentrations may increase well beyond those of the original application as the irrigation water travels down irrigation ditches. Higher levels of solids can also clog irrigation devices and might become so high that irrigated plant roots will lose water rather than gain it.

A high concentration of total solids will make drinking water unpalatable and might have an adverse effect on people who are not used to drinking such water. Levels of total solids that are too high or too low can also reduce the efficiency of wastewater treatment plants, as well as the operation of industrial processes that use raw water.

Total solids affect water clarity. Higher solids decrease the passage of light through water, thereby slowing photosynthesis by aquatic plants. Water heats up more rapidly and holds more heat; this, in turn, might adversely affect aquatic life adapted to a lower temperature regime.

Sources of total solids include industrial discharges, sewage, fertilizers, road runoff, and soil erosion. Total solids are measured in milligrams per liter (mg/L).

Solids Sampling and Equipment Considerations

When conducting solids testing, there are many factors that affect the accuracy of the test or result in wide variations in results for a single sample. These include the following:

1. Drying temperature
2. Length of drying time
3. Condition of desiccator and desiccant
4. Lack of consistency of nonrepresentative samples in test procedure
5. Failure to achieve constant weight prior to calculating results

There are several precautions that can help increase the reliability of test results:

1. Use extreme care when measuring samples, weighing materials, and drying or cooling samples.
2. Check and regulate oven and furnace temperatures frequently to maintain the desired range.
3. Use an indicator drying agent in the desiccator that changes color when it is no longer good—change or regenerate the desiccant when necessary.
4. Keep the desiccator cover greased with the appropriate type of grease—this will seal the desiccator and prevent moisture from entering the desiccator as the test glassware cools.
5. Check ceramic glassware for cracks and glass fiber filter for possible holes. A hole in a glass filter will cause solids to pass through and give inaccurate results.
6. Follow the manufacturer's recommendation for care and operation of analytical balances.

Total solids are important to measure in areas where discharges from sewage treatment plants, industrial plants, or extensive crop irrigation may occur. In particular, streams and rivers, in arid regions where water is scarce and evaporation is high, tend to have higher concentrations of solids, and are more readily affected by human introduction of solids from land-use activities.

Total solids measurements can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activities, sewage treatment plant discharges, and other sources. As with turbidity, concentrations often increase sharply during rainfall, especially in developed watersheds. They can also rise sharply during dry weather if earth-disturbing activities occur in or near the stream without erosion control practices in place. Regular monitoring of total solids can help detect trends that might indicate increasing erosion in developing watersheds. Total solids are closely related to stream flow and velocity, and should be correlated with these factors. Any change in total solids over time should be measured at the same site at the same flow.

Total solids are measured by weighing the amount of solids present in a known volume of sample; this is accomplished by weighing a beaker, filling it with a known volume, evaporating the water in an oven and completely drying the residue, then weighing the beaker with the residue. The total solids concentration is equal to the difference between the weight of the beaker with the residue and the weight of the beaker without it. Since the residue is so light in weight, the lab needs a balance that is sensitive to weights in the range of 0.0001 g. Balances of this type are called analytical or Mettler balances and they are expensive (around $3000). The technique requires that the beakers be kept in a desiccator, a sealed glass container that contains material that absorbs moisture and ensures that the weighing is not biased by water condensing on the beaker. Some desiccants change color to indicate moisture content.

The measurement of total solids cannot be done in the field. Samples must be collected using clean glass or plastic bottles, or Whirl-pak bags and taken to a laboratory where the test can be run.

Total Suspended Solids

As mentioned, the term solids means any material suspended or dissolved in water and wastewater. Although normal domestic wastewater contains a very small amount of solids (usually less than 0.1%), most treatment processes are designed specifically to remove or convert solids to a form that can be removed or discharged without causing environmental harm.

In sampling for total suspended solids (TSS), samples may be either grab or composite and can be collected in either glass or plastic containers. TSS samples can be preserved by refrigeration at or below 4°C (not frozen). However, composite samples must be refrigerated during collection. The maximum holding time for preserved samples is 7 days.

Test Procedure

In short, to conduct a TSS test procedure, a well-mixed measured sample is poured into a filtration apparatus and with the aid of a vacuum pump or aspirator, is drawn through a preweighed glass fiber filter. After filtration, the glass filter is dried at 103–105°C, cooled, and reweighed. The increase in weight of the filter and solids compared to the filter alone represents the TSS.

An example of the specific test procedure used for TSS is given below.

1. Select a sample volume that will yield between 10 and 200 mg of residue with a filtration time of 10 min or less.

√ **Note:** If filtration time exceeds 10 min, increase filter area or decrease volume to reduce filtration time.

√ **Note:** For nonhomogenous samples or samples with very high solids concentrations (i.e., raw wastewater or mixed liquor), use a larger filter to ensure a representative sample volume can be filtered.

2. Place preweighed glass fiber filter on the filtration assembly in a filter flask.
3. Mix the sample well and measure the selected volume of sample.
4. Apply suction to the filter flask, and wet the filter with a small amount of laboratory-grade water to seal it.
5. Pour the selected sample volume into the filtration apparatus.
6. Draw the sample through the filter.
7. Rinse the measuring device into the filtration apparatus with three successive 10-mL portions of laboratory-grade water. Allow complete drainage between rinsings.
8. Continue suction for 3 min after filtration of final rinse is completed.
9. Remove the glass filter from the filtration assembly (membrane filter funnel or clean Gooch crucible). If using the large disks and membrane filter assembly, transfer the glass filter to a support (aluminum pan or evaporating dish) for drying.
10. Place the glass filter with solids and support (pan, dish, or crucible) in a drying oven.
11. Dry the filter and solids to a constant weight at 103–105°C (at least 1 h).

12. Cool to room temperature in a desiccator.
13. Weigh the filter and support and record the constant weight in the test record.

TSS Calculations

To determine the TSS concentration in milligrams per liter, we use the following equations:

1. To determine weight of dry solids in grams

$$\text{Dry solids, g} = \text{wt. of dry solids and filter, g} - \text{wt. of dry filter, g} \tag{8.7}$$

2. To determine weight of dry solids in milligrams (mg)

$$\text{Dry solids, mg} = \text{wt. of solids and filter, g} - \text{wt. of dry filter, g} \tag{8.8}$$

3. To determine the TSS concentration in mg/L

$$\text{TSS, mg/L} = \frac{\text{Dry Solids, mg} \times 1000 \text{ mL}}{\text{mL sample}} \tag{8.9}$$

Example 8.4

Problem:

Using the data provided below, calculate TSS:

Sample volume, mL	250 mL
Weight of dry solids and filter, g	2.305 g
Weight of dry filter, g	2.297 g

Solution:

$$\text{Dry solids, g} = 2.305\text{ g} - 2.297\text{ g} = 0.008\text{ g}$$
$$\text{Dry solids, mg} = 0.008\text{ g} \times 1{,}000\text{ mg/g} = 8\text{ mg}$$

$$\text{TSS, mg/L} = \frac{8.0 \times 1000 \text{ mL/L}}{250 \text{ mL}} = 32.0 \text{ mg/L}$$

Volatile Suspended Solids Testing

When the TSS are ignited at 550 ± 50°C, the volatile (organic) suspended solids of the sample are converted to water vapor and carbon dioxide and are released into the atmosphere. The solids that remain after the ignition (ash) are the inorganic or fixed solids.

In addition to the equipment and supplies required for the TSS test, you need the following:

1. Muffle furnace (550 ± 50°C)
2. Ceramic dishes
3. Furnace tongs
4. Insulated gloves

Test Procedure

An example of the test procedure used for volatile suspended solids is given below:

1. Place the weighed filter with solids and support from the TSS test in the muffle furnace.
2. Ignite filter, solids, and support at 550 ± 50°C for 15–20 min.

3. Remove the ignited solids, filter, and support from the furnace, and partially air cool.
4. Cool to room temperature in a desiccator.
5. Weigh ignited solids, filter, and support on an analytical balance.
6. Record weight of ignited solids, filter, and support.

Total Volatile Suspended Solids Calculations

To calculate total volatile suspended solids (TVSS) requires the following information:

1. Weights of dry solids, filter, and support in grams
2. Weight of ignited solids, filter, and support in grams

$$\text{Tot. Vol. Susp. Solids, mg/L} = \frac{(\text{A} - \text{C}) \times 1000\ \text{mg/g} \times 1000\ \text{mL/L}}{\text{Sample Vol., mL}} \qquad (8.10)$$

where A is the weight of dried solids, filter, and support and C the weight of ignited solids, filter, and support.

Example 8.5

$$\begin{aligned}\text{Tot. Vol. Susp. Solids} &= \frac{(1.6530\ \text{g} - 1.6330\ \text{g}) \times 1000\ \text{mg/g} \times 1000}{100\ \text{mL}}\\ &= \frac{0.02 \times 1000{,}000\ \text{mg/L}}{100}\\ &= 200\ \text{mg/L}\end{aligned}$$

√ **Note:** Total fixed suspended solids (TFSS) is the difference between the TVSS and the TSS concentrations.

$$\text{Fixed Suspended Solids} = \text{Total Suspended Solids} - \text{Volatile Suspended Solids} \qquad (8.11)$$

Example 8.6

Given:

Total Suspended Solids = 202 mg/L
Total Volatile Suspended Solids = 200 mg/L
Total Fixed Suspended Solids, mg/L = 202 mg/L − 200 mg/L = 2 mg/L

Conductivity Testing

Conductivity is a measure of the capacity of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge), or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well, and therefore have a low conductivity when in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity.

Conductivity in streams and rivers is affected primarily by the geology of the area through which the water flows. Streams that run through areas with granite bedrock tend to have lower conductivity because granite is composed of more inert materials that do not ionize (dissolve into ionic components) when washed into the water. On the other hand, streams that run through areas with clay soils tend to have higher conductivity, because of the presence of materials that ionize when washed into the water. Groundwater inflows can have the same effects, depending on the bedrock they flow through.

Discharges to streams can change the conductivity depending on their make-up. A failing sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate: an oil spill would lower conductivity.

The basic unit of measurement of conductivity is the mho or siemens. Conductivity is measured in micromhos per centimeter (µmhos/cm) or microsiemens per centimeter (µs/cm). Distilled water has conductivity in the range of 0.5–3 µmhos/cm. The conductivity of rivers in the United States generally ranges from 50 to 1500 µmhos/cm. Studies of inland freshwaters indicated that streams supporting good mixed fisheries have a range between 150 and 500 µmhos/cm. Conductivity outside this range could indicate that the water is not suitable for certain species of fish or macroinvertebrates. Industrial waters can range as high as 10,000 µmhos/cm.

Sampling, Testing, and Equipment Considerations

Conductivity is useful as a general measure of source water quality. Each stream tends to have a relatively constant range of conductivity that, once established, can be used as a baseline for comparison with regular conductivity measurements. Significant changes in conductivity could indicate that a discharge or some other source of pollution has entered a stream.

The conductivity test is not routine in potable water treatment, but when performed on source water is a good indicator of contamination. Conductivity readings can also be used to indicate wastewater contamination or saltwater intrusion.

√ **Note:** Distilled water used for potable water analyses at public water supply facilities must have a conductivity of no more than 1 µmho/cm.

Conductivity is measured with a probe and a meter. Voltage is applied between two electrodes in a probe immersed in the sample water. The drop in voltage caused by the resistance of the water is used to calculate the conductivity per centimeter. The meter converts the probe measurement to micromhos per centimeter (µmhos/cm) and displays the result for the user.

√ **Note:** Some conductivity meters can also be used to test for total dissolved solids and salinity. The total dissolved solids concentration in milligrams per liter (mg/L) can also be calculated by multiplying the conductivity result by a factor between 0.55 and 0.9, which is empirically determined (see *Standard Methods* no. 2510).

A suitable conductivity meter costs about $350. Meters in this price range should also measure temperature and automatically compensate for temperature in the conductivity reading. Conductivity can be measured in the field or the lab. In most cases, collecting samples in the field and taking them to a lab for testing is probably better. In this way, several teams can collect samples simultaneously. If testing in the field is important, meters designed for field use can be obtained for about the same cost mentioned above.

If samples are collected in the field to be measured later, the sample bottle should be a glass or polyethylene bottle that has been washed in phosphate-free detergent and rinsed thoroughly with both tap and distilled water. Factory-prepared Whirl-pak bags may be used.

Total Alkalinity

As mentioned, alkalinity is defined as the ability of water to resist a change in pH when acid is added; it relates to the pH buffering capacity of the water. Almost all natural waters have some alkalinity. These alkaline compounds in the water such as bicarbonates (baking soda is one type), carbonates, and hydroxides remove H^+ ions and lower the acidity of the water (which means increased pH). They usually do this by combining with the H^+ ions to make new compounds. Without this acid-neutralizing capacity, any acid added to a stream would cause an immediate change in the pH. Measuring alkalinity is important in determining a stream's ability to neutralize acidic pollution from rainfall or wastewater—one of the best measures of the sensitivity of the stream to acid inputs.

Alkalinity in streams is influenced by rocks and soils, salts, certain plant activities, and certain industrial wastewater discharges.

Total alkalinity is determined by measuring the amount of acid (e.g., sulfuric acid) needed to bring the sample to a pH of 4.2. At this pH, all the alkaline compounds in the sample are "used up." The result is reported as milligrams per liter of calcium carbonate (mg/L $CaCO_3$).

Alkalinity is important in water treatment plant operations. For example, testing for alkalinity in potable water treatment is most important for its relation to coagulant addition; that is, it is important that there exists enough natural alkalinity in the water to buffer chemical acid addition so that floc formation will be optimum, and the turbidity removal can proceed. In water softening, proper chemical dosage will depend on the type and amount of alkalinity in the water. For corrosion control, the presence of adequate alkalinity in a water supply neutralizes any acid tendencies and prevents it from becoming corrosive.

Analytical and Equipment Considerations

For total alkalinity, a double end point titration using a pH meter (or pH "pocket pal") and a digital titrator or burette is recommended. This can be done in the field or in the lab. If alkalinity must be analyzed in the field, a digital titrator should be used instead of a burette, because burettes are fragile and more difficult to set up. The alkalinity method described below was developed by the Acid Rain Monitoring Project of the University of Massachusetts Water Resources Research Center (From River Watch Network: Total Alkalinity and pH Field and Laboratory Procedures, July 1992).

Burettes, Titrators, and Digital Titrators for Measuring Alkalinity

The total alkalinity analysis involves titration. In this test, titration is the addition of small, precise quantities of sulfuric acid (the reagent) to the sample, until the sample reaches a certain pH (known as an end point). The amount of acid used corresponds to the total alkalinity of the sample. Alkalinity can be measured using a burette, titrator, or digital titrator (described below).

1. A burette is a long, graduated glass tube with a tapered tip like a pipette and a valve that opens to allow the reagent to drop out of the tube. The amount of reagent used is calculated by subtracting the original volume in the burette from the volume left after the end point has been reached. Alkalinity is calculated based on the amount used.
2. Titrators forcefully expel the reagent by using a manual or mechanical plunger. The amount of reagent used is calculated by subtracting the original volume in the titrator from the volume left after the end point has been reached. Alkalinity is then calculated based on the amount used or is read directly from the titrator.
3. Digital titrators have counters that display numbers. A plunger is forced into a cartridge containing the reagent by turning a knob on the titrator. As the knob turns, the counter changes in proportion to the amount of reagent used. Alkalinity is then calculated based on the amount used. Digital titrators cost approximately $100.

Digital titrators and burettes allow for much more precision and uniformity in the amount of titrant that is used.

Fecal Coliform Bacteria Testing*

Note: Fecal coliform bacteria are nondisease-causing organisms, which are found in the intestinal tract of all warm-blooded animals. Each discharge of body wastes contains large amounts of these organisms. The presence of fecal coliform bacteria in a stream or lake indicates the presence of

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* Much of the information in this section is from USEPA Test Methods for *Escherichia coli* and Enterococci in Water by the Membrane Filter Procedure (Method no. 1103.1), EPA 600/4-85-076, 1985, and USEPA Bacteriological Ambient Water Quality Criteria for Marine and Fresh Recreational Waters, EPA 440/5-84-002, Cincinnati, OH, Environmental Protection Agency, Office of Research and Development, 1986.

human or animal wastes. The number of fecal coliform bacteria present is a good indicator of the amount of pollution present in the water.

USEPA's 816-F-01-035, November 2001 Total Coliform Rule specifies the following:

1. The purpose of the Total Coliform Rule is to improve public health protection by reducing fecal pathogens to minimal levels through control of total coliform bacteria, including fecal coliforms and *Escherichia coli* (*E. coli*).
2. Establishes a maximum contaminant level (MCL) based on the presence or absence of total coliforms, modifies monitoring requirements including testing for fecal coliforms or *E. coli*, requires use of a sample siting plan, and also requires sanitary surveys for systems collecting fewer than five samples per month.
3. The Total Coliform Rule applies to all public water systems.
4. Implementation of the Total Coliform Rule has resulted in reduction in the risk of illness from disease-causing organisms associated with sewage or animal wastes. Disease symptoms may include diarrhea, cramps, nausea, and possibly jaundice, and associated headaches and fatigue.

Fecal Coliforms: General Information

As mentioned, fecal coliforms are used as indicators of possible sewage contamination because they are commonly found in human and animal feces. Although they are not generally harmful themselves, they indicate the possible presence of pathogenic (disease-causing) bacteria and protozoans that also live in human and animal digestive systems. Their presence in streams suggests that pathogenic microorganisms might also be present, and that swimming in or eating shellfish from the waters might present a health risk. Since testing directly for the presence of a large variety of pathogens is difficult, time-consuming, and expensive, water is usually tested for coliforms and fecal streptococci instead. Sources of fecal contamination in surface waters include wastewater treatment plants, on-site septic systems, domestic and wild animal manure, and storm runoff.

In addition to the possible health risks associated with the presence of elevated levels of fecal bacteria, they can also cause cloudy water, unpleasant odors, and an increased oxygen demand.

√ **Note:** In addition to the most commonly tested fecal bacteria indicators, total coliforms, fecal coliforms, and *E. coli*, fecal streptococci and enterococci are also commonly used as bacteria indicators. The focus of this presentation is on total coliforms and fecal coliforms.

Fecal Coliforms

Fecal coliforms are widespread in nature. All members of the total coliform group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood, and in other places outside the human body. The usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacterial species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as an indicator. For drinking water, total coliforms are still the standard test, because their presence indicates contamination of a water supply by an outside source.

Fecal coliforms, a subset of total coliform bacteria, are more fecal-specific in origin. However, even this group contains a genus, *Klebsiella*, with species that are not necessarily fecal in origin. *Klebsiella* are commonly associated with textile and pulp and paper mill wastes. If these sources discharge to a local stream, consideration should be given to monitoring more fecal and human-specific bacteria. For recreational waters, this group was the primary bacterial indicator until relatively recently, when the USEPA began recommending *E. coli* and enterococci as better indicators of health risk from water contact. Fecal coliforms are still being used in many states as indicator bacteria.

Sampling and Equipment Considerations

Under the EPA's Total Coliform Rule, sampling requirements are specified as follows:

Routine Sampling Requirements

1. Total coliform samples must be collected at sites, which are representative of water quality throughout the distribution system according to a written sample siting plan subject to state review and revision.
2. Samples must be collected at regular time intervals throughout the month except groundwater systems serving 4900 persons or fewer may be collected on the same day.
3. Monthly sampling requirements are based on population served.
4. A reduced monitoring frequency may be available for systems serving 1000 persons or fewer and using only groundwater if a sanitary survey within the past 5 years shows that the system is free of sanitary defects (the frequency may be no less than 1 sample/quarter for community and 1 sample/year for noncommunity systems).
5. Each total coliform-positive routine sample must be tested for the presence of fecal coliforms or *E. coli*.

Repeat Sampling Requirements

1. Within 24 h of learning of a total coliform-positive ROUTINE sample result, at least three REPEAT samples must be collected and analyzed for total coliforms.
2. One REPEAT sample must be collected from the same tap as the original sample.
3. One REPEAT sample must be collected within five service connections upstream.
4. One REPEAT sample must be collected within five service connections downstream.
5. Systems that collect 1 ROUTINE sample per month or fewer must collect a fourth REPEAT sample.
6. If any REPEAT sample is total coliform-positive:
   a. The system must analyze that total coliform-positive culture for fecal coliforms or *E. coli*.
   b. The system must collect another set of REPEAT samples, as before, unless the MCL has been violated and the system has notified the state.

Additional Routine Sample Requirements

A positive ROUTINE or REPEAT total coliform result requires a minimum of five ROUTINE samples be collected the following month the system provides water to the public unless waived by the state. Public system ROUTINE monitoring frequency is shown in Table 8.9.

Other Total Coliform Rule Provisions

1. Systems collecting fewer than five ROUTINE samples per month must have a sanitary survey every 5 years (or every 10 years if it is a noncommunity water system using protected and disinfected groundwater).
2. Systems using surface water or groundwater under the direct influence of surface water (GWUDI) and meeting filtration avoidance criteria must collect and have one coliform sample analyzed each day if the turbidity of the source water exceeds 1 NTU. This sample must be collected from a tap near the first service connection.

Compliance

Compliance is based on the presence or absence of total coliforms. Moreover, compliance is determined each calendar month the system serves water to the public (or each calendar month that sampling occurs for systems on reduced monitoring). The results of ROUTINE and REPEAT samples are used to calculate compliance.

With regard to violations, a monthly MCL violation is triggered if a system collecting fewer than 40 samples per month has greater than 1 ROUTINE/REPEAT sample per month, which is total coliform-positive. In addition, if a system collecting at least 40 samples per month has greater than 5% of the ROUTINE/REPEAT samples in a month total coliform-positive, it is technically in violation of the Total Coliform Rule. An acute MCL violation is triggered if any public water system

TABLE 8.9
Public Water System ROUTINE Monitoring Frequencies

Population	Minimum Samples/Month
25–1,000[a]	1
25–1,000[a]	1
1001–2500	2
2501–3300	3
3301–4100	4
4101–4900	5
4901–5800	6
5801–6700	7
6701–7600	8
7601–8500	9
8501–12,900	10
12,901–17,200	15
17,201–21,500	20
21,501–25,000	25
25,001–33,000	30
33,001–41,000	40
41,001–50,000	50
50,001–59,000	60
59,001–70,000	70
70,001–83,000	80
83,001–96,000	90
96,001–130,000	100
130,000–220,000	120
220,001–320,000	150
320,001–450,000	180
450,001–600,000	210
600,001–780,000	240
780,001–970,000	270
970,001–1,230,000	330
1,520,001–1,850,000	360
1,850,001–2,270,000	390
2,270,001–3,020,000	420
3,020,001–3,960,000	450
≥3,960,001	480

[a] Includes PWSs, which have at least 15 service connections but serve <25 people.

has any fecal coliform- or *E. coli*-positive REPEAT sample or has a fecal coliform- or *E. coli*-positive ROUTINE sample followed by a total coliform-positive REPEAT sample.

The Total Coliform Rule also has requirements for public notification and reporting. For example, for a monthly MCL violation, the violation must be reported to the state no later than the end of the next business day after the system learns of the violation. The public must be notified within 14 days. For an acute MCL violation, the violation must be reported to the state no later than the end of the next business day after the system learns of the violation. The public must be notified within 72 h. Systems with ROUTINE or REPEAT samples that are fecal coliform- or *E. coli*-positive must notify the state by the end of the day they are notified of the result or by the end of the next business day if the state office is already closed.

Sampling and Equipment Considerations

Bacteria can be difficult to sample and analyze for many reasons. Natural bacteria levels in streams can vary significantly; bacterial conditions are strongly correlated with rainfall, making the comparison of wet and dry weather bacteria data a problem; many analytical methods have a low level of precision, yet can be quite complex to accomplish; and absolutely sterile conditions are essential to maintain while collecting and handling samples.

The primary equipment decision to make when sampling for bacteria is what type and size of sample container you will use. Once you have made that decision, the same straightforward collection procedure is used, regardless of the type of bacteria being monitored.

When monitoring bacteria, it is critical that all containers and surfaces with which the sample will come into contact be sterile. Containers made of either some form of plastic or Pyrex glass are acceptable to the USEPA. However, if the containers are to be reused, they must be sturdy enough to survive sterilization using heat and pressure. The containers can be sterilized by using an autoclave, a machine that sterilizes with pressurized steam. If using an autoclave, the container material must be able to withstand high temperatures and pressure. Plastic containers—either high-density polyethylene or polypropylene—might be preferable to glass from a practical standpoint because they will better withstand breakage. In any case, be sure to check the manufacturer's specifications to see whether the container can withstand 15 minutes in an autoclave at a temperature of 121°C without melting. (Extreme caution is advised when working with an autoclave.) Disposable, sterile, plastic Whirl-pak bags are used by a number of programs. The size of the container depends on the sample amount needed for the bacterial analysis method you choose and the amount needed for other analyses.

The two basic methods for analyzing water samples for bacteria in common use are the membrane filtration and multiple tube fermentation methods (described later).

Given the complexity of the analysis procedures and the equipment required, field analysis of bacteria is not recommended. Bacteria can either be analyzed by the volunteer at a well-equipped lab or sent to a state-certified lab for analysis. If you send a bacteria sample to a private lab, make sure that the lab is certified by the state for bacteria analysis. Consider state water quality labs, university and college labs, private labs, wastewater treatment plant labs, and hospitals. You might need to pay these labs for analysis.

On the other hand, if you have a modern lab with the proper equipment and properly trained technicians, the fecal coliform testing procedures described in the following section will be helpful. A note of caution: if you decide to analyze your samples in your own lab, be sure to carry out a quality assurance/quality control program.

Fecal Coliform Testing

Federal regulations cite two approved methods for the determination of fecal coliform in water: (1) multiple tube fermentation or most probable number (MPN) procedure, and (2) membrane filter (MF) procedure.

√ **Note:** Because the MF procedure can yield low or highly variable results for chlorinated wastewater, the USEPA requires verification of results using the MPN procedure to resolve any controversies. However, do not attempt to perform the fecal coliform test using the summary information provided in this handbook. Instead, refer to the appropriate reference cited in the Federal Regulations for a complete discussion of these procedures.

Testing Preparations

The preparations for fecal coliform testing are described below.

Equipment and Techniques

Whenever microbiological testing of water samples is performed, certain general considerations and techniques will be required. Because these are basically the same for each test procedure, they are reviewed here prior to discussion of the two methods.

1. Reagents and Media—All reagents and media utilized in performing microbiological tests on water samples must meet the standards specified in the reference cited in Federal Regulations.
2. Reagent Grade Water—Deionized water that is tested annually and found to be free of dissolved metals and bactericidal or inhibitory compounds is preferred for use in preparing culture media and test reagents, although distilled water may be used.
3. Chemicals—All chemicals used in fecal coliform monitoring must be ACS reagent grade or equivalent.
4. Media—To ensure uniformity in the test procedures, the use of dehydrated media is recommended. Sterilized, prepared media in sealed test tubes, ampoules, or dehydrated media pads are also acceptable for use in this test.
5. Glassware and Disposable Supplies—All glassware, equipment, and supplies used in microbiological testing should meet the standards specified in the references cited in Federal Regulations.

Preparation of Equipment and Chemicals

All glassware used for bacteriological testing must be thoroughly cleaned using a suitable detergent and hot water. The glassware should be rinsed with hot water to remove all traces of residue from the detergent and, finally, should be rinsed with distilled water. Laboratories should use a detergent certified to meet bacteriological standards or, at a minimum, rinse all glassware after washing with two tap water rinses followed by five distilled water rinses.

For sterilization of equipment, the hot air sterilizer or autoclave can be used. When using the hot air sterilizer, all equipment should be wrapped in high-quality (Kraft) paper or placed in containers prior to hot air sterilization. All glassware, except those in metal containers, should be sterilized for a minimum of 60 min at 170°C. Sterilization of glassware in metal containers should require a minimum of 2 h. Hot air sterilization cannot be used for liquids.

When using an autoclave, sample bottles, dilution water, culture media, and glassware may be sterilized by autoclaving at 121°C for 15 min.

Sterile Dilution Water Preparation

The dilution water used for making serial dilutions of the sample is prepared by adding 1.25 mL of stock buffer solution and 5.0 mL of magnesium chloride solution to 1000 mL of distilled or deionized water. The stock solutions of each chemical should be prepared as outlined in the reference cited by the Federal Regulations. The dilution water is then dispensed in sufficient quantities to produce 9 or 99 mL in each dilution bottle following sterilization. If the membrane filter procedure is used, additional 60- to 100-mL portions of dilution water should be prepared and sterilized to provide rinse water required by the procedure.

Serial Dilution Procedure

At times, the density of organisms in a sample makes it difficult to accurately determine the actual number of organisms in the sample. When this occurs, the sample size may need to be reduced to as one millionth of a milliliter. To obtain such small volumes, a technique known as serial dilutions has been developed.

Bacteriological Sampling

Proper technique, equipment, and sample preservation are critical to obtain valid test results that can be utilized in the evaluation of process efficiency of water quality. These factors are especially critical in bacteriological sampling.

1. Sample dechlorination—When samples of chlorinated, effluents are to be collected and tested and the sample must be dechlorinated. Prior to sterilization, place enough sodium thiosulfate solution (10%) in a clean sample container to produce a concentration of 100 mg/L in the sample (for a 120-mL sample bottle, 0.1 mL is usually sufficient). Sterilize the sample container as previously described.

2. Sample procedure:
   - A. Keep the sample bottle unopened after sterilization until the sample is to be collected.
   - B. Remove the bottle stopper and hood or cap as one unit. Do not touch or contaminate the cap or the neck of the bottle.
   - C. Submerge the sample bottle in the water to be sampled.
   - D. Fill the sample bottle approximately three quarters full, but not less than 100 mL.
   - E. Aseptically replace the stopper or cap on the bottle.
   - F. Record the date, time, and location of sampling, as well as the sampler's name and any other descriptive information pertaining to the sample.
3. Sample preservation and storage—examination of bacteriological water samples should be performed immediately after collection. If testing cannot be started within one hour of sampling, the sample should be iced or refrigerated at 4°C or less. The maximum recommended holding time for fecal coliform samples from wastewater is 6 h. The storage temperature and holding time should be recorded as part of the test data.

Multiple Tube Fermentation Technique

The multiple fermentation technique for fecal coliform testing is useful in determining the fecal coliform density in most water, solid, or semisolid samples. Wastewater testing normally requires use of the presumptive and confirming test procedures. It is recognized as the method of choice for any sample that may be controversial (enforcement related). The technique is based on the most probable number of bacteria present in a sample that produces gas in a series of fermentation tubes with various volumes of diluted sample. The MPN is obtained from charts based on statistical studies of known concentrations of bacteria.

The technique utilizes a two-step incubation procedure. The sample dilutions are first incubated in lauryl (sulfonate) tryptose broth for 24–48 h (presumptive test). Positive samples are then transferred to EC broth and incubated for an additional 24 h (confirming test). Positive samples from this second incubation are used to statistically determine the MPN from the appropriate reference chart.

A single media, 24-h procedure is also acceptable. In this procedure, sample dilutions are inoculated in A-1 media and are incubated for 3 h at 35°C, then incubated the remaining 20 h at 44.5°C. Positive samples from these inoculations are then used to statistically determine the MPN value from the appropriate chart.

Fecal Coliform MPN Presumptive Test Procedure

1. Prepare dilutions and inoculate five fermentation tubes for each dilution.
2. Cap all tubes, and transfer to incubator.
3. Incubate 24 + 2 h at 35 ± 0.5°C.
4. Examine tubes for gas.
   - A. Gas present = Positive test—transfer
   - B. No gas = Continue incubation
5. Incubate total time 48 ± 3 h at 35 ± 0.5°C
6. Examine tubes for gas.
   - A. Gas present = Positive test—transfer
   - B. No gas = Negative test

√ **Note:** Keep in mind that the fecal coliform MPN confirming procedure using A-1 broth test is used to determine the MPN/100 mL. The MPN procedure for fecal coliform determinations requires a minimum of three dilutions with five tubes/dilution.

Calculation of Most Probable Number (MPN)/100 mL

The calculation of the MPN test results requires selection of a valid series of three consecutive dilutions. The number of positive tubes in each of the three selected dilution inoculations is used to determine the MPN/100 mL. In selecting the dilution inoculations to be used in the calculation, each dilution is expressed as a ratio of positive tubes per tubes inoculated in the dilution, i.e., three positive/five inoculated (3/5). There are several rules to follow for determining the most valid series of dilutions. In the following examples, four dilutions were used for the test.

1. Using the confirming test data, select the highest dilution showing all positive results (no lower dilution showing less than all positive) and the next two higher dilutions.
2. If a series shows all negative values with the exception of one dilution, select the series that places the only positive dilution in the middle of the selected series.
3. If a series shows a positive result in a dilution higher than the selected series (using rule no. 1), it should be incorporated into the highest dilution of the selected series.

After selecting the valid series, the MPN/1000 mL is determined by locating the selected series on the MPN reference chart. If the selected dilution series matches the dilution series of the reference chart, the MPN value from the chart is the reported value for the test. If the dilution series used for the test does not match the dilution series of the chart, the test result must be calculated.

$$\text{MPN/10 mL} = \text{MPNchart} \times \frac{\text{Sample vol. in 1st dilution}_{\text{chart}}}{\text{Sample vol. in 1st dilution}_{\text{sample}}} \tag{8.12}$$

Membrane Filtration Technique

The membrane filtration technique can be useful for determining the fecal coliform density in wastewater effluents, except for primary treated wastewater that has not been chlorinated, or wastewater containing toxic metals or phenols. Chlorinated secondary or tertiary effluents may be tested using this method, but results are subject to verification by MPN technique.

The membrane filter technique utilizes a specially designed filter pad with uniformly sized pores (openings) that are small enough to prevent bacteria from entering the filter. Another unique characteristic of the filter allows liquids, such as the media, placed under the filter to pass upward through the filter to provide nourishment required for bacterial growth.

√ **Note:** In the membrane filter method, the number of colonies grown estimates the number of coliforms.

Membrane Filter Procedure

1. Sample filtration
   - A. Select a filter and aseptically separate it from the sterile package.
   - B. Place the filter on the support plate with the grid side up.
   - C. Place the funnel assembly on the support; secure as needed.
   - D. Pour 100 mL of sample or serial dilution onto the filter; apply vacuum.

√ **Note:** The sample size and necessary serial dilution should produce a growth of 20–60 fecal coliform colonies on at least one filter. The selected dilutions must also be capable of showing permit excursions.

   - E. Allow all of the liquid to pass through the filter.
   - F. Rinse the funnel and filter with three portions (20–30 mL) of sterile, buffered dilution water. (Allow each portion to pass through the filter before the next addition.)

√ **Note:** Filtration units should be sterile at the start of each filtration series and should be sterilized again if the series is interrupted for 30 min or more. A rapid interim sterilization can be accomplished by 2 min exposure to ultraviolet (UV) light, flowing steam, or boiling water.

2. Incubation
   - A. Place absorbent pad into culture dish using sterile forceps.
   - B. Add 1.8–2.0 mL M-FC media to the absorbent pad.
   - C. Discard any media not absorbed by the pad.

D. Filter sample through sterile filter.
E. Remove filter from assembly, and place on absorbent pad (grid up).
F. Cover culture dish.
G. Seal culture dishes in a weighed plastic bag.
H. Incubate filters in a water bath for 24 h at 44.5 ± 0.2°C.

Colony Counting

Upon completion of the incubation period, the surface of the filter will have growths of both fecal coliform and nonfecal coliform bacterial colonies. The fecal coliform will appear blue in color, while nonfecal coliform colonies will appear gray or cream colored.

When counting the colonies, the entire surface of the filter should be scanned using a 10–15x binocular, wide-field dissecting microscope.

The desired range of colonies for the most valid fecal coliform determination is 20–60 colonies per filter. If multiple sample dilutions are used for the test, counts for each filter should be recorded on the laboratory data sheet.

1. Too many colonies—Filters that show a growth over the entire surface of the filter with no individually identifiable colonies should be recorded as “confluent growth.” Filters that show a very high number of colonies (greater than 200) should be recorded as TNTC (too numerous to count).
2. Not enough colonies—If no single filter meets the desired minimum colony count (20 colonies), the sum of the individual filter counts and the respective sample volumes can be used in the formula to calculate the colonies/100 mL.

√ **Note:** In each of these cases, adjustments in sample dilution volumes should be made to ensure future tests meet the criteria for obtaining a valid test result.

Calculation

The fecal coliform density can be calculated using the following formula:

$$\text{Colonies/100 mL} = \frac{\text{Colonies counted}}{\text{Sample volume, mL}} \times 100 \text{ mL} \tag{8.13}$$

EXAMPLE 8.7

Problem:

Using the data shown below, calculate the colonies per 100 mL for the influent and effluent samples noted.

Sample Location	Influent	Sample	Dilutions	Effluent	Sample	Dilutions
Sample (mL)	1.0	0.1	0.01	10	1.0	0.1
Colonies counted	97	48	16	10	5	3

Solution:

Step 1: Influent sample

Select the influent sample filter that has a colony count in the desired range (20–60). Because one filter meets this criterion, the remaining influent filters that did not meet the criterion are discarded.

$$\text{Colonies/100 mL} = \frac{48 \text{ colonies}}{0.1 \text{ mL}} \times 100 \text{ mL}$$

$$= 48000 \text{ colonies/100 mL}$$

Step 2: Effluent sample

Because none of the filters for the effluent sample meets the minimum test requirement, the colonies/100 mL must be determined by totaling the colonies on each filter and the sample volumes used for each filter.

$$\text{Total colonies} = 10 + 5 + 3 = 18 \text{ colonies}$$

$$\text{Total sample} = 10.0\,\text{mL} + 1.0\,\text{mL} + 0.1\,\text{mL} = 11.1\,\text{mL}$$

$$\text{colonies/100 mL} = \frac{18 \text{ colonies}}{11.1 \text{ mL}} \times 100$$

$$= 162 \text{ colonies/100 mL}$$

√ **Note:** The USEPA criterion for fecal coliform bacteria in bathing waters is a logarithmic mean of 200/100 mL, based on the minimum of five samples taken over a 30-day period, with not more than 10% of the total samples exceeding 400/100 mL. Because shellfish may be eaten without being cooked, the strictest coliform criterion applies to shellfish cultivation and harvesting. The USEPA criterion states that the mean fecal coliform concentration should not exceed 14/100 mL, with not more than 10% of the samples exceeding 43/100 mL.

Interferences

Large amounts of turbidity, algae, or suspended solids may interfere with this technique, blocking the filtration of the sample through the membrane filter. Dilution of these samples to prevent this problem may make the test inappropriate for samples with low fecal coliform densities because the sample volumes after dilution may be too small to give representative results. The presence of large amounts of noncoliform group bacteria in the samples may also prohibit the use of this method.

√ **Note:** Many NPDES discharge permits require fecal coliform testing. Results for fecal coliform testing must be reported as a geometric mean (average) of all the test results obtained during a reporting period. A geometric mean, unlike an arithmetic mean or average, dampens the effect of very high or low values that otherwise might cause a nonrepresentative result.

Apparent Color Testing/Analysis

As mentioned, color in water often originates from organic sources: decomposition of leaves, and other forest debris such as bark and pine needles. Tannins and lignins, organic compounds, dissolve in water. Some organics bond to iron to produce soluble color compounds. Biodegrading algae from recent bloom may cause significant color. Though less likely a source of color in water, possible inorganic sources of color are salts of iron, copper, and potassium permanganate added in excess at the treatment plant.

√ **Note:** Noticeable color is an objectionable characteristic that makes the water psychologically unacceptable to the consumer.

Recall that true color is dissolved. It is measured colorimetrically and compared against an EPA color standard.

Apparent color may be caused by suspended material (turbidity) in the water. It is important to point out that even though it may also be objectionable in the water supply, it is not meant to be measured in the color analysis or test. Probably the most common cause of apparent color is particulate oxidized iron.

Over the years, several attempts to standardize the method of describing the "apparent" color of water using comparisons to color standards have been made. *Standard Methods* recognizes the visual comparison method as a reliable method of analyzing water from the distribution system.

One of the visual comparison methods is the Forel-Ule Color Scale, consisting of a dozen shades ranging from deep blue to khaki green, typical of offshore and coastal bay waters. By using established color standards, people in different areas can compare test results.

Another visual comparison method is the Borger Color System, which provides an inexpensive, portable color reference for shades typically found in natural waters; it can also be used for its original purpose—describing the colors of insects and larvae found in streams of lakes. The Borger Color System also allows the recording of the color of algae and bacteria on streambeds.

√ **Note:** Do not leave color standard charts and comparators in direct sunlight.

Measured levels of color in water can serve as indicators for a number of conditions. For example, transparent water with a low accumulation of dissolved minerals and particulate matter usually appears blue, and indicates low productivity. Yellow to brown color normally indicates that the water contains dissolved organic materials, humic substances from soil, peat, or decaying plant material. Deeper yellow to reddish colors indicates some algae and dinoflagellates. A variety of yellows, reds, browns, and grays are indicative of soil runoff.

√ **Note:** Color by itself has no health significance in drinking waters. A secondary MCL is set at 15 color units, and it is recommended that community supplies provide water that has less color.

To ensure reliable and accurate descriptions of apparent color, use a system of color comparisons that is reproducible and comparable to the systems used by other groups.

In treating for color in water, alum and ferric coagulation is often effective. It removes apparent color and often much of the true color. Oxidation of color causing compounds to a noncolored version is sometimes effective. Activated carbon treatment may adsorb some of the organics causing color. For apparent color problems, filtration is usually effective in trapping the colored particles.

Odor Analysis of Water

Odor is expected in wastewater—the fact is, any water containing waste, especially human waste, has a detectable (expected) odor associated with it. Odor in a raw water source (for potable water) is caused by a number of constituents. For example, chemicals that may come from municipal and industrial waste discharges, or natural sources such as decomposing vegetable matter or microbial activity may cause odor problems. Odor affects the acceptability of drinking water, the aesthetics of recreation water, and the taste of aquatic foodstuffs.

The human nose can accurately detect a wide variety of smells and is the best odor-detection and testing device presently available. To measure odor, collect a sample in a large-mouthed jar. After waving off the air above the water sample with your hand, smell the sample. Use the list of odors provided in Table 8.10—a system of qualitative description that helps monitors describe and record detected odors to describe the smells. Record all observations. (See *Standard Methods*.)

In treating for odor in water, removal depends upon the source of the odor. Some organic substances that cause odor can be removed with powdered activated carbon. If the odor is of gaseous origin, scrubbing (aeration) may remove it. Some odor-causing chemicals can be oxidized to odorless chemicals with chlorine, potassium permanganate, or other oxidizers. Settling may remove some material that when later dissolved in the water may have potential odor-causing capacity.

Unfortunately, the test for odor in water is subjective. There is no scientific means of measurement and no method is very accurate.

TABLE 8.10
Descriptions of Odors

Nature of Odor	Description	Examples
Aromatic	Spicy	Camphor, cloves, lavender
Balsamic	Flowery	Geranium, violet, vanilla
Chemical	Industrial wastes or chlorinous treatments	Chlorine
	Hydrocarbon	Oil refinery wastes
	Medicinal	Phenol and iodine
	Sulfur	Hydrogen sulfide
Disagreeable	Fishy	Dead algae
	Pigpen	Algae
	Septic	Stale sewage
Earthy	Damp earth	
	Peaty	Peat
Grassy	Crushed grass	
Musty	Decomposing straw	
Moldy		
Vegetable	Root vegetables	Damp cellar

Source: Adapted from American Public Health Association, *Standard Methods*, 20th ed., American Public Health Association, Washington, DC, 1998.

In testing odor in water intended for potable water use, a sample is generally heated to 60°C. Odor is observed and recorded. A threshold odor number (TON) is assigned. TON is found by using the following equation:

$$\text{TON} = \frac{\text{Total Volume of Water Sample}}{\text{Lowest Sample Volume with Odor}} \tag{8.14}$$

Chlorine Residual Testing/Analysis

Chlorination is the most widely used means of disinfecting water in the United States. When chlorine gas is dissolved into (pure) water, if forms hypochlorous acid, hypochlorite ion, and hydrogen chloride (hydrochloric acid).

The total concentration of HOCl and OCl ion is known as free chlorine residual.

Currently, federal regulations cite six approved methods for determination of total residual chlorine (TRC):

1. DPD—spectrophotometric
2. Titrimetric—amperometric direct
3. Titrimetric—iodometric direct
4. Titrimetric—iodometric back
   A. Starch iodine endpoint—iodine titrant
   B. Starch iodine endpoint—iodate titrant
5. Amperometric endpoint
6. DPD-FAS titration
7. Chlorine electrode

All of these test procedures are approved methods, and unless prohibited by the plant's NPDES discharge permit, can be used for effluent testing. Based on the current most popular method usage in the United States, discussion is limited to the following:

1. DPD-spectrophotometric
2. DPD-FAS titration
3. Titrimetric—amperometric direct

√ **Note:** Treatment facilities required to meet "nondetectable" total residual chlorine limitations must use one of the test methods specified in the plant's NPDES discharge permit.

For information on any of the other approved methods, refer to the appropriate reference cited in the CFRs.

Fluorides

It has long been accepted that a moderate amount of fluoride ions (F^-) in drinking water contributes to good dental health—it has been added to many community water supplies throughout the United States to prevent dental caries in children's teeth. Fluoride is seldom found in appreciable quantities of surface waters and appears in groundwater in only a few geographical regions. Fluorides are used to make ceramics and glass. In large quantities fluoride is toxic to humans and to some animals.

The chemicals added to potable water in treatment plants are:

NaF	Sodium fluoride, solid
Na_2SiF_6	Sodium silicofluoride, solid
H_2SiF_6	Hydrofluosilicic acid; most widely used

Analysis of the fluoride content of water can be performed using the colorimetric method. In this test, fluoride ion reacts with zirconium ion and produces zirconium fluoride, which bleaches an organic red dye in direct proportion to its concentration. This can be compared to standards and read colorimetrically.

RECOMMENDED READING

American Public Health Association, 1998. *Standard Methods*, 20th ed. Washington, DC: American Public Health Association.

AWWA, 1995. *Water Treatment*. Denver: American Water Works Association.

Barbour, M.T., Gerritsen, J., Snyder, B.D., and Stibling, J.B., 1997. *Revision to Rapid Bioassessment Protocols for Use in Streams and Rivers, Periphyton, Benthic, Microinvertebrates, and Fish*. EPA 841-D-97-002. Washington, DC: U.S. Environmental Protection Agency.

Bly, T.D. and Smith, G.F., 1994. *Biomonitoring Our Streams: What's It All About*? Nashville, TN: U.S. Geological Survey.

Botkin, D.B., 1990. *Discordant Harmonies*. New York: Oxford University Press.

Camann, M., 1996. *Freshwater Aquatic Invertebrates: Biomonitoring*. Available at http://www.humboldt.edu.

Harr, J., 1995. *A Civil Action*. New York: Vintage Books.

Hillborn, R. and Mangel, M., 1997. *The Ecological Detective: Confronting Models with Data*. Princeton, NJ: Princeton University Press.

Huff, W.R., 1993. Biological Indices Define Water Quality Standard. *Water Environ. Technol.*, 5:21–22.

Huston, M.A., 1994. *Biological Diversity: The Coexistence of Species on Changing Landscapes*. New York: Cambridge University Press.

Kittrell, F.W., 1969. *A Practical Guide to Water Quality Studies of Streams*. Washington, DC: U.S. Department of Interior.

O'Toole, C. (ed.), 1986. *The Encyclopedia of Insects*. New York: Facts on File.

Pimm, S., 1991. *The Balance of Nature: Ecological Issues in the Conservation of Species and Communities.* Chicago: University of Chicago.

Robert B. Annis Water Resources Institute, 2000. *Plankton Sampling.* Allendale, MI: Robert B. Annis Water Resources Institute, Grand Valley State University, pp. 1–3.

Spellman, F.R., 1999. *Spellman's Standard Handbook for Wastewater Operators*, Vol. 1. Boca Raton: CRC Press.

Spellman, F.R., 2003. *Handbook of Water and Wastewater Treatment Plant Operations.* Boca Raton: Lewis Publishers.

Spellman, F.R. and Drinan, J.E., 2001. *Stream Ecology and Self-Purification: An Introduction.* Boca Raton: CRC Press.

Tchobanoglous, F. and Schroeder, E.D., 1985. *Water Quality.* Reading, MA: Addison-Wesley.

USEPA, 1991. *Methods for Chemical Analysis of Water and Wastes*, 2nd ed, Method 365.2. Washington, DC: U.S. Environmental Protection Agency.

USEPA, 1998. *Standard Methods for the Examination of Water and Wastewater*, 20th ed. Washington, DC: American Public Health Association, pp. 4–129.

USEPA, 2000a. *Monitoring Water Quality: Intensive Stream Bioassay.* Washington, DC: U.S. Environmental Protection Agency.

USEPA, 2000b. *Volunteer Stream Monitoring: A Methods Manual.* Washington, DC: U.S. Environmental Protection Agency, pp. 1–35.

Velz, C.J., 1970. *Applied Stream Sanitation.* New York: Wiley-Interscience.

Running Water. White Oak Canyon Trail. Shenandoah National Forest, Virginia.
(Photo by Revonna M. Bieber.)

9 Water Treatment

If you visit American city,
You will find it very pretty.
Just one thing of which you must beware:
Don't drink the water…

—T. Lehrer (1966)

INTRODUCTION*

He wandered the foggy, filthy, corpse-ridden streets of 1854 London searching, making notes, always looking … seeking a murdering villain—and find the miscreant, he did. He took action; he removed the handle from a water pump. And, fortunately for untold thousands of lives, his was the correct action—the lifesaving action.

He was a detective—of sorts. No, not Sherlock Holmes—but absolutely as clever, as skillful, as knowledgeable, as intuitive—and definitely as driven. His real name: Dr. John Snow. His middle name? Common Sense. Snow's master criminal, his target—a mindless, conscienceless, brutal killer: cholera.

Let us take a closer look at this medical super sleuth and at his quarry, the deadly killer cholera—and at Doctor Snow's actions to contain the spread of cholera. More to the point, let us look at Dr. Snow's subsequent impact on water treatment (disinfection) of raw water used for potable and other purposes.

DR. JOHN SNOW

Dr. John Snow (1813–1858), an unassuming—and creative—London obstetrician, achieved prominence in the mid-19th century for proving his theory (in his *On the Mode of Communication of Cholera*) that cholera is a contagious disease caused by a "poison" that reproduces in the human body and is found in the vomitus and stools of cholera patients. He theorized that the main (although not the only) means of transmission was water contaminated with this poison. His theory was not held in high regard at first because a commonly held and popular countertheory stated that diseases are transmitted by inhalation of vapors. Many theories of cholera's cause were expounded. In the beginning, Snow's argument did not cause a great stir; it was only one of many hopeful theories proposed during a time when cholera was causing great distress. Eventually, Snow was able to prove his theory. We describe how Snow accomplished this later, but for now, let us take a look at Snow's target: cholera.

Cholera

According to the U.S. Centers for Disease Control and Prevention (CDC), cholera is an acute, diarrheal illness caused by infection of the intestine with the bacterium *Vibrio cholera*. The infection is often mild or without symptoms, but it sometimes can be severe. Approximately 1 in 20 infected persons have severe disease symptoms characterized by profuse watery diarrhea, vomiting, and leg cramps. In these persons, rapid loss of body fluids leads to dehydration and shock. Without treatment, death can occur within hours.

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* Adapted from Spellman, F.R., *Choosing Disinfection Alternatives for Water/Wastewater Treatment*, Boca Raton, FL, CRC Press, 1999.

√ **Note:** You don't need to be a rocket scientist to figure out just how deadly cholera was during the London cholera outbreak of 1854. Comparing the state of "medicine" at that time to ours is like comparing the speed potential of a horse and buggy to a state-of-the-art NASCAR race car today. Simply stated, cholera was the classic epidemic disease of the nineteenth century, as the plague had been for the fourteenth. Its defeat was a reflection of both common sense and of progress in medical knowledge—and of the enduring changes in European and American social thought.

How does a person contract cholera? Good question. Again, we refer to the CDC for our answer. A person may contract cholera (even today) by drinking water or eating food contaminated with the cholera bacterium. In an epidemic, the source of the contamination is usually feces of an infected person. The disease can spread rapidly in areas with inadequate treatment of sewage and drinking water. Disaster areas often pose special risks. The aftermath of Hurricane Katrina, for example, in New Orleans caused concern for a potential cholera problem.

Cholera bacterium also lives in brackish river and coastal waters. Shellfish eaten raw have been a source of cholera, and a few people in the United States have contracted cholera after eating raw shellfish from the Gulf of Mexico. The disease is not likely to spread directly from one person to another; therefore, casual contact with an infected person is not a risk for transmission of the disease.

Flashback to 1854 London

The information provided in the preceding section was updated and provided by the CDC in 1996. Basically, for our purposes, the CDC confirms the fact that cholera is a waterborne disease. Today, we know quite a lot about cholera and its transmission, how to prevent infection, and how to treat it. But what did they know about cholera in the 1850s? Not much—however, one thing is certain: They knew cholera was a deadly killer. That was just about all they knew—until Dr. John Snow proved his theory. Recall that Snow theorized that cholera is a contagious disease caused by a poison that reproduces in the human body and is found in the vomitus and stools of cholera victims. He also believed that the main means of transmission was water contaminated with this poison.

Dr. Snow's theory was correct, of course, as we know today. The question is, how did he prove his theory correct? The answer to this provides us with an account of one of the all-time legendary quests for answers in epidemiological research—and an interesting story.

Dr. Snow proved his theory in 1854, during yet another severe cholera epidemic in London. Although ignorant of the concept of bacteria carried in water, Snow traced an outbreak of cholera to a water pump located at an intersection of Cambridge and Broad Street (London).

How did he isolate this source to this particular pump? He accomplished this by mapping the location of deaths from cholera. His map indicated that the majority of the deaths occurred within 250 yards of that water pump. The water pump was used regularly by most of the area residents. Those who did not use the pump remained healthy. Suspecting the Broad Street pump as the plague's source, Snow had the water pump handle removed and ended the cholera epidemic.

Sounds like a rather simple solution, doesn't it? For us, it is simple, but remember, in that era, aspirin had not yet been formulated—to say nothing of other medical miracles we take for granted—for example, antibiotics. Dr. John Snow, by the methodical process of elimination and linkage (Sherlock Holmes would have been impressed—and he was), proved his point, his theory. Specifically, through painstaking documentation of cholera cases and correlation of the comparative incidence of cholera among subscribers to the city's two water companies, Snow showed that cholera occurred much more frequently in customers of the water company that drew its water from the lower Thames, where the river had become contaminated with London sewage. The other company obtained water from the upper Thames. Snow tracked and pinpointed the Broad Street pump's water source. You guessed it: the contaminated lower Thames, of course.

Dr. Snow, the obstetrician, became the first effective practitioner of scientific epidemiology. His creative use of logic, common sense, and scientific information enabled him to solve a major medical mystery—to discern the means by which cholera was transmitted.

PUMP HANDLE REMOVAL—TO WATER TREATMENT (DISINFECTION)

Dr. John Snow's major contribution to the medical profession, to society, and to humanity, in general, can be summarized rather succinctly: He determined and proved that the deadly disease cholera is a waterborne disease. (Dr. John Snow's second medical accomplishment was that he was the first person to administer anesthesia during childbirth.)

What does all of this have to do with water treatment (disinfection)? Actually, Dr. Snow's discovery—his stripping of a mystery to its barest bones—has quite a lot to do with water treatment. Combating any disease is rather difficult without a determination on how the disease is transmitted—how it travels from vector or carrier to receiver. Dr. Snow established this connection, and from his work, and the work of others, progress was made in understanding and combating many different waterborne diseases.

Today, sanitation problems in developed countries (those with the luxury of adequate financial and technical resources) deal more with the consequences that arise from inadequate commercial food preparation, and the results of bacteria becoming resistant to disinfection techniques and antibiotics. We simply flush our toilets to rid ourselves of unwanted wastes, and turn on our taps to take in high-quality drinking water supplies, from which we have all but eliminated cholera and epidemic diarrheal diseases. This is generally the case in most developed countries today—but it certainly wasn't true in Dr. Snow's time.

The progress in water treatment from that notable day in 1854 (when Snow made the "connection" [actually the "disconnection" of handle from pump] between deadly cholera and its means of transmission) to the present reads like a chronology of discovery leading to our modern water treatment practices. This makes sense, of course, because with the passage of time, pivotal events and discoveries occur—events that have a profound effect on how we live today. Let us take a look at a few elements of the important chronological progression that evolved from the simple removal of a pump handle to the advanced water treatment (disinfection) methods we employ today to treat our water supplies.

After Snow's discovery (that cholera is a waterborne disease emanating primarily from human waste), events began to drive the water/wastewater treatment process. In 1859, 4 years after Snow's discovery, the British Parliament was suspended during the summer because the stench coming from the Thames was unbearable. According to one account, the river began to "seethe and ferment under a burning sun." As was the case in many cities at this time, storm sewers carried a combination of storm water, sewage, street debris, and other wastes to the nearest body of water. In the 1890s, Hamburg, Germany suffered a cholera epidemic. Detailed studies by Koch tied the outbreak to the contaminated water supply. In response to the epidemic, Hamburg was among the first cities to use chlorine as part of a wastewater treatment regimen. About the same time, the town of Brewster, New York became the first U.S. city to disinfect its treated wastewater. Chlorination of drinking water was used on a temporary basis in 1896, and its first known continuous use for water supply disinfection occurred in Lincoln, England and Chicago in 1905. Jersey City, New Jersey became one of the first routine users of chlorine in 1908.

Time marched on, and with it came an increased realization of the need to treat and disinfect both water supplies and wastewater. Between 1910 and 1915, technological improvements in gaseous and then solution feed of chlorine made the process more practical and efficient. Disinfection of water supplies and chlorination of treated wastewater for odor control increased over the next several decades. In the United States, disinfection, in one form or another, is now being used by more than 15,000 out of approximately 16,000 publicly owned treatment works (POTWs).

The significance of this number becomes apparent when you consider that fewer than 25 of the 600+ POTWs in the United States in 1910 were using disinfectants.

CONVENTIONAL WATER TREATMENT

This section focuses on water treatment operations and the various unit processes currently used to treat raw source water before it is distributed to the user. In addition, the reasons for water treatment and the basic theories associated with individual treatment unit processes are discussed. Water treatment systems are installed to remove those materials that cause disease or create nuisances. At its simplest level, the basic goal of water treatment operations is to protect public health, with a broader goal to provide potable and palatable water. The bottom line is properly operated water treatment procedures provide water that is safe to drink and is pleasant in appearance, taste, and odor.

In this chapter, water treatment is defined as any unit process that changes/alters the chemical, physical, and bacteriological quality of water with the purpose of making it safe for human consumption and appealing to the customer. Treatment also is used to protect the water distribution system components from corrosion.

Many water treatment processes are commonly used today. Treatment processes used depend upon the evaluation of the nature and quality of the particular water to be treated and the desired quality of the finished water.

In water treatment unit processes employed to treat raw water, one thing is certain: as new USEPA regulations take effect, many more processes will come into use in the attempt to produce water that complies with all the regulations, despite source water conditions.

Small water systems tend to use a smaller number of the wide array of unit treatment processes available, in part because they usually rely on groundwater as the source and in part because small makes many sophisticated processes impractical (i.e., too expensive to install, too expensive to operate, and too sophisticated for limited operating staff). This section concentrates on those individual treatment unit processes usually found in conventional water treatment systems, corrosion control methods, and fluoridation.

WATERWORKS OPERATORS

Operation of a water treatment system, no matter the size or complexity, requires operators. To perform their functions at the highest knowledge and experience level possible, operators must understand the basic concepts and theories behind many complex water treatment concepts and treatment systems. Under new regulations, waterworks operators must be certified/licensed.

Actual water treatment protocols and procedures are important; however, without proper implementation, they are nothing more than hollow words occupying space on reams of paper. This is where the waterworks operator comes in. To successfully treat water requires skill, dedication, and vigilance. The waterworks operator must not only be highly trained and skilled, but also conscientious—the ultimate user demands nothing less.

PURPOSE OF WATER TREATMENT

As mentioned, the purpose of water treatment is to condition, modify, or remove undesirable impurities, to provide water that is safe, palatable, and acceptable to users. While this is the obvious purpose of treating water, various regulations also require water treatment. Some regulations state that if the contaminants listed under the various regulations are found in excess of maximum contaminant levels (MCLs), the water must be treated to reduce the levels. If a well or spring source is surface-influenced, treatment is required, regardless of the actual presence of contamination. Some impurities affect the aesthetic qualities of the water; if they exceed secondary MCLs established by the USEPA and the state, the water may need to be treated.

If we assume that the water source used to feed a typical water supply system is groundwater (usually the case in the United States), a number of common groundwater problems may require water treatment. Keep in mind that water that must be treated for one of these problems may also exhibit several other problems, including:

- Bacteriological contamination
- Hydrogen sulfide odor
- Hard water
- Corrosive water
- Iron and manganese

STAGES OF WATER TREATMENT

Earlier it was stated that the focus in this chapter is on the "conventional" model of water treatment. Figure 9.1 presents the "conventional" model discussed in this text. Figure 9.1 illustrates that water treatment is carried out in various stages or unit processes combined to form one treatment system. Note that a given waterworks may contain all the unit processes discussed in the following or any combination of them. One or more of these stages may be used to treat any one or more of the source water problems listed above. Also, note that the model shown in Figure 9.1 does not necessarily apply to very small water systems. In some small systems, water treatment may consist of nothing more than removal of water via pumping from a groundwater source to storage to distribution. In some small water supply operations, disinfection may be added because it is required. While the water treatment model shown in Figure 9.1 may not exactly mimic the type of treatment process used in most small systems, it is used in this text for illustrative and instructive purposes.

PRETREATMENT

Simply stated, water pretreatment (also called preliminary treatment) is any physical, chemical, or mechanical process used before main water treatment processes. It can include screening, presedimentation, and chemical addition, and usually consists of oxidation or other treatment for the removal of tastes and odors, iron and manganese, trihalomethane precursors, or entrapped gases (like hydrogen sulfide). Treatment processes may include chlorine, potassium permanganate or ozone oxidation, activated carbon addition, aeration, and presedimentation.

Pretreatment of surface water supplies accomplishes the removal of certain constituents and materials that interfere with or place an unnecessary burden on conventional water treatment facilities.

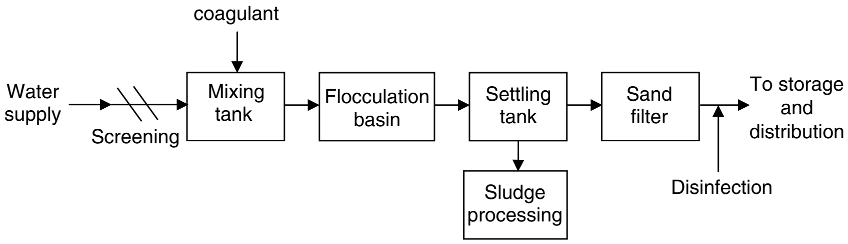

FIGURE 9.1 The conventional water treatment model.

Based on experience and according to the Texas Water Utilities Association's *Manual of Water Utility Operations*, 8th edition, typical pretreatment processes include the following:

1. Removal of debris from water from rivers and reservoirs that would clog pumping equipment.
2. Destratification of reservoirs to prevent anaerobic decomposition that could result in reducing iron and manganese from the soil to a state that would be soluble in water. This can cause subsequent removal problems in the treatment plant. The production of hydrogen sulfide and other taste- and odor-producing compounds also results from stratification.
3. Chemical treatment of reservoirs to control the growth of algae and other aquatic growths that could result in taste and odor problems.
4. Presedimentation to remove excessively heavy silt loads prior to the treatment processes.
5. Aeration to remove dissolved odor-causing gases such as hydrogen sulfide and other dissolved gases or volatile constituents, and to aid in the oxidation of iron and manganese, although manganese or high concentrations of iron are not removed in the detention provided in conventional aeration units.
6. Chemical oxidation of iron and manganese, sulfides, taste- and odor-producing compounds, and organic precursors that may produce trihalomethanes upon the addition of chlorine.
7. Adsorption for removal of tastes and odors.

√ **Note:** An important point to keep in mind is that in small systems, using groundwater as a source, pretreatment may be the only treatment process used or required.

√ **Note:** Pretreatment generally involves aeration or the addition of chemicals to oxidize contaminants that exist in the raw water. It may be incorporated as part of the total treatment process or it may be located adjacent to the source before the water is sent to the treatment facility.

AERATION

Aeration is commonly used to treat water that contains trapped gases (such as hydrogen sulfide) that can impart an unpleasant taste and odor to the water. Just allowing the water to rest in a vented tank will (sometimes) drive off much of the gas, but usually some form of forced aeration is needed. Aeration works well (about 85% of the sulfides may be removed) whenever the pH of the water is <6.5.

Aeration may also be useful in oxidizing iron and manganese, oxidizing humic substances that might form trihalomethanes when chlorinated, eliminating other sources of taste and odor, or imparting oxygen to oxygen-deficient water.

√ **Note:** Iron is a naturally occurring mineral found in many water supplies. When the concentration of iron exceeds 0.3 mg/L, red stains will occur on fixtures and clothing. This increases customer costs for cleaning and replacement of damaged fixtures and clothing.

Manganese, like iron, is a naturally occurring mineral found in many water supplies. When the concentration of manganese exceeds 0.05 mg/L, black stains occur on fixtures and clothing. As with iron, this increases customer costs for cleaning and replacement of damaged fixtures and clothing. Iron and manganese are commonly found together in the same water supply. Iron and manganese are discussed in detail later.

SCREENING

Screening is usually the first important step in the water pretreatment process (see Figure 9.1). It is defined as the process whereby relatively large and suspended debris is removed from the water before it enters the plant. River water, for example, typically contains suspended and floating debris varying in size from small rags to logs. Removing these solids is important not only because these items have no place in potable water, but also because this river trash may cause damage to downstream equipment (clogging and damaging pumps, etc.), increase chemical requirements, impede hydraulic flow in open channels or pipes, or hinder the treatment process. The most important criteria used in the selection of a particular screening system for water treatment technology are the screen opening size and flow rate. Other important criteria include costs related to operation and equipment; plant hydraulics; debris handling requirements; and operator qualifications and availability.

Large surface water treatment plants may employ a variety of screening devices including trash screens (or trash rakes), traveling water screens, drum screens, bar screens, or passive screens.

CHEMICAL ADDITION

Two of the major chemical pretreatment processes used in treating water for potable use are iron and manganese and hardness removal. Another chemical treatment process that is not necessarily part of the pretreatment process, but is also discussed in this section, is corrosion control. Corrosion prevention is accomplished through chemical treatment—not only in the treatment process but also in the distribution process. Before discussing each of these treatment methods in detail, however, it is important to describe chemical addition, chemical feeders, and chemical feeder calibration.

When chemicals are used in the pretreatment process, they must be the proper ones, fed in the proper concentration and introduced to the water at the proper locations. Determining the proper amount of chemical to be used is accomplished by testing. The operator must test the raw water periodically to determine if the chemical dosage should be adjusted. For surface supplies, this checking must be done more frequently than for groundwater (remember, surface water supplies are subject to change on short notice, while groundwaters generally remain stable). The operator must be aware of the potential for interactions between various chemicals and how to determine the optimum dosage (e.g., adding both chlorine and activated carbon at the same point will minimize the effectiveness of both processes, as the adsorptive power of the carbon will be used to remove the chlorine from the water).

√ **Note:** Sometimes using too many chemicals can be worse than not using enough.

Prechlorination (distinguished from chlorination used in disinfection at the end of treatment) is often used as an oxidant to help with the removal of iron and manganese. However, currently, concern for systems that prechlorinate is prevalent because of the potential for the formation of total trihalomethanes (TTHMs), which form as a by-product of the reaction between chlorine and naturally occurring compounds in raw water.

√ **Note:** TTHMs, such as chloroform, are known or suspected to be carcinogenic and are limited by water and state regulations.

The USEPA's TTHM standard does not apply to water systems that serve less than 10,000 people, but operators should be aware of the impact and causes of TTHMs. Chlorine dosage or application point may be changed to reduce problems with TTHMs.

√ **Note:** To be effective, pretreatment chemicals must be thoroughly mixed with the water. Short-circuiting or slug flows of chemicals that do not come in contact with most of the water will not provide proper treatment.

All chemicals intended for use in drinking water must meet certain standards. Thus, when ordering water treatment chemicals, the operator must be assured that chemicals meet all appropriate standards for drinking water use.

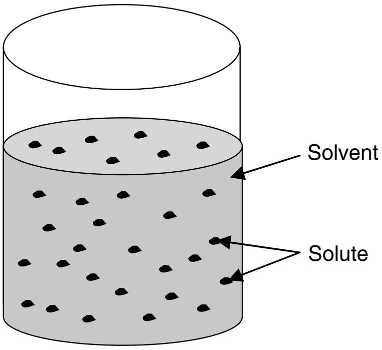

FIGURE 9.2 Solution with two components: solvent and solute.

Chemicals are normally fed with dry chemical feeders or solution (metering) pumps. Operators must be familiar with all the adjustments needed to control the rate at which the chemical is fed to the water. Some feeders are manually controlled and must be adjusted by the operator when the raw water quality or the flow rate changes; other feeders are paced by a flow meter to adjust the chemical feed so it matches the water flow rate. Operators must also be familiar with chemical solution and feeder calibration.

As mentioned, a significant part of the waterworks operator's important daily operational functions includes measuring quantities of chemicals and applying them to water at preset rates. Normally accomplished semiautomatically by use of chemical feed devices, the waterworks operator must still know what chemicals to add, how much to add to the water, and the purpose of the chemical addition.

CHEMICAL SOLUTIONS

A water solution is a homogeneous liquid made of the solvent (the substance that dissolves another substance) and the solute (the substance that dissolves in the solvent). Water is the solvent (see Figure 9.2). The solute (whatever it may be) may dissolve up to a certain limit. This is called its solubility, that is, the solubility of the solute in the particular solvent (water) at a particular temperature and pressure.

Remember, in chemical solutions, the substance being dissolved is called the solute, and the liquid present in the greatest amount in a solution (and that does the dissolving) is called the solvent. We should also be familiar with another term, *concentration*—the amount of solute dissolved in a given amount of solvent. Concentration is measured as

$$\begin{aligned}\%\ \text{Strength} &= \frac{\text{wt. of solute}}{\text{wt. of solution}} \times 100 \\ &= \frac{\text{wt. of solute}}{\text{wt. of solute} + \text{solvent}} \times 100\end{aligned} \tag{9.1}$$

EXAMPLE 9.1

Problem:

If 30 lb of chemical is added to 400 lb of water, what is the percent strength (by weight) of the solution?

Solution:

$$
\begin{aligned}
\%\ \text{Strength} &= \frac{30\ \text{lb solute}}{400\ \text{lb water}} \times 100 \\
&= \frac{30\ \text{lb solute}}{30\ \text{lb solute} + 400\ \text{lb water}} \times 100 \\
&= \frac{30\ \text{lb solute}}{430\ \text{lb solute/water}} \times 100 \\
&= 7.0\ \text{(rounded)}
\end{aligned}
$$

Important to making accurate computations of chemical strength is a complete understanding of the dimensional units involved. For example, you should understand exactly what milligrams per liter (mg/L) signifies.

$$
\text{Milligrams per liter (mg/L)} = \frac{\text{milligrams of solute}}{\text{liters of solution}} \tag{9.2}
$$

Another important dimensional unit commonly used when dealing with chemical solutions is parts per million (ppm).

$$
\text{Parts per million (ppm)} = \frac{\text{parts of solute}}{\text{million parts of solution}} \tag{9.3}
$$

√ **Note:** "Parts" is usually a weight measurement.

For example,

$$
9\ \text{ppm} = \frac{9\ \text{lb solids}}{1{,}000{,}000\ \text{lb solution}}
$$

or

$$
9\ \text{ppm} = \frac{9\ \text{mg solids}}{1{,}000{,}000\ \text{mg solution}}
$$

This leads to two important parameters that water practitioners should commit to memory:

$$
\begin{gathered}
\text{Concentrations—Units and conversions} \\
1\ \text{mg/L} = 1\ \text{ppm} \\
1\% = 10{,}000\ \text{mg/L}
\end{gathered}
$$

When working with chemical solutions, you should also be familiar with two chemical properties briefly described earlier: density and specific gravity. *Density* is defined as the weight of a substance per unit of its volume; for example, pounds per cubic foot or pounds per gallon. *Specific gravity* is defined as the ratio of the density of a substance to a standard density.

$$\text{Density} = \frac{\text{mass of substance}}{\text{volume of substance}} \tag{9.4}$$

Here are a few key facts about density (of water):

- Measured in units of pounds per cubic foot, pounds per gallon, or milligrams per liter
- Density of water = 62.5 lb/f^3 = 8.34 lb/gal
- Other densities: concrete = 130 lb/f^3, alum (liquid at 60°F) = 1.33, and hydrogen peroxide (35%) = 1.132

$$\text{Specific gravity} = \frac{\text{density of substance}}{\text{density of water}} \tag{9.5}$$

Here are a few facts about specific gravity:

- Has no units
- Specific gravity of water = 1.0
- Other specific gravities: concrete = 2.08, alum (liquid at 60°F) = 1.33, and hydrogen peroxide (355) = 1.132

CHEMICAL FEEDERS

Simply put, a chemical feeder is a mechanical device for measuring a quantity of chemical and applying it to water at a preset rate.

Types of Chemical Feeders

Two types of chemical feeders are commonly used: solution (or liquid) feeders and dry feeders. Liquid feeders apply chemicals in solutions or suspensions. Dry feeders apply chemicals in granular or powdered forms.

1. *Solution feeder*—Chemical enters and leaves feeder in a liquid state.
2. *Dry feeder*—Chemical enters and leaves feeder in a dry state.

Solution Feeders

Solution feeders are small, positive displacement metering pumps of three types: (1) reciprocating (piston-plunger or diaphragm types); (2) vacuum-type (e.g., gas chlorinator); or (3) gravity feed rotameter (e.g., drip feeder).

Positive displacement pumps are used in high-pressure, low-flow applications; they deliver a specific volume of liquid for each stroke of a piston or rotation of an impeller.

Dry Feeders

Two types of dry feeders are volumetric and gravimetric, depending on whether the chemical is measured by volume (volumetric-type) or weight (gravimetric-type). Simpler and less expensive than gravimetric pumps, volumetric dry feeders are also less accurate. Gravimetric dry feeders are extremely accurate, deliver high feed rates, and are more expensive than volumetric feeders.

CHEMICAL FEEDER CALIBRATION

Chemical feeder calibration ensures effective control of the treatment process. Obviously, chemical feed without some type of metering and accounting of chemical used adversely affects the water treatment process. Chemical feeder calibration also optimizes economy of operation; it ensures the optimum use of expensive chemicals. Finally, operators must have accurate knowledge of each individual feeder's capabilities at specific settings. When a certain dose must be administered, the operator must rely on the feeder to feed the correct amount of chemical. Proper calibration ensures chemical dosages can be set with confidence.

At a minimum, chemical feeders must be calibrated on an annual basis. During operation, when the operator changes chemical strength or chemical purity or makes any adjustment to the feeder, or when the treated water flow changes, the chemical feeder should be calibrated. Ideally, any time maintenance is performed on chemical feed equipment, calibration should be performed.

What factors affect chemical feeder calibration (feed rate)? For solution feeders, calibration is affected any time solution strength changes, any time a mechanical change is introduced in the pump (change in stroke length or stroke frequency), or whenever flow rate changes. In the dry chemical feeder, calibration is affected any time chemical purity changes, mechanical damage occurs (e.g., belt change), or whenever flow rate changes.

In the calibration process, calibration charts are usually used or made up to fit the calibration equipment. The calibration chart is also affected by certain factors, including change in chemical, change in flow rate of water being treated, and a mechanical change in the feeder.

EXAMPLE 9.2

To demonstrate that performing the chemical feed procedure is not necessarily as simple as opening a bag of chemicals and dumping the contents into the feed system, a real-world example is provided below.

Problem:

Consider the chlorination dosage rates below:

Setting (%)		Dosage (mg/L)
100	111/121	0.93
70	78/121	0.66
50	54/121	0.45
20	20/121	0.16

Solution:

This is not a good dosage setup for a chlorination system. Maintenance of a chlorine residual at the ends of the distribution system should be within 0.5–1.0 ppm. At 0.9 ppm, dosage will probably result in this range—depending on the chlorine demand of the raw water and detention time in the system. However, the pump is set at its highest setting. We have room to decrease the dosage, but no ability to increase the dosage without changing the solution strength in the solution tank. In this example, doubling the solution strength to 1% provides the ideal solution, resulting in the following chart changes.

Setting (%)		Dosage (mg/L)
100	222/121	1.86
70	154/121	1.32
50	108/121	0.90
20	40/121	0.32

This is ideal, because the dosage we want to feed is at the 50% setting for our chlorinator. We can now easily increase or decrease the dosage, whereas the previous setup only allowed the dosage to be decreased.

IRON AND MANGANESE REMOVAL

Iron and manganese are frequently found in groundwater and in some surface waters. They do not cause health-related problems but are objectionable because they may cause aesthetic problems. Severe aesthetic problems may cause consumers to avoid an otherwise safe water supply in favor of one of unknown or of questionable quality, or may cause them to incur unnecessary expense for bottled water.

Aesthetic problems associated with iron and manganese include the discoloration of water (iron, reddish water; manganese, brown or black water); staining of plumbing fixtures; imparting a bitter taste to the water; and stimulating the growth of microorganisms.

As mentioned, there are no direct health concerns associated with iron and manganese, although the growth of iron bacteria slimes may cause indirect health problems.

Economic problems include damage to textiles, dye, paper, and food. Iron residue (or tuberculation) in pipes increases pumping head, decreases carrying capacity, may clog pipes, and may corrode through pipes.

√ **Note:** Iron and manganese are secondary contaminants. Their secondary maximum contaminant levels (SMCLs) are iron = 0.3 mg/L and manganese = 0.05 mg/L.

Iron and manganese are most likely found in groundwater supplies, industrial waste, and acid mine drainage, and as by-products of pipeline corrosion. They may accumulate in lake and reservoir sediments, causing possible problems during lake/reservoir turnover. They are not usually found in running waters (streams, rivers, etc.).

Iron and Manganese Removal Techniques

Chemical precipitation treatments for iron and manganese removal are called deferrization and demanganization. The usual process is aeration; dissolved oxygen in the chemical causing precipitation; and chlorine or potassium permanganate may be required.

Precipitation

Precipitation (or pH adjustment) of iron and manganese from water in their solid forms can be effected in treatment plants by adjusting the pH of the water by adding lime or other chemicals. Some of the precipitate will settle out with time, while the rest is easily removed by sand filters. This process requires the pH of the water to be in the range 10–11.

√ **Note:** While the precipitation or pH adjustment technique for treating water containing iron and manganese is effective, note that the pH level must be adjusted higher (10–11 range) to cause the precipitation, which means that the pH level must then also be lowered (to the 8.5 range or a bit lower) to use the water for consumption.

Oxidation

One of the most common methods of removing iron and manganese is through the process of oxidation (another chemical process), usually followed by settling and filtration. Air, chlorine, or potassium permanganate can oxidize these minerals. Each oxidant has advantages and disadvantages, and each operates slightly differently. We will discuss each oxidant in turn.

Air—To be effective as an oxidant, the air must come in contact with as much of the water as possible. Aeration is often accomplished by bubbling diffused air through the water by spraying the water up into the air or by trickling the water over rocks, boards, or plastic packing materials in an aeration tower. The more finely divided the drops of water, the more oxygen comes in contact with the water and the dissolved iron and manganese.

Chlorine—This is one of the most popular oxidants for iron and manganese control because it is also widely used as a disinfectant; iron and manganese control by prechlorination can be as simple as adding a new chlorine feed point in a facility already feeding chlorine. It also provides a predisinfecting step that can help control bacterial growth through the rest of the treatment system. The downside to chorine use, however, is that when chlorine reacts with the organic materials found in surface water and some groundwaters, it forms TTHMs. This process also requires the pH of the water to be in the range 6.5–7; because many groundwaters are more acidic than this, pH adjustment with lime, soda ash, or caustic soda may be necessary when oxidizing with chlorine.

Potassium permanganate—This is the best oxidizing chemical to use for manganese control removal. As an extremely strong oxidant, it has the additional benefit of producing manganese dioxide during the oxidation reaction. Manganese dioxide acts as an adsorbent for soluble manganese ions. This attraction for soluble manganese provides removal to extremely low levels.

The oxidized compounds form precipitates that are removed by a filter. Note that sufficient time should be allowed from the addition of the oxidant to the filtration step. Otherwise, the oxidation process will be completed after filtration, creating insoluble iron and manganese precipitates in the distribution system.

Ion Exchange

While the ion exchange process is used mostly to soften hard waters, it will also remove soluble iron and manganese. The water passes through a bed of resin that adsorbs undesirable ions from the water, replacing them with less troublesome ions. When the resin has given up all its donor ions, it is regenerated with strong salt brine (sodium chloride); the sodium ions from the brine replace the adsorbed ions and restore the ion exchange capabilities.

Sequestering

Sequestering or stabilization may be used when the water contains mainly low concentration of iron, and the volumes needed are relatively small. This process does not actually remove the iron or manganese from the water but complexes (binds it chemically) it with other ions in a soluble form that is not likely to come out of solution (i.e., not likely oxidized).

Aeration

The primary physical process uses air to oxidize the iron and manganese. The water is either pumped up into the air or allowed to fall over an aeration device. The air oxidizes the iron and manganese that is then removed by using a filter. The addition of lime to raise the pH is often added to the process. While this is called a physical process, removal is accomplished by chemical oxidation.

Potassium Permanganate Oxidation and Manganese Greensand

The continuous regeneration potassium greensand filter process is another commonly used filtration technique for iron and manganese control. Manganese greensand is a mineral (gluconite) that has been treated with alternating solutions manganous chloride and potassium permanganate.

The result is a sand-like (zeolite) material coated with a layer of manganese dioxide—an adsorbent for soluble iron and manganese. Manganese greensand has the ability to capture (adsorb) soluble iron and manganese that may have escaped oxidation as well as the capability of physically filtering out the particles of oxidized iron and manganese. Manganese greensand filters are generally set up as pressure filters, totally enclosed tanks containing the greensand.

The process of adsorbing soluble iron and manganese "uses up" the greensand by converting the manganese dioxide coating into manganic oxide, which does not have the adsorption property.

The greensand can be regenerated in much the same way as ion exchange resins, by washing the sand with potassium permanganate.

HARDNESS TREATMENT

Hardness in water is caused by the presence of certain positively charged metallic ions in solution in the water. The most common of these hardness-causing ions are calcium and magnesium; others include iron, strontium, and barium.

As a general rule, groundwaters are harder than surface waters, so hardness is frequently of concern to the small water system operator. This hardness is derived from contact with soil and rock formations such as limestone. Although rainwater itself will not dissolve many solids, the natural carbon dioxide in the soil enters the water and forms carbonic acid (HCO), which is capable of dissolving minerals. Where soil is thick (contributing more carbon dioxide to the water) and limestone is present, hardness is likely to be a problem. The total amount of hardness in water is expressed as the sum of its calcium carbonate ($CaCO_3$) and its magnesium hardness. However, for practical purposes, hardness is expressed as calcium carbonate. This means that regardless of the amount of the various components that make up hardness, they can be related to a specific amount of calcium carbonate (e.g., hardness is expressed as milligrams per liter as calcium carbonate—mg/L as $CaCO_3$).

√ **Note:** The two types of water hardness are temporary hardness and permanent hardness. Temporary hardness is also known as carbonate hardness (hardness that can be removed by boiling); permanent hardness is also known as noncarbonate hardness (hardness that cannot be removed by boiling).

Hardness is of concern in domestic water consumption because hard water increases soap consumption, leaves a soapy scum in the sink or tub, can cause water heater electrodes to burn out quickly, can cause discoloration of plumbing fixtures and utensils, and is perceived as a less desirable water. In industrial water use, hardness is a concern because it can cause boiler scale and damage to industrial equipment.

The objection of customers to hardness is often dependent on the amount of hardness to which they are accustomed. People familiar with water with a hardness of 20 mg/L might think that a hardness of 100 mg/L is too much. In contrast, a person who has been using water with a hardness of 200 mg/L might think that 100 mg/L was very soft. Table 9.1 lists the classifications of hardness.

Hardness Calculation

Recall that hardness is expressed in mg/L in $CaCO_3$. The mg/L of Ca and Mg must be converted into mg/L as $CaCO_3$ before they can be added.

TABLE 9.1
Classification of Hardness

Classification	mg/L $CaCO_3$
Soft	0–75
Moderately hard	75–150
Hard	150–300
Very hard	Over 300

Source: From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators*, CRC Press, Boca Raton, FL, 1999.

The hardness (in mg/L as $CaCO_3$) for any given metallic ion is calculated using the formula:

$$\begin{aligned}\text{Hardness (mg/L as CaCO}_3) &= M\ (\text{mg/L}) \times \frac{50}{\text{eq. wt. of } M} \\ &= \frac{\text{gram molecular weight}}{\text{valence}}\end{aligned} \tag{9.6}$$

where M is the metal ion concentration (mg/L) and eq. wt. is the equivalent weight.

Treatment Methods

Two common methods used to reduce hardness are ion exchange and cation exchange processes.

Ion Exchange Process

The ion exchange process is the most frequently used process for softening water. Accomplished by charging a resin with sodium ions, the resin exchanges the sodium ions for calcium and magnesium ions. Naturally occurring and synthetic cation exchange resins are available.

Natural exchange resins include substances such as aluminum silicate, zeolite clays (zeolites are hydrous silicates found naturally in the cavities of lavas [greensand]; glauconite zeolites; or synthetic, porous zeolites), humus, and certain types of sediments. These resins are placed in a pressure vessel. Salt brine is flushed through the resins. The sodium ions in the salt brine attach to the resin. The resin is now said to be charged. Once charged, water is passed through the resin and the resin exchanges the sodium ions attached to the resin for calcium and magnesium ions, thus removing them from the water.

The zeolite clays are most common because they are quite durable, can tolerate extreme ranges in pH, and are chemically stable. They have relatively limited exchange capacities, however, so they should be used only for water with a moderate total hardness. One of the results is that the water may be more corrosive than before. Another concern is that addition of sodium ions to the water may increase the health risk of those with high blood pressure.

Cation Exchange Process

The cation exchange process takes place with little or no intervention from the treatment plant operator. Water containing hardness-causing cations (Ca^{2+}, Mg^{2+}, and Fe^{3+}) is passed through a bed of cation exchange resin. The water coming through the bed contains hardness near zero, although it will have elevated sodium content. (The sodium content is not likely to be high enough to be noticeable, but it could be high enough to pose problems to people on highly restricted salt-free diets.) The total lack of hardness in the finished water is likely to make it very corrosive, so normal practice bypasses a portion of the water around the softening process. The treated and untreated waters are blended to produce an effluent with a total hardness around 50–75 mg/L as $CaCO_3$.

CORROSION CONTROL

Water operators add chemicals (e.g., lime or sodium hydroxide) to water at the source or at the waterworks to control corrosion. Using chemicals to achieve slightly alkaline chemical balance prevents the water from corroding distribution pipes and consumers' plumbing. This keeps substances like lead from leaching out of plumbing and into the drinking water.

For our purpose, corrosion is defined as the conversion of a metal into a salt or oxide with a loss of desirable properties such as mechanical strength. Corrosion may occur over an entire exposed surface or may be localized at micro- or macroscopic discontinuities in metal. In all types of corrosion, a gradual decomposition of the material occurs, often due to an electrochemical reaction. Corrosion may be caused by (1) stray current electrolysis; (2) galvanic corrosion caused by dissimilar metals; or (3) differential concentration cells. Corrosion starts at the surface of a material and moves inward.

The adverse effects of corrosion can be categorized according to health, aesthetics, economic effects, and other effects.

The corrosion of toxic metal pipe made from lead creates a serious health hazard. Lead tends to accumulate in the bones of humans and animals. Signs of lead intoxication include gastrointestinal disturbances, fatigue, anemia, and muscular paralysis. Lead is not a natural contaminant in either surface waters or groundwaters, and the MCL of 0.005 mg/L in source waters is rarely exceeded. It is a corrosion by-product from high lead solder joints in copper and lead piping. Small dosages of lead can lead to developmental problems in children. The USEPA's Lead and Copper Rule addresses the matter of lead in drinking water exceeding specified action levels.

√ **Note:** The USEPA's Lead and Copper Rule requires that a treatment facility achieve optimum corrosion control.

Cadmium is the only other toxic metal found in samples from plumbing systems. Cadmium is a contaminant found in zinc. Its adverse health effects are best known for being associated with severe cone and kidney syndrome in Japan. The primary maximum contaminant level (PMCL) for cadmium is 0.01 mg/L.

Aesthetic effects that are a result of corrosion of iron are characterized by "pitting" and are a consequence of the deposition of ferric hydroxide and other products and the solution of iron; this is known as *tuberculation*. Tuberculation reduces the hydraulic capacity of the pipe. Corrosion of iron can cause customer complaints of reddish or reddish-brown staining of plumbing fixtures and laundry. Corrosion of copper lines can cause customer complaints of bluish or blue-green stains on plumbing fixtures. Sulfide corrosion of copper and iron lines can cause a blackish color in the water. The by-products of microbial activity (especially iron bacteria) can cause foul tastes and odors in the water.

The economic effects of corrosion may include the need for water main replacement, especially when tuberculation reduces the flow capacity of the main. Tuberculation increases pipe roughness, causing an increase in pumping costs and reducing distribution system pressure. Tuberculation and corrosion can cause leaks in distribution mains and household plumbing. Corrosion of household plumbing may require extensive treatment, public education, and other actions under the Lead and Copper Rule.

Other effects of corrosion include short service life of household plumbing caused by pitting. Buildup of mineral deposits in the hot water system may eventually restrict hot water flow. The structural integrity of steel water storage tanks may deteriorate, causing structural failures. Steel ladders in clear wells or water storage tanks may corrode, introducing iron into the finished water. Steel parts in flocculation tanks, sedimentation basins, clarifiers, and filters may also corrode.

Types of Corrosion

Three types of corrosion occur in water mains: galvanic, tuberculation, and pitting.

1. *Galvanic*—When two dissimilar metals are in contact and are exposed to a conductive environment, a potential exists between them and current flows. This type of corrosion is the result of an electrochemical reaction when the flow of electric current itself is an essential part of the reaction.
2. *Tuberculation*—This refers to the formation of localized corrosion products scattered over the surface in the form of knob-like mounds. These mounds increase the roughness of the inside of the pipe, increasing resistance to water flow, and decreasing the C-factor of the pipe.
3. *Pitting*—Localized corrosion is generally classified as pitting when the diameter of the cavity at the metal surface is the same as or less than the depth.

Factors Affecting Corrosion

The primary factors affecting corrosion are pH, alkalinity, hardness (calcium), dissolved oxygen, and total dissolved solids. Secondary factors include temperature, velocity of water in pipes, and carbon dioxide (CO_2).

Determination of Corrosion Problems

To determine if corrosion is taking place in water mains, materials removed from the distribution system should be examined for signs of corrosion damage. A primary indicator of corrosion damage is pitting. (Note: Measure depth of pits to gauge the extent of damage.) Another common method used to determine if corrosion or scaling is taking place in distribution lines is by inserting special steel specimens of known weight (called coupons) in the pipe and examining them for corrosion after a period of time.

Evidence of leaks, conducting flow tests and chemical tests for dissolved oxygen and toxic metals as well as customer complains (red or black water or laundry and fixture stains) are also used to indicate corrosion problems.

Formulas can also be used to determine corrosion (to an extent). The Langlier saturation index (L.I.) and aggressive index (A.I.) are two of the commonly used indices. The L.I. is a method used to determine if water is corrosive. A.I. refers to waters that have low natural pH, are high in dissolved oxygen, are low in total dissolved solids, and have low alkalinity and low hardness. These waters are very aggressive and can be corrosive. Both L.I. and A.I. are typically used as starting points in determining the adjustments required to produce a film.

1. L.I. approximately 0.5
2. A.I. value of 12 or higher

√ **Note:** L.I. and A.I. are based on the dissolving of and precipitation of calcium carbonate; therefore, the respective indices may not actually reflect the corrosive nature of the particular water for a specific pipe material. However, they can be useful tools in selecting materials or treatment options for corrosion control.

Corrosion Control

As mentioned, one method used to reduce the corrosive nature of water is chemical addition. Selection of chemicals depends on the characteristics of the water where the chemicals can be applied, how they can be applied and mixed with water, and the cost of the chemicals.

Another corrosion control method is aeration. Aeration works to remove carbon dioxide (CO_2); it can be reduced to about 5 mg/L.

Cathodic protection, often employed to control corrosion, is achieved by applying an outside electric current to the metal to reverse the electromechanical corrosion process. The application of D-C current prevents normal electron flow. Cathodic protection uses a sacrificial metal electrode (a magnesium anode) that corrodes instead of the pipe or tank.

Linings, coatings, and paints can also be used in corrosion control. Slip-line with plastic liner, cement mortar, zinc or magnesium, polyethylene, epoxy, and coal tar enamels are some of the materials that can be used.

√ **Caution:** Consult the district engineer before using any protective coatings!

Several corrosive resistant pipe materials are used to prevent corrosion, including:

1. PVC plastic pipe
2. Aluminum

3. Nickel
4. Silicon
5. Brass
6. Bronze
7. Stainless steel
8. Reinforced concrete

In addition to internal corrosion problems, waterworks operators must also be concerned with external corrosion problems. The primary culprit involved with external corrosion of distribution system pipes is soil. The measure of corrosivity of the soil is the soil resistivity. If soil resistivity is >5000 Ω/cm, serious corrosion is unlikely. Steel pipe may be used under these conditions. If soil resistivity is <500 Ω/cm, plastic PVC pipe should be used. For intermediate ranges of soil resistivity (500–5000 Ω/cm), use ductile iron pipe, lining, and coating.

Common operating problems associated with corrosion control include the following:

1. *$CaCO_3$ not depositing a film*—Usually a result of poor pH control (out of the normal range of 6.5–8.5). This may also cause excessive film deposition.
2. *Persistence of red water problems*—Most probably a result of poor flow patterns, insufficient velocity, tuberculation of pipe surface, and presence of iron bacteria.
   A. *Velocity*—Chemicals need to make contact with pipe surface. Dead ends and low-flow areas should have flushing program; dead ends should be looped.
   B. *Tuberculation*—The best approach is to clean with "pig." In extreme cases, clean pipe with metal scrapers and install cement-mortar lining.
   C. *Iron bacteria*—Slime prevents film contact with pipe surface. Slime will grow and lose coating. Pipe cleaning and disinfection program are needed.

COAGULATION

The primary purpose in surface water treatment is chemical clarification by coagulation and mixing, flocculation, sedimentation, and filtration. These units processes, along with disinfection, work to remove particles, naturally occurring organic matter (NOM—i.e., bacteria, algae, zooplankton, and organic compounds), and microbes from water. These units also help to produce water that is noncorrosive. Specifically, coagulation/flocculation work to destabilize particles and agglomerate dissolved and particulate matter. Sedimentation removes solids and provides 1/2 log *Giardia* and 1 log virus removal. Filtration removes solids and provides 2 log *Giardia* and 1 log virus removal. Finally, disinfection provides microbial inactivation and 1/2 *Giardia* and 2 log virus removal.

From Figure 9.3, it can be seen that following screening and the other pretreatment processes, the next unit process in a conventional water treatment system is a mixer where chemicals are added in what is known as coagulation. The exception to this unit process configuration occurs in small

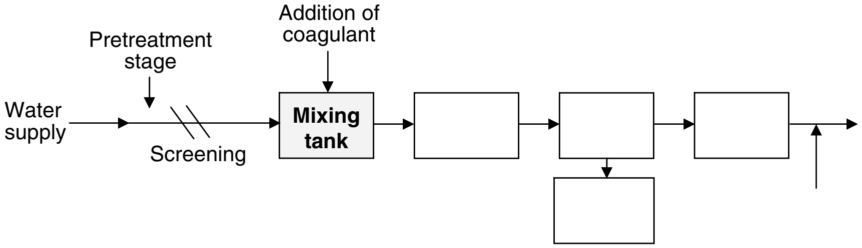

FIGURE 9.3 Coagulation.

systems using groundwater, when chlorine or other taste and odor control measures are introduced at the intake and are the extent of treatment.

Materials present in raw water may vary in size, concentration, and type. Dispersed substances in the water may be classified as suspended, colloidal, or solution.

Suspended particles may vary in mass and size and are dependent on the flow of water. High flows and velocities can carry larger material. As velocities decrease, the suspended particles settle according to size and mass.

Other material may be in solution, for example, salt dissolves in water. Matter in the colloidal state does not dissolve, but the particles are so small they will not settle out of the water. Color (as in tea-colored swamp water) is mainly due to colloids or extremely fine particles of matter in suspension. Colloidal and solute particles in water are electrically charged. Because most of the charges are alike (negative) and repel one another, the particles stay dispersed and remain in the colloidal or soluble state.

Suspended matter will settle without treatment, if the water is still enough to allow it to settle. The rate of settling of particles can be determined, as this settling follows certain laws of physics. However, much of the suspended matter may be so slow in settling that the normal settling processes become impractical, and if colloidal particles are present, settling will not occur. Moreover, water drawn from a raw water source often contains many small unstable (unsticky) particles. Therefore, sedimentation alone is usually an impractical way to obtain clear water in most locations, and another method of increasing the settling rate must be used: coagulation. Simply, coagulation is designed to convert stable (unsticky) particles into unstable (sticky) particles.

The term coagulation refers to the series of chemical and mechanical operations by which coagulants are applied and made effective. These operations consist of two distinct phases: (1) rapid mixing to disperse coagulant chemicals by violent agitation into the water being treated; and (2) flocculation to agglomerate small particles into well-defined floc by gentle agitation for a much longer time.

The coagulant must be added to the raw water and perfectly distributed into the liquid; such uniformity of chemical treatment is reached through rapid agitation or mixing.

Coagulation results from adding salts of iron or aluminum to the water. Common coagulants (salts) are:

- Alum (aluminum sulfate)
- Sodium aluminate
- Ferric sulfate
- Ferrous sulfate
- Ferric chloride
- Polymers

Coagulation is the reaction between one of these salts and water. The simplest coagulation process occurs between alum and water. Alum or aluminum sulfate is made by a chemical reaction of bauxite ore and sulfuric acid. The normal strength of liquid alum is adjusted to 8.3%, while the strength of dry alum is 17%.

When alum is placed in water, a chemical reaction occurs that produces positively charged aluminum ions. The overall result is the reduction of electrical charges and the formation of a sticky substance—the formation of floc, which when properly formed, will settle. These two destabilizing factors are the major contributions that coagulation makes to the removal of turbidity, color, and microorganisms.

Liquid alum is preferred in water treatment because it has several advantages over other coagulants, including:

1. Ease of handling
2. Lower costs

3. Less labor required to unload, store, and convey
4. Elimination of dissolving operations
5. Less storage space required
6. Greater accuracy in measurement and control provided
7. Elimination of the nuisance and unpleasantness of handling dry alum
8. Easier maintenance

The formation of floc is the first step of coagulation; for greatest efficiency, rapid, intimate mixing of the raw water and the coagulant must occur. After mixing, the water should be slowly stirred so that the very small, newly formed particles can attract and enmesh colloidal particles, holding them together to form larger floc. This slow mixing is the second stage of the process (flocculation) and is covered later in this chapter.

A number of factors influence the coagulation process: pH, turbidity, temperature, alkalinity, and the use of polymers. The degree to which these factors influence coagulation depends upon the coagulant use.

The raw water conditions, optimum pH for coagulation, and other factors must be considered before deciding which chemical is to be fed and at what levels.

To determine the correct chemical dosage, a jar test or coagulation test is performed. Jar tests (widely used for many years by the water treatment industry) simulate full-scale coagulation and flocculation processes to determine optimum chemical dosages. It is important to note that jar testing is only an attempt to achieve a ballpark approximation of correct chemical dosage for the treatment process. The test conditions are intended to reflect the normal operation of a chemical treatment facility.

The test can be used to:

1. Select the most effective chemical
2. Select the optimum dosage
3. Determine the value of a flocculant aid and the proper dose

The testing procedure requires a series of samples to be placed in testing jars (see Figure 9.4) and mixed at 100 ppm. Varying amounts of the process chemical or specified amounts of several flocculants are added (one volume/sample container). The mix is continued for 1 min. Next, the mixing is slowed to 30 r/min to provide gentle agitation, and then the floc is allowed to settle. The flocculation period and settling process are observed carefully to determine the floc strength, settleability, and clarity of the supernatant liquor (defined as the water that remains above the settled floc).

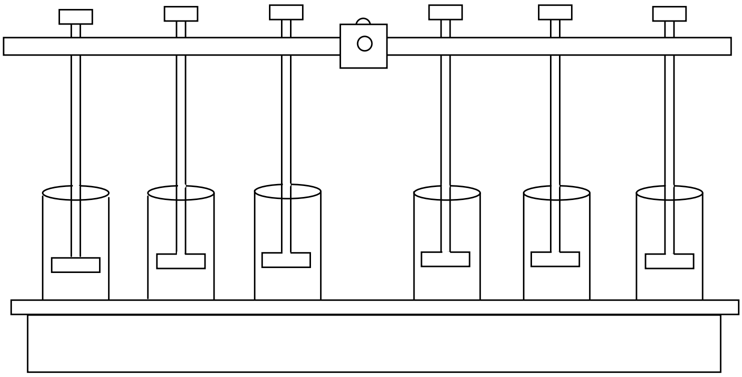

FIGURE 9.4 Variable speed paddle mixer used in jar testing procedure.

Additionally, the supernatant can be tested to determine the efficiency of the chemical addition for removal of total suspended solids (TSS), biochemical oxygen demand, 5/d (BOD_5), and phosphorus.

The equipment required for the jar test includes a 6-position variable speed paddle mixer (see Figure 9.4), six 2-qt wide-mouthed jars, an interval timer, and assorted glassware, pipettes, graduates, and so forth.

JAR TESTING PROCEDURE

1. Place an appropriate volume of water sample in each of the jars 250- to 1000-mL samples may be used, depending upon the size of the equipment being use). Start mixers and set for 100 r/min.
2. Add previously selected amounts of the chemical being evaluated. (Initial tests may use wide variations in chemical volumes to determine the approximate range. This is then narrowed in subsequent tests.)
3. Continue mixing for 1 min.
4. Reduce the mixer speed to a gentle agitation (30 r/min), and continue mixing for 20 min. Again, time and mixer speed may be varied to reflect the facility.

√ **Note:** During this time, observe the floc formation—how well the floc holds together during the agitation (floc strength).

5. Turn off the mixer and allow solids to settle for 20–30 min. Observe the settling characteristics, the clarity of the supernatant, the settleability of the solids, the flocculation of the solids, and the compactability of the solids.
6. Perform phosphate tests to determine removals.
7. Select the dose that provided the best treatment based upon the observations made during the analysis.

√ **Note:** After initial ranges and chemical selections are completed, repeat the test using a smaller range of dosages to optimize performance.

FLOCCULATION

As we see in Figure 9.5, flocculation follows coagulation in the conventional water treatment process. Flocculation is the physical process of slowly mixing the coagulated water to increase the probability of particle collision—unstable particles collide and stick together to form fewer larger flocs. Through experience, we see that effective mixing reduces the required amount of chemicals and greatly improves the sedimentation process, which results in longer filter runs and higher quality finished water.

The goal of flocculation is to form a uniform, feather-like material similar to snowflakes—a dense, tenacious floc that entraps the fine, suspended, and colloidal particles and carries them down rapidly in the settling basin.

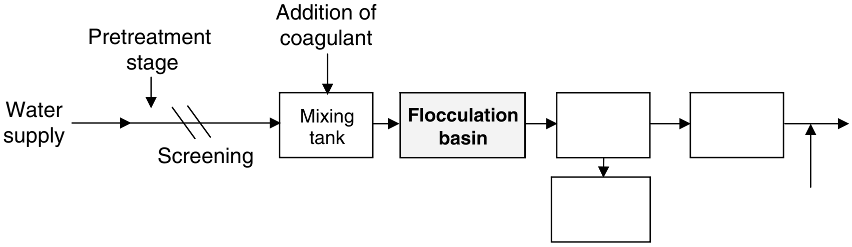

FIGURE 9.5 Flocculation.

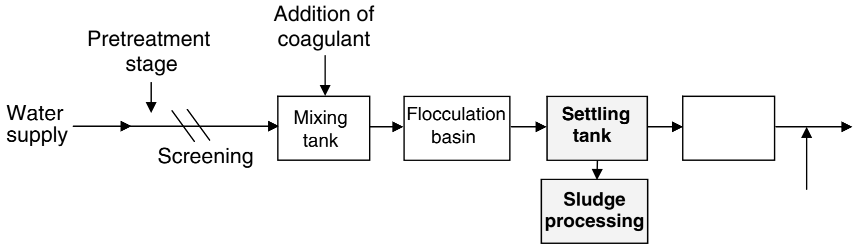

FIGURE 9.6 Sedimentation.

Proper flocculation requires from 15 to 45 min. The time is based on water chemistry, water temperature, and mixing intensity. Temperature is the key component in determining the amount of time required for floc formation.

Polymers are often added to increase the speed of floc formation and the strength and weight of the floc.

SEDIMENTATION

After raw water and chemicals have been mixed and the floc formed, the water containing the floc (because it has a higher specific gravity than water) flows to the sedimentation or settling basin (see Figure 9.6).

Sedimentation is also called clarification. Sedimentation removes settleable solids by gravity. Water moves slowly though the sedimentation tank/basin with a minimum of turbulence at entry and exit points with minimum short-circuiting. Sludge accumulates at the bottom of the tank/basin. Typical tanks or basins used in sedimentation include conventional rectangular basins, conventional center-feed basins, peripheral-feed basins, and spiral-flow basins.

In conventional treatment plants, the amount of detention time required for settling can vary from 2 to 6 h. Detention time should be based on the total filter capacity when the filters are passing 2 gpm/ft^2 of superficial sand area. For plants with higher filter rates, the detention time is based on a filter rate of 3–4 gpm/ft^2 of sand area. The time requirement is dependent on the weight of the floc, the temperature of the water, and how quiescent (still) the basin.

A number of conditions affect sedimentation: (1) uniformity of flow of water through the basin; (2) stratification of water due to difference in temperature between water entering and water already in the basin; (3) release of gases that may collect in small bubbles on suspended solids, causing them to rise and float as scum rather than settle as sludge; (4) disintegration of previously formed floc; and (5) size and density of the floc.

FILTRATION

In the conventional water treatment process, filtration usually follows coagulation, flocculation, and sedimentation (see Figure 9.7). At present, filtration is not always used in small water systems. However, recent regulatory requirements under the USEPA's Interim Enhanced Surface Water Treatment (IESWT) rules may make water filtering necessary at most water supply systems.

Water filtration is a physical process of separating suspended and colloidal particles from water by passing water through a granular material. The process of filtration involves straining, settling, and adsorption. As floc passes into the filter, the spaces between the filter grains become clogged, reducing this opening and increasing removal. Some material is removed merely because it settles on a media grain. One of the most important processes is adsorption of the floc onto the surface of individual filter grains. This helps collect the floc and reduces the size of the openings between the filter media grains.

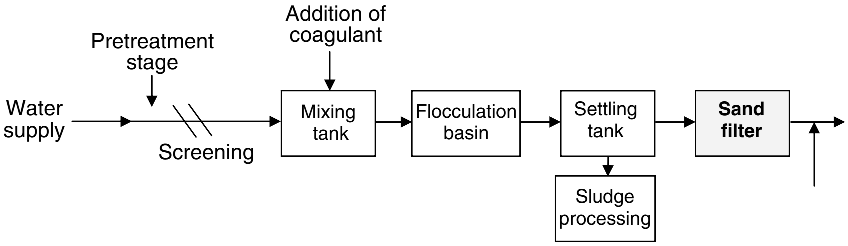

FIGURE 9.7 Filtration.

In addition to removing silt and sediment, floc, algae, insect larvae, and any other large elements, filtration also contributes to the removal of bacteria and protozoans such as *Giardia lamblia* and *Cryptosporidium*. Some filtration processes are also used for iron and manganese removal.

TYPES OF FILTER TECHNOLOGIES

The Surface Water Treatment Rule (SWTR) specifies four filtration technologies, although SWTR also allows the use of alternate filtration technologies, e.g., cartridge filters. These include slow sand filtration/rapid sand filtration, pressure filtration, diatomaceous earth filtration, and direct filtration. Of these, all but rapid sand filtration are commonly employed in small water systems that use filtration. Each type of filtration system has advantages and disadvantages. Regardless of the type of filter, however, filtration involves the processes of straining (where particles are captured in the small spaces between filter media grains), sedimentation (where the particles land on top of the grains and stay there), and adsorption (where a chemical attraction occurs between the particles and the surface of the media grains).

Slow Sand Filters

The first slow sand filter was installed in London in 1829 and was used widely throughout Europe but not in the United States. By 1900, rapid sand filtration began taking over as the dominant filtration technology, and a few slow sand filters are in operation today. However, with the advent of the Safe Drinking Water Act and its regulations (especially the SWTR) and the recognition of the problems associated with *G. lamblia* and *Cryptosporidium* in surface water, the water industry is reexamining slow sand filters. Low-technology requirements may prevent many state water systems from using this type of equipment.

On the plus side, slow sand filtration is well suited for small water systems. It is a proven, effective filtration process with relatively low construction costs and low operating costs (it does not require constant operator attention). It is quite effective for water systems as large as 5000 people, beyond that, surface area requirements and manual labor required to recondition the filters make rapid sand filters more effective. The filtration rate is generally in the range of 45–150 gal/day/ft^2.

Components making up a slow sand filter include the following:

1. A covered structure to hold the filter media
2. An underdrain system
3. Graded rock that is placed around and just above the underdrain
4. The filter media consisting of 30–55 in. of sand with a grain size of 0.25–0.35 mm
5. Inlet and outlet piping to convey the water to and from the filter, and the means to drain filtered water to waste

Flooding the area above the top of the sand layer with water to a depth of 3–5 ft and allowing it to trickle down through the sand operates slow sand filters. An overflow device prevents excessive water depth. The filter must have provisions for filling it from the bottom up, and it must be equipped with a loss-of-head gauge, rate-of-flow control devices (such as a weir, orifice, or butterfly valve), a weir or effluent pipe that assures that the water level cannot drop below the sand surface, and filtered waste sample taps.

When the filter is first placed in service, the head loss through the media caused by the resistance of the sand is about 0.2 ft (i.e., a layer of water 0.2 ft deep on top of the filter will provide enough pressure to push the water downward through the filter). As the filter operates, the media becomes clogged with the material being filtered out of the water, and the head loss increases. When it reaches about 4–5 ft, the filter needs to be cleaned.

For efficient operation of a slow sand filter, the water being filtered should have a turbidity average <5 TU, with a maximum of 30 TU.

Slow sand filters are not backwashed the way conventional filtration units are. The 1–2 inches of material must be removed on a periodic basis to keep the filter operating.

Rapid Sand Filters

The rapid sand filter, which is similar in some ways to the slow sand filter, is one of the most widely used filtration units. The major difference is in the principle of operation, that is, in the speed or rate at which water passes through the media. In operation, water passes downward through a sand bed that removes the suspended particles. The suspended particles consist of the coagulated matter remaining in the water after sedimentation, as well as a small amount of uncoagulated suspended matter.

Some significant differences exist in construction, control, and operation between slow sand filters and rapid sand filters. Because of the construction and operation of the rapid sand filtration with its higher filtration the land area needed to filter the same quantity of water is reduced.

The rapid sand filter structure and equipment include the following:

- Structure to house media
- Filter media
- Travel media support layer
- Underdrain system
- Valves and piping system
- Filter backwash system
- Waste disposal system

Usually 2–3 ft deep, the filter media is supported by approximately 1 ft of gravel. The media may be fine sand or a combination of sand, anthracite coal, and coal (dual-multimedia filter).

Water is applied to a rapid sand filter at a rate of 1.5 gal/min/ft^2 of filter media surface. When the rate is between 4 and 6 gpm/ft^2, the filter is referred to as a high-rate filter; at a rate over 6 gpm/ft^2, the filter is called ultrahigh-rate. These rates compare to the slow sand filtration rate of 45–150 gal/day/ft^2. High-rate and ultrahigh-rate filters must meet additional conditions to assure proper operation.

Generally, raw water turbidity is not that high. However, even if raw water turbidity values exceed 1000 TU, properly operated rapid sand filters can produce filtered water with a turbidity or well under 0.5 TU. The time the filter is in operation between cleanings (filter runs) usually lasts from 12 to 72 h, depending on the quality of the raw water; the end of the run is indicated by the head loss approaching 6–8 ft. Filter breakthrough (when filtered material is pulled through the filter into the effluent) can occur if the head loss becomes too great. Operation with head loss too high can also cause air binding (which blocks part of the filter with air bubbles), increasing the flow rate through the remaining filter area.

Rapid sand filters have the advantage of lower land requirement, and they have other advantages, too. For example, rapid sand filters cost less, are less labor intensive to clean, and offer higher efficiency with highly turbid waters. On the downside, operation and maintenance costs of rapid sand filters are much higher because of the increased complexity of the filter controls and backwashing system.

In backwashing a rapid sand filter, cleaning the filter is accomplished by passing treated water backward (upward) through the filter media and agitating the top of the media. The need for backwashing is determined by a combination of filter run time (i.e., the length of time since the last backwashing), effluent turbidity, and head loss through the filter. Depending on the raw water quality, the run time varies from one filtration plant to another (and may even vary from one filter to another in the same plant).

√ **Note:** Backwashing usually requires 3–7% of the water produced by the plant.

Pressure Filter Systems

When raw water is pumped or piped from the source to a gravity filter, the head (pressure) is lost as the water enters the floc basin. When this occurs, pumping the water from the plant clear well to the reservoir is usually necessary. One way to reduce pumping is to place the plant components into pressure vessels, thus maintaining the head. This type of arrangement is called a pressure filter system. Pressure filters are also quite popular for iron and manganese removal and for filtration of water from wells. They may be placed directly in the pipeline from the well or pump with little head loss. Most pressure filters operate at a rate of about 3 gpm/ft^2.

Operationally the same, and consisting of components similar to those of a rapid sand filter, the main difference between a rapid sand filtration system and a pressure filtration system is that the entire pressure filter is contained within a pressure vessel. These units are often highly automated and are usually purchased as self-contained units with all necessary piping, controls, and equipment contained in a single unit. They are backwashed in much the same manner as the rapid sand filter.

The major advantage of the pressure filter is its low initial cost. They are usually prefabricated, with standardized designs. A major disadvantage is that the operator is unable to observe the filter in the pressure filter and so is unable to determine the condition of the media. Unless the unit has an automatic shutdown feature on high effluent turbidity, driving filtered material through the filter is possible.

Diatomaceous Earth Filters

Diatomaceous earth is a white material made from the skeletal remains of diatoms. The skeletons are microscopic, and in most cases, porous. There are different grades of diatomaceous earth, and the grade is selected based on filtration requirements.

These diatoms are mixed in water slurry and fed onto a fine screen called a septum, usually of stainless steel, nylon, or plastic. The slurry is fed at a rate of 0.2 lb/ft^2 of filter area. The diatoms collect in a precoat over the septum, forming an extremely fine screen. Diatoms are fed continuously with the raw water, causing the buildup of a filter cake approximately 1/8–1/5 in. thick. The openings are so small that the fine particles that cause turbidity are trapped on the screen. Coating the septum with diatoms gives it the ability to filter out very small microscopic material. The fine screen and the buildup of filtered particles cause a high head loss through the filter. When the head loss reaches a maximum level (30 psi on a pressure-type filter or 15 in. or mercury on a vacuum-type filter), the filter cake must be removed by backwashing.

Slurry of diatoms is fed with raw water during filtration in a process called *body feed*. The body feed prevents premature clogging of the septum cake. These diatoms are caught on the septum, increasing the head loss and preventing the cake from clogging too rapidly by filtering of the particles. While the body feed increases head loss, head loss increases are more gradual than if body feed were not used.

Although diatomaceous earth filters are relatively low in cost to construct, they have high operating costs and can give frequent operating problems if not properly operated and maintained. They can be used to filter raw surface waters or surface-influenced groundwaters, with low turbidity (<5 NTU) and low coliform concentrations (not more than 50 coliforms/100 mL), and may also be used for iron and manganese removal following oxidation. Filtration rates are between 1.0 and 1.5 gpm/ft^2.

Direct Filtration

The term direct filtration refers to a treatment scheme that omits the flocculation and sedimentation steps prior to filtration. Coagulant chemicals are added, and the water is passed directly onto the filter. All solids removal takes place on the filter, which can lead to much shorter filter runs, more frequent backwashing, and a greater percentage of finished water used for backwashing. The lack of a flocculation process and sedimentation basin reduces construction cost but increases the requirement for skilled operators and high-quality instrumentation. Direct filtration must be used only where the water flow rate and raw water quality are fairly consistent and where the incoming turbidity is low.

Alternate Filters

A cartridge filter system can be employed as an alternate filtering system to reduce turbidity and remove *Giardia*. A cartridge filter is made of a synthetic media contained in a plastic or metal housing. These systems are normally installed in a series of three or four filters. Each filter contains a media that is successively smaller than the previous filter. The media sizes typically range from 50 to 5 µm or less. The filter arrangement is dependent on the quality of the water, the capability of the filter, and the quantity of water needed. The USEPA and state agencies have established criteria for the selection and use of cartridge filters. Generally, cartridge filter systems are regulated in the same manner as other filtration systems.

Because of new regulatory requirements and the need to provide more efficient removal of pathogenic protozoans (e.g., *Giardia* and *Cryptosporidium*) from water supplies, membrane filtration systems are finding increased application in water treatment systems. A membrane is a thin film separating two different phases of a material acting as a selective barrier to the transport of matter operated by some driving force. Simply stated, a membrane can be regarded as a sieve with very small pores. Membrane filtration processes are typically pressure, electrically, vacuum, or thermally driven. The types of drinking water membrane filtration systems include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. In a typical membrane filtration process, there are one input and two outputs. Membrane performance is largely a function of the properties of the materials to be separated and can vary throughout operation.

COMMON FILTER PROBLEMS

Two common types of filter problems occur: those caused by filter runs that are too long (infrequent backwash) and those caused by inefficient backwash (cleaning).

Too long a filter run can cause breakthrough (the pushing of debris removed from the water through the media and into the effluent) and air binding (the trapping of air and other dissolved gases in the filter media).

Air binding occurs when the rate at which water exits the bottom of the filter exceeds the rate at which the water penetrates the top of the filter. When this happens, a void and partial vacuum occurs inside the filter media. The vacuum causes gases to escape from the water and fill the void. When the filter is backwashed, the release of these gases may cause a violent upheaval in the media and destroy the layering of the media bed, gravel, or underdrain.

Two solutions to the problems are as follows: (1) check the filtration rates to assure they are within the design specifications; and (2) remove the top 1 in. of media and replace with new

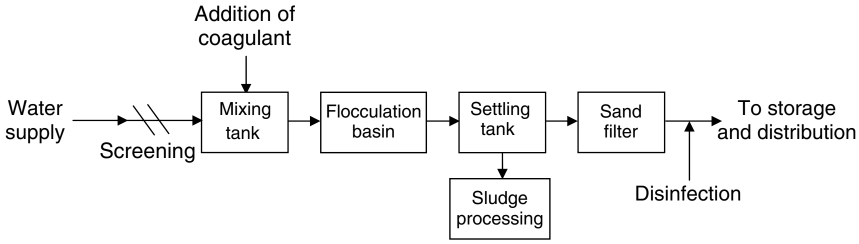

FIGURE 9.8 Disinfection.

media. This keeps the top of the media from collecting the floc and sealing the entrance into the filter media.

Another common filtration problem is associated with poor backwashing practices: the formation of mud balls that get trapped in the filter media. In severe cases, mud balls can completely clog a filter. Poor agitation of the surface of the filter can form a crust on top of the filter; the crust later cracks under the water pressure, causing uneven distribution of water through the filter media. Filter cracking can be corrected by removing the top 1 in. of the filter media, increasing the backwash rate, or checking the effectiveness of the surface wash (if installed). Backwashing at too high a rate can cause the filter media to wash out of the filter over the effluent troughs and may damage the filter underdrain system.

Two possible solutions are as follows: (1) check the backwash rate to be sure that it meets the design criteria; and (2) check the surface wash (if installed) for proper operation.

DISINFECTION*

The chemical or physical process used to control waterborne pathogenic organisms and prevent waterborne disease is called *disinfection*. The goal in proper disinfection in a water system is to destroy all disease-causing organisms. Disinfection should not be confused with sterilization. Sterilization is the complete killing of all living organisms. Waterworks operators disinfect by destroying organisms that might be dangerous; they do not attempt to sterilize water.

In water treatment, disinfection is almost always accomplished by adding chlorine or chlorine compounds after all other treatment steps (see Figure 9.8), although in the United States ultraviolet (UV) light and ozone processes may be encountered.

The effectiveness of disinfection in a drinking water system is measured by testing for the presence or absence of coliform bacteria.

Coliform bacteria found in water are generally not pathogenic, though they are good indicators of contamination. Their presence indicates the possibility of contamination, and their absence indicates the possibility that the water is potable—if the source is adequate, the waterworks history is good, and an acceptable chlorine residual is present.

Desired characteristics of a disinfectant include the following:

- It must be able to deactivate or destroy any type or number of disease-causing microorganisms that may be in a water supply in reasonable time, within expected temperature ranges, and despite changes in the character of the water (for example, pH).
- It must be nontoxic.

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* Disinfection is a unit process used in both water and wastewater treatment. Many of the terms, practices, and applications discussed in this section apply to both water and wastewater treatment. There are also some differences—mainly in the types of disinfectants used and applications—between the use of disinfection in water and wastewater treatment. Thus, in this section we discuss disinfection as it applies to water treatment.

- It must not add unpleasant taste or odor to the water.
- It must be readily available at a reasonable cost and be safe and easy to handle, transport, store, and apply.
- It must be quick and easy to determine the concentration of the disinfectant in the treated water.
- It should persist within the disinfected water at a high enough concentration to provide residual protection through the distribution.

√ **Note:** Disinfection is effective in reducing waterborne diseases because most pathogenic organisms are more sensitive to disinfection than are nonpathogens. However, disinfection is only as effective as the care used in controlling the process and assuring that all of the water supply is continually treated with the amount of disinfectant required, producing safe water.

The methods of disinfection are as follows:

1. *Heat*—Possibly the first method of disinfection. Disinfection is accomplished by boiling water for 5–10 min. Good, obviously, only for household quantities of water when bacteriological quality is questionable.
2. *UV light*—While a practical method of treating large quantities, adsorption of UV light is very rapid, so the use of this method is limited to nonturbid waters close to the light source.
3. *Metal ions*—Silver, copper, and mercury.
4. *Alkalis and acids.*
5. *pH adjustment*—To under 3.0 or over 11.0.
6. *Oxidizing agents*—Bromine, ozone, potassium permanganate, and chlorine.

The vast majority of water systems in the United States use chlorine for disinfection. Along with meeting the desired characteristics listed above, chlorine has the added advantage of a long history of use—it is fairly well understood. Although some small water systems may use other disinfectants, we concentrate on chlorine.

CHLORINATION

Chlorine is the most commonly used substance for disinfection of water in the United States. The addition of chlorine or chlorine compounds to water is called chlorination. Chlorination is considered to be the single most important process for preventing the spread of waterborne disease.

Chlorine deactivates microorganisms through several mechanisms, assuring that it can destroy most biological contaminants:

- It causes damage to the cell wall.
- It alters the permeability (the ability to pass water in and out through the cell wall) of the cell.
- It alters the cell protoplasm.
- It inhibits the enzyme activity of the cell so it is unable to use its food to produce energy.
- It inhibits cell reproduction.

Chlorine is available in a number of different forms: (1) as pure elemental gaseous chlorine (a greenish-yellow gas possessing a pungent and irritating odor that is heavier than air, nonflammable, and nonexplosive); when released to the atmosphere, this form is toxic and corrosive; (2) as solid calcium hypochlorite (in tablets or granules); or (3) as a liquid sodium hypochlorite solution (in various strengths).

The selection of one form of chlorine over the others for a given water system depends on the amount of water to be treated, configuration of the water system, the local availability of the chemicals, and the skill of the operator.

One of the major advantages of using chlorine is the effective residual that it produces. A residual indicates that disinfection is completed, and the system has an acceptable bacteriological quality. Maintaining a residual in the distribution system provides another line of defense against pathogenic organisms that could enter the distribution system and helps prevent regrowth of those microorganisms that were injured but not killed during the initial disinfection stage.

Common chlorination terms include the following:

- *Chlorine reaction*—Regardless of the form of chlorine used for disinfection, the reaction in water is basically the same. The same amount of disinfection can be expected, provided the same amount of available chlorine is added to the water. The standard term for the concentration of chlorine in water is milligrams per liter (mg/L) or parts per million (ppm); these terms indicate the same quantity.
- *Chlorine dose*—The amount of chlorine added to the system. It can be determined by adding the desired residual for the finished water to the chlorine demand of the untreated water. Dosage can be either milligrams per liter (mg/L) or pounds per day. The most common is mg/L.
- *Chlorine demand*—The amount of chlorine used by iron, manganese, turbidity, algae, and microorganisms in the water. Because the reaction between chlorine and microorganisms is not instantaneous, demand is relative to time. For instance, the demand 5 min after applying chlorine will be less than the demand after 20 min. Demand, like dosage, is expressed in mg/L. The chlorine demand is as follows:

$$\text{Cl}_2 \text{ demand} = \text{Cl}_2 \text{ dose} - \text{Cl}_2 \text{ residual} \tag{9.7}$$

- *Chlorine residual*—The amount of chlorine (determined by testing) that remains after the demand is satisfied. Residual, like demand, is based on time. The longer the time after dosage, the lower the residual will be, until all of the demand has been satisfied. Residual, like dosage and demand, is expressed in milligrams per liter. The presence of a free residual of at least 0.2–0.4 ppm usually provides a high degree of assurance that the disinfection of the water is complete. Combined residual is the result of combining free chlorine with nitrogen compounds. Combined residuals are also called chloramines. Total chlorine residual is the mathematical combination of free and combined residuals. Total residual can be determined directly with standard chlorine residual test kits.
- *Chlorine contact time (CT)*—One of the key items in predicting the effectiveness of chlorine on microorganisms. It is the interval (usually only a few minutes) between the time when chlorine is added to the water and the time the water passes by the sampling point, contact time is the "*T*" in CT. CT is calculated based on the free chlorine residual prior to the first customer times the contact time in minutes.

$$\text{CT} = \text{concentration} \times \text{contact time} = \text{milligram per liter} \times \text{minutes} \tag{9.8}$$

√ **Note:** A certain minimum time period is required for the disinfecting action to be completed. The contact time is usually a fixed condition determined by the rate of flow of the water and the distance from the chlorination point to the first consumer connection. Ideally, the contact time should not be <30 min, but even more time is needed at lower chlorine doses, in cold weather, or under other conditions.

Pilot studies have shown that specific CT values are necessary for the inactivation of viruses and *Giardia*. The required CT value will vary depending on pH, temperature, and the organisms to be killed. Charts and formulae are available to make this determination.

The USEPA has set a CT value of 3 log ($CT_{99.9}$) inactivation to ensure the water is free of *Giardia*. State drinking water regulations include charts giving this value for different pH and temperature combinations. Filtration, in combination with disinfection, must provide a 3 log removal/inactivation of *Giardia*. Charts in the USEPA SWTR *Guidance Manual* list the required CT values for various filter systems. Under the 1996 IESWT rules, the USEPA requires systems that filter to remove 99% (2 log) of *Cryptosporidium oocysts*. To ensure that the water is free of viruses, a combination of filtration and disinfection to provide a 4 log removal of viruses has been judged the best for drinking water safety—99.99% removal. Viruses are inactivated (killed) more easily than cysts or oocysts.

Chlorine Chemistry

The reactions of chlorine with water and the impurities that might be in the water are quite complex, but a basic understanding of these reactions can aid the operator in keeping the disinfection process operating at its highest efficiency.

When dissolved in pure water, chlorine reacts with the H^+ ions and the OH^- radicals in the water. Two of the products of this reaction (the actual disinfecting agents) are hypochlorous acid (HOCl) and the hypochlorite radical (OCl^-). If microorganisms are present in the water, the HOCl and the OCl^- penetrate the microbial cells and react with certain enzymes. This reaction disrupts the organisms' metabolism and kills them.

The chemical equation for hypochlorous acid is as follows:

$$\underset{\text{chlorine}}{Cl_2} + \underset{\text{water}}{H_2O} \leftrightarrow \underset{\text{hypochlorous acid}}{HOCl} + \underset{\text{hydrochloric acid}}{HCl} \tag{9.9}$$

Note: The symbol ↔ indicates that the reactions are reversible.

Hypochlorous acid (HOCl) is a weak acid but a strong oxidizing and germicidal agent. Hydrochloric acid (HCl) in the above equation is a strong acid and retains more of the properties of chlorine. HCl tends to lower the pH of the water, especially in swimming pools where the water is recirculated and continually chlorinated. The total hypochlorous acid and hypochlorite ions in water constitute the free available chlorine.

Hypochlorites act in a manner similar to HCl when added to water because hypochloric acid is formed.

When chlorine is first added to water containing some impurities, the chlorine immediately reacts with the dissolved inorganic or organic substances and is then unavailable for disinfection. The amount of chlorine used in this initial reaction is the chlorine demand of the water. If dissolved ammonia (NH_3) is present in the water, the chlorine will react with it to form compounds called chloramines. Only after the chlorine demand is satisfied and the reaction with all the dissolved ammonia is complete is the chlorine actually available in the form of HOCl and OCl^-. The equation for the reaction of hypochlorous acid (HOCl) and ammonia (NH_3) is as follows:

$$\underset{\text{hypochlorous acid}}{HOCl} + \underset{\text{ammonia}}{NH_3} \leftrightarrow \underset{\text{monochloramine}}{NH_2Cl} + \underset{\text{water}}{H_2O} \tag{9.10}$$

Note: The chlorine as hypochlorous acid and hypochlorite ions remaining in the water after the above reactions are complete is known as free available chlorine, and it is a very active disinfectant.

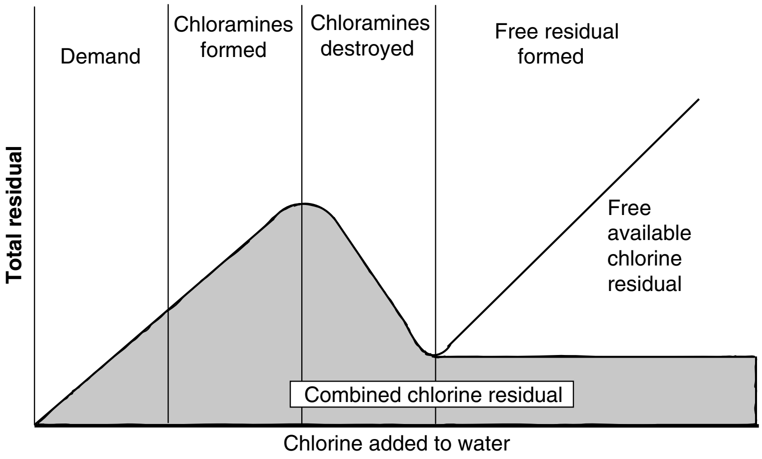

FIGURE 9.9 Breakpoint chlorination curve.

Breakpoint Chlorination

To produce a free chlorine residual, enough chlorine must be added to the water to produce what is referred to as breakpoint chlorination (i.e., the point at which near complete oxidation of nitrogen compounds is reached; any residual beyond breakpoint is mostly free chlorine [see Figure 9.9]). When chlorine is added to natural waters, the chlorine begins combining with and oxidizing the chemicals in the water before it begins disinfecting. Although residual chlorine will be detectable in the water, the chlorine will be in the combined form with a weak disinfecting power. As we see in Figure 9.9, adding more chlorine to the water at this point actually decreases the chlorine residual as the additional chlorine destroys the combined chlorine compounds. At this stage, water may have a strong swimming pool or medicinal taste and odor. To avoid this taste and odor, add still more chlorine to produce a free residual chlorine. Free chlorine has the highest disinfecting power. The point at which most of the combined chlorine compounds have been destroyed and the free chlorine starts to form is the breakpoint.

The chlorine breakpoint of water can only be determined by experimentation. This simple experiment requires 20 1000-mL beakers and a solution of chlorine. Place the raw water in the beakers and dose with progressively larger amounts of chlorine. For instance, you might start with 0 in the first beaker, then 0.5 mg/L and 1.0 mg/L, and so on. After a period of time, say 20 min, test each beaker for total chlorine residual and plot the results.

Breakpoint Chlorination Curve[*]

When the curve starts, no residual exists, even though there was a dosage. This is called the initial demand and is microorganisms and interfering agents using the result of the chlorine.

After the initial demand, the curve slopes upward. Chlorine combining to form chloramines produces this part of the curve. All of the residual measured on this part of the curve is combined residual.

At some point, the curve begins to drop back toward zero. This portion of the curve results from a reduction in combined residual, which occurs because enough chlorine has been added to destroy (oxidize) the nitrogen compounds used to form combined residuals.

The breakpoint is the point where the downward slope of the curve breaks upward. At this point, all of the nitrogen compounds that could be destroyed have been destroyed.

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[*] Refer to Figure 9.9 for the following explanation.

After breakpoint, the curve starts upward again, usually at a 45° angle. Only on this part of the curve can free residuals be found.

Notice that the breakpoint is not zero. The distance that the breakpoint is above zero is a measure of the remaining combined residual in the water. This combined residual exists because some of the nitrogen compound will not have been oxidized by chlorine. If irreducible combined residual is more than 15% of the total residual, chlorine odor and taste complaints will be high.

Gas Chlorination

Gas chlorine is provided in 100-lb or 1-ton containers. Chlorine is placed in the container as a liquid. The liquid boils at room temperature, reducing to a gas and building pressure in the cylinder. At room temperature of 70°F, a chlorine cylinder will have a pressure of 85 psi; 100/150-lb cylinders should be maintained in an upright position and chained to the wall. To prevent a chlorine cylinder from rupturing in a fire, the cylinder valves are equipped with special fusible plugs that melt between 158 and 164°F.

Chlorine gas is 99.9% chlorine. A gas chlorinator meters the gas flow and mixes it with water, which is then injected as a water solution of pure chlorine. As the compressed liquid chlorine is withdrawn from the cylinder, it expands as a gas, withdrawing heat from the cylinder. Care must be taken not to withdraw the chlorine at too fast a rate: if the operator attempts to withdraw more than about 40 lb of chlorine per day from a 150-lb cylinder, it will freeze up.

√ **Note:** All chlorine gas feed equipment sold today is vacuum operated. This safety feature ensures that if a break occurs in one of the components in the chlorinator, the vacuum will be lost, and the chlorinator will shut down without allowing gas to escape.

Chlorine gas is a highly toxic lung irritant, and special facilities are required for storing and housing it. Chlorine gas will expand to 500 times its original compressed liquid volume at room temperature (1 gal of liquid chlorine will expand to about 67 ft^3). Its advantage as a drinking water disinfectant is the convenience afforded by a relatively large quantity of chlorine available for continuous operation for several days or weeks without the need for mixing chemicals. Where water flow rates are highly variable, the chlorination rate can be synchronized with the flow.

Chlorine gas has a very strong, characteristic odor that can be detected by most people at concentrations as low as 3.5 ppm. Highly corrosive in moist air, it is extremely toxic and irritating in concentrated form. Its toxicity ranges from throat irritation at 15 ppm to rapid death at 1000 ppm. Although chlorine does not ignite and burn, it supports combustion, so open flames should never be used around chlorination equipment.

While changing chlorine cylinders, an accidental release of chlorine may occasionally occur. To handle this type of release, a NIOSH-approved, self-contained breathing apparatus (SCBA) must be worn. Special emergency repair kits are available from the Chlorine Institute for use by emergency response teams dealing with chlorine leaks. Because chlorine gas is 2.5 times heavier than air, exhaust and inlet air ducts should be installed at floor level. A leak of chlorine gas from cylinders or piping can be found by using the fumes from a strong ammonia solution. A white cloud develops when ammonia and chlorine combine.

Hypochlorination

Combining chlorine with calcium or sodium produces hypochlorites. Calcium hypochlorites are sold in powdered or tablet forms and can contain chlorine concentrations up to 67%. Sodium hypochlorite is a liquid (for example, bleach) and is found in concentrations up to 16%. Chlorine concentrations of household bleach range from 4.75 to 5.25%. Most small system operators find using these liquid or dry chlorine compounds more convenient and safer than chlorine gas.

The compounds are mixed with water and fed into the water with inexpensive solution feed pumps. These pumps are designed to operate against high system pressures, but can also be used to inject chlorine solutions into tanks, although injecting chlorine into the suction side of a pump is not recommended as the chlorine may corrode the pump impeller.

Calcium hypochlorite can be purchased as tablets or granules, with approximately 65% available chlorine (10 lb of calcium hypochlorite granules contain only 6.5 lb of chlorine). Normally, 6.5 lb of calcium hypochlorite will produce a concentration of 50 mg/L chlorine in 10,000 gal of water. Calcium hypochlorite can burn (at 350°F) if combined with oil or grease. When mixing calcium hypochlorite, operators must wear chemical safety goggles, a cartridge breathing apparatus, and rubberized gloves. Always place the powder in the water. Placing the water into the dry powder could cause an explosion.

Sodium hypochlorite is supplied as a clear, greenish-yellow liquid in strengths from 5.25 to 16% available chlorine. Often referred to as "bleach," it is, in fact, used for bleaching. As we stated earlier, common household bleach is a solution of sodium hypochlorite containing 5.25% available chlorine. The amount of sodium hypochlorite needed to produce a 50 mg/L chlorine concentration in 10,000 gal of water can be calculated using the solutions equation:

$$C_1V_1 = C_2V_2 \tag{9.11}$$

where C is the solution concentration in milligrams per liter or percent and V the solution volume in the liters, gallons, quarts, etc.

$$1.0\% = 10{,}000 \text{ mg/L}$$

In this example, C_1 and V_1 are associated with the sodium hypochlorite and C_2 and V_2 with the 10,000 gal of water with a 50 mg/L chlorine concentration. Therefore,

$$C_1 = 5.25\%$$

$$C_1 = \frac{(5.25\%)(10{,}000 \text{ mg/L})}{1.0\%}$$

$$= 52{,}500 \text{ mg/L}$$

$$V_1 = \text{Unknown volume of sodium hypochlorite}$$

$$C_2 = 50 \text{ mg/L}$$

$$V_2 = 10{,}000 \text{ gal}$$

$$(52{,}500 \text{ mg/L})(V_1) = (50 \text{ mg/L})(10{,}000 \text{ gal})$$

$$V_1 = \frac{(50 \text{ mg/L})(10{,}000 \text{ gal})}{52{,}500 \text{ mg/L}}$$

$$V_1 = 9.52 \text{ gal of sodium hypochlorite}$$

Sodium hypochlorite solutions are introduced to the water in the same manner as calcium hypochlorite solutions. The purchased stock "bleach" is usually diluted with water to produce a feed solution that is pumped into the water system.

Hypochlorites must be stored properly to maintain their strengths. Calcium hypochlorite must be stored in airtight containers in cool, dry, dark locations. Sodium hypochlorite degrades relatively quickly even when properly stored; it can lose more than half of its strength in 3–6 months.

Operators should purchase hypochlorites in small quantities to ensure they are used while still strong. Old chemicals should be discarded safely.

A chemical metering pump's pumping rate is usually manually adjusted by varying the length of the piston or diaphragm stroke. Once the stroke is set, the hypochlorinator feeds accurately at that rate. However, chlorine measurements must be made occasionally at the beginning and end of the well pump cycle to ensure correct dosage. A metering device may be used to vary the hypochlorinator feed rate, synchronized with the water flow rate. Where a well pump is used, the hypochlorinator is connected electrically with the pump's on-off controls to assure that chlorine solution is not fed into the pipe when the well is not pumping.

Determining Chlorine Dosage

Proper disinfection requires calculation of the amount of chlorine that must be added to the water to produce the required dosage. The type of calculation used depends on the form of chlorine being used.

The basic chlorination calculation used is the same one used for all chemical addition calculations—the pounds formula. The pounds formula is

$$\text{Pounds} = \text{mg/L} \times 8.34 \times \text{MG} \tag{9.12}$$

where

pounds = pounds of available chlorine required
mg/L = desired concentration in milligrams per liter
8.24 = conversion factor
MG = millions of gallons of water to be treated

Example 9.3

Problem:

Calculate the number of pounds of gaseous chlorine needed to treat 250,000 gal of water with 1.2 mg/L of chlorine.

Solution:

$$\begin{aligned}\text{Pounds} &= 1.2\ \text{mg/L} \times 8.34 \times 0.25\ \text{MG}\\ &= 2.5\ \text{lb}\end{aligned}$$

Note: Hypochlorites contain <100% available chlorine. Thus, we must use more hypochlorite to get the same number of pounds of chlorine into the water.

Using the same problem in Example 9.3, but substituting calcium hypochlorite with 65% available chlorine: 2.5 lb of available chlorine is still needed, but more than 2.5 lb of calcium hypochlorite is needed to provide that much chlorine. Determine how much of the chemical is needed by dividing the pounds of chlorine needed by the decimal form of the percent available chlorine. Since 65% is the same as 0.65, we need to add

$$\frac{2.5\,\text{lb}}{0.65\ \text{available chlorine}} = 3.85\,\text{lb Ca(OCl)} \tag{9.13}$$

to get that much chlorine.

In practice, because most hypochlorites are fed as solutions, we often need to know how much chlorine solution we need to feed. In addition, the practical problems faced in day-to-day operation are never so clearly stated as the practice problems we work. For example, small water systems do not usually deal with water flow in million gallons per day. Real-world problems usually require a lot of intermediate calculations to get everything ready to plug into the pounds formula.

REFERENCE

Spellman, F.R., 1999. *Choosing Disinfection Alternatives for Water/Wastewater Treatment*. Boca Raton, FL: CRC Press.

FURTHER READING

Craun, G.F., 1981. Outbreaks of Waterborne Disease in the United States. *J. Amer. Water Works Assoc.*, 73:360.

Culp, G.L. and Culp, R.L., 1974. Outbreaks of Waterborne Disease in the United States. *J. Amer. Water Works Assoc.*, 73:360.

Harr, J., 1995. *A Civil Action*. New York: Vintage Books.

Montgomery, J.M., 1985. *Water Treatment Principles and Design*. New York: John Wiley & Sons.

Singer, P.C. and Harrington, G.W., 1989. Correlations between Trihalomethanes and Total Organic Halides Formed during Water Treatment. *J. Amer. Water Works Assoc.*, 81:61–65.

Snead, M.C. et al., 1980. *Benefits of Maintaining a Chlorine Residual in Water Supply Systems*. EPA-600/2-80-010.

USEPA, 1997. *Community Water System Survey*, Vols. I and II; Overview, EPA 815-R-97-001a, 97-001b.

USEPA, 1998. National Drinking Water Regulations: Interim Enhanced Surface Water Treatment Final Rule. *Fed. Register*, 63:69477.

Running Water. White Oak Canyon Trail. Shenandoah National Forest, Virginia. (Photo by Revonna M. Bieber.)

10 Water Treatment Calculations

Gupta (1997) points out that because of huge volume and flow conditions the quality of natural water cannot be modified significantly within the body of water. Consequently, the quality control approach is directed to the water withdrawn from a source for a specific use. The drawn water is treated prior to use.

INTRODUCTION

In the following sections we present the basic often-used daily operational calculations along with engineering calculations used for solving more complex computations. This presentation method is in contrast to the presentation methods used in typical water mathematics texts. The author deviates from the norm based on and because of practical real-world experience; that is, experience demonstrates that the environmental engineer tasked with managing a water or wastewater treatment plant is not only responsible for computation of many complex math operations (engineering calculations) but also for overseeing proper plant operation (including math operations at the operator level). Obviously, engineers are well versed in basic math operations; however, they often need to refer to example plant operation calculations in a variety of texts. In this text, the format used, though unconventional, is designed to provide both basic operations math and more complex engineering math in "one" ready format.

WATER SOURCE AND STORAGE CALCULATIONS

Approximately 40 million cubic miles of water cover or are found within the Earth. The oceans contain about 97% of all water on the Earth. The other 3% is fresh water: (1) snow and ice on the surface of the Earth contain about 2.25% of the water; (2) usable groundwater is approximately 0.3%; and (3) surface fresh water is <0.5%.

In the United States, for example, average rainfall is ~2.6 ft (a volume of 5900 km^3). Of this amount, ~71% evaporates (about 4200 km^3), and 29% goes to stream flow (about 1700 km^3).

Beneficial freshwater uses include manufacturing, food production, domestic and public needs, recreation, hydroelectric power production, and flood control. Stream flow withdrawn annually is about 7.5% (440 km^3). Irrigation and industry use almost half of this amount (3.4% or 200 km^3/year). Municipalities use only about 0.6% (35 km^3/year) of this amount.

Historically, in the United States, water usage is increasing (as might be expected). For example, in 1900, 40 billion gal of freshwater were used. In 1975, the total increased to 455 billion gal. Projected use in 2000 is about 720 billion gal.

The primary sources of freshwater include the following:

- Captured and stored rainfall in cisterns and water jars
- Groundwater from springs, artesian wells, and drilled or dug wells
- Surface water from lakes, rivers, and streams
- Desalinized seawater or brackish groundwater
- Reclaimed wastewater

WATER SOURCE CALCULATIONS

Water source calculations covered in this section apply to wells and pond/lake storage capacity. Specific well calculations discussed include well drawdown, well yield, specific yield, well casing disinfection, and deep-well turbine pump capacity.

Well Drawdown

Drawdown is the drop in the level of water in a well when water is being pumped. Drawdown is usually measured in feet or meters.

One of the most important reasons for measuring drawdown is to make sure that the source water is adequate and not being depleted. The data that are collected to calculate drawdown can indicate if the water supply is slowly declining. Early detection can give the system time to explore alternative sources, establish conservation measures, or obtain any special funding that may be needed to get a new water source.

Well drawdown, the difference between the pumping water level and the static water level, is calculated as follows:

$$\text{Drawdown, ft} = \text{pumping water level, ft} - \text{static water level, ft} \tag{10.1}$$

EXAMPLE 10.1

Problem:

The static water level for a well is 70 ft. If the pumping water level is 90 ft, what is the drawdown?

Solution:

$$\begin{aligned}\text{Drawdown, ft} &= \text{pumping water level, ft} - \text{static water level, ft}\\ &= 90\text{ ft} - 70\text{ ft}\\ &= 20\text{ ft}\end{aligned}$$

EXAMPLE 10.2

Problem:

The static water level of a well is 122 ft. The pumping water level is determined using the sounding line. The air pressure applied to the sounding line is 4.0 psi and the length of the sounding line is 180 ft. What is the drawdown?

Solution:

First calculate the water depth in the sounding line and the pumping water level:

1. Water depth in sounding line = (4.0 psi) (2.31 ft/psi) = 9.2 ft
2. Pumping water level = 180 ft − 9.2 ft = 170.8 ft

Then calculate drawdown as usual:

$$\begin{aligned}\text{Drawdown, ft} &= \text{pumping water level, ft} - \text{static water level, ft}\\ &= 170.8\text{ ft} - 122\text{ ft}\\ &= 48.8\text{ ft}\end{aligned}$$

Well Yield

Well yield is the volume of water per unit of time that is produced from the well pumping. Usually well yield is measured in terms of gallons per minute (gpm) or gallons per hour (gph). Sometimes large flows are measured in cubic feet per second (cfs).

Well yield is determined by using the following equation:

$$\text{Well yield, gpm} = \frac{\text{gallons produced}}{\text{duration of test, min}} \tag{10.2}$$

Example 10.3

Problem:

Once the drawdown level of a well stabilized, it was determined that the well produced 400 gal during a 5-min test.

Solution:

$$\begin{aligned}\text{Well yield, gpm} &= \frac{\text{gallons produced}}{\text{duration of test, min}}\\ &= \frac{400\text{ gal}}{5\text{ min}}\\ &= 80\text{ gpm}\end{aligned}$$

Example 10.4

Problem:

During a 5-min test for well yield, a total of 780 gal are removed from the well. What is the well yield in gpm and in gph?

Solution:

$$\begin{aligned}\text{Well yield, gpm} &= \frac{\text{gallons produced}}{\text{duration of test, min}}\\ &= \frac{780\text{ gal}}{5\text{ min}}\\ &= 156\text{ gpm}\end{aligned}$$

Then convert gpm flow into gph flow:

$$\begin{aligned}&\frac{156\text{ gal/min}}{60/\text{h}}\\ &= 9360\text{ gph}\end{aligned}$$

Specific Yield

Specific yield is the discharge capacity of the well per foot of drawdown. The specific yield may range from 1 gpm/ft drawdown to more than 100 gpm/ft drawdown for a properly developed well. Specific yield is calculated using the following equation:

$$\text{Specific yield, gpm/ft} = \frac{\text{well yield, gpm}}{\text{drawdown, ft}} \tag{10.3}$$

EXAMPLE 10.5

Problem:

A well produces 260 gpm. If the drawdown for the well is 22 ft, what is the specific yield in gpm/ft of drawdown?

Solution:

$$\text{Specific yield, gpm/ft} = \frac{\text{well yield, gpm}}{\text{drawdown, ft}}$$

$$= \frac{260\text{ gpm}}{22\text{ ft}}$$

$$= 118\text{ gpm/ft}$$

EXAMPLE 10.6

Problem:

The yield for a particular well is 310 gpm. If the drawdown for this well is 30 ft, what is the specific yield in gpm/ft of drawdown?

Solution:

$$\text{Specific yield, gpm/ft} = \frac{\text{well yield, gpm}}{\text{drawdown, ft}}$$

$$= \frac{310\text{ gpm}}{30\text{ ft}}$$

$$= 10.3\text{ gpm/ft}$$

Well Casing Disinfection

A new, cleaned, or a repaired well normally contains contamination, which may remain for weeks unless the well is thoroughly disinfected. This may be accomplished by ordinary bleach in a concentration of 100 parts per million (ppm) of chlorine. The amount of disinfectant required is determined by the amount of water in the well.

The following equation is used to calculate the pounds of chlorine required for disinfection:

$$\text{Chlorine, lb} = (\text{chlorine, mg/L})(\text{casing volume, MG})(8.34\text{ lb/gal}) \tag{10.4}$$

EXAMPLE 10.7

Problem:

A new well is to be disinfected with chlorine at a dosage of 50 mg/L. If the well casing diameter is 8 in. and the length of the water-filled casing is 110 ft, how many pounds of chlorine will be required?

Solution:

First calculate the volume of the water-filled casing:

$$(0.785)(0.67)(0.67)(110\text{ ft})(7.48\text{ gal/ft}^3) = 290\text{ gal}$$

Then, determine the pounds of chlorine required using the mg/L to lb equation:

$$\text{Chlorine, lb} = (\text{chlorine, mg/L})(\text{volume, MG})(8.34\ \text{lb/gal})$$

$$(50\ \text{mg/L})(0.000290\ \text{MG})(8.34\ \text{lb/gal}) = 0.12\ \text{lb chlorine}$$

Deep-Well Turbine Pump Calculations

The deep-well turbine pump is used for high-capacity deep wells. The pump, consisting usually of more than one stage of centrifugal pump, is fastened to a pipe called the *pump column*; the pump is located in the water. The pump is driven from surface through a shaft running inside the pump column. The water is discharged from the pump up through the pump column to surface. The pump may be driven by a vertical shaft, electric motor at the top of the well, or by some other power source, usually through a right angle gear drive located at the top of the well.

A modern version of the deep-well turbine pump is the submersible-type pump in which the pump, along with a close-coupled electric motor built as a single unit, is located below water level in the well. The motor is built to operate submerged in water.

Vertical Turbine Pump Calculations

The calculations pertaining to well pumps include head, horsepower, and efficiency calculations.

Discharge head is measured to the pressure gage located close to the pump discharge flange. The pressure (psi) can be converted into feet of head using the equation:

$$\text{Discharge head, ft} = (\text{pressure, psi})(2.31\ \text{ft/psi}) \tag{10.5}$$

Total pumping head (field head) is a measure of the lift *below* the discharge head pumping water level (discharge head). Total pumping head is calculated as follows:

$$\text{Pumping head, ft} = \text{pumping water level, ft} + \text{discharge head, ft} \tag{10.6}$$

Example 10.8

Problem:

The pressure gauge reading at a pump discharge head is 4.1 psi. What is this discharge head expressed in feet?

Solution:

$$(4.1\ \text{psi})(2.31\ \text{ft/psi}) = 9.5\ \text{ft}$$

Example 10.9

Problem:

The static water level of a pump is 100 ft. The well drawdown is 26 ft. If the gauge reading at the pump discharge head is 3.7 psi, what is the total pumping head?

Solution:

$$\begin{aligned}\text{Total pumping head, ft} &= (\text{pumping water level, ft}) + (\text{discharge head, ft})\\ &= (100\ \text{ft} + 26\ \text{ft}) + (3.7\ \text{psi})(2.31\ \text{ft/psi})\\ &= 126\ \text{ft} + 8.5\ \text{ft}\\ &= 134.5\ \text{ft}\end{aligned} \tag{10.7}$$

There are five types of *horsepower* calculations for vertical turbine pumps. It is important to have a general understanding of these five horsepower types:

- *Motor horsepower* refers to the horsepower supplied to the motor. The following equation is used to calculate motor horsepower:

$$\text{Motor hp (input hp)} = \frac{\text{field bhp}}{\text{motor efficiency/100}} \tag{10.8}$$

- *Total bhp* refers to horsepower output of the motor. The following equation is used to calculate total brake horsepower:

$$\text{Total bhp} = \text{field bhp} + \text{thrust-bearing loss (hp)} \tag{10.9}$$

- *Field horsepower* refers to the horsepower required at the top of the pump shaft. The following equation is used to calculate field horsepower:

$$\text{Field bhp} = \text{bowl bhp} + \text{shaft loss (hp)} \tag{10.10}$$

- *Bowl or laboratory horsepower* refers the horsepower at the entry to the pump bowls. The following equation is used to calculate bowl horsepower:

$$\text{Bowl bhp (lab bhp)} = \frac{\text{(bowl head, ft)(capacity, gpm)}}{\text{3960 (bowl efficiency/100)}} \tag{10.11}$$

- *Water horsepower* refers to the horsepower at the pump discharge. The following equation is used to calculate water hp:

$$\text{Water hp} = \frac{\text{(field head, ft)(capacity, gpm)}}{3960} \tag{10.12}$$

Or use the equivalent equation:

$$\text{Water hp} = \frac{\text{(field head, ft)(capacity, gpm)}}{\text{33,000 ft-lb/min}}$$

EXAMPLE 10.10

Problem:

The pumping water level for a well pump is 150 ft and the discharge pressure measured at the pump discharge centerline is 3.5 psi. If the flow rate from the pump is 700 gpm, what is the water horsepower? (Use Equation 10.12.)

Solution:

First calculate the field head. The discharge head must be converted from psi to ft:

$$\text{(3.5 psi)(2.31 ft/psi)} = 8.1\text{ ft}$$

The water horsepower is, therefore:

$$150\text{ ft} + 8.1\text{ ft} = 158.1\text{ ft}$$

The water horsepower can now be determined:

$$= \frac{(158.1\text{ ft})(700\text{ gpm})(8.34\text{ lb/gal})}{33{,}000\text{ ft-lb/min}}$$

$$= 28\text{ whp}$$

EXAMPLE 10.11

Problem:

The pumping water level for a pump is 170 ft. The discharge pressure measured at the pump discharge head is 4.2 psi. If the pump flow rate is 800 gpm, what is the water horsepower? (Use Equation 10.12.)

Solution:

The field head must first be determined. To determine field head, the discharge head must be converted from psi to ft:

$$(4.2\text{ psi})(2.31\text{ ft/psi}) = 9.7\text{ ft}$$

The field head can now be calculated:

$$170\text{ ft} + 9.7\text{ ft} = 179.7\text{ ft}$$

Then the water horsepower can be calculated:

$$\text{whp} = \frac{(179.7\text{ ft})(800\text{ gpm})}{3960}$$

$$= 36\text{ whp}$$

EXAMPLE 10.12

Problem:

A deep-well vertical turbine pump delivers 600 gpm. If the lab head is 185 ft and the bowl efficiency is 84%. What is the bowl horsepower? (Use Equation 10.11.)

Solution:

$$\text{Bowl bhp} = \frac{(\text{bowl head, ft}) \times (\text{capacity, gpm})}{(3960)(\text{bowl efficiency}/100)}$$

$$= \frac{(185\text{ ft} \times 600\text{ gpm})}{(3960)(84.0/100)}$$

$$= \frac{(185 \times 600\text{ gpm})}{(3960 \times 0.84)}$$

$$= 33.4\text{ bowl bhp}$$

EXAMPLE 10.13

Problem:

The bowl bhp is 51.8 bhp. If the 1-in. diameter shaft is 170 ft long and is rotating at 960 rpm with a shaft fiction loss of 0.29 hp loss per 100 ft, what is the field bhp?

Solution:

Before field bhp can be calculated, the shaft loss must be factored in:

$$\left(\frac{0.29\text{ hp loss}}{100}\right)(170\text{ ft}) = 0.5\text{ hp loss}$$

Now the field bhp can be determined:

$$\begin{aligned}\text{Field bhp} &= \text{bowl bhp} + \text{shaft loss, hp}\\ &= 51.8\text{ bhp} + 0.5\text{ hp}\\ &= 52.3\text{ bhp}\end{aligned}$$

EXAMPLE 10.14

Problem:

The field horsepower for a deep-well turbine pump is 62 bhp. If the thrust-bearing loss is 0.5 hp and the motor efficiency is 88%, what is the motor input horsepower? (Use Equation 10.8.)

Solution:

$$\begin{aligned}\text{mhp} &= \frac{\text{field (total) bhp}}{\text{motor efficiency/100}}\\ &= \frac{62\text{ bhp} + 0.5\text{ hp}}{0.88}\\ &= 71\text{ mhp}\end{aligned}$$

When speaking of the *efficiency* of any machine, we are speaking primarily of a comparison of what is put out by the machine (e.g., energy output) compared to its input (e.g., energy input). Horsepower efficiency, for example, is a comparison of horsepower output of the unit or system with horsepower input to that unit or system—the unit's efficiency. In regard to vertical turbine pumps, there are four types of efficiencies to be considered:

- Bowl efficiency
- Field efficiency
- Motor efficiency
- Overall efficiency

The general equation used in calculating percent efficiency is:

$$\% = \frac{\text{part}}{\text{whole}} \times 100 \tag{10.13}$$

Vertical turbine pump *bowl efficiency* is easily determined using a pump performance curve chart—provided by the pump manufacturer.

Field efficiency is determined using Equation 10.14:

$$\text{Field efficiency, }\% = \frac{\text{(field head, ft)(capacity, gpm)/3960}}{\text{total bhp}} \times 100 \tag{10.14}$$

EXAMPLE 10.15

Problem:

Given the data below, calculate the field efficiency of the deep-well turbine pump.

Field head—180 ft
Capacity—850 gpm
Total bhp—61.3 bhp

Solution:

$$\text{Field efficiency, \%} = \frac{(\text{field head, ft})(\text{capacity, gpm})}{(3960)\ (\text{total bhp})} \times 100$$

$$= \frac{(180\ \text{ft})(850\ \text{gpm})}{(3960)(61.3\ \text{bhp})} \times 100$$

$$= 63\%$$

The overall efficiency is a comparison of the horsepower output of the system with that entering the system. Equation 10.15 is used to calculate overall efficiency:

$$\text{Overall efficiency, \%} = \frac{(\text{field efficiency, \%})(\text{motor efficiency, \%})}{100} \tag{10.15}$$

EXAMPLE 10.16

Problem:

The efficiency of a motor is 90%. If the field efficiency is 83%, what is the overall efficiency of the unit?

Solution:

$$\text{Overall efficiency, \%} = \frac{(\text{field efficiency, \%})(\text{motor efficiency, \%})}{100} \times 100\%$$

$$= \frac{(83)(90)}{100}$$

$$= 74.7\%$$

WATER STORAGE

Water storage facilities for water distribution systems are required primarily to provide for fluctuating demands of water usage (to provide a sufficient amount of water to average or equalize daily demands on the water supply system). In addition, other functions of water storage facilities include increasing operating convenience, leveling pumping requirements (to keep pumps from running 24 h a day), decreasing power costs, providing water during power source or pump failure, providing large quantities of water to meet fire demands, providing surge relief (to reduce the surge associated with stopping and starting pumps), increasing detention time (to provide chlorine contact time and satisfy the desired CT (contact time), value requirements, and blending water sources.

WATER STORAGE CALCULATIONS

The storage capacity, in gallons, of a reservoir, pond, or small lake can be estimated using Equation 10.16.

$$\text{Still water body, gal} = (\text{average length, ft})(\text{average width, ft})(\text{average depth, ft})(7.48\ \text{gal/ft}^3) \tag{10.16}$$

EXAMPLE 10.17

Problem:

A pond has an average length of 250 ft, an average width of 110 ft, and an estimated average depth of 15 ft. What is the estimated volume of the pond in gallons?

Solution:

$$\begin{aligned}\text{Volume, gal} &= (\text{average length, ft})(\text{average width, ft})(\text{average depth, ft})(7.48\ \text{gal/ft}^3)\\ &= (250\ \text{ft})(110\ \text{ft})(15\ \text{ft})(7.48\ \text{gal/ft}^3)\\ &= 3{,}085{,}500\ \text{gal}\end{aligned}$$

EXAMPLE 10.18

Problem:

A small lake has an average length of 300 ft and an average width of 95 ft. If the maximum depth of the lake is 22 ft, what is the estimated volume, in gallons, of the lake?

Note: For small ponds and lakes, the average depth is generally about 0.4 times the greatest depth. Therefore, to estimate the average depth, we measure the greatest depth, then multiply that number by 0.4.

Solution:

First, the average depth of the lake must be estimated:

$$\begin{aligned}\text{Estimated average depth, ft} &= (\text{greatest depth, ft})(0.4\ \text{depth, ft})\\ &= (22\ \text{ft})(0.4\ \text{ft})\\ &= 8.8\ \text{ft}\end{aligned}$$

Then the lake volume can be determined:

$$\begin{aligned}\text{Volume, gal} &= (\text{average length, ft})(\text{average width, ft})(\text{average depth, ft})(7.48\ \text{gal/ft}^3)\\ &= (300\ \text{ft})(95\ \text{ft})(8.8\ \text{ft})(7.48\ \text{ft}^3)\\ &= 1{,}875{,}984\ \text{gal}\end{aligned}$$

Copper Sulfate Dosing

Algal control is perhaps the most common *in situ* treatment of lakes, ponds, and reservoirs by application of copper sulfate—the copper ions in the water kill the algae. Copper sulfate application methods and dosages will vary depending on the specific surface water body being treated. The desired copper sulfate dosage may be expressed in mg/L copper, lb copper sulfate/ac-ft, or lb copper sulfate/ac.

For a dose expressed as mg/L copper, the following equation is used to calculate lb copper sulfate required:

$$\text{Copper sulfate, lb} = \frac{(\text{copper, mg/L})(\text{volume, MG})(8.34\ \text{lb/gal})}{\%\ \text{available copper}/100} \tag{10.17}$$

Example 10.19

Problem:

For alga control in a small pond, a dosage of 0.5 mg/L copper is desired. The pond has a volume of 15 MG. How many pounds of copper sulfate will be required? (Copper sulfate contains 25% available copper.)

Solution:

$$\text{Copper sulfate, lb} = \frac{(\text{copper, mg/L})(\text{volume, MG})(8.34\ \text{lb/gal})}{\%\ \text{available copper}/100}$$

$$= \frac{(0.5\ \text{mg/L})(15\ \text{MG})(8.34\ \text{lb/gal})}{25/100}$$

$$= 250\ \text{lb copper sulfate}$$

For calculating pounds copper sulfate/ac-ft, use the following equation (assume the desired copper sulfate dosage is 0.9 lb/ac-ft):

$$\text{Copper sulfate, lb} = \frac{(0.9\ \text{lb copper sulfate})(\text{ac-ft})}{1\ \text{ac-ft}} \tag{10.18}$$

Example 10.20

Problem:

A pond has a volume of 35 ac-ft. If the desired copper sulfate dose is 0.9 lb/ac-ft, how many pounds of copper sulfate will be required?

Solution:

$$\text{Copper sulfate, lb} = \frac{(0.9\ \text{lb copper sulfate})(\text{ac-ft})}{1\ \text{ac-ft}}$$

$$\frac{0.9\ \text{lb copper sulfate}}{1\ \text{ac-ft}} = \frac{x\ \text{lb copper sulfate}}{35\ \text{ac-ft}}$$

Then solve for x:

$$(0.9)(35) = x$$

$$31.5\ \text{lb copper sulfate}$$

The desired copper sulfate dosage may also be expressed in terms of lb copper sulfate/ac. The following equation is used to determine lb copper sulfate (assume a desired dose of 5.2 lb copper sulfate/ac):

$$\text{Copper sulfate, lb} = \frac{(5.2 \text{ lb copper sulfate})(\text{ac})}{1 \text{ ac}} \tag{10.19}$$

Example 10.21

Problem:

A small lake has a surface area of 6.0 ac. If the desired copper sulfate dose is 5.2 lb/ac, how many pounds of copper sulfate are required?

Solution:

$$\text{Copper sulfate, lb} = \frac{(5.2 \text{ lb copper sulfate})(6.0 \text{ ac})}{1 \text{ ac}}$$

$$= 31.2 \text{ lb copper sulfate}$$

COAGULATION, MIXING, AND FLOCCULATION CALCULATIONS

Coagulation

Following screening and the other pretreatment processes, the next unit process in a conventional water treatment system is a mixer where the first chemicals are added in what is known as coagulation. The exception to this situation occurs in small systems using groundwater, when chlorine or other taste and odor control measures are introduced at the intake and are the extent of treatment.

The term *coagulation* refers to the series of chemical and mechanical operations by which coagulants are applied and made effective. These operations consist of two distinct phases: (1) rapid mixing to disperse coagulant chemicals by violent agitation into the water being treated; and (2) flocculation to agglomerate small particles into well-defined floc by gentle agitation for a much longer time.

The coagulant must be added to the raw water and perfectly distributed into the liquid; such uniformity of chemical treatment is reached through rapid agitation or mixing.

Coagulation results from adding salts of iron or aluminum to the water. Common coagulants (salts) are as follows (coagulation is the reaction between one of these salts and water):

- Alum—aluminum sulfate
- Sodium aluminate
- Ferric sulfate
- Ferrous sulfate
- Ferric chloride
- Polymers

Mixing

To ensure maximum contact between the reagent and suspended particles, coagulants and coagulant aids must be rapidly dispersed (mixed) throughout the water; otherwise, the coagulant will react with water and dissipate some of its coagulating power.

To ensure complete mixing and optimum plug flow reactor operation, proper detention time in the basin is required. Detention time can be calculated using the following procedures.

For complete mixing:

$$t = \frac{V}{Q} = \frac{1}{K}\left(\frac{C_\mathrm{i} - C_\mathrm{e}}{C_\mathrm{e}}\right) \tag{10.20}$$

For plug flow:

$$t = \frac{V}{Q} = \frac{L}{v} = \frac{1}{K}\left(\frac{C_\mathrm{i}}{C_\mathrm{e}}\right) \tag{10.21}$$

where

t = detention time of the basin, min
V = volume of basin, m^3 or ft^3
Q = flow rate, m^3/s or cfs
K = rate constant
C_i = influent reactant concentration, mg/L
C_e = effluent reactant concentration, mg/L
L = length of rectangular basin, m or ft
v = horizontal velocity of flow, m/s or ft/s

EXAMPLE 10.22

Problem:

Alum dosage is 40 mg/L $K = 90$ per day based on lab tests. Compute the detention times for complete mixing and plug flow reactor for 90% reduction.

Solution:

Step 1. Find C_e.

$$C_\mathrm{e} = (1 - 0.9)C_\mathrm{i} = 0.1 \times C_\mathrm{i} = 0.1 \times 40\ \mathrm{mg/L} = 4\ \mathrm{mg/L}$$

Step 2. Calculate t for complete mixing (using Equation 10.20).

$$\begin{aligned} t &= \frac{1}{k}(C_\mathrm{i} - C_\mathrm{e}) = \frac{1}{90d}\left(\frac{40\ \mathrm{mg/L} - 4\ \mathrm{mg/L}}{4\ \mathrm{mg/L}}\right) \\ &= \frac{1d}{90} \times \frac{1440\ \mathrm{min}}{1d} \times 9 \\ &= 144\ \mathrm{min} \end{aligned}$$

Step 3. Calculate t for plug flow using the following formula.

$$\begin{aligned} t &= \frac{1}{K}\left(\ln \frac{C_\mathrm{i}}{C_\mathrm{e}}\right) \\ &= \frac{1440}{90}\left(\ln \frac{40}{4}\right) \\ &= 36.8\ \mathrm{min} \end{aligned}$$

FLOCCULATION

Flocculation follows coagulation in the conventional water treatment process. *Flocculation* is the physical process of slowly mixing the coagulated water to increase the probability of particle collision. Through experience, we see that effective mixing reduces the required amount of chemicals and greatly improves the sedimentation process, which results in longer filter runs and higher-quality finished water.

The goal of flocculation is to form a uniform, feather-like material similar to snowflakes—a dense, tenacious floc that entraps the fine, suspended, and colloidal particles and carries them down rapidly in the settling basin.

Polymers are often added to increase the speed of floc formation and the strength and weight of the floc.

COAGULATION AND FLOCCULATION GENERAL CALCULATIONS

In the proper operation of the coagulation and flocculation unit processes, calculations are performed to determine chamber or basin volume, chemical feed calibration, chemical feeder settings, and detention time.

Chamber and Basin Volume Calculations

To determine the volume of a square or rectangular chamber or basin, use Equation 10.22 or 10.23:

$$\text{Volume, ft}^3 = (\text{length, ft})(\text{width, ft})(\text{depth, ft}) \tag{10.22}$$

$$\text{Volume, gal} = (\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\ \text{gal/ft}^3) \tag{10.23}$$

EXAMPLE 10.23

Problem:

A flash mix chamber is 4 ft^2 with water to a depth of 3 ft. What is the volume of water (in gallons) in the chamber?

Solution:

$$\begin{aligned}\text{Volume, gal} &= (\text{length, ft})(\text{width, ft})(\text{depth, ft}) \times (7.48\ \text{gal/ft}^3)\\ &= (4\ \text{ft})(4\ \text{ft})(3\ \text{ft})(7.48\ \text{gal/ft}^3)\\ &= 359\ \text{gal}\end{aligned}$$

EXAMPLE 10.24

Problem:

A flocculation basin is 40 ft long, 12 ft wide, with water to a depth of 9 ft. What is the volume of water (in gallons) in the basin?

Solution:

$$\begin{aligned}\text{Volume, gal} &= (\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\ \text{gal/ft}^3)\\ &= (40\ \text{ft})(12\ \text{ft})(9\ \text{ft})(7.48\ \text{gal/ft}^3)\\ &= 32{,}314\ \text{gal}\end{aligned}$$

Example 10.25

Problem:

A flocculation basin is 50 ft long, 22 ft wide, and contains water to a depth of 11 ft 6 in. How many gallons of water are there in the tank?

Solution:

First convert the 6 in. portion of the depth measurement into feet:

$$\frac{6\text{ in.}}{12\text{ in./ft}} = 0.5\text{ ft}$$

Then calculate basin volume:

$$\begin{aligned}\text{Volume, ft} &= (\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\text{ gal/ft}^3)\\ &= (50\text{ ft})(22\text{ ft})(11.5\text{ ft})(7.48\text{ gal/ft}^3)\\ &= 94{,}622\text{ gal}\end{aligned}$$

Detention Time

Because coagulation reactions are rapid, detention time for flash mixers is measured in seconds, whereas the detention time for flocculation basins is generally between 5 and 30 min. The equation used to calculate detention time is shown below.

$$\text{Detention time, min} = \frac{\text{volume of tank, gal}}{\text{flow rate, gpm}} \tag{10.24}$$

Example 10.26

Problem:

The flow to a flocculation basin 50 ft long, 12 ft wide, and 10 ft deep is 2100 gpm. What is the detention time in the tank, in minutes?

Solution:

$$\begin{aligned}\text{Tank volume, gal} &= (50\text{ ft})(12\text{ ft})(10\text{ ft})(7.48\text{ gal/ft}^3)\\ &= 44{,}880\text{ gal}\end{aligned}$$

$$\begin{aligned}\text{Detention time, min} &= \frac{\text{volume of tank, gal}}{\text{flow rate, gpm}}\\ &= \frac{44{,}880\text{ gal}}{2100\text{ gpm}}\\ &= 21.4\text{ min}\end{aligned}$$

Example 10.27

Problem:

Assuming the flow is steady and continuous, a flash mix chamber is 6 ft long, 4 ft wide, with water to a depth of 3 ft. If the flow to the flash mix chamber is 6 million gallons per day (MGD), what is the chamber detention time in seconds?

Solution:

First, convert the flow rate from gallons per day (gpd) to gallons per second (gps) so that time units will match:

$$\frac{6{,}000{,}000}{(1440\text{ min/day})(60\text{ s/min})} = 69\text{ gps}$$

Then calculate detention time:

$$\begin{aligned}\text{Detention time, s} &= \frac{\text{volume of tank, gal}}{\text{flow rate, gps}}\\ &= \frac{(6\text{ ft})(4\text{ ft})(3\text{ ft})(7.48\text{ gal/ft}^3)}{69\text{ gps}}\\ &= 7.8\text{ s}\end{aligned}$$

Determining Dry Chemical Feeder Setting, lb/day

In adding (dosing) chemicals to the water flow, a measured amount of chemical is called for. The amount of chemical required depends on such factors as the type of chemical used, the reason for dosing, and the flow rate being treated. To convert from mg/L to lb/day, use the following equation:

$$\text{Chemical added, lb/day} = (\text{chemical, mg/L})(\text{flow, MGD})(8.34\text{ lb/gal}) \qquad (10.25)$$

Example 10.28

Problem:

Jar tests indicate that the best alum dose for a water sample is 8 mg/L. If the flow to be treated is 2,100,000 gpd, what should the lb/day setting be on the dry alum feeder?

Solution:

$$\begin{aligned}\text{lb/day} &= (\text{chemical, mg/L})(\text{flow, MGD})(8.34\text{ lb/gal})\\ &= (8\text{ mg/L})(2.10\text{ MGD})(8.34\text{ lb/gal})\\ &= 140\text{ lb/d}\end{aligned}$$

Example 10.29

Problem:

Determine the desired lb/day setting on a dry chemical feeder if jar tests indicate an optimum polymer dose of 12 mg/L and the flow to be treated is 4.15 MGD.

Solution:

$$\text{Polymer (lb/day)} = (12\text{ mg/L})(4.15\text{ MGD})(8.34\text{ lb/gal})$$

$$= 415\text{ lb/day}$$

Determining Chemical Solution Feeder Setting, gpd

When solution concentration is expressed as lb chemical/gal solution, the required feed rate can be determined using the following equations:

$$\text{Chemical, lb/day} = (\text{chemical, mg/L})(\text{flow, MGD})(8.34\text{ lb/gal}) \tag{10.26}$$

Then convert the lb/day dry chemical into gpd solution:

$$\text{Solution (gpd)} = \frac{\text{chemical (lb/day)}}{\text{lb chemical/gal solution}} \tag{10.27}$$

Example 10.30

Problem:

Jar tests indicate that the best alum dose for a water sample is 7 mg/L. The amount to be treated is 1.52 MGD. Determine the gpd setting for the alum solution feeder if the liquid alum contains 5.36 lb of alum per gallon of solution.

Solution:

First calculate the lb/day of dry alum required, using the mg/L to lb/day equation:

$$\text{Dry alum, lb/day} = (\text{mgL})(\text{flow, MGD})(8.34\text{ lb/gal})$$

$$= (7\text{ mg/L})(1.52\text{ MGD})(8.34\text{ lb/gal})$$

$$= 89\text{ lb/day}$$

Then calculate the gpd solution required.

$$\text{Alum solution (gpd)} = \frac{89\text{ lb/day}}{5.36\text{ lb alum/gal solution}}$$

$$= 16.6\text{ gpd}$$

Determining Chemical Solution Feeder Setting, mL/min

Some solution chemical feeders dispense chemical as milliliters per minute (mL/min). To calculate the mL/min solution required, use the following procedure:

$$\text{Solution, mL/min} = \frac{(\text{gpd})(3785\text{ mL/gal})}{1440\text{ min/day}} \tag{10.28}$$

Example 10.31

Problem:

The desired solution feed rate was calculated to be 9 gpd. What is this feed rate expressed as mL/min?

Solution:

$$\frac{\text{mL}}{\text{min}} = \frac{(\text{gpd})(3785\ \text{mL/gal})}{1440\ \text{min/day}}$$

$$= \frac{(9\ \text{gpd})(3785\ \text{mL/gal})}{1440\ \text{min/day}}$$

$$= 24\ \text{mL/min feed rate}$$

Example 10.32

Problem:

The desired solution feed rate has been calculated to be 25 gpd. What is this feed rate expressed as mL/min?

Solution:

$$\frac{\text{mL}}{\text{min}} = \frac{(\text{gpd})(3785\ \text{mL/gal})}{1440\ \text{min/day}}$$

$$= \frac{(25\ \text{gpd})(3785\ \text{mL/gal})}{1440\ \text{min/day}}$$

$$= 65.7\ \text{mL/min feed rate}$$

Sometimes we will need to know mL/min solution feed rate but we will not know the gpd solution feed rate. In such cases, calculate the gpd solution feed rate first, using the following equation:

$$\text{gpd} = \frac{(\text{chemical, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})}{(\text{chemical, lb})/(\text{solution, gal})} \tag{10.29}$$

Determining Percent of Solutions

The strength of a solution is a measure of the amount of chemical solute dissolved in the solution. We use the following equation to determine % strength of solution:

$$\%\ \text{Strength} = \frac{\text{chemical (lb)}}{\text{water (lb)} + \text{chemical (lb)}} \times 100 \tag{10.30}$$

Example 10.33

Problem:

If a total of 10 oz of dry polymer are added to 15 gal of water, what is the percent strength (by weight) of the polymer solution?

Solution:

Before calculating percent strength, the ounces chemical must be converted into lb chemical:

$$\frac{10\ \text{oz}}{16\ \text{oz/lb}} = 0.625\ \text{lb chemical}$$

Now calculate percent strength:

$$
\begin{aligned}
\%\text{ Strength} &= \frac{\text{chemical (lb)}}{\text{water (lb)} + \text{chemical (lb)}} \times 100 \\
&= \frac{0.625\text{ lb chemical}}{(15\text{ gal} \times 8.34\text{ lb/gal}) + 0.625\text{ lb}} \times 100 \\
&= \frac{0.625\text{ lb chemical}}{125.7\text{ lb solution}} \times 100 \\
&= 0.5\%
\end{aligned}
$$

EXAMPLE 10.34

Problem:

If 90 g (1 g = 0.0022 lb) of dry polymer are dissolved in 6 gal of water, what percent strength is the solution?

Solution:

First, convert grams chemical into pounds chemical. Since 1 g = 0.0022 lb, 90 g is 90 times 0.0022 lb:

$$(90\text{ g polymer})(0.0022\text{ lb/g}) = 0.198\text{ lb polymer}$$

Now calculate percent strength of the solution:

$$
\begin{aligned}
\%\text{ Strength} &= \frac{\text{lb polymer}}{\text{lb water } + \text{ lb polymer}} \times 100 \\
&= \frac{0.198\text{ lb polymer}}{(6\text{ gal})(8.34\text{ lb/gal}) \; + \; 0.198\text{ lb}} \times 100 \\
&= 4\%
\end{aligned}
$$

DETERMINING PERCENT STRENGTH OF LIQUID SOLUTIONS

When using liquid chemicals to make up solutions (e.g., liquid polymer), a different calculation is required, as shown below:

$$
\begin{aligned}
&\text{Liquid polymer, lb } \frac{\text{liquid polymer (\% strength)}}{100} \\
&= \text{polymer solid, lb } \frac{\text{polymer solution (\% strength)}}{100}
\end{aligned}
\tag{10.31}
$$

EXAMPLE 10.35

Problem:

A 12% liquid polymer is to be used in making up a polymer solution. How many pounds of liquid polymer should be mixed with water to produce 120 lb of a 0.5% polymer solution?

Solution:

$$
\begin{aligned}
&(\text{Liquid polymer, lb})(\text{liquid polymer \% strength}/100)\\
&\qquad = (\text{polymer solid, lb})(\text{polymer solid \% strength}/100)\\
&(x\ \text{lb})(12/100) = (120\ \text{lb})(0.5/100)\\
&x = \frac{(120)(0.005)}{0.12}\\
&x = 5\ \text{lb}
\end{aligned}
$$

DETERMINING PERCENT STRENGTH OF MIXED SOLUTIONS

The percent strength of solution mixture is determined using the following equation:

$$
\begin{aligned}
\%\ \text{Strength of mix} &= \frac{(\text{solution 1, lb})(\%\ \text{strength of solution }1/100)}{\text{lb solution 1}}\\
&\quad + \frac{(\text{solution 2, lb})(\%\ \text{strength of solution }2/100)}{\text{lb solution 2}} \times 100
\end{aligned}
\tag{10.32}
$$

EXAMPLE 10.36

Problem:

If 12 lb of a 10% strength solution are mixed with 40 lb of a 1% strength solution, what is the percent strength of the solution mixture?

Solution:

$$
\begin{aligned}
\%\ \text{Strength of mix} &= \frac{(\text{solution 1, lb})(\%\ \text{strength of solution }1/100)}{\text{lb solution 1}}\\
&\quad + \frac{(\text{solution 2, lb})(\%\ \text{strength of solution }2/100)}{\text{lb solution 2}} \times 100\\
&= \frac{(12\ \text{lb})(0.1) + (40\ \text{lb})(0.01)}{12\ \text{lb} + 40\ \text{lb}} \times 100\\
&= \frac{12\ \text{lb} + 0.40}{52\ \text{lb}} \times 100\\
&= 3.1\%
\end{aligned}
$$

DRY CHEMICAL FEEDER CALIBRATION

Occasionally, we need to perform a calibration calculation to compare the actual chemical feed rate with the feed rate indicated by the instrumentation. To calculate the actual feed rate for a dry chemical feeder, place a container under the feeder, weigh the container when empty, then weigh the container again after a specified length of time (e.g., 30 min).

The actual chemical feed rate can be calculated using the following equation:

$$\text{Chemical feed rate, lb/min} = \frac{\text{chemical applied, lb}}{\text{length of application, min}} \tag{10.33}$$

If desired, the chemical feed rate can be converted into lb/day:

$$\text{Feed rate, lb/day} = (\text{feed rate, lb/min})(1440\ \text{min/day}) \tag{10.34}$$

EXAMPLE 10.37

Problem:

Calculate the actual chemical feed rate, lb/day, if a container is placed under a chemical feeder and a total of 2 lb is collected during a 30-min period.

Solution:

First calculate the lb/min feed rate:

$$\begin{aligned}\text{Chemical feed rate, lb/min} &= \frac{\text{chemical applied, lb}}{\text{length of application, min}}\\ &= \frac{2\ \text{lb}}{30\ \text{min}}\\ &= 0.06\ \text{lb/min feed rate}\end{aligned}$$

Then calculate the lb/day feed rate:

$$\begin{aligned}\text{Chemical feed rate, lb/day} &= (0.06\ \text{lb/min})(1440\ \text{min/day})\\ &= 86.4\ \text{lb/day feed rate}\end{aligned}$$

EXAMPLE 10.38

Problem:

Calculate the actual chemical feed rate, lb/day, if a container is placed under a chemical feeder and a total of 1.6 lb is collected during a 20-min period.

Solution:

First calculate the lb/min feed rate:

$$\begin{aligned}\text{Chemical feed rate, lb/min} &= \frac{\text{chemical applied, lb}}{\text{length of application, min}}\\ &= \frac{1.6\ \text{lb}}{20\ \text{min}}\\ &= 0.08\ \text{lb/min feed rate}\end{aligned}$$

Then calculate the lb/day feed rate:

$$\begin{aligned}\text{Chemical feed rate, lb/day} &= (0.08\ \text{lb/min})(1440\ \text{min/day})\\ &= 115\ \text{lb/day feed rate}\end{aligned}$$

SOLUTION CHEMICAL FEEDER CALIBRATION

As with other calibration calculations, the actual solution chemical feed rate is determined and then compared with the feed rate indicated by the instrumentation. To calculate the actual solution chemical feed rate, first express the solution feed rate in MGD. Once the MGD solution flow rate has been calculated, use the mg/L equation to determine chemical dosage in lb/day.

If solution feed is expressed as mL/min, first convert mL/min flow rate into gpd flow rate.

$$\text{gpd} = \frac{(\text{mL/min})(1440\ \text{min/day})}{3785\ \text{mL/gal}} \tag{10.35}$$

Then calculate chemical dosage, lb/day.

$$\text{Chemical, lb/day} = (\text{chemical, mg/L})(\text{flow, MGD})(8.34\ \text{lb/day}) \tag{10.36}$$

EXAMPLE 10.39

Problem:

A calibration test is conducted for a solution chemical feeder. During a 5-min test, the pump delivered 940 mg/L of the 1.20% polymer solution. (Assume the polymer solution weighs 8.34 lb/gal.) What is the polymer dosage rate in lb/day?

Solution:

The flow rate must be expressed as MGD. Therefore, the mL/min solution flow rate must first be converted into gpd and then into MGD. The mL/min flow rate is calculated as:

$$\frac{940\ \text{mL}}{5\ \text{min}} = 188\ \text{mL/min}$$

Next convert the mL/min flow rate into gpd flow rate:

$$\frac{(188\ \text{mL/min})(1440\ \text{min/day})}{3785\ \text{mL/gal}} = 72\ \text{gpd flow rate}$$

Then calculate the lb/day polymer feed rate:

$$(12{,}000\ \text{mg/L})(0.000072\ \text{MGD})(8.34\ \text{lb/day}) = 7.2\ \text{lb/day polymer}$$

EXAMPLE 10.40

Problem:

A calibration test is conducted for a solution chemical feeder. During a 24-h period, the solution feeder delivers a total of 100 gal of solution. The polymer solution is a 1.2% solution. What is the lb/day feed rate? (Assume the polymer solution weighs 8.34 lb/gal.)

Solution:

The solution feed rate is 100 gallons per day or 100 gpd. Expressed as MGD, this is 0.000100 MGD. Use the mg/L to lb/day equation to calculate actual feed rate, lb/day:

$$\begin{aligned}\text{lb/day chemical} &= (\text{chemical, mg/L})(\text{flow, MGD})(8.34\ \text{lb/day})\\ &= (12{,}000\ \text{mg/L})(0.000100\ \text{MGD})(8.34\ \text{lb/day})\\ &= 10\ \text{lb/day polymer}\end{aligned}$$

The actual pumping rates can be determined by calculating the volume pumped during a specified time frame. For example, if 60 gal are pumped during a 10-min test, the average pumping rate during the test is 6 gpm.

Actual volume pumped is indicated by drop in tank level. By using the following equation, we can determine the flow rate in gpm.

$$\text{Flow rate, gpm} = \frac{(0.785)(D^2)(\text{drop in level, ft})(7.48\ \text{gal/ft}^3)}{\text{duration of test, min}} \tag{10.37}$$

Example 10.41

Problem:

A pumping rate calibration test is conducted for a 15-min period. The liquid level in the 4-ft diameter solution tank is measured before and after the test. If the level drops 0.5 ft during the 15-min test, what is the pumping rate in gpm?

Solution:

$$\begin{aligned}\text{Flow rate, gpm} &= \frac{(0.785)(D^2)(\text{drop in level, ft})(7.48\ \text{gal/ft}^3)}{\text{duration of test, min}}\\ &= \frac{(0.785)(4\ \text{ft})(4\ \text{ft})(0.5\ \text{ft})(7.48\ \text{gal/ft}^3)}{15\ \text{min}}\\ &= 3.1\ \text{gpm pumping rate}\end{aligned}$$

DETERMINING CHEMICAL USAGE

One of the primary functions performed by water operators is the recording of data. The lb/day or gpd chemical use is part of these data. From these data, the average daily use of chemicals and solutions can be determined. This information is important in forecasting expected chemical use, comparing it with chemicals in inventory, and determining when additional chemicals will be required.

To determine average chemical use, use Equation 10.38 (lb/day) or Equation 10.39 (gpd):

$$\text{Average use, lb/day} = \frac{\text{total chemical used, lb}}{\text{number of days}} \tag{10.38}$$

$$\text{Average use, gpd} = \frac{\text{total chemical used, gal}}{\text{number of days}} \tag{10.39}$$

Then we can calculate days' supply in inventory:

$$\text{Days' supply in inventory} = \frac{\text{total chemical in inventory, lb}}{\text{average use, lb/day}} \tag{10.40}$$

Or

$$\text{Days' supply in inventory} = \frac{\text{total chemical in inventory, gal}}{\text{average use, gal/day}} \tag{10.41}$$

EXAMPLE 10.42

Problem:

The chemical used for each day during a week is given below. Based on these data, what was the average lb/day chemical use during the week?

Monday—88 lb/day
Tuesday—93 lb/day
Wednesday—91 lb/day
Thursday—88 lb/day
Friday—96 lb/day
Saturday—92 lb/day
Sunday—86 lb/day

Solution:

$$\begin{aligned} \text{Average use, lb/day} &= \frac{\text{total chemical used, lb}}{\text{number of days}} \\ &= \frac{634\text{ lb}}{7\text{ days}} \\ &= 90.6\text{ lb/days average use} \end{aligned}$$

EXAMPLE 10.43

Problem:

The average chemical use at a plant is 77 lb/day. If the chemical inventory is 2800 lb, how many days' supply is this?

Solution:

$$\begin{aligned} \text{Days' supply in inventory} &= \frac{\text{total chemical in inventory, lb}}{\text{average use, lb/day}} \\ &= \frac{2800\text{ lb in inventory}}{77\text{ lb/day average use}} \\ &= 36.4\text{ days' supply in inventory} \end{aligned}$$

PADDLE FLOCCULATOR CALCULATIONS

The gentle mixing required for flocculation is accomplished by a variety of devices. Probably the most common device in use is the basin equipped with mechanically driven paddles. Paddle flocculators have individual compartments for each set of paddles. The useful power input imparted by a paddle to the water depends on the drag force and the relative velocity of the water with respect to the paddle (Droste, 1997).

In regard to paddle flocculator design and operation, environmental engineers are mainly interested in determining the velocity of a paddle at a set distance, the drag force of the paddle on the water, and the power input imparted to the water by the paddle.

Because of slip, factor k, the velocity of the water, will be less than the velocity of the paddle. If baffles are placed along the walls in a direction perpendicular to the water movement, the value of k decreases because the baffles obstruct the movement of the water (Droste, 1997). The frictional dissipation of energy depends on the relative velocity, v. The relative velocity can be determined using Equation 10.42:

$$v = v_p - v_t = v_p - kv_p = v_p(1-k) \tag{10.42}$$

where v_t is the water velocity and v_p is the paddle velocity.

To determine the velocity of the paddle at a distance r from the shaft, we use Equation 10.43:

$$v_p = \frac{2\pi N}{60} r \tag{10.43}$$

where N is the rate of revolution of the shaft (rpm).

To determine the drag force of the paddle on the water, we use Equation 10.44:

$$F_D = \frac{1}{2} pC_D A v^2 \tag{10.44}$$

where

A = area of the paddle

F_D = drag force

C_D = drag coefficient

To determine the power input imparted to the water by an elemental area of the paddle, we usually use Equation 10.45:

$$dP = dF_D V = \frac{1}{2} pC_D v^3 dA \tag{10.45}$$

SEDIMENTATION CALCULATIONS

Sedimentation, the solid–liquid separation by gravity, is one of the most basic processes of water and wastewater treatment. In water treatment, plain sedimentation, such as the use of a presedimentation basin for grit removal and sedimentation basin following coagulation–flocculation, is the most commonly used.

TANK VOLUME CALCULATIONS

The two common shapes of sedimentation tanks are rectangular and cylindrical. The equations for calculating the volume for each type tank are shown below.

CALCULATING TANK VOLUME

For rectangular sedimentation basins, we use Equation 10.46:

$$\text{Volume, gal} = (\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\ \text{gal/ft}^3) \tag{10.46}$$

For circular clarifiers, we use Equation 10.47:

$$\text{Volume, gal} = (0.785)(D^2)(\text{depth, ft})(7.48\ \text{gal/ft}^3) \tag{10.47}$$

EXAMPLE 10.44

Problem:

A sedimentation basin is 25 ft wide and 80 ft long, and contains water to a depth of 14 ft. What is the volume of water in the basin, in gallons?

Solution:

$$\begin{aligned}\text{Volume, gal} &= (\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\ \text{gal/ft}^3)\\ &= (80\ \text{ft})(25\ \text{ft})(14\ \text{ft})(7.48\ \text{gal/ft}^3)\\ &= 209{,}440\ \text{gal}\end{aligned}$$

EXAMPLE 10.45

Problem:

A sedimentation basin is 24 ft wide and 75 ft long. What is the water depth when the basin contains 140,000 gal?

Solution:

$$\begin{aligned}\text{Volume, gal} &= (\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\ \text{gal/ft}^3)\\ 140{,}000\ \text{gal} &= (75\ \text{ft})(24\ \text{ft})(x\ \text{ft})(7.48\ \text{gal/ft}^3)\\ x\ \text{ft} &= \frac{140{,}000}{(75)(24)(7.48)}\\ x\ \text{ft} &= 10.4\ \text{ft}\end{aligned}$$

DETENTION TIME

Detention time for clarifiers varies from 1 to 3 h. The equations used to calculate detention time are shown below.

The basic detention time equation is:

$$\text{Detention time, h} = \frac{\text{volume of tank, gal}}{\text{flow rate, gph}} \tag{10.48}$$

The rectangular sedimentation basin equation is:

$$\text{Detention time, h} = \frac{(\text{length, ft})(\text{width, ft})(\text{depth, ft})(7.48\ \text{gal/ft}^3)}{\text{flow rate, gph}} \tag{10.49}$$

The circular basin equation is:

$$\text{Detention time, h} = \frac{(0.785)(D^2)(\text{depth, ft})(7.48\ \text{gal/ft}^3)}{\text{flow rate, gph}} \tag{10.50}$$

EXAMPLE 10.46

Problem:

A sedimentation tank has a volume of 137,000 gal. If the flow to the tank is 121,000 gph, what is the detention time in the tank in hours?

Solution:

$$\text{Detention time, h} = \frac{\text{volume of tank, gal}}{\text{flow rate, gph}}$$

$$= \frac{137{,}000\ \text{gal}}{121{,}000\ \text{gph}}$$

$$= 1.1\ \text{h}$$

EXAMPLE 10.47

Problem:

A sedimentation basin is 60 ft long and 22 ft wide, and has water to a depth of 10 ft. If the flow to the basin is 1,500,000 gpd, what is the sedimentation basin detention time?

Solution:

First, convert the flow rate from gpd to gph so that times units will match (1,500,000 gpd/24 h/day = 62,500 gph). Then calculate detention time:

$$\text{Detention time, h} = \frac{\text{volume of tank, gal}}{\text{flow rate, gph}}$$

$$= \frac{(60\ \text{ft})(22\ \text{ft})(10\ \text{ft})(7.48\ \text{gal/ft}^3)}{62{,}500\ \text{gph}}$$

$$= 1.6\ \text{h}$$

SURFACE OVERFLOW RATE

Surface loading rate—similar to hydraulic loading rate (flow per unit area)—is used to determine loading on sedimentation basins and circular clarifiers. Hydraulic loading rate, however, measures the total water entering the process whereas surface overflow rate measures only the water overflowing the process (plant flow only).

Note: Surface overflow rate calculations do not include recirculated flows. Other terms used synonymously with surface overflow rate are surface loading rate and surface settling rate.

Surface overflow rate is determined using the following equation:

$$\text{Surface overflow rate} = \frac{\text{flow, gpm}}{\text{area, ft}^2} \tag{10.51}$$

EXAMPLE 10.48

Problem:

A circular clarifier has a diameter of 80 ft. If the flow to the clarifier is 1800 gpm, what is the surface overflow rate in gpm/ft^2?

Solution:

$$\begin{aligned}\text{Surface overflow rate} &= \frac{\text{flow, gpm}}{\text{area, ft}^2}\\ &= \frac{1800\text{ gpm}}{(0.785)(80\text{ ft})(80\text{ ft})}\\ &= 0.36\text{ gpm/ft}^2\end{aligned}$$

EXAMPLE 10.49

Problem:

A sedimentation basin 70 ft by 25 ft receives a flow of 1000 gpm. What is the surface overflow rate in gpm/ft^2?

Solution:

$$\begin{aligned}\text{Surface overflow rate} &= \frac{\text{flow, gpm}}{\text{area, ft}^2}\\ &= \frac{1000\text{ gpm}}{(70\text{ ft})(25\text{ ft})}\\ &= 0.6\text{ gpm/ft}^2\ \text{(rounded)}\end{aligned}$$

MEAN FLOW VELOCITY

The measure of average velocity of the water as it travels through a rectangular sedimentation basin is known as *mean flow velocity*. Mean flow velocity is calculated using Equation 10.52:

$$\begin{aligned}&Q\ \text{(flow), ft}^3\text{/min} = A\ \text{(cross-sectional area), ft}^2 \times V\ \text{(volume) ft/min}\\ &Q = AV\end{aligned} \tag{10.52}$$

EXAMPLE 10.50

Problem:

A sedimentation basin 60 ft long and 18 ft wide has water to a depth of 12 ft. When the flow through the basin is 900,000 gpd, what is the mean flow velocity in the basin, in ft/min?

Solution:

Because velocity is desired in ft/min, the flow rate in the $Q = AV$ equation must be expressed in cu ft/min (cfm):

$$\frac{900{,}000\text{ gpd}}{(1440\text{ min/day})(7.48\text{ gal/ft}^3)} = 84\text{ cfm}$$

Then use the $Q = AV$ equation to calculate velocity:

$$Q = AV$$

$$84 \text{ cfm} = (18 \text{ ft})(12 \text{ ft})(x \text{ fpm})$$

$$x = \frac{84}{(18)(12)}$$

$$= 0.4 \text{ fpm}$$

Example 10.51

Problem:

A rectangular sedimentation basin 50 ft long and 20 ft wide has a water depth of 9 ft. If the flow to the basin is 1,880,000 gpd, what is the mean flow velocity in ft/min?

Solution:

Because velocity is desired in ft/min, the flow rate in the $Q = AV$ equation must be expressed in cfm:

$$\frac{1{,}880{,}000 \text{ gpd}}{(1440 \text{ min/day})(7.48 \text{ gal/ft}^3)} = 175 \text{ cfm}$$

Then use the $Q = AV$ equation to calculate velocity:

$$Q = AV$$

$$175 \text{ cfm} = (20 \text{ ft})(9 \text{ ft})(x \text{ fpm})$$

$$x = \frac{175 \text{ cfm}}{(20)(9)}$$

$$= 0.97 \text{ fpm}$$

WEIR LOADING RATE (WEIR OVERFLOW RATE)

Weir loading rate (weir overflow rate) is the amount of water leaving the settling tank per linear foot of weir. The result of this calculation can be compared with design. Normally, weir overflow rates of 10,000–20,000 gal/day/ft are used in the design of a settling tank. Typically, *weir loading rate* is a measure of the gpm flow over each foot (ft) of weir. Weir loading rate is determined using the following equation:

$$\text{Weir loading rate, gpm/ft} = \frac{\text{flow, gpm}}{\text{weir length, ft}} \tag{10.53}$$

Example 10.52

Problem:

A rectangular sedimentation basin has a total of 115 ft of weir. What is the weir loading rate in gpm/ft when the flow is 1,110,000 gpd?

Solution:

$$\frac{1{,}110{,}000\text{ gpd}}{1440\text{ min/day}} = 771\text{ gpm}$$

$$\begin{aligned}\text{Weir loading rate} &= \frac{\text{flow, gpm}}{\text{weir length, ft}}\\ &= \frac{771\text{ gpm}}{115\text{ ft}}\\ &= 6.7\text{ gpm/ft}\end{aligned}$$

Example 10.53

Problem:

A circular clarifier receives a flow of 3.55 MGD. If the diameter of the weir is 90 ft, what is the weir loading rate in gpm/ft?

Solution:

$$\frac{3{,}550{,}000\text{ gpd}}{1440\text{ min/day}} = 2465\text{ gpm}$$

$$\begin{aligned}\text{ft of weir} &= (3.14)(90\text{ ft})\\ &= 283\text{ ft}\end{aligned}$$

$$\begin{aligned}\text{Weir loading rate} &= \frac{\text{flow, gpm}}{\text{weir length, ft}}\\ &= \frac{2465\text{ gpm}}{283\text{ ft}}\\ &= 8.7\text{ gpm/ft}\end{aligned}$$

Percent Settled Biosolids

The percent settled biosolids test (a.k.a. "volume over volume" test, or *V/V* test) is conducted by collecting a 100-mL slurry sample from the solids contact unit and allowing it to settle for 10 min. After 10 min, the volume of settled biosolids at the bottom of the 100-mL graduated cylinder is measured and recorded. The equation used to calculate percent settled biosolids is shown below.

$$\%\text{ Settled biosolids} = \frac{\text{settled biosolids volume, mL}}{\text{total sample volume, mL}} \times 100 \tag{10.54}$$

Example 10.54

Problem:

A 100-mL sample of slurry from a solids contact unit is placed in a graduated cylinder and allowed to set for 10 min. The settled biosolids at the bottom of the graduated cylinder after 10 min is 22 mL. What is the percent of settled biosolids of the sample?

Solution:

$$\begin{aligned}\%\text{ Settled biosolids} &= \frac{\text{settled biosolids, mL}}{\text{total sample, mL}} \times 100 \\ &= \frac{22\text{ mL}}{100\text{ mL}} \times 100 \\ &= 22\%\text{ settled biosolids}\end{aligned}$$

Example 10.55

Problem:

A 100-mL sample of slurry from a solids contact unit is placed in a graduated cylinder. After 10 min, a total of 21 mL of biosolids settled to the bottom of the cylinder. What is the percent settled biosolids of the sample?

Solution:

$$\begin{aligned}\%\text{ Settled biosolids} &= \frac{\text{settled biosolids, mL}}{\text{total sample, mL}} \times 100 \\ &= \frac{21\text{ mL}}{100\text{ mL}} \times 100 \\ &= 21\%\text{ settled biosolids}\end{aligned}$$

Determining Lime Dosage, mg/L

During the alum dosage process, lime is sometimes added to provide adequate alkalinity (HCO_3^-) in the solids contact clarification process for the coagulation and precipitation of the solids. To determine the lime dose required, in mg/L, three steps are required.

In *Step 1*, the total alkalinity required is required is calculated. Total alkalinity required to react with the alum to be added and provide proper precipitation is determined using the following equation:

$$\begin{aligned}\text{Total alkalinity required, mg/L} &= \text{alkalinity reacting w/alum, mg/L} \\ &\quad + \text{alkalinity in the water, mg/L} \qquad (10.55)\end{aligned}$$

$$(1\text{ mg/L alum reacts w/}0.45\text{ mg/L alkalinity})$$

Example 10.56

Problem:

Raw water requires an alum dose of 45 mg/L, as determined by jar testing. If a residual 30 mg/L alkalinity must be present in the water to ensure complete precipitation of alum added, what is the total alkalinity required, in mg/L?

Solution:

First, calculate the alkalinity that will react with 45 mg/L alum:

$$\frac{0.45\text{ mg/L alkalinity}}{1\text{ mg/L alum}} = \frac{x\text{ mg/L alkalinity}}{45\text{ mg/L alum}}$$

$$(0.45)(45) = x$$

$$= 20.25\text{ mg/L alkalinity}$$

Next, calculate the total alkalinity required:

$$\text{Total alkalinity required, mg/L} = \text{alkalinity to react with alum, mg/L} + \text{residual alkalinity, mg/L}$$

$$= 20.25\text{ mg/L} + 30\text{ mg/L}$$

$$= 50.25\text{ mg/L}$$

EXAMPLE 10.57

Problem:

Jar tests indicate that 36 mg/L alum is optimum for particular raw water. If a residual 30 mg/L alkalinity must be present to promote complete precipitation of the alum added, what is the total alkalinity required, in mg/L?

Solution:

First, calculate the alkalinity that will react with 36 mg/L alum:

$$\frac{0.45\text{ mg/L alkalinity}}{1\text{ mg/L alum}} = \frac{x\text{ mg/L alkalinity}}{36\text{ mg/L alum}}$$

$$(0.45)(36) = x$$

$$= 16.2$$

Then, calculate the total alkalinity required:

$$\text{Total alkalinity required, mg/L} = 16.2\text{ mg/L} + 30\text{ mg/L}$$

$$= 46.2\text{ mg/L}$$

In *Step 2*, we make a comparison between required alkalinity and alkalinity already in the raw water to determine how many mg/L alkalinity should be added to the water. The equation used to make this calculation is shown below:

$$\text{Alkalinity to be added to the water, mg/L} = \text{total alkalinity required, mg/L} - \text{alkalinity present in the water, mg/L} \quad (10.56)$$

Example 10.58

Problem:

A total of 44 mg/L alkalinity is required to react with alum and ensure proper precipitation. If the raw water has an alkalinity of 30 mg/L as bicarbonate, how many mg/L alkalinity should be added to the water?

Solution:

$$\begin{aligned}\text{Alkalinity to be added, mg/L} &= \text{total alkalinity required, mg/L} - \text{alkalinity present in the water, mg/L}\\ &= 44\text{ mg/L} - 30\text{ mg/L}\\ &= 14\text{ mg/L alkalinity to be added}\end{aligned}$$

In *Step 3*, after determining the amount of alkalinity to be added to the water, we determine how much lime (the source of alkalinity) needs to be added. We accomplish this by using the ratio shown in Example 10.59.

Example 10.59

Problem:

It has been calculated that 16 mg/L alkalinity must be added to a raw water. How much mg/L lime will be required to provide this amount of alkalinity? (1 mg/L alum reacts with 0.45 mg/L and 1 mg/L alum reacts with 0.35 mg/L lime.)

Solution:

First, determine the mg/L lime required by using a proportion that relates bicarbonate alkalinity to lime:

$$\frac{0.45\text{ mg/L alkalinity}}{0.35\text{ mg/L lime}} = \frac{16\text{ mg/L alkalinity}}{x\text{ mg/L lime}}$$

Next, we cross-multiply:

$$0.45x = (16)(0.35)$$

$$x = \frac{(16)(0.35)}{0.45}$$

$$x = 12.4\text{ mg/L lime}$$

In Example 10.60, we use all three steps to determine lime dosage (mg/L) required.

Example 10.60

Problem:

Given the following data, calculate the lime dose required, in mg/L:

Alum dose required (determined by jar tests)—52 mg/L
Residual alkalinity required for precipitation—30 mg/L

1 mg/L alum reacts with 0.35 mg/L lime
1 mg/L alum reacts with 0.45 mg/L alkalinity
Raw water alkalinity—36 mg/L

Solution:

To calculate the total alkalinity required, you must first calculate the alkalinity that will react with 52 mg/L alum:

$$\frac{0.45\text{ mg/L alkalinity}}{1\text{ mg/L alum}} = \frac{x\text{ mg/L alkalinity}}{52\text{ mg/L alum}}$$

$$(0.45)(52) = x$$

$$23.4\text{ mg/L alkalinity} = x$$

The total alkalinity requirement can now be determined:

$$\begin{aligned}\text{Total alkalinity required, mg/L} &= \text{alkalinity to react with alum, mg/L} + \text{residual alkalinity, mg/L}\\ &= 23.4\text{ mg/L} + 30\text{ mg/L}\\ &= 53.4\text{ mg/L total alkalinity required}\end{aligned}$$

Next, calculate how much alkalinity must be *added* to the water:

$$\begin{aligned}\text{Alkalinity to be added, mg/L} &= \text{total alkalinity required, mg/L} - \text{alkalinity present, mg/L}\\ &= 53.4\text{ mg/L} - 36\text{ mg/L}\\ &= 17.4\text{ mg/L alkalinity to be added to the water}\end{aligned}$$

Finally, calculate the lime required to provide this additional alkalinity:

$$\frac{0.45\text{ mg/L alkalinity}}{0.35\text{ mg/L lime}} = \frac{17.4\text{ mg/L alkalinity}}{x\text{ mg/L lime}}$$

$$0.45x = (17.4)(0.35)$$

$$x = \frac{(17.4)(0.35)}{0.45}$$

$$x = 13.5\text{ mg/L lime}$$

DETERMINING LIME DOSAGE, lb/day

After the lime dose has been determined in terms of mg/L, it is a fairly simple matter to calculate the lime dose in lb/day, which is one of the most common calculations in water and wastewater treatment. To convert from mg/L to lb/day lime dose, we use the following equation:

$$\text{Lime, lb/day} = (\text{lime, mg/L})(\text{flow, MGD})(8.34\text{ lb/gal}) \tag{10.57}$$

Example 10.61

Problem:

The lime dose for a raw water has been calculated to be 15.2 mg/L. If the flow to be treated is 2.4 MGD, how many lb/day lime will be required?

Solution:

$$\begin{aligned}\text{Lime, lb/day} &= (\text{lime, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})\\ &= (15.2\ \text{mg/L})(2.4\ \text{MGD})(8.34\ \text{lb/gal})\\ &= 304\ \text{lb/day lime}\end{aligned}$$

Example 10.62

Problem:

The flow to a solids contact clarifier is 2,650,000 gpd. If the lime dose required is determined to be 12.6 mg/L, how many lb/day lime will be required?

Solution:

$$\begin{aligned}\text{Lime, lb/day} &= (\text{lime, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})\\ &= (12.6\ \text{mg/L})(2.65\ \text{MGD})(8.34\ \text{lbs/gal})\\ &= 278\ \text{lb/day lime}\end{aligned}$$

Determining Lime Dosage, g/min

In converting mg/L lime into grams/min (g/min) lime, use Equation 10.58.

Key Point: 1 lb = 453.6 g.

$$\text{Lime, g/min} = \frac{(\text{lime, lb/day})(453.6\ \text{g/lb})}{1440\ \text{min/day}} \tag{10.58}$$

Example 10.63

Problem:

A total of 275 lb/day lime will be required to raise the alkalinity of the water passing through a solids-contact clarification process. How many g/min lime does this represent?

Solution:

$$\begin{aligned}\text{Lime, g/min} &= \frac{(\text{lb/day})(453.6\ \text{g/lb})}{1440\ \text{min/day}}\\ &= \frac{(275\ \text{lb/day})(453.6\ \text{g/lb})}{1440\ \text{min/day}}\\ &= 86.6\ \text{g/min lime}\end{aligned}$$

Example 10.64

Problem:

A lime dose of 150 lb/day is required for a solids-contact clarification process. How many g/min lime does this represent?

Solution:

$$\text{Lime, g/min} = \frac{\text{(lb/day)(453.6 g/lb)}}{\text{1440 min/day}}$$

$$= \frac{\text{(150 lb/day)(453.6 g/lb)}}{\text{1440 min/day}}$$

$$= 47.3 \text{ g/min lime}$$

√ **Note:** Much of the information presented in the following section is based on the USEPA's *Turbidity Provisions* (EPA Guidance Manual, April 1999).

Particle Settling (Sedimentation)

Particle settling (sedimentation) may be described for a singular particle by the Newton equation (Equation 10.64) for terminal settling velocity of a spherical particle. For the engineer, knowledge of this velocity is basic in the design and performance of a sedimentation basin.

The rate at which discrete particles will settle in a fluid of constant temperature is given by the equation:

$$u = \frac{(4g(p_P - p)d)^{0.5}}{3C_D p} \tag{10.59}$$

where

u = settling velocity of particles, m/s or ft/s
g = gravitational acceleration, m/s^2 or ft/s^2
p_p = density of particles, kg/m^3 or lb/ft^3
p = density of water, kg/m^3 or lb/ft^3
d = diameter of particles, m or ft
C_D = coefficient of drag

The terminal settling velocity is derived by equating the drag, buoyant, and gravitational forces acting on the particle. At low settling velocities, the equation is not dependent on the shape of the particle and most sedimentation processes are designed so as to remove small particles, ranging from 1.0 to 0.5 μm, which settle slowly. Larger particles settle at higher velocity and will be removed whether or not they follow Newton's law, or Stokes' law, the governing equation when the drag coefficient is sufficiently small (0.5 or less) as is the case for colloidal products (McGhee, 1991).

Typically, a large range of particle sizes will exist in the raw water supply. There are four types of sedimentation: Type 1—discrete particle settling (particles of various sizes, in a dilute suspension, which settle without flocculating; Type 2—flocculant settling (heavier particles coalesced with smaller and lighter particles); Type 3—hindered settling (high densities of particles in suspension resulting in an interaction of particles); Type 4—compression settling (Gregory and Zabel, 1990).

The values of drag coefficient depend on the density of water (p), relative velocity (u), particle diameter (d), and viscosity of water (μ), which gives the Reynolds number **R** as:

$$\mathbf{R} = \frac{pud}{\mu} \tag{10.60}$$

As the Reynolds number increases, the value of C_D increases. For $\mathbf{R} < 2$, C_D is related to **R** by the linear expression as follows:

$$C_D = \frac{24}{\mathbf{R}} \tag{10.61}$$

At low levels of **R**, the Stokes' equation, for laminar flow conditions, is used (Equations 10.60 and 10.61 substituted into 10.59).

$$u = \frac{g(\rho_p - \rho)d^2}{18\mu} \tag{10.62}$$

In the region of higher Reynolds numbers ($2 < \mathbf{R} <$ 500–1000), C_D becomes (Fair et al., 1968):

$$C_D = \frac{24}{\mathbf{R}} + \frac{3}{\sqrt{\mathbf{R}}} + 0.34 \tag{10.63}$$

√ **Key Point:** In the region of turbulent flow (500–1000 $< \mathbf{R} <$ 200,000), the C_D remains approximately constant at 0.44.

The velocity of settling particles results in Newton's equation (AWWA & ASCE, 1990):

$$u = 1.74\left[\frac{(p_p - p)gd}{p}\right]^{0.5} \tag{10.64}$$

√ **Key Point:** When the Reynolds number >200,000, the drag force decreases substantially and C_D becomes 0.10. There is no settling at this condition.

Example 10.65

Problem:

Estimate the terminal settling velocity in water at a temperature of 21°C of spherical particles with specific gravity 2.40 and average diameter of (a) 0.006 mm and (b) 1.0 mm.

Solution:

Step 1. Use Equation 10.62 for (a).

Given: At temperature (T) = 21°C

$\rho = 998$ kg/m^3
$\mu = 0.00098$ N s/m^2
$d = 0.06$ mm $= 6 \times 10^{-5}$ m
$g = 9.81$ m/s^2

$$\begin{aligned}
\text{(a) } u &= \frac{g(\rho_p - \rho)d^2}{18\mu} \\
&= \frac{9.81 \text{ m/s}^2 (2400 - 998) \text{ kg/m}^3 \ (6 \times 10^{-5} \text{ m})^2}{18 \times 0.00098 \text{ N s/m}^2} \\
&= 0.00281 \text{ m/s}
\end{aligned}$$

Step 2. Use Equation 10.60 to check the Reynolds number.

$$\mathbf{R} = \frac{pud}{\mu} = \frac{998 \times 0.00281 \times 6 \times 10^{-5}}{0.00098} = 0.172$$

(a) Stokes' law applies, since $\mathbf{R} < 2$.

Step 3. Using Stokes' law for (b):

$$\begin{aligned}
u &= \frac{9.81 \ (2400 - 998)(0.001)^2}{18 \times 0.00098} \\
&= \frac{0.0137536}{0.01764} \\
&= 0.779 \text{ m/s}
\end{aligned}$$

Step 4. Check the Reynolds number.

Assume the irregularities of the particles $\phi = 0.80$:

$$\begin{aligned}
\frac{\phi\rho ud}{\mu} &= \frac{0.80 \times 998 \times 0.779 \times 0.001}{0.00098} \\
&= 635
\end{aligned}$$

Because $\mathbf{R} > 2$, Stokes' law does not apply. Use Equation 10.59 to calculate u.

Step 5. Using Equation 10.63:

$$C_D = \frac{24}{\mathbf{R}} + \frac{3}{\sqrt{\mathbf{R}}} + 0.34 = \frac{24}{635} + \frac{3}{\sqrt{\mathbf{R}}} + 0.34 = 0.50$$

$$\begin{aligned}
u^2 &= \frac{4g(\rho_p - \rho)d}{3C_D\rho} \\
u^2 &= \frac{4 \times 9.81 \times (2400 - 998) \times 0.001}{3 \times 0.50 \times 998} \\
u &= 0.192 \text{ m/s}
\end{aligned}$$

Step 6. Recheck **R**.

$$\mathbf{R} = \frac{\phi p u d}{\mu} = \frac{0.80 \times 998 \times 0.192 \times 0.001}{0.00098} = 156$$

Step 7. Repeat Step 5 with new **R**.

$$C_\mathrm{D} = \frac{24}{156} + \frac{3}{\sqrt{156}} + 0.34 = 0.73$$

$$u^2 = \frac{4 \times 9.81 \times 1402 \times 0.001}{3 \times 0.73 \times 998} = 159 \text{ m/s}$$

Step 8. Recheck **R**.

$$\mathbf{R} = \frac{0.80 \times 998 \times 0.159 \times 0.001}{0.00098} = 130$$

Step 9. Repeat Step 7.

$$C_\mathrm{D} = \frac{24}{130} + \frac{3}{\sqrt{130}} + 0.34 = 0.79$$

$$u^2 = \frac{4 \times 9.81 \times 1402 \times 0.001}{3 \times 0.79 \times 998}$$

$$u = 0.152 \text{ m/s}$$

(b) The estimated velocity is approximately 0.15 m/s.

OVERFLOW RATE (SEDIMENTATION)

Overflow rate, along with detention time, horizontal velocity, and weir loading rate are the parameters typically used for sizing sedimentation basin. The Theoretical Detention Time (plug flow theory) is computed from the volume of the basin divided by average daily flow.

$$t = \frac{24V}{Q} \tag{10.65}$$

where

t = detention time, h

24 = 24 h/day

V = volume of basin, m^3 or million gallon (MG)

Q = average daily flow, m^3/d or Mgal/d (MGD)

The overflow rate is a standard design parameter that can be determined from discrete particle settling analysis. The overflow rate or surface loading rate is calculated by dividing the average daily flow by the total area of the sedimentation basin.

$$u = \frac{Q}{A} = \frac{Q}{lw} \tag{10.66}$$

where

u = overflow rate, $m^3(m^2\ d)$ or gpd/ft
Q = average daily flow, m^3/d or gpd
A = total surface area of basin, m^2 or ft^2
l and w = length and width of basin, m or ft

√ **Key Point:** All particles having a settling velocity greater than the overflow rate will settle and be removed.

Hudson (1989) points out that rapid particle density changes due to temperature, solid concentration, or salinity can induce density current, which can cause severe short-circuiting in horizontal tanks.

Example 10.66

Problem:

A water treatment plant has two clarifiers treating 2.0 MGD of water. Each clarifier is 14 ft wide, 80 ft long, and 17 ft deep. Determine: (a) detention time, (b) overflow, (c) horizontal velocity, and (d) weir loading rate assuming the weir length is 2.5 times the basin width.

Solution:

Step 1. Compute detention time (t) for each clarifier.

$$Q = \frac{2\text{ mgd}}{2} = \frac{1{,}000{,}000\text{ gal}}{d} \times \frac{1\text{ ft}}{7.48\text{ gal}} \times \frac{1d}{24h}$$

$$= 5570\text{ ft}^3/\text{h}$$

$$= 92.8\text{ ft}^3/\text{min}$$

$$\text{(a) } t = \frac{V}{Q} = \frac{14\text{ ft} \times 80\text{ ft} \times 17\text{ ft}}{5570\text{ ft}^3/\text{h}}$$

Step 2. Compute overflow rate u.

$$\text{(b) } u = \frac{Q}{lw} = \frac{1{,}000{,}000\text{ gpd}}{14\text{ ft} \times 80\text{ ft}} = 893\text{ gpd/ft}$$

Step 3. Compute horizontal velocity V.

$$\text{(c) } V = \frac{Q}{wd} = \frac{92.8\text{ ft}^3/\text{min}}{14\text{ ft} \times 17\text{ ft}} = 0.39\text{ ft/min}$$

Step 4. Compute weir loading rate u_w.

$$\text{(d) } u_w = \frac{Q}{2.5w} = \frac{1{,}000{,}000\text{ gpd}}{2.5 \times 14\text{ ft}} = 28{,}571\text{ gpd/ft}$$

WATER FILTRATION CALCULATIONS

Water filtration is a physical process of separating suspended and colloidal particles from waste by passing the water through a granular material. The process of filtration involves straining, settling, and adsorption. As floc passes into the filter, the spaces between the filter grains become clogged, reducing this opening and increasing removal. Some material is removed merely because it settles on a media grain. One of the most important processes is adsorption of the floc onto the surface of individual filter grains.

In addition to removing silt and sediment, flock, algae, insect larvae, and any other large elements, filtration also contributes to the removal of bacteria and protozoans such as *Giardia lamblia* and *Cryptosporidium*. Some filtration processes are also used for iron and manganese removal.

The Surface Water Treatment Rule (SWTR) specifies four filtration technologies, although SWTR also allows the use of alternate filtration technologies, e.g., cartridge filters. These include slow sand filtration/rapid sand filtration, pressure filtration, diatomaceous earth filtration, and direct filtration. Of these, all but rapid sand filtration are commonly employed in small water systems that use filtration. Each type of filtration system has advantages and disadvantages. Regardless of the type of filter, however, filtration involves the processes of *straining* (where particles are captured in the small spaces between filter media grains), *sedimentation* (where the particles land on top of the grains and stay there), and *adsorption* (where a chemical attraction occurs between the particles and the surface of the media grains).

FLOW RATE THROUGH A FILTER, gpm

Flow rate in gpm through a filter can be determined by simply converting the gpd flow rate, as indicated on the flow meter. The flow rate (gpm) can be calculated by taking the meter flow rate (gpd) and dividing by 1440 min/day as shown in Equation 10.67.

$$\text{Flow rate, gpm} = \frac{\text{flow rate, gpd}}{1440\ \text{min/day}} \tag{10.67}$$

EXAMPLE 10.67

Problem:

The flow rate through a filter is 4.25 MGD. What is this flow rate expressed as gpm?

Solution:

$$\text{Flow rate, gpm} = \frac{4.25\ \text{MGD}}{1440\ \text{min/day}}$$

$$= \frac{4{,}250{,}000\ \text{gpd}}{1440\ \text{min/day}}$$

$$= 2951\ \text{gpm}$$

EXAMPLE 10.68

Problem:

During a 70-hour filter run, a total of 22.4 million gal of water are filtered. What is the average flow rate through the filter in gpm during this filter run?

Solution:

$$\text{Flow rate, gpm} = \frac{\text{total gallons produced}}{\text{filter run, min}}$$

$$= \frac{22{,}400{,}000 \text{ gal}}{(70 \text{ h})(60 \text{ min/h})}$$

$$= 5333 \text{ gpm}$$

Example 10.69

Problem:

At an average flow rate of 4000 gpm, how long a filter run (in hours) would be required to produce 25 MG of filtered water?

Solution:

Write the equation as usual, filling in the known data:

$$\text{Flow rate, gpm} = \frac{\text{total gallons produced}}{\text{filter run, min}}$$

$$4000 \text{ gpm} = \frac{25{,}000{,}000 \text{ gal}}{(x \text{ h})(60 \text{ min/h})}$$

Then solve for *x:*

$$= \frac{25{,}000{,}000 \text{ gal}}{(4000)(60)}$$

$$= 104 \text{ h}$$

Example 10.70

Problem:

A filter box is 20 ft × 30 ft (including the sand area). If the influent valve is shut, the water drops 3.0 in./min. What is the rate of filtration in MGD?

Solution:

Given:

$$\text{Filter box} = 20 \text{ ft} \times 30 \text{ ft}$$
$$\text{Water drops} = 3.0 \text{ in./min}$$

Find the volume of water passing through the filter:

$$\text{Volume} = \text{area} \times \text{height}$$
$$\text{Area} = \text{width} \times \text{length}$$

√ **Note:** The best way to perform calculations for this type of problem is step by step, breaking down the problem into what is given and what is to be found.

Step 1.

$$\text{Area} = 20\text{ ft} \times 30\text{ ft} = 600\text{ ft}^2$$

Convert 3.0 in. into ft

Divide 3.0 by 12 to find feet.

$$3.0/12 = 0.25\text{ ft}$$

$$\begin{aligned}\text{Volume} &= 600\text{ ft}^2 \times 0.25\text{ ft}\\ &= 150\text{ ft}^3 \text{ of water passing through the filter in 1 min}\end{aligned}$$

Step 2.

Convert cubic feet into gallons

$$150\text{ ft}^3 \times 7.48\text{ gal/ft}^3 = 1122\text{ gal/min}$$

Step 3.

The problem asks for the rate of filtration in MGD. To find MGD, multiply the number of gpm by the number of min/day:

$$1122\text{ gal/min} \times 1{,}440\text{ min/day} = 1.62\text{ MGD}$$

EXAMPLE 10.71

Problem:

The influent valve to a filter is closed for 5 min. During this time the water level in the filter drops 0.8 ft (10 in.). If the filter is 45 ft long and 15 ft wide, what is the gpm flow rate through the filter? Water drop equals 0.16 ft/min.

Solution:

First calculate cfm flow rate using the $Q = AV$ equation:

$$\begin{aligned}Q\text{, cfm} &= (\text{length, ft})(\text{width, ft})(\text{drop velocity, ft/min})\\ &= (45\text{ ft})(15\text{ ft})(0.16\text{ ft/min})\\ &= 108\text{ cfm}\end{aligned}$$

Then convert cfm flow rate into gpm flow rate:

$$(108\text{ cfm})(7.48\text{ gal/ft}^3) = 808\text{ gpm}$$

FILTRATION RATE

One measure of filter production is filtration rate (generally range from 2 to 10 gpm/ft^2). Along with filter run time, it provides valuable information for operation of filters. It is the gallons per minute of water filtered through each square foot of filter area. Filtration rate is determined using Equation 10.68.

$$\text{Filtration rate, gpm/ft}^2 = \frac{\text{flow rate, gpm}}{\text{filter surface area, ft}^2} \qquad (10.68)$$

Example 10.72

Problem:

A filter 18 ft by 22 ft receives a flow of 1750 gpm. What is the filtration rate in gpm/ft^2?

Solution:

$$\text{Filtration rate, gpm/ft}^2 = \frac{\text{flow rate, gpm}}{\text{filter surface area, ft}^2}$$

$$= \frac{1750 \text{ gpm}}{(18 \text{ ft})(22 \text{ ft})}$$

$$= 4.4 \text{ gpm/ft}^2$$

Example 10.73

Problem:

A filter 28 ft long and 18 ft wide treats a flow of 3.5 MGD. What is the filtration rate in gpm/ft^2?

Solution:

$$\text{Flow rate} = \frac{3{,}500{,}000 \text{ gpd}}{1440 \text{ min/day}} = 2431 \text{ gpm}$$

$$\text{Filtration rate, gpm/ft}^2 = \frac{\text{flow rate, gpm}}{\text{filter surface area, sq ft}}$$

$$= \frac{2431 \text{ gpm}}{(28 \text{ ft})(18 \text{ ft})}$$

$$= 4.8 \text{ gpm/ft}^2$$

Example 10.74

Problem:

A filter 45 ft long and 20 ft wide produces a total of 18 MG during a 76-h filter run. What is the average filtration rate in gpm/ft^2 for this filter run?

Solution:

First calculate the gpm flow rate through the filter:

$$\text{Flow rate, gpm} = \frac{\text{total gallons produced}}{\text{filter run, min}}$$

$$= \frac{18{,}000{,}000 \text{ gal}}{(76)(60 \text{ min/h})}$$

$$= 3947 \text{ gpm}$$

Then calculate filtration rate:

$$\text{Filtration rate} = \frac{\text{flow rate, gpm}}{\text{filter area, ft}^2}$$

$$= \frac{3947 \text{ gpm}}{(45 \text{ ft})(20 \text{ ft})}$$

$$= 4.4 \text{ gpm/ft}^2$$

Example 10.75

Problem:

A filter is 40 ft long and 20 ft wide. During a test of flow rate, the influent valve to the filter is closed for 6 min. The water level drop during this period is 16 in. What is the filtration rate for the filter in gpm/ft^2?

Solution:

First calculate gpm flow rate, using the $Q = AV$ equation:

$$Q\text{, gpm} = (\text{length, ft})(\text{width, ft})(\text{drop velocity, ft/min})(7.48 \text{ gal/ft}^3)$$

$$= \frac{(40 \text{ ft})(20 \text{ ft})(1.33 \text{ ft})(7.48 \text{ gal/ft}^2)}{6 \text{ min}}$$

$$= 1326 \text{ gpm}$$

Then calculate filtration rate:

$$\text{Filtration rate} = \frac{\text{flow rate, gpm}}{\text{filter area, ft}^2}$$

$$= \frac{1326 \text{ gpm}}{(40 \text{ ft})(20 \text{ ft})}$$

$$= 1.66 \text{ gpm/ft}^2$$

UNIT FILTER RUN VOLUME

The unit filter run volume (UFRV) calculation indicates the total gallons passing through each square foot of filter surface area during an entire filter run. This calculation is used to compare and evaluate filter runs. UFRV value is usually at least 5000 gal/ft^2 and generally in the range of 10,000 gpd/ft^2. The UFRV value will begin to decline as the performance of the filter begins to deteriorate. The equation to be used in these calculations is shown below.

$$\text{UFRV} = \frac{\text{total gallons filtered}}{\text{filter surface area, ft}^2} \qquad (10.69)$$

Example 10.76

Problem:

The total water filtered during a filter run (between backwashes) is 2,220,000 gal. If the filter is 18 ft by 18 ft, what is the unit filter run volume (UFRV) in gal/ft^2?

Solution:

$$
\begin{aligned}
\text{UFRV} &= \frac{\text{total gallons filtered}}{\text{filter surface area, ft}^2} \\
&= \frac{2{,}220{,}000 \text{ gal}}{(18 \text{ ft})(18 \text{ ft})} \\
&= 6852 \text{ gal/ft}^2
\end{aligned}
$$

Example 10.77

Problem:

The total water filtered during a filter run is 4,850,000 gal. If the filter is 28 ft by 18 ft, what is the unit filter run volume in gal/ft^2?

Solution:

$$
\begin{aligned}
\text{UFRV} &= \frac{\text{total gallons filtered}}{\text{filter surface area, ft}^2} \\
&= \frac{4{,}850{,}000 \text{ gal}}{(28 \text{ ft})(18 \text{ ft})} \\
&= 9623 \text{ gal/ft}^2
\end{aligned}
$$

Equation 10.69 can be modified as shown in Equation 10.70 to calculate the unit filter run volume given filtration rate and filter run data.

$$
\text{UFRV} = (\text{filtration rate, gpm/ft}^2)(\text{filter run time, min}) \tag{10.70}
$$

Example 10.78

Problem:

The average filtration rate for a filter was determined to be 2.0 gpm/ft^2. If the filter run time was 4250 min, what was the unit filter run volume in gal/ft^2?

Solution:

$$
\begin{aligned}
\text{UFRV} &= (\text{filtration rate, gpm/ft}^2)(\text{filter run time, min}) \\
&= (2.0 \text{ gpm/ft}^2)(4250 \text{ min}) \\
&= 8500 \text{ gal/ft}^2
\end{aligned}
$$

The problem indicates that at an average filtration rate of 2.0 gal entering each square foot of filter each minute, the total gallons entering during the total filter run is 4250 times that amount.

Example 10.79

Problem:

The average filtration rate during a particular filter run was determined to be 3.2 gpm/ft^2. If the filter run time was 61.0 h, what was the UFRV in gal/ft^2 for the filter run?

Solution:

$$\begin{aligned}\text{UFRV} &= (\text{filtration rate, gpm/ft}^2)(\text{filter run, h})(60\text{ min/h})\\ &= (3.2\text{ gpm/ft}^2)(61.0\text{ h})(60\text{ min/h})\\ &= 11{,}712\text{ gal/ft}^2\end{aligned}$$

BACKWASH RATE

In filter backwashing, one of the most important operational parameters to be determined is the amount of water in gallons required for each backwash. This amount depends on the design of the filter and the quality of the water being filtered. The actual washing typically lasts 5–10 min and uses amounts to 1 to 5% of the flow produced.

EXAMPLE 10.80

Problem:

A filter has the following dimensions:

Length = 30 ft
Width = 20 ft
Depth of filter media = 24 in.

Assuming a backwash rate of 15 gal/ft^2/min is recommended, and 10 min of backwash is required, calculate the amount of water in gallons required for each backwash.

Solution:

Given:

Length = 30 ft
Width = 20 ft
Depth of filter media = 24 in.
Rate = 15 gal/ft^2/min

Find the amount of water in gallons required:

Step 1: Area of filter = 30 ft × 20 ft = 600 ft^2
Step 2: Gallons of water used per square foot of filter = 15 gal/ft^2/min × 10 min = 150 gal/ft^2
Step 3: Gallons required = 150 gal/ft^2 × 600 ft^2 = 90,000 gal required for backwash

Typically, backwash rates will range from 10 to 25 gpm/ft^2. The backwash rate is determined by using Equation 10.71:

$$\text{Backwash rate, gpm/ft}^2 = \frac{\text{flow rate, gpm}}{\text{filter area, ft}^2} \tag{10.71}$$

EXAMPLE 10.81

Problem:

A filter 30 ft by 10 ft has a backwash rate of 3120 gpm. What is the backwash rate in gpm/ft^2?

Solution:

$$\begin{aligned}\text{Backwash rate, gpm/ft}^2 &= \frac{\text{flow rate, gpm}}{\text{filter area, ft}^2}\\ &= \frac{3120\text{ gpm}}{(30\text{ ft})(10\text{ ft})}\\ &= 10.4\text{ gpm/ft}^2\end{aligned}$$

EXAMPLE 10.82

Problem:

A filter 20 ft long and 20 ft wide has a backwash flow rate of 4.85 MGD. What is the filter backwash rate in gpm/ft^2?

Solution:

$$\text{Backwash rate} = \frac{\text{flow rate, gpm}}{\text{filter area, ft}^2}$$

$$= \frac{4{,}850{,}000 \text{ gpd}}{1440 \text{ min/day}}$$

$$= 3368 \text{ gpm}$$

$$= \frac{3368 \text{ gpm}}{(20 \text{ ft})(20 \text{ ft})}$$

$$= 8.42 \text{ gpm/ft}^2$$

BACKWASH RISE RATE

Backwash rate is occasionally measured as the upward velocity of the water during backwashing—expressed as inches per minute (in./min) rise. To convert from gpm/ft^2 backwash rate to in./min rise rate, use either Equation 10.72 or 10.73:

$$\text{Backwash rate, in./min} = \frac{(\text{backwash rate, gpm/ft}^2)(12 \text{ in./ft})}{7.48 \text{ gal/ft}} \tag{10.72}$$

$$\text{Backwash rate, in./min} = (\text{backwash rate, gpm/ft}^2)(1.6) \tag{10.73}$$

EXAMPLE 10.83

Problem:

A filter has a backwash rate of 16 gpm/ft^2. What is this backwash rate expressed as in./min rise rate?

Solution:

$$\text{Backwash rate, in./min} = \frac{(\text{backwash rate, gpm/ft}^2)(12 \text{ in./ft})}{7.48 \text{ gal/ft}}$$

$$= \frac{(16 \text{ gpm/ft}^2)(12 \text{ in./ft})}{7.48 \text{ gal/ft}^3}$$

$$= 25.7 \text{ in./min}$$

EXAMPLE 10.84

Problem:

A filter 22 ft long and 12 ft wide has a backwash rate of 3260 gpm. What is this backwash rate expressed as in./min rise?

Solution:

First calculate the backwash rate as gpm/ft^2:

$$\text{Backwash rate} = \frac{\text{flow rate, gpm}}{\text{filter area, ft}^2}$$

$$= \frac{3260 \text{ gpm}}{(22 \text{ ft})(12 \text{ ft})}$$

$$= 12.3 \text{ gpm/ft}^2$$

Then convert gpm/ft^2 into in./min rise rate:

$$\frac{(12.3 \text{ gpm/ft}^2)(12 \text{ in./ft})}{7.48 \text{ gal/ft}^3} = 19.7 \text{ in./min}$$

VOLUME OF BACKWASH WATER REQUIRED, gal

To determine the volume of water required for backwashing, we must know both the desired backwash flow rate, gpm, and the duration of backwash, min:

$$\text{Backwash water volume, gal} = (\text{backwash, gpm})(\text{duration of backwash, min}) \tag{10.74}$$

EXAMPLE 10.85

Problem:

For a backwash flow rate of 9000 gpm and a total backwash time of 8 min, how many gallons of water will be required for backwashing?

Solution:

$$\text{Backwash water volume, gal} = (\text{backwash, gpm})(\text{duration of backwash, min})$$

$$= (9000 \text{ gpm})(8 \text{ min})$$

$$= 72{,}000 \text{ gal}$$

EXAMPLE 10.86

Problem:

How many gallons of water would be required to provide a backwash flow rate of 4850 gpm for a total of 5 min?

Solution:

$$\text{Backwash water volume, gal} = (\text{backwash, gpm})(\text{duration of backwash, min})$$

$$= (4850 \text{ gpm})(7 \text{ min})$$

$$= 33{,}950 \text{ gal}$$

REQUIRED DEPTH OF BACKWASH WATER TANK, ft

The required depth of water in the backwash water tank is determined from the volume of water required for backwashing. To make this calculation, use Equation 10.75:

$$\text{Volume, gal} = (0.785)(D^2)(\text{Depth, ft})(7.48\ \text{gal/ft}^3) \tag{10.75}$$

EXAMPLE 10.87

Problem:

The volume of water required for backwashing has been calculated to be 85,000 gal. What is the required depth of water in the backwash water tank to provide this amount of water if the diameter of the tank is 60 ft?

Solution:

Use the volume equation for a cylindrical tank, filling in known data; then solve for *x:*

$$\text{Volume, gal} = (0.785)(D^2)(\text{depth, ft})(7.48\ \text{gal/ft}^3)$$

$$85{,}000\ \text{gal} = (0.785)(60\ \text{ft})(60\ \text{ft})(x\ \text{ft})(7.48\ \text{gal/ft}^3)$$

$$= \frac{85{,}000}{(0.785)(60)(60)(7.48)}$$

$$x = 4\ \text{ft}$$

EXAMPLE 10.88

Problem:

A total of 66,000 gal of water will be required for backwashing a filter at a rate of 8000 gpm for a 9-min period. What depth of water is required in the backwash tank that has a diameter of 50 ft?

Solution:

Use the volume equation for cylindrical tanks:

$$\text{Volume, gal} = (0.785)(D^2)(\text{depth, ft})(7.48\ \text{gal/ft}^3)$$

$$66{,}000\ \text{gal} = (0.785)(50\ \text{ft})(50\ \text{ft})(x\ \text{ft})(7.48\ \text{gal/ft}^3)$$

$$x = \frac{66{,}000}{(0.785)(50)(50)(7.48)}$$

$$x = 4.5\ \text{ft}$$

BACKWASH PUMPING RATE, gpm

The desired backwash pumping rate, gpm, for a filter depends on the desired backwash rate in gpm/ft^2 and the ft^2 area of the filter. The backwash pumping rate, gpm can be determined by using Equation 10.76.

$$\text{Backwash pumping rate, gpm} = (\text{desired backwash rate, gpm/ft}^2)(\text{filter area, ft}^2) \tag{10.76}$$

Example 10.89

Problem:

A filter is 25 ft long and 20 ft wide. If the desired backwash rate is 22 gpm/ft^2, what backwash pumping rate, gpm, will be required?

Solution:

The desired backwash flow through each square foot of filter area is 20 gpm. The total gpm flow through the filter is therefore 20 gpm times the entire square foot area of the filter:

$$\begin{aligned}\text{Backwash pumping rate, gpm} &= (\text{desired backwash rate, gpm/ft}^2)(\text{filter area, sq ft})\\ &= (20\ \text{gpm/ft}^2)(25\ \text{ft})(20\ \text{ft})\\ &= 10{,}000\ \text{gpm}\end{aligned}$$

Example 10.90

Problem:

The desired backwash pumping rate for a filter is 12 gpm/ft^2. If the filter is 20 ft long and 20 ft wide, what backwash pumping rate, gpm, will be required?

Solution:

$$\begin{aligned}\text{Backwash pumping rate, gpm} &= (\text{desired backwash rate, ft}^2)(\text{filter area, ft}^2)\\ &= (12\ \text{gpm/ft}^2)(20\ \text{ft})(20\ \text{ft})\\ &= 4800\ \text{gpm}\end{aligned}$$

Percent Product Water Used for Backwashing

Along with measuring filtration rate and filter run time, another aspect of filter operation that is monitored for filter performance is the percent of product water used for backwashing. The equation for percent of product water used for backwashing calculations is shown below.

$$\text{Backwash water, \%} = \frac{\text{backwash water, gal}}{\text{water filtered, gal}} \times 100 \tag{10.77}$$

Example 10.91

Problem:

A total of 18,100,000 gal of water were filtered during a filter run. If 74,000 gal of this product water were used for backwashing, what percent of the product water was used for backwashing?

Solution:

$$\begin{aligned}\text{Backwash water, \%} &= \frac{\text{backwash water, gal}}{\text{water filtered, gal}} \times 100\\ &= \frac{74{,}000\ \text{gal}}{18{,}100{,}000\ \text{gal}} \times 100\\ &= 0.4\%\end{aligned}$$

Example 10.92

Problem:

A total of 11,400,000 gal of water are filtered during a filter run. If 48,500 gal of product water are used for backwashing, what percent of the product water is used for backwashing?

Solution:

$$\text{Backwash water, \%} = \frac{\text{backwash water, gal}}{\text{water filtered, gal}} \times 100$$

$$= \frac{48{,}500\text{ gal}}{11{,}400{,}000\text{ gal}} \times 100$$

$$= 0.43\%\text{ backwash water}$$

PERCENT MUD BALL VOLUME

Mud balls are heavier deposits of solids near the top surface of the medium that break into pieces during backwash, resulting in spherical accretions (usually less than 12 in. in diameter) of floc and sand. The presence of mud balls in the filter media is checked periodically. The principal objection to mudballs is that they diminish the effective filter area. To calculate the percent mud ball volume we use Equation 10.78:

$$\text{\% Mud ball volume} = \frac{\text{mud ball volume, mL}}{\text{total sample volume, mL}} \times 100 \tag{10.78}$$

Example 10.93

Problem:

A 3350-mL sample of filter media was taken for mud ball evaluation. The volume of water in the graduated cylinder rose from 500 mL to 525 mL when mud balls were placed in the cylinder. What is the percent mud ball volume of the sample?

Solution:

First determine the volume of mud balls in the sample:

$$525\text{ mL} - 500\text{ mL} = 25\text{ mL}$$

Then calculate the percent mud ball volume:

$$\text{\% Mud ball volume} = \frac{\text{mud ball volume, mL}}{\text{total sample volume, mL}} \times 100$$

$$= \frac{25\text{ mL}}{3350\text{ mL}} \times 100$$

$$= 0.75\%$$

Example 10.94

Problem:

A filter is tested for the presence of mud balls. The mud ball sample has a total sample volume of 680 mL. Five samples were taken from the filter. When the mud balls were placed in 500 mL of water, the water level rose to 565 mL. What is the percent mud ball volume of the sample?

Solution:

$$\text{\% Mud ball volume} = \frac{\text{mud ball volume, mL}}{\text{total sample volume, mL}} \times 100$$

The mud ball volume is the volume the water rose:

$$565\text{ mL} - 500\text{ mL} = 65\text{ mL}$$

Since five samples of media were taken, the total sample volume is five times the sample volume:

$$(5)(680\text{ mL}) - 3400\text{ mL}$$

$$\begin{aligned}\text{\% Mud ball volume} &= \frac{65\text{ mL}}{3400\text{ mL}} \times 100 \\ &= 1.9\%\end{aligned}$$

Filter Bed Expansion

In addition to backwash rate, it is also important to expand the filter media during the wash to maximize the removal of particles held in the filter or by the media; that is, the efficiency of the filter wash operation depends on the expansion of the sand bed. Bed expansion is determined by measuring the distance from the top of the unexpanded media to a reference point (e.g., top of the filter wall) and from the top of the expanded media to the same reference. A proper back wash rate should expand the filter 20–25% (AWWA & ASCE, 1990). Percent bed expansion is given by dividing the bed expansion by the total depth of expandable media (i.e., media depth less support gravels) and multiplied by 100 as follows:

Expanded measurement = depth to top of media during backwash (in.)
Unexpanded measurement = depth to top of media before backwash (in.)
Bed expanded = unexpanded measurement (in.) – expanded measurement (in.)

$$\text{Bed expansion (\%)} = \frac{\text{bed expansion measurement (in.)}}{\text{total depth of expandable media (in.)}} \times 100 \tag{10.79}$$

Example 10.95

Problem:

The backwashing practices for a filter with 30 in. of anthracite and sand is being evaluated. While at rest, the distance from the top of the media to the concrete floor surrounding the top of filter is measured to be 41 in. After the backwash has been started and the maximum backwash rate is achieved, a probe containing a white disk is slowly lowered into the filter bed until anthracite is observed on the disk. The distance from the expanded media to the concrete floor is measured to be 34 in. What is the percent bed expansion?

Solution:

Given:

Unexpanded measurement = 41 in.
Expanded measurement = 34.5 in.
Bed expansion = 6.5

$$\text{Bed expansion (\%)} = (6.5\text{ in.}/30\text{ in.}) \times 100 = 22\%$$

Source: USEPA (1999).

FILTER LOADING RATE

Filter loading rate is the flow rate of water applied to the unit area of the filter. It is the same value as the flow velocity approaching the filter surface and can be determined by using Equation 10.80.

$$u = \frac{Q}{A} \tag{10.80}$$

where
u = loading rate, $\text{m}^3/(\text{m}^2\text{ d})$ or gpm/ft^2
Q = flow rate, m^3/d or ft^3/d of gpm
A = surface area of filter, m^2 or ft^2

Filters are classified as slow sand filters, rapid sand filters, and high-rate sand filters on the basis of loading rate. Typically, the loading rate for rapid sand filters is 120 $\text{m}^3/(\text{m}^2\text{ d})$(83 L/($\text{m}^2$ min) or 2 gpm/ft^2. The loading rate may be up to five times this rate for high-rate filters.

EXAMPLE 10.96

Problem:

A sanitation district is to install rapid sand filters downstream of the clarifiers. The design-loading rate is selected to be 150 m^3/m^2. The design capacity of the waterworks is 0.30 m^3/s (6.8 MGD). The maximum surface per filter is limited to 45 m^2. Design the number and size of filters and calculate the normal filtration rate.

Solution:

Step 1. Determine the total surface area required.

$$A = \frac{Q}{u} = \frac{0.30\text{ m}^3\text{/s (85,400 s/d)}}{150\text{ m}^3/\text{m}^2\text{d}}$$

$$= \frac{25620}{150}$$

$$= 171\text{ m}^2$$

Step 2. Determine the number of filters.

$$\frac{171\text{ m}^2}{45\text{ m}} = 3.8$$

Select 4 m.
The surface area (a) for each filter is

$$a = 173 \text{ m}^2/4 = 43.25 \text{ m}^2$$

We can use 6 m × 7 m or 6.4 m × 7 m or 6.42 m × 7 m.

Step 3. If a 6-m × 7-m filter is installed, the normal filtration rate is

$$u = \frac{Q}{A} = \frac{0.30 \text{ m}^3/\text{s} \times 86{,}400 \text{ s/d}}{4 \times 6 \text{ m} \times 7 \text{ m}}$$
$$= 154.3 \text{ m}^3/(\text{m}^2\text{d})$$

FILTER MEDIUM SIZE

Filter medium grain size has an important effect on the filtration efficiency and on backwashing requirements for the medium. The actual medium selected is typically determined by performing a grain size distribution analysis—sieve size and percentage passing by weight relationships are plotted on logarithmic-probability paper. The most common parameters used in the United States to characterize the filter medium are effective size (ES) and uniformity coefficient (UC) of medium size distribution. The ES is that grain size for which 10% of the grains are smaller by weight; it is often abbreviated as d_{10}. The UC is the ratio of the 60-percentile (d_{60}) to the 10-percentile. The 90-percentile, d_{90}, is the size for which 90% of the grains are smaller by weight. The d_{90} size is used for computing the required filter backwash rate for a filter medium.

Values of d_{10}, d_{60}, and d_{90} can be read from an actual sieve analysis curve. If such a curve is not available and if a linear log-probability plot is assumed, the values can be interrelated by Equation 10.81 (Cleasby, 1990).

$$d_{90} = d_{10}(10^{1.67 \log \text{UC}}) \tag{10.81}$$

EXAMPLE 10.97

Problem:

A sieve analysis curve of a typical filter sand gives $d_{10} = 0.52$ mm and $d_{60} = 0.70$ mm. What are its uniformity coefficient and d_{90}?

Solution:

Step 1.

$$\text{UC} = \frac{d_{60}}{d_{10}} = \frac{0.70 \text{ mm}}{0.52 \text{ mm}} = 1.35$$

Step 2. Find d_{90} using Equation 10.81.

$$d_{90} = d_{10}(10^{1.67 \log \text{UC}})$$
$$= 0.52 \text{ mm}(10^{1.67 \log 1.35})$$
$$= 0.52 \text{ mm}(10^{0.218})$$
$$= 0.86 \text{ mm}$$

MIXED MEDIA

Recently, a new innovation in filtering systems has offered a significant improvement and economic advantage to rapid rate filtration. This is the mixed media filter bed. Mixed media filter beds offer specific advantages in specific circumstances, but will give excellent operating results at a filtering rate of 5 gal/ft^2/min. Moreover, the mixed media filtering unit is more tolerant to handling higher turbidities in the settled water. For improved process performance, activated carbon or anthracite is added on the top of the sand bed. The approximate specific gravity (*s*) of ilmenite (Chavara, <60% TiO_2), silica sand, anthracite, and water are 4.2, 2.6, 1.5, and 1.0, respectively. The economic advantage of the mixed bed media filter is based upon filter area; it will safely produce 2½ times as much filtered water as a rapid sand filter.

When settling velocities are equal, the particle sizes for media of different specific gravity can be computed by using Equation 10.82:

$$\frac{d_1}{d_2} = \left(\frac{s_2 - s}{s_1 - s}\right)^{2/3} \tag{10.82}$$

where d_1, d_2 are the diameters of particles 1 and 2, and water, respectively, and s_1 and s_2 are the specific gravities of particles 1 and 2, and water, respectively.

EXAMPLE 10.98

Problem:

Estimate the particle size of ilmenite sand (specific gravity = 4.2) that has the same settling velocity of silica sand 0.60 mm in known diameter (specific gravity = 2.6).

Solution:

Find the diameter on ilmenite sand by using Equation 10.82:

$$d = (0.6\text{ mm})\left(\frac{2.6-1}{4.2-1}\right)^{2/3} = 0.38\text{ mm settling size}$$

HEAD LOSS FOR FIXED BED FLOW

When water is pumped upward through a bed of fine particles at a very low flow rate the water percolates through the pores (void spaces) without disturbing the bed. This is a fixed bed process.

The head loss (pressure drop) through a clean granular-media filter is generally less than 0.9 m (3 ft). With the accumulation of impurities, head loss gradually increases until the filter is backwashed. The Kozeny equation, shown below, is typically used for calculating head loss through a clean fixed-bed flow filter.

$$\frac{h}{L} = \frac{k\mu(1-\varepsilon)^2}{gp\varepsilon}\left(\frac{A}{V}\right)^2 u \tag{10.83}$$

where

h = head loss in filter depth L, m or ft

k = dimensionless Kozeny constant, 5 for sieve openings, 6 for size of separation

g = acceleration of gravity, 9.81 m/s or 32.2 ft/s

μ = Absolute viscosity of water, N s/m^2 or lb s/ft^2
p = Density of water, kg/m^3 or lb/ft^3
ε = Porosity, dimensionless
A/V = Grain surface area per unit volume of grain
= specific surface S (or shape factor = 6.0 – 7.7)
= $6/d$ for spheres
= $6/\psi d_{eq}$ for irregular grains
ψ = Grain sphericity or shape factor
d_{eq} = Grain diameter of spheres of equal volume
u = Filtration (superficial) velocity, m/s or fps

Example 10.99

Problem:

A dual medium filter is composed of 0.3 m anthracite (mean size of 2.0 mm) that is placed over a 0.6 m layer of sand (mean size 0.7 mm) with a filtration rate of 9.78 m/h. Assume the grain sphericity is $\psi = 0.75$ and a porosity for both is 0.42. Although normally taken from the appropriate table at 15°C, we provide the head loss data of the filter at 1.131×10^{-6} m^2 s.

Solution:

Step 1. Determine head loss through anthracite layer using the Kozeny equation (Equation 10.83).

$$\frac{h}{L} = \frac{k\mu(1-\varepsilon)^2}{gp\varepsilon^3}\left(\frac{A}{V}\right)^2 u$$

where
$k = 6$
$g = 9.81$ m/s^2
$\varepsilon = 0.40$
$A/V = 6/0.75d = 8/d = 8/0.002$
$u = 9.78$ m/h $= 0.00272$ m/s
$L = 0.3$ m
then

$$h = 6 \times \frac{1.13 \times 10^6}{9.81} \times \frac{(1-0.42)^2}{0.42^3} \times \left(\frac{8}{0.002}\right)^2 (0.00272)(0.2)$$
$$= 0.0410 \text{ m}$$

Step 2. Compute the head loss passing through the sand.

Use data in Step 1, except insert:

$k = 5$
$d = 0.0007$ m
$L = 0.6$ m

$$h = 5 \times \frac{1.131 \times 10^6}{9.81} \times \frac{0.58^2}{0.42^3} \times \left(\frac{8}{d}\right)^2 (0.00272)(0.4)$$
$$= 0.5579 \text{ m}$$

Step 3. Compute total head loss.

$$h = 0.0410\text{ m} + 0.5579\text{ m}$$

$$= 0.599\text{ m}$$

HEAD LOSS THROUGH A FLUIDIZED BED

If the upward water flow rate through a filter bed is very large the bed mobilizes pneumatically and may be swept out of the process vessel. At an intermediate flow rate the bed expands and is in what we call an *expanded* state. In the fixed bed the particles are in direct contact with one another, supporting one another's weight. In the expanded bed, the particles have a mean free distance between particles and the drag force of the water supports the particles. The expanded bed has some of the properties of the water (i.e., of a fluid) and is called a fluidized bed (Chase, 2002). Simply, *fluidization* is defined as upward flow through a granular filter bed at sufficient velocity to suspend the grains in the water. Minimum fluidizing velocity (U_{mf}) is the superficial fluid velocity needed to start fluidization; it is important in determining the required minimum backwashing flow rate. Wen and Yu proposed the U_{mf} equation including the near constants (over a wide rang of particles) 33.7 and 0.0408, but excluding porosity of fluidization and shape factor (Wen and Yu, 1966):

$$U_{\text{mf}} = \frac{\mu}{pd_{\text{eq}}}(1135.69 + 0.0408G_{\text{n}})^{0.5} - \frac{33.7\mu}{pd_{\text{eq}}} \tag{10.84}$$

where

μ = absolute viscosity of water, N s/m^2 or lb s/ft^2
p = density of water, kg/m^3 or lb/ft^3
d_{eq} = d_{90} sieve size is used instead of d_{eq}
G_{n} = Galileo number

$$G_{\text{n}} = d_{\text{eq}}^3 p(p_{\text{s}} - p)g/\mu^2 \tag{10.85}$$

Other variables used are expressed in Equation 10.83.

√ **Note:** Based on the studies of Cleasby and Fan (1981), we use a safety factor of 1.3 to ensure adequate movement of the grains.

EXAMPLE 10.100

Problem:

Estimate the minimum fluidized velocity and backwash rate for the sand filter. The d_{90} size of sand is 0.90 mm. The density of sand is 2.68 g/cm^3.

Solution:

Step 1. Compute the Galileo number.

From given data and the applicable table, at 15°C:

p = 0.999 g/cm^3
μ = 0.0113 N s/m^2 = 0.00113 kg/ms = 0.0113 g/cm s
μp = 0.0113 cm^2/s

$g = 981\ \text{cm/s}^2$
$d = 0.90\ \text{cm}$
$p_s = 2.68\ \text{g/cm}^3$

Using Equation 10.85:

$$G_n = \frac{d_{eq}^3 p(p_s - p)g}{m^2}$$

$$= \frac{(0.090)^3(0.999)(2.68 - 0.999)(981)}{(0.0113)^2}$$

$$= 9405$$

Step 2. Compute U_{mf} using Equation 10.84.

$$U_{mf} = \frac{0.0113}{0.999 \times 0.090}(1135.69 + 0.0408 \times 9405)^{0.5} - \frac{33.7 \times 0.0113}{0.999 \times 0.090}$$

$$= 0.660\ \text{cm/s}$$

Step 3. Compute backwash rate.

Apply a safety factor of 1.3 to U_{mf} as backwash rate:

$$\text{Backwash rate} = 1.3 \times 0.660\ \text{cm/s} = 0.858\ \text{cm/s}$$

$$0.858\frac{\text{cm}^3}{\text{cm}^2} \times \frac{\text{L}}{1000\ \text{cm}^3} \times \frac{1}{3.785} \times \frac{\text{gal}}{\text{L}} \times 929 \times \frac{\text{cm}^2}{\text{ft}^2} \times \frac{60\ \text{s}}{\text{min}} = 12.6\ \text{pgm/ft}^2$$

Horizontal Washwater Troughs

Wastewater troughs are used to collect backwash water as well as to distribute influent water during the initial stages of filtration. Washwater troughs are normally placed above the filter media, specifically in the United States. Proper placement of these troughs is very important to ensure that the filter media is not carried into the troughs during the backwash and removed from the filter. These backwash troughs are constructed from concrete, plastic, fiberglass, or other corrosion-resistant materials. The total rate of discharge in a rectangular trough with free flow can be calculated by using Equation 10.86.

$$Q = Cwh^{1.5} \tag{10.86}$$

where
Q = flow rate, cfs
C = constant (2.49)
w = trough width, ft
h = maximum water depth in trough, ft

Example 10.101

Problem:

Troughs are 18 ft long, 18 in. wide, and 8 ft to the center with a horizontal flat bottom. The backwash rate is 24 in./min. Estimate (1) the water depth of the troughs with free flow into the gullet, and (2) the distance between the top of the troughs and the 30-in. sand bed. Assume 40% expansion and 6 in. of freeboard in the troughs and 6 in. of thickness.

Solution:

Step 1. Estimate the maximum water depth, h, in the trough.

$$v = 24 \text{ in./min} = 2 \text{ ft/60 s} = \frac{1}{30} \text{ fps}$$

$$A = 18 \text{ ft} \times 8 \text{ ft} = 144 \text{ ft}^2$$

$$Q = VA = 144/30 \text{ cfs}$$

$$= 4.8 \text{ cfs}$$

Using Equation 10.86:

$$Q = 2.49wh^{1.5}, \; w = 1.5 \text{ ft}$$

$$h = \left(\frac{Q}{2.49w}\right)^{2/3}$$

$$= \left[\frac{4.8}{(2.49 \times 1.5)}\right]^{2/3}$$

$$= 1.18 \text{ ft (or approximately 14 in.} = 1.17 \text{ ft)}$$

Step 2. Determine the distance (y) between the sand bed surface and the top troughs.

Freeboard = 6 in. = 0.5 ft

Thickness = 8 in. = 0.67 ft (the bottom of trough)

$$y = 2.5 \text{ ft} \times 0.4 + 1.17 \text{ ft} + 0.5 \text{ ft} + 0.5 \text{ ft}$$

$$= 3.2 \text{ ft}$$

Filter Efficiency

Water treatment filter efficiency is defined as the effective filter rate divided by the operation filtration rate as shown in Equation 10.87 (AWWA and ASCE, 1998).

$$E = \frac{R_e}{R_o} = \frac{\text{UFRV} - \text{UBWU}}{\text{UFRV}} \tag{10.87}$$

where

E = filter efficiency, %
R_e = effective filtration rate, gpm/ft^2
R_o = operating filtration rate, gpm/ft^2
UFRV = unit filter run volume, gal/ft^2
UBWV = unit backwash volume, gal/ft^2

Example 10.102

Problem:

A rapid sand filter operates at 3.9 gpm/ft^2 for 48 h. Upon completion of the filter run, 300 gal/ft^2 of backwash water is used. Find the filter efficiency.

Solution:

Step 1. Calculate the operating filtration rate, R_o.

$$
\begin{aligned}
R_o &= 3.9 \text{ gpm/ft}^2 \times 60 \text{ min/h} \times 48 \text{ h} \\
&= 11{,}232 \text{ gal/ft}
\end{aligned}
$$

Step 2. Calculate the effective filtration rate, R_e.

$$
\begin{aligned}
R_e &= (11{,}232 - 300) \text{ gal/ft}^2 \\
&= 10{,}932 \text{ gal/ft}^2
\end{aligned}
$$

Step 3. Calculate the filter efficiency, E, using Equation 10.87.

$$
\begin{aligned}
E &= \frac{10{,}932}{11{,}232} \\
&= 97.3\%
\end{aligned}
$$

WATER CHLORINATION CALCULATIONS

Chlorine is the most commonly used substance for disinfection of water in the United States. The addition of chlorine or chlorine compounds to water is called chlorination. Chlorination is considered the single most important process for preventing the spread of waterborne disease.

Chlorine Disinfection

Chlorine deactivates microorganisms through several mechanisms, ensuring that it can destroy most biological contaminants:

- It causes damage to the cell wall.
- It alters the permeability of the cell (the ability to pass water in and out through the cell wall).
- It alters the cell protoplasm.
- It inhibits the enzyme activity of the cell so it is unable to use its food to produce energy.
- It inhibits cell reproduction.

Chlorine is available in a number of different forms: (1) as pure elemental gaseous chlorine (a greenish-yellow gas possessing a pungent and irritating odor that is heavier than air, nonflammable, and nonexplosive)—when released to the atmosphere, this form is toxic and corrosive; (2) as solid calcium hypochlorite (in tablets or granules); or (3) as a liquid sodium hypochlorite solution (in various strengths).

The strengths of one form of chlorine over the others for a given water system depends on the amount of water to be treated, configuration of the water system, the local availability of the chemicals, and the skill of the operator.

One of the major advantages of using chlorine is the effective residual that it produces. A residual indicates that disinfection is completed, and the system has an acceptable bacteriological quality. Maintaining a residual in the distribution system helps prevent regrowth of those microorganisms that were injured but not killed during the initial disinfection stage.

DETERMINING CHLORINE DOSAGE (FEED RATE)

The expressions milligrams per liter (mg/L) and pounds per day (lb/day) are most often used to describe the amount of chlorine added or required. Equation 10.88 can be used to calculate either mg/L or lb/day chlorine dosage.

$$\text{Chlorine feed rate, lb/day} = (\text{Cl, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal}) \tag{10.88}$$

EXAMPLE 10.103

Problem:

Determine the chlorinator setting (lb/day) needed to treat a flow of 4 MGD with a chlorine dose of 5 mg/L.

Solution:

$$\begin{aligned}\text{Chlorine, lb/day} &= (\text{chlorine, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})\\ &= (5\ \text{mg/L})(4\ \text{MGD})(8.34\ \text{lb/gal})\\ &= 167\ \text{lb/day}\end{aligned}$$

EXAMPLE 10.104

Problem:

A pipeline 12 in. in diameter and 1400 ft long is to be treated with a chlorine dose of 48 mg/L. How many pounds of chlorine will this require?

Solution:

Determine the volume, in gallons, of the pipeline.

$$\begin{aligned}\text{Volume, gal} &= (0.785)\ (D^2)(\text{length, ft})(7.48\ \text{gal/ft}^3)\\ &= (0.785)(1\ \text{ft})(1\ \text{ft})(1400\ \text{ft})(7.48\ \text{gal/ft}^3)\\ &= 8221\ \text{gal}\end{aligned}$$

Now calculate the chlorine, lb, required:

$$\begin{aligned}\text{Chlorine, lb} &= (\text{chlorine, mg/L})(\text{volume, MG})(8.34 \text{ lb/gal})\\ &= (48 \text{ mg/L})(0.008221 \text{ MG})(8.34 \text{ lb/gal})\\ &= 3.3 \text{ lb}\end{aligned}$$

Example 10.105

Problem:

A chlorinator setting is 30 lb/24 h. If the flow being chlorinated is 1.25 MGD, what is the chlorine dosage expressed in mg/L?

Solution:

$$\text{Chlorine, lb/day} = (\text{chlorine, mg/L})(\text{flow, MGD})(8.34 \text{ lb/gal})$$

$$30 \text{ lb/d} = (x \text{ mg/L}) \times \text{flow (MGD)} \times 8.34 \text{ lb/gal}$$

$$x = \frac{30}{(1.25)(8.34)}$$

$$x = 2.9 \text{ mg/L}$$

Example 10.106

Problem:

A flow of 1600 gpm is to be chlorinated. At a chlorinator setting of 48 lb per 24 h, what would be the chlorine dosage in mg/L?

Solution:

Convert the gpm flow rate into MGD flow rate:

$$\begin{aligned}(1600 \text{ gpm})(1440 \text{ min/day}) &= 2{,}304{,}000 \text{ gpd}\\ &= 2.304 \text{ MGD}\end{aligned}$$

Calculate the chlorine dosage in mg/L:

$$\text{Chlorine (lb/day)} = \text{chlorine (mg/L)} \times \text{flow (MGD)}$$

$$(x \text{ mg/L})(2.304 \text{ MGD})(8.34 \text{ lb/gal}) = 48 \text{ lb/day}$$

$$x = \frac{48}{(2.304)(8.34)}$$

$$x = 2.5 \text{ mg/L}$$

CALCULATING CHLORINE DOSE, DEMAND, AND RESIDUAL

Common terms used in chlorination include the following:

- *Chlorine dose*—The amount of chlorine added to the system. It can be determined by adding the desired residual for the finished water to the chlorine demand of the untreated water. Dosage can be either milligrams per liter (mg/L) or pounds per day (lb/day). The most common is mg/L.

$$\text{Chlorine dose, mg/L} = \text{chlorine demand, mg/L} + \text{chlorine, mg/L}$$

- *Chlorine demand*—The amount of chlorine used by iron, manganese, turbidity, algae, and microorganisms in the water. Because the reaction between chlorine and microorganisms is not instantaneous, demand is relative to time. For instance, the demand 5 min after applying chlorine will be less than the demand after 20 min. Demand, like dosage, is expressed in mg/L. The chlorine demand is as follows:

$$\text{Chlorine demand} = \text{chlorine dose} - \text{chlorine residual}$$

- *Chlorine residual*—The amount of chlorine (determined by testing) remaining after the demand is satisfied. Residual, like demand, is based on time. The longer the time after dosage, the lower the residual will be, until all of the demand has been satisfied. Residual, like dosage and demand, is expressed in mg/L. The presence of a *free residual* of at least 0.2–0.4 ppm usually provides a high degree of assurance that the disinfection of the water is complete. *Combined residual* is the result of combining free chlorine with nitrogen compounds. Combined residuals are also called chloramines. *Total chlorine residual* is the mathematical combination of free and combined residuals. Total residual can be determined directly with standard chlorine residual test kits.

The following examples, using Equation 10.89, show the calculation of chlorine dose, demand, and residual.

$$\text{Chlorine dose, mg/L} = \text{Cl demand, mg/L} + \text{Cl residual, mg/L} \tag{10.89}$$

EXAMPLE 10.107

Problem:

A water sample is tested and found to have a chlorine demand of 1.7 mg/L. If the desired chlorine residual is 0.9 mg/L, what is the desired chlorine dose in mg/L?

Solution:

$$\begin{aligned}\text{Chlorine dose, mg/L} &= \text{chlorine demand, mg/L} + \text{chlorine residual, mg/L}\\ &= 1.7\text{ mg/L} + 0.9\text{ mg/L}\\ &= 2.6\text{ mg/L chlorine dose}\end{aligned}$$

Example 10.108

Problem:

The chlorine dosage for water is 2.7 mg/L. If the chlorine residual after 30 min contact time is found to be 0.7 mg/L, what is the chlorine demand expressed in mg/L?

Solution:

$$\text{Chlorine dose, mg/L} = \text{chlorine demand, mg/L} + \text{chlorine residual, mg/L}$$

$$2.7\text{ mg/L} = x\text{ mg/L} + 0.6\text{ mg/L}$$

$$2.7\text{ mg/L} - 0.7\text{ mg/L} = x\text{ mg/L}$$

$$x\text{ chlorine demand (mg/L)} = 2.0\text{ mg/L}$$

Example 10.109

Problem:

What should the chlorinator setting be (lb/day) to treat a flow of 2.35 MGD if the chlorine demand is 3.2 mg/L and a chlorine residual of 0.9 mg/L is desired?

Solution:

Determine the chlorine dosage in mg/L:

$$\begin{aligned}\text{Chlorine dose, mg/L} &= \text{chlorine demand, mg/L} + \text{chlorine residual, mg/L}\\ &= 3.2\text{ mg/L} + 0.9\text{ mg/L}\\ &= 4.1\text{ mg/L}\end{aligned}$$

Calculate the chlorine dosage (feed rate) in lb/day:

$$\begin{aligned}\text{Chlorine, lb/day} &= (\text{chlorine, mg/L})(\text{flow, MGD})(8.34\text{ lb/gal})\\ &= (4.1\text{ mg/L})(2.35\text{ MGD})(8.34\text{ lb/gal})\\ &= 80.4\text{ lb/day chlorine}\end{aligned}$$

BREAKPOINT CHLORINATION CALCULATIONS

To produce a free chlorine residual, enough chlorine must be added to the water to produce what is referred to as *breakpoint chlorination* (i.e., the point at which near complete oxidation of nitrogen compounds is reached; any residual beyond breakpoint is mostly free chlorine). When chlorine is added to natural waters, the chlorine begins combining with and oxidizing the chemicals in the water before it begins disinfecting. Although residual chlorine will be detectable in the water, the chlorine will be in the combined form with a weak disinfecting power. Adding more chlorine to the water at this point actually decreases the chlorine residual as the additional chlorine destroys the combined chlorine compounds. At this stage, water may have a strong swimming pool or medicinal taste and odor. To avoid this taste and odor, add still more chlorine to produce a free residual chlorine. Free chlorine has the highest disinfecting power. The point at which most of the combined chlorine compounds have been destroyed and the free chlorine starts to form is the *breakpoint*.

Key Point: The actual chlorine breakpoint of water can only be determined by experimentation.

To calculate the actual increase in chlorine residual that would result from an increase in chlorine dose, we use the mg/L to lb/day equation, as shown below.

$$\text{Increase in Cl dose, lb/day} = (\text{expected increase, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal}) \qquad (10.90)$$

Key Point: The actual increase in residual is simply a comparison of new and old residual data.

Example 10.110

Problem:

A chlorinator setting is increased by 2 lb/day. The chlorine residual before the increased dosage was 0.2 mg/L. After the increased chlorine dose, the chlorine residual was 0.5 mg/L. The average flow rate being chlorinated is 1.25 MGD. Is the water being chlorinated beyond the breakpoint?

Solution:

Calculate the expected increase in chlorine residual. Use the mg/L to lb/day equation:

$$\text{Increase, lb/day} = (\text{increase, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})$$

$$2\ \text{lb/day} = (x\ \text{mg/L})(1.25\ \text{MGD})(8.34\ \text{lb/gal})$$

$$x = \frac{2}{(1.25)\ (8.34)}$$

$$x = 0.19\ \text{mg/L}$$

The actual increase in residual is:

$$0.5\ \text{mg/L} - 0.19\ \text{mg/L} = 0.31\ \text{mg/L}$$

Example 10.111

Problem:

A chlorinator setting of 18 lb chlorine per 24 h results in a chlorine residual of 0.3 mg/L. The chlorinator setting is increased to 22 lb per 24 h. The chlorine residual increased to 0.4 mg/L at this new dosage rate. The average flow being treated is 1.4 MGD. On the basis of these data, is the water being chlorinated past the breakpoint?

Solution:

Calculate the expected increase in chlorine residual:

$$\text{Increase, lb/day} = (\text{increase, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})$$

$$4\ \text{lb/d} = (x\ \text{mg/L})(1.4\ \text{MGD})(8.34\ \text{lb/gal})$$

$$x = \frac{4}{(1.4\ \text{MGD})\ (8.34)}$$

$$x = 0.34\ \text{mg/L}$$

The actual increase in residual is:

$$0.4\ \text{mg/L} - 0.3\ \text{mg/L} = 0.1\ \text{mg/L}$$

CALCULATING DRY HYPOCHLORITE FEED RATE

The most commonly used dry hypochlorite, calcium hypochlorite, contains about 65–70% available chlorine, depending on the brand. Because hypochlorites are not 100% pure chorine, more lb/day must be fed into the system to obtain the same amount of chlorine for disinfection. The equation used to calculate the hypochlorite, lb/day, needed can be found using Equation 10.91.

$$\text{Hypochlorite (lb/day)} = \frac{\text{chlorine, lb/day}}{\text{\% available chlorine/100}} \tag{10.91}$$

EXAMPLE 10.112

Problem:

A chlorine dosage of 110 lb/day is required to disinfect a flow of 1,550,000 gpd. If the calcium hypochlorite to be used contains 65% available chlorine, how many lb/day hypochlorite will be required for disinfection?

Solution:

Because only 65% of the hypochlorite is chlorine, more than 110 lb of hypochlorite will be required:

$$\text{Hypochlorite (lb/day)} = \frac{\text{chlorine, lb/day}}{\text{\% available chlorine/100}}$$

$$= \frac{110\ \text{lb/day}}{65/100}$$

$$= \frac{110}{6.5}$$

$$= 169\ \text{lb/day hypochlorite}$$

Example 10.113

Problem:

A water flow of 900,000 gpd requires a chlorine dose of 3.1 mg/L. If calcium hypochlorite (65% available chlorine) is to be used, how many lb/day of hypochlorite are required?

Solution:

Calculate the lb/day of chlorine required.

$$\begin{aligned}\text{Chlorine, lb/day} &= (\text{chlorine, mg/L})(\text{flow, MGD})(8.34\ \text{lb/gal})\\ &= (3.1\ \text{mg/L})(0.90\ \text{MGD})(8.34\ \text{lb/gal})\\ &= 23\ \text{lb/day}\end{aligned}$$

The lb/day of hypochlorite required is:

$$\begin{aligned}\text{Hypochlorite, lb/day} &= \frac{\text{chlorine, lb/day}}{\%\ \text{available chlorine}/100}\\ &= \frac{23\ \text{lb/day chlorine}}{0.65\ \text{available chlorine}}\\ &= 35\ \text{lb/available day hypochlorite}\end{aligned}$$

Example 10.114

Problem:

A tank contains 550,000 gal of water and is to receive a chlorine dose of 2.0 mg/L. How many pounds of calcium hypochlorite (65% available chlorine) will be required?

Solution:

$$\begin{aligned}\text{Hypochlorite (lb)} &= \frac{(\text{chlorine, mg/L})(\text{volume, MG})\ (8.34\ \text{lb/gal})}{\%\ \text{available chlorine}/100}\\ &= \frac{(2.0\ \text{mg/L})(0.550\ \text{MG})(8.34\ \text{lb/gal})}{65/100}\\ &= \frac{9.2\ \text{lb}}{0.65}\\ &= 14.2\ \text{lb hypochlorite}\end{aligned}$$

Example 10.115

Problem:

A total of 40 lb of calcium hypochlorite (65% available chlorine) are used in a day. If the flow rate treated is 1,100,000 gpd, what is the chlorine dosage in mg/L?

Solution:

Calculate the lb/day chlorine dosage:

$$\text{Hypochlorite, lb/day} = \frac{\text{chlorine, lb/day}}{\text{\% available chlorine/100}}$$

$$\text{40 lb/d hypochlorite} = \frac{x \text{ lb/day chlorine}}{0.65}$$

$$(0.65)(40) = x$$

$$\text{26 lb/day chlorine} = x$$

Then calculate mg/L chlorine, using the mg/L to lb/day equation and filling in the known information:

$$\text{26 lb/day chlorine} = (x \text{ mg/L chlorine})(1.10 \text{ MGD})(8.34 \text{ lb/gal})$$

$$x = \frac{\text{26 lb/d}}{(1.10 \text{ MGD})(8.34 \text{ lb/gal})}$$

$$= 2.8 \text{ mg/L chlorine}$$

Example 10.116

Problem:

A flow of 2,550,000 gpd is disinfected with calcium hypochlorite (65% available chlorine). If 50 lb of hypochlorite are used in a 24-h period, what is the mg/L chlorine dosage?

Solution:

The lb/day chlorine dosage is:

$$\text{50 lb/day hypochlorite} = \frac{x \text{ lb/d chlorine}}{0.65}$$

$$x = 32.5 \text{ chlorine}$$

The mg/L chlorine dosage required is:

$$(x \text{ mg/L chlorine})(2.55 \text{ MGD})(8.34 \text{ lb/gal}) = 32.5 \text{ lb/day}$$

$$x = 1.5 \text{ mg/L chlorine}$$

Calculating Hypochlorite Solution Feed Rate

Liquid hypochlorite (i.e., sodium hypochlorite) is supplied as a clear, greenish-yellow liquid in strengths from 5.25 to 16% available chlorine. Often referred to as “bleach,” it is, in fact, used for bleaching—common household bleach is a solution of sodium hypochlorite containing 5.25% available chlorine.

When calculating gpd liquid hypochlorite the lb/day hypochlorite required must be converted into gpd hypochlorite required. This conversion is accomplished using Equation 10.92:

$$\text{Hypochlorite (gpd)} = \frac{\text{hypochlorite (lb/day)}}{8.34\ \text{lb/gal}} \tag{10.92}$$

Example 10.117

Problem:

A total of 50 lb/day-sodium hypochlorite are required for disinfection of a 1.5-MGD flow. How many gpd hypochlorite is this?

Solution:

Because lb/day hypochlorite has already has been calculated, we simply convert lb/day to gpd hypochlorite required:

$$\begin{aligned}\text{Hypochlorite (gpd)} &= \frac{\text{hypochlorite (lb/day)}}{8.34\ \text{lb/gal}}\\ &= \frac{50\ \text{lb/day}}{8.34\ \text{lb/gal}}\\ &= 6.0\ \text{gpd hypochlorite}\end{aligned}$$

Example 10.118

Problem:

A hypochlorinator is used to disinfect the water pumped from a well. The hypochlorite solution contains 3% available chlorine. A chlorine dose of 1.3 mg/L is required for adequate disinfection throughout the system. If the flow being treated is 0.5 MGD, how many gpd of the hypochlorite solution will be required?

Solution:

Calculate the lb/day chlorine required:

$$(1.3\ \text{mg/L})(0.5\ \text{MGD})(8.34\ \text{lb/gal}) = 5.4\ \text{lb/day chlorine}$$

Calculate the lb/day hypochlorite solution required:

$$\begin{aligned}\text{Hypochlorite (lb/d)} &= \frac{5.4\ \text{lb/d chlorine}}{0.03}\\ &= 80\ \text{lb/d hypochlorite}\end{aligned}$$

Calculate the gpd hypochlorite solution required:

$$= \frac{180 \text{ lb/day}}{8.34 \text{ lb/gal}}$$

$$= 21.6 \text{ gpd hypochlorite}$$

CALCULATING PERCENT STRENGTH OF SOLUTIONS

If a teaspoon of salt is dropped into a glass of water it gradually disappears. The salt dissolves in the water. A microscopic examination of the water would not show the salt. Only examination at the molecular level, which is not easily done, would show salt and water molecules intimately mixed. If we taste the liquid, of course, we would know that the salt is there, and we could recover the salt by evaporating the water. In a solution, the molecules of the salt, the *solute*, are homogeneously dispersed among the molecules of water, the *solvent*. This mixture of salt and water is homogenous on a molecular level. Such a homogenous mixture is called a *solution*. The composition of a solution can be varied within certain limits.

There are three common states of matter—gas, liquid, and solid. In this discussion, of course, we are only concerned, at the moment, with solid (calcium hypochlorite) and liquid (sodium hypochlorite).

CALCULATING PERCENT STRENGTH USING DRY HYPOCHLORITE

In calculating the percent strength of a chlorine solution, we use Equation 10.93.

$$\% \text{ Cl strength} = \frac{(\text{hypochlorite, lb})(\% \text{ available chlorine}/100)}{\text{Water, lb} + (\text{hypochlorite, lb})(\% \text{ available chlorine}/100)} \times 100 \qquad (10.93)$$

EXAMPLE 10.119

Problem:

If a total of 72 oz of calcium hypochlorite (65% available chlorine) are added to 15 gal of water, what is the percent chlorine strength (by weight) of the solution?

Solution:

Convert the ounces of hypochlorite into pounds of hypochlorite:

$$\frac{72 \text{ oz}}{16 \text{ oz/lb}} = 4.5 \text{ lb chemical}$$

$$\% \text{ Cl strength} = \frac{(\text{hypochlorite, lb})(\% \text{ available chlorine}/100)}{\text{water, lb} + (\text{hypochlorite, lb})(\% \text{ available chlorine}/100)} \times 100$$

$$= \frac{(4.5 \text{ lb})(0.65)}{(15 \text{ gal})(8.34 \text{ lb/gal}) + (4 \text{ lb})(0.65)} \times 100$$

$$= \frac{2.9 \text{ lb}}{125.1 \text{ lb} + 2.9 \text{ lb}} \times 100$$

$$= \frac{(2.9)(100)}{126}$$

$$= 2.3 \text{ chlorine strength}$$

Calculating Percent Strength Using Liquid Hypochlorite

In calculating percent strength using liquid solutions, such as liquid hypochlorite, a different equation is required. We use Equation 10.94:

$$\begin{aligned}&(\text{Liquid hypochlorite, gal})(8.34\ \text{lb/gal})\left(\frac{\%\ \text{strength of hypochlorite}}{100}\right)\\&\quad=(\text{hypochlorite solution, gal})(8.34\ \text{lb/gal})\left(\frac{\%\ \text{strength of hypochlorite}}{100}\right)\end{aligned}\qquad(10.94)$$

Example 10.120

Problem:

12% liquid hypochlorite solution is to be used in making up a hypochlorite solution. If 3.3 gal of liquid hypochlorite are mixed with water to produce 25 gal of hypochlorite solution, what is the percent strength of the solution?

Solution:

$$\begin{aligned}&(\text{Liquid hypochlorite, gal})(8.34\ \text{lb/gal})\left(\frac{\%\ \text{strength of hypochlorite}}{100}\right)\\&\quad=(\text{hypochlorite solution, gal})(8.34\ \text{lb/gal})\left(\frac{\%\ \text{strength of hypochlorite}}{100}\right)\end{aligned}$$

$$(3.3\ \text{gal})(8.34\ \text{lb/gal})\frac{12}{100}=(25\ \text{gal})(8.34\ \text{lb/gal})\frac{x}{100}$$

$$x=\frac{(100)(3.3)(8.34)(12)}{(25)(8.34)(100)}$$

$$x=1.6\%$$

CHEMICAL USE CALCULATIONS

In typical plant operation, chemical use, in lb/day or gpd, is recorded each day. These data provide a record of daily use from which the average daily use of the chemical or solution can be calculated. To calculate average use in lb/day we use Equation 10.95. To calculate average use in gpd we use Equation 10.96:

$$\text{Average use, lb/day}=\frac{\text{total chemicals used, lb}}{\text{number of days}}\qquad(10.95)$$

$$\text{Average use, gpd}=\frac{\text{total chemicals used, gal}}{\text{number of days}}\qquad(10.96)$$

To calculate the days' supply in inventory, we use Equation 10.97 or 10.98:

$$\text{Days' supply in inventory}=\frac{\text{total chemical in inventory, lb}}{\text{average use, lb/day}}\qquad(10.97)$$

$$\text{Days' supply in inventory} = \frac{\text{total chemical in inventory, gal}}{\text{average use, gpd}} \tag{10.98}$$

Example 10.121

Problem:

The pounds (lb) calcium hypochlorite used for each day during a week is given below. Based on these data, what was the average lb/day hypochlorite chemical use during the week?

Monday—50 lb/day
Tuesday—55 lb/day
Wednesday—51 lb/day
Thursday—46 lb/day
Friday—56 lb/day
Saturday—51 lb/day
Sunday—48 lb/day

Solution:

$$\text{Average use, lb/day} = \frac{\text{total chemical used, lb}}{\text{number of days}}$$

$$= \frac{357}{7}$$

$$= 51\ \text{lb/day average use}$$

Example 10.122

Problem:

The average calcium hypochlorite use at a plant is 40 lb/day. If the chemical inventory in stock is 1100 lb, how many days' supply is this?

Solution:

$$\text{Days' supply in inventory} = \frac{\text{total chemical in inventory, lb}}{\text{average use, lb/day}}$$

$$\text{Days' supply in inventory} = \frac{\text{1100 lb in inventory}}{\text{40 lb/day average use}}$$

$$= 27.5\ \text{days' supply in inventory}$$

CHLORINATION CHEMISTRY

As mentioned, chlorine is used in the form of free elemental chlorine or as hypochlorites. Temperature, pH, and organic content in the water influence its chemical form in water. When chlorine gas is dissolved in water, it rapidly hydrolyzes to hydrochloric acid (HCl) and hypochlorous acid (HOCl):

$$Cl_2 + H_2O \leftrightarrow H^+ + Cl^- + HOCl \tag{10.99}$$

According to G.C. White (1972), the equilibrium constant is:

$$\begin{aligned} K_H &= \frac{[H^+][Cl^-][HOCl]}{[Cl_{2(aq)}]} \\ &= 4.48 \times 104 \times \text{at } 25°C \end{aligned} \tag{10.100}$$

Henry's law is used to explain the dissolution of gaseous chlorine, $Cl_{2(aq)}$. Henry's law describes the effect of the pressure on the solubility of the gases: There is a linear relationship between the partial pressure of gas above a liquid and the mole fraction of the gas dissolved in the liquid (Fetter, 1998).

The Henry's law constant K_H (as shown in Equation 10.100) is the measure unit of the compound transfer between the gaseous and aqueous phases. K_H is presented as a ratio of the compound's concentration in the gaseous phase to that in the aqueous phase at equilibrium:

$$K_{\mathrm{H}} = \frac{P}{C_{\text{water}}} \tag{10.101}$$

where

K_H = Henry's law constant
P = compound's partial pressure in the gaseous phase
C_{water} = compound's concentration in the aqueous solution

√ **Note:** The unit of the Henry's law constant is dependent on the choice of measure; however, it can also be dimensionless.

For our purpose, Henry's law can be expressed as (Downs and Adams, 1973):

$$\mathrm{Cl}_{2(aq)} = \frac{\mathrm{Cl}_{2(aq)}}{\mathrm{H(mole/L\ atm)}} = \frac{[\mathrm{Cl}_{2(aq)}]}{\mathrm{PCl}_2} \tag{10.102}$$

where $[Cl_{2(aq)}]$ is the molar concentration of Cl_2 and PCl_2 is the partial pressure of chlorine in atmosphere.

Water (1978) points out that the disinfection capabilities of hypochlorous acid (HOCl) are generally higher than that of hypochlorite ions (OCl^-):

$$\text{Henry's (H) law constant (mole/L atm)} = 4.805 \times 10^{-6} \exp \frac{2818.48}{T} \tag{10.103}$$

Hypochlorous acid is a weak acid and subject to further dissociation to hypochlorite ions (OCl^-) and hydrogen ions:

$$\mathrm{HOCl} \leftrightarrow \mathrm{OCl}^- + \mathrm{H}^+ \tag{10.104}$$

Its acid dissociation constant K_a is:

$$\begin{aligned} K_a &= \frac{[\mathrm{OCl}^-][\mathrm{H}^+]}{[\mathrm{HOCl}]} \\ &= 3.7 \times 10^{-8} \text{ at } 25^\circ\mathrm{C} \\ &= 2.61 \times 10^{-8} \text{ at } 20^\circ\mathrm{C} \end{aligned} \tag{10.105}$$

Morris (1966) points out that the value of K_a for hypochlorous acid is a function of temperature in kelvin (K) as follows:

$$\text{In } K_a = 23.184 - 0.058T - \frac{6908}{T} \tag{10.106}$$

REFERENCES

AWWA and ASCE (American Water Works Association and American Society of Civil Engineers), 1990. *Water Treatment Plant Design*, 2nd ed. New York: McGraw-Hill.

AWWA and ASCE (American Water Works Association and American Society of Civil Engineers), 1998. *Water Treatment Plant Design*, 3rd ed. New York: McGraw-Hill.

Chase, G.L., 2002. *Solids Notes: Fluidization*. Akron, OH: The University of Akron.

Cleasby, J.L., 1990. Filtration. In *Water Quality and Treatment*, AWWA (ed.). New York: McGraw-Hill.

Cleasby, J.L. and Fan, K.S., 1981. Predicting Fluidization and Expansion of Filter Media. *J. Environ. Eng. Div. ASCE*, 107 (EE3):355–471.

Downs, A.J. and Adams, C.J., 1973. *The Chemistry of Chlorine, Bromine, Iodine and Astatine*. Oxford: Pergamon.

Droste, R.L., 1997. *Theory and Practice of Water and Wastewater Treatment*. New York: John Wiley & Sons.

Fair, G.M., Geyer, J.C., and Okun, D.A., 1968. *Water and Wastewater Engineering, Vol. 2*: *Water Purification and Wastewater Treatment and Disposal*. New York: John Wiley & Sons.

Fetter, C.W., 1998. *Handbook of Chlorination*. New York: Litton Educational.

Gregory, R. and Zabel, T.R., 1990. Sedimentation and Flotation. In *Water Quality and Treatment, A Handbook of Community Water Supplies*, 4th ed. AWWA, Pontius, F.W. (ed.). New York: McGraw-Hill.

Gupta, R.S., 1997. *Environmental Engineering and Science: An Introduction*. Rockville, MD: Government Institutes.

Hudson, H.E., Jr., 1989. Density considerations in sedimentation. *J. Amer. Water Works Assoc.*, 64(6): 382–386.

McGhee, T.J., 1991. *Water Resources and Environmental Engineering*, 6th ed. New York: McGraw-Hill.

Morris, J.C., 1966. The acid ionization constant of HOCl from 5°C to 35°C. *J. Phys. Chem.*, 70(12):3789.

USEPA, 1999. *Individual Filter Self Assessment. EPA Guidance Manual, Turbidity Provisions*, pp. 5–12.

Water, G.C., 1978. *Disinfection of Wastewater and Water for Reuse*. New York: Van Nostrand Reinhold.

Wen, C.Y. and Yu, Y.H., 1966. Minimum Fluidization Velocity. *AIChE J.*, 12(3):610–612.

White, G.C., 1972. *Handbook of Chlorination*. New York: Litton Educational.

Glossary

A

Absorption Any process by which one substance penetrates the interior of another substance.

Acid Has a pH of water less than 5.5; pH modifier used in the U.S. Fish and Wildlife Service wetland classification system; in common usage, acidic water has a pH less than 7.

Acidic deposition The transfer of acidic or acidifying substances from the atmosphere to the surface of the Earth or to objects on its surface. Transfer can be either by wet-deposition processes (rain, snow, dew, fog, frost, or hail) or by dry deposition (gases, aerosols, or fine to coarse particles).

Acid rain Precipitation with higher than normal acidity, caused primarily by sulfur and nitrogen dioxide air pollution.

Acre-foot (acre-ft.) The volume of water needed to cover an acre of land to a depth of 1 ft; equivalent to 43,560 ft^3 or 32,851 gal.

Activated carbon A very porous material that after being subjected to intense heat to drive off impurities can be used to adsorb pollutants from water.

Adsorption The process by which one substance is attracted to and adheres to the surface of another substance, without actually penetrating its internal structure.

Aeration A physical treatment method that promotes biological degradation of organic matter. The process may be passive (when waste is exposed to air), or active (when a mixing or bubbling device introduces the air).

Aerobic bacteria A type of bacteria that requires free oxygen to carry out metabolic function.

Algae Chlorophyll-bearing nonvascular, primarily aquatic species that have no true roots, stems, or leaves; most algae are microscopic, but some species can be as large as vascular plants.

Algal bloom The rapid proliferation of passively floating, simple plant life, such as blue-green algae, in and on a body of water.

Alkaline Has a pH greater than 7; pH modifier in the U.S. Fish and Wildlife Service wetland classification system; in common usage, a pH of water greater than 7.4.

Alluvial aquifer A water-bearing deposit of unconsolidated material (sand and gravel) left behind by a river or other flowing water.

Alluvium General term for sediments of gravel, sand, silt clay, or other particulate rock material deposited by flowing water, usually in the beds of rivers and streams, on a flood plain, on a delta, or at the base of a mountain.

Alpine snow glade A marshy clearing between slopes above the timberline in mountains.

Amalgamation The dissolving or blending of a metal (commonly gold and silver) in mercury to separate it from its parent material.

Ammonia A compound of nitrogen and hydrogen (NH_3) that is a common by-product of animal waste. Ammonia readily converts to nitrate in soils and streams.

Anadromous fish Migratory species that are born in fresh water, live mostly in estuaries and ocean water, and return to fresh water to spawn.

Anaerobic Pertaining to, taking place in, or caused by the absence of oxygen.

Anomalies As related to fish, externally visible skin or subcutaneous disorders, including deformities, eroded fins, lesions, and tumors.

Anthropogenic Having to do with or caused by humans.

Anticline A fold in the Earth's crust, convex upward, whose core contains stratigraphically older rocks.

Aquaculture The science of farming organisms that live in water, such as fish, shellfish, and algae.

Aquatic Living or growing in or on water.

Aquatic guidelines Specific levels of water quality, which, if reached, may adversely affect aquatic life. These are nonenforceable guidelines issued by a governmental agency or other institution.

Aquifer A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to springs and wells.

Arroyo A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream, usually with nearly vertical banks cut into unconsolidated material.

Artificial recharge Augmentation of natural replenishment of groundwater storage by some method of construction, spreading of water, or by pumping water directly into an aquifer.

Atmospheric deposition The transfer of substances from the air to the surface of the Earth, either in wet form (rain, fog, snow, dew, frost, hail) or in dry form (gases, aerosols, particles).

Atmospheric pressure The pressure exerted by the atmosphere on any surface beneath or within it; equal to 14.7 lb/in^2 at sea level.

Average discharge As used by the U.S. Geological Survey, the arithmetic average of all complete water years of record of surface water discharge whether consecutive or not. The term "average" generally is reserved for average of record and "mean" is used for averages of shorter periods, namely, daily, monthly, or annual mean discharges.

B

Background concentration A concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources.

Backwater A body of water in which the flow is slowed or turned back by an obstruction such as a bridge or dam, an opposing current, or the movement of the tide.

Bacteria Single-celled microscopic organisms.

Bank The sloping ground that borders a stream and confines the water in the natural channel when the water level, or flow, is normal.

Bank storage The change in the amount of water stored in an aquifer adjacent to a surface water body resulting from a change in stage of the surfacewater body.

Barrier bar An elongate offshore ridge, submerged at least at high tide, built up by the action of waves or currents.

Base flow The sustained low flow of a stream, usually groundwater inflow to the stream channel.

Basic The opposite of acidic; water that has a pH greater than 7.

Basin and range physiography A region characterized by a series of generally north-trending mountain ranges separated by alluvial valleys.

Bed material Sediment comprising the streambed.

Bed sediment The material that temporarily is stationary in the bottom of a stream or other watercourse.

Bedload Sediment that moves on or near the streambed and is in almost continuous contact with the bed.

Bedrock A general term used for solid rock that underlies soils or other unconsolidated material.

Benthic invertebrates Insects, mollusks, crustaceans, worms, and other organisms without a backbone that live in, on, or near the bottom of lakes, streams, or oceans.

Benthic organism A form of aquatic life that lives on or near the bottom of stream, lakes, or oceans.

Bioaccumulation The biological sequestering of a substance at a higher concentrations than that at which it occurs in the surrounding environment or medium. Also, the process whereby a substance enters organisms through the gills, epithelial tissues, dietary, or other sources.

Bioavailability The capacity of a chemical constituent to be taken up by living organisms either through physical contact or by ingestion.

Biochemical Chemical processes that occur inside or are mediated by living organisms.

Biochemical process A process characterized by, produced by, or involving chemical reactions in living organisms.

Biochemical oxygen demand (BOD) The amount of oxygen required by bacteria to stabilize decomposable organic matter under aerobic conditions.

Biodegradation Transformation of a substance into new compounds through biochemical reactions or the actions of microorganisms such as bacteria.

Biological treatment A process that uses living organisms to bring about chemical changes.

Biomass The amount of living matter, in the form of organisms, present in a particular habitat, usually expressed as weight per unit area.

Biota All living organisms of an area.

Bog A nutrient-poor, acidic wetland dominated by a waterlogged, spongy mat of sphagnum moss that ultimately forms a thick layer of acidic peat; generally has no inflow or outflow; fed primarily by rain water.

Brackish water Water with a salinity intermediate between seawater and freshwater (containing from 1000 to 10,000 mg/L of dissolved solids).

Breakdown product A compound derived by chemical, biological, or physical action upon a pesticide. The breakdown is a natural process that may result in a more toxic or a less toxic compound and a more persistent or less persistent compound.

Breakpoint chlorination The addition of chlorine to water until the chlorine demand has been satisfied and free chlorine residual is available for disinfection.

C

Calcareous A rock or substance formed of calcium carbonate or magnesium carbonate by biological deposition or inorganic precipitation, or containing those minerals in sufficient quantities to effervesce when treated with cold hydrochloric acid.

Capillary fringe The zone above the water table in which water is held by surface tension. Water in the capillary fringe is under a pressure less than atmospheric.

Carbonate rocks Rocks (such as limestone or dolostone) that are composed primarily of minerals (such as calcite and dolomite) containing a carbonate ion.

Center pivot irrigation An automated sprinkler system involving a rotating pipe or boom that supplies water to a circular area of an agricultural field through sprinkler heads or nozzles.

Channel scour Erosion by flowing water and sediment on a stream channel; results in removal of mud, silt, and sand on the outside curve of a stream bend and the bed material of a stream channel.

Channelization The straightening and deepening of a stream channel to permit the water to move faster or to drain a wet area for farming.

Chemical treatment A process that results in the formation of a new substance or substances. The most common chemical water treatment processes include coagulation, disinfection, water softening, and filtration.

Chlordane Octachlor-4,7-methanotetrahydroindane. An organochlorine insecticide no longer registered for use in the United States. Technical chlordane is a mixture in which the primary components are cis- and trans-chlordane, cis- and trans-nonachlor, and heptachlor.

Chlorinated solvent A volatile organic compound containing chlorine. Some common solvents are trichloroethylene, tetrachloroethylene, and carbon tetrachloride.

Chlorofluorocarbons A class of volatile compounds consisting of carbon, chlorine, and fluorine. Commonly called freons, they have been used in refrigeration mechanisms, as blowing agents in the fabrication of flexible and rigid foams, and, until banned from use several years ago, as propellants in spray cans.

Chlorination The process of adding chlorine to water to kill disease-causing organisms or to act as an oxidizing agent.

Chlorine demand A measure of the amount of chlorine that will combine with impurities, and is therefore unavailable to act as a disinfectant.

Cienaga A marshy area where the ground is wet due to the presence of seepage of springs.

Clean Water Act (CWA) Federal law dating to 1972 (with several amendments) with the objective to restore and maintain the chemical, physical, and biological integrity of the nation's waters. Its long-range goal is to eliminate the discharge of pollutants into navigable waters and to make national waters fishable and swimmable.

Climate The sum total of the meteorological elements that characterize the average and extreme conditions of the atmosphere over a long period of time at any one place or region of the Earth's surface.

Coagulants Chemicals that cause small particles to stick together to form larger particles.

Coagulation A chemical water treatment method that causes very small suspended particles to attract one another and form larger particles. This is accomplished by the addition of a coagulant that neutralizes the electrostatic charges that cause particles to repel one another.

Coliform bacteria A group of bacteria predominantly inhabiting the intestines of humans or animals, but also occasionally found elsewhere. Presence of the bacteria in water is used as an indication of fecal contamination (contamination by animal or human wastes).

Color A physical characteristic of water. Color is most commonly tan or brown from oxidized iron, but contaminants may cause other colors, such as green or blue. Color differs from turbidity, which is water's cloudiness.

Combined sewer overflow A discharge of untreated sewage and stormwater to a stream when the capacity of a combined storm/sanitary sewer system is exceeded by storm runoff.

Communicable diseases Usually caused by *microbes*—microscopic organisms including bacteria, protozoa, and viruses. Most microbes are essential components of our environment and do not cause disease. Those that do are called pathogenic organisms, or simply *pathogens*.

Community In ecology, the species that interact in a common area.

Community water system A public water system that serves at least 15 service connections used by year-round residents or that regularly serves at least 25 year-round residents.

Composite sample A series of individual or grab samples taken at different times from the same sampling point and mixed together.

Concentration The ratio of the quantity of any substance present in a sample of a given volume or a given weight compared to the volume or weight of the sample.

Cone of depression The depression of heads around a pumping well caused by withdrawal of water.

Confined aquifer (artesian aquifer) An aquifer that is completely filled with water under pressure and that is overlain by material that restricts the movement of water.

Confining layer A body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers that restricts the movement of water into and out of the aquifers.

Confluence The flowing together of two or more streams; the place where a tributary joins the main stream.

Conglomerate A coarse-grained sedimentary rock composed of fragments larger than 2 mm in diameter.

Constituent A chemical or biological substance in water, sediment, or biota that can be measured by an analytical method.

Consumptive use The quantity of water that is not available for immediate rescue because it has evaporated, transpired, or been incorporated into products, plant tissue, or animal tissue.

Contact recreation Recreational activities, such as swimming and kayaking, in which contact with water is prolonged or intimate, and in which there is a likelihood of ingesting water.

Contaminant A toxic material found as an unwanted residue in or on a substance.

Contamination Degradation of water quality compared to original or natural conditions due to human activity.

Contributing area The area in a drainage basin that contributes water to streamflow or recharge to an aquifer.

Core sample A sample of rock, soil, or other material obtained by driving a hollow tube into the undisturbed medium and withdrawing it with its contained sample.

Criterion A standard rule or test on which a judgment or decision can be based.

Cross connection Any connection between safe drinking water and a nonpotable water or fluid.

C×T value The product of the residual disinfectant concentration C, in milligrams per liter, and the corresponding disinfectant contact time T, in minutes. Minimum C×T values are specified by the Surface Water Treatment Rule as a means of ensuring adequate killing or inactivation of pathogenic microorganisms in water.

D

Datum plane A horizontal plane to which ground elevations or water surface elevations are referenced.

Deepwater habitat Permanently flooded lands lying below the deepwater boundary of wetlands.

Degradation products Compounds resulting from transformation of an organic substance through chemical, photochemical, and/or biochemical reactions.

Denitrification A process by which oxidized forms of nitrogen such as nitrate are reduced to form nitrites, nitrogen oxides, ammonia, or fee nitrogen: commonly brought about by the action of denitrifying bacteria and usually resulting in the escape of nitrogen to the air.

Detection limit The concentration of a constituent or analyte below which a particular analytical method cannot determine, with a high degree of certainty, the concentration.

Diatoms Single-celled, colonial, or filamentous algae with siliceous cell walls constructed of two overlapping parts.

Direct runoff The runoff entering stream channels promptly after rainfall or snowmelt.

Discharge The volume of fluid passing a point per unit of time, commonly expressed in cubic feet per second, million gallons per day, gallons per minute, or seconds per minute per day.

Discharge area (groundwater) Area where subsurface water is discharged to the land surface, to surface water, or to the atmosphere.

Disinfectants-disinfection by-products (D-DBPs) A term used in connection with state and federal regulations designed to protect public health by limiting the concentration of either disinfectants or the by-products formed by the reaction of disinfectants with other substances in the water (such as trihalomethanes—THMs).

Disinfection A chemical treatment method. The addition of a substance (e.g., chlorine, ozone, or hydrogen peroxide) that destroys or inactivates harmful microorganisms, or inhibits their activity.

Dispersion The extent to which a liquid substance introduced into a groundwater system spreads as it moves through the system.

Dissociate The process of ion separation that occurs when an ionic solid is dissolved in water.

Dissolved constituent Operationally defined as a constituent that passes through a 0.45-micrometer filter.

Dissolved oxygen (DO) The oxygen dissolved in water usually expressed in milligrams per liter, parts per million, or percent of saturation.

Dissolved solids Any material that can dissolve in water and be recovered by evaporating the water after filtering the suspended material.

Diversion A turning aside or alteration of the natural course of a flow of water, normally considered physically to leave the natural channel. In some states, this can be a consumptive use direct from another stream, such as by livestock watering. In other states, a diversion must consist of such actions as taking water through a canal, pipe, or conduit.

Dolomite A sedimentary rock consisting chiefly of magnesium carbonate.

Domestic withdrawals Water used for normal household purposes, such a drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens. The water may be obtained from a public supplier or may be self-supplied. Also called residential water use.

Drainage area The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

Drainage basin The land area drained by a river or stream.

Drainage divide Boundary between adjoining drainage basins.

Drawdown The difference between the water level in a well before pumping and the water level in the well during pumping. Also, for flowing wells, the reduction of the pressure head as a result of the discharge of water.

Drinking water standards Water quality standards measured in terms of suspended solids, unpleasant taste, and microbes harmful to human health. Drinking water standards are included in state water quality rules.

Drinking water supply Any raw or finished water source that is or may be used as a public water system or as drinking water by one or more individuals.

Drip irrigation An irrigation system in which water is applied directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, or perforate pipe) operated under low pressure. The applicators can be placed on or below the surface of the ground or can be suspended from supports.

Drought A prolonged period of less-than-normal precipitation such that the lack of water causes a serious hydrologic imbalance.

E

Ecoregion An area of similar climate, landform, soil, potential natural vegetation, hydrology, or other ecologically relevant variables.

Ecosystem A community of organism considered together with the nonliving factors of its environment.

Effluent Outflow from a particular source, such as a stream that flows from a lake or liquid waste that flows from a factory or sewage-treatment plant.

Effluent limitations Standards developed by the EPA to define the levels of pollutants that could be discharged into surface waters.

Electrodialysis The process of separating substances in a solution by dialysis, using an electric field as the driving force.

Electronegativity The tendency for atoms that do not have a complete octet of electrons in their outer shell to become negatively charged.

Emergent plants Erect, rooted, herbaceous plants that may be temporarily or permanently flooded at the base but do not tolerate prolonged inundation of the entire plant.

Enhanced Surface Water Treatment Rule (ESWTR) A revision of the original Surface Water Treatment Rule that includes new technology and requirements to deal with newly identified problems.

Environment The sum of all conditions and influences affecting the life of organisms.

Environmental sample A water sample collected from an aquifer or stream for the purpose of chemical, physical, or biological characterization of the sampled resource.

Environmental setting Land area characterized by a unique combination of natural and human-related factors, such as row-crop cultivation or glacial-till soils.

Ephemeral stream A stream or part of a stream that flows only in direct response to precipitation; it receives little or no water from springs, melting snow, or other sources; its channel is at all times above the water table.

EPT richness index An index based on the sum of the number of taxa in three insect orders, Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), that are composed primarily of species considered relatively intolerant to environmental alterations.

Erosion The process whereby materials of the Earth's crust are loosened, dissolved, or worn away and simultaneously moved from one place to another.

Eutrophication The process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.

Evaporite minerals (deposits) Minerals or deposits of minerals formed by evaporation of water containing salts. Three deposits are common in arid climates.

Evaporites A class of sedimentary rocks composed primarily of minerals precipitated from a saline solution as a result of extensive or total evaporation of water.

Evapotranspiration The process by which water is discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and transpiration by plants.

F

Facultative bacteria A type of anaerobic bacteria that can metabolize its food either aerobically or anaerobically.

Fall line Imaginary line marking the boundary between the ancient, resistant crystalline rocks of the Piedmont province of the Appalachian Mountains, and the younger, softer sediments of the Atlantic Coastal Plain province in the eastern United States. Along rivers, this line commonly is reflected by waterfalls.

Fecal bacteria Microscopic single-celled organisms (primarily fecal coliforms and fecal streptococci) found in the wastes of warm-blooded animals. Their presence in water is used to assess the sanitary quality of water for body-contact recreation or for consumption. Their presence indicates contamination by the wastes of warm-blooded animals and the possible present of pathogenic (disease-producing) organisms.

Federal Water Pollution Control Act (1972) This act outlines the objective "to restore and maintain the chemical, physical, and biological integrity of the nation's waters." This 1972 act and subsequent Clean Water Act amendments are the most far-reaching water pollution control legislation ever enacted. They provide comprehensive programs for water pollution control, uniform laws, and interstate cooperation. They provide grants for research, investigations, training, and information on national programs on surveillance, the effects of pollutants, pollution control, and the identification and measurement of pollutants. Additionally, they allot grants and loans for the construction of treatment works. The act established national discharge standards with enforcement provisions.

The Federal Water Pollution Control Act established several milestone achievement dates. It required secondary treatment of domestic waste by publicly owned treatment works (POTWs), and application of the "best practicable" water pollution control technology by the industry by 1977. Virtually all industrial sources have achieved compliance (because of economic difficulties and cumbersome federal requirements, certain POTWs obtained an extension to July 1, 1988 for compliance). The act also called for new levels of technology to be imposed during the 1980s and 1990s, particularly for controlling toxic pollutants.

The act mandates a strong pretreatment program to control toxic pollutants discharged by industry into POTWs. The 1987 amendments require that storm water from industrial activity must be regulated.

Fertilizer Any of a large number of natural or synthetic materials, including manure and nitrogen, phosphorus, and potassium compound, spread on or worked into soil to increase its fertility.

Filtrate Liquid that has been passed through a filter.

Filtration A physical treatment method for removing solid (particulate) matter from water by passing the water through porous media such as sand or a man-made filter.

Flocculation The water treatment process following coagulation. It uses gentle stirring to bring suspended particles together so that they will form larger, more settleable clumps called floc.

Flood Any relatively high streamflow that overflows the natural or artificial banks of a stream.

Flood attenuation A weakening or reduction in the force or intensity of a flood.

Flood irrigation The application of irrigation water whereby the entire surface of the soil is covered by ponded water.

Flood plain A strip of relatively flat land bordering a stream channel that is inundated at times of high water.

Flow line The idealized path followed by particles of water.

Flowpath An underground route for groundwater movement, extending from a recharge (intake) zone to a discharge (output) zone such as a shallow stream.

Fluvial Pertaining to a river or stream.

Fresh water Water that contains less than 1000 mg/L of dissolved solids.

Freshwater chronic criteria The highest concentration of a contaminant that freshwater aquatic organisms can be exposed to for an extended period of time (4 days) without adverse effects.

G

Grab sample A single water sample collected at one time from a single point.

Groundwater The fresh water found under the Earth's surface, usually in aquifers. Groundwater is a major source of drinking water, and a source of a growing concern in areas where leaching agricultural or industrial pollutants or substances from leaking underground storage tanks are contaminating groundwater.

H

Habitat The part of the physical environment in which a plant or animal lives.

Hardness A characteristic of water caused primarily by the salts of calcium and magnesium. It causes deposition of scale in boilers, damage in some industrial processes, and sometimes objectionable taste. It may also decrease soap's effectiveness.

Headwaters The source and upper part of a stream.

Hydraulic conductivity The capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient The change of hydraulic head per unit of distance in a given direction.

Hydrogen bonding The term used to describe the weak but effective attraction that occurs between polar covalent molecules.

Hydrograph Graph showing variation of water elevation, velocity, streamflow, or other property of water with respect to time.

Hydrologic cycle Literally the water–earth cycle. The movement of water in all three physical forms through the various environmental mediums (air, water, biota, and soil).

Hydrology The science that deals with water as it occurs in the atmosphere, on the surface of the ground, and underground.

Hydrostatic pressure The pressure exerted by the water at any given point in a body of water at rest.

Hygroscopic A substance that readily absorbs moisture.

I

Impermeability The incapacity of a rock to transmit a fluid.

Index of biotic integrity (IBI) An aggregated number, or index, based on several attributes or metrics of a fish community that provides an assessment of biological conditions.

Indicator sites Stream sampling sites located at outlets of drainage basins with relatively homogeneous land use and physiographic conditions; most indicator-site basins have drainage areas ranging from 20 to 200 square miles.

Infiltration The downward movement of water from the atmosphere into soil or porous rock.

Influent Water flowing into a reservoir, basin, or treatment plant.

Inorganic Containing no carbon; matter other than plant or animal.

Inorganic chemical A chemical substance of mineral origin not having carbon in its molecular structure.

Inorganic soil Soil with less than 20% organic matter in the upper 16 in.

Ionic bond The attractive forces between oppositely charged ions—for example, the forces between the sodium and chloride ions in a sodium chloride crystal.

Instantaneous discharge The volume of water that passes a point at a particular instant of time.

Instream use Water use taking place within the stream channel for such purposes as hydroelectric power generation, navigation, water-quality improvement, fish propagation, and recreation. Sometimes called nonwithdrawal use or in-channel use.

Intermittent stream A stream that flows only when it receives water from rainfall runoff or springs, or from some surface source such as melting snow.

Internal drainage Surface drainage whereby the water does not reach the ocean, such as drainage toward the lowermost or central part of an interior basin or closed depression.

Intertidal Alternately flooded and exposed by tides.

Intolerant organisms Organisms that are not adaptable to human alterations to the environment and thus decline in numbers where alterations occur.

Invertebrate An animal having no backbone or spinal column.

Ion A positively or negatively charged atom or group of atoms.

Irrigation Controlled application of water to arable land to supply requirements of crops not satisfied by rainfall.

Irrigation return flow The part of irrigation applied to the surface that is not consumed by evapotranspiration or uptake by plants and that migrates to an aquifer or surface-water body.

Irrigation withdrawals Withdrawals of water for application on land to assist in the growing of crops and pastures or to maintain recreational lands.

K

Kill Dutch term for stream or creek.

L

Lacustrine Pertaining to, produced by, or formed in a lake.

Leachate A liquid that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution.

Leaching The removal of materials in solution from soil or rock; also refers to movement of pesticides or nutrients from land surface to groundwater.

Limnetic The deepwater zone (>2 m deep).

Littoral The shallow-water zone (<2 m deep).

Load Material that is moved or carried by streams, reported as weight of material transported during a specified time period, such as tons per year.

M

Main stem The principal trunk of a river or a stream.

Marsh A water-saturated, poorly drained area, intermittently or permanently water covered, having aquatic and grasslike vegetation.

Maturity (stream) The stage in the development of a stream at which it has reached its maximum efficiency, when velocity is just sufficient to carry the sediment delivered to it by tributaries; characterized by a broad, open, flat-floored valley having a moderate gradient and gentle slope.

Maximum contaminant level (MCL) The maximum allowable concentration of a contaminant in drinking water, as established by state and/or federal regulations. Primary MCLs are health related and mandatory. Secondary MCLs are related to the aesthetics of the water and are highly recommended but not required.

Mean discharge The arithmetic mean of individual daily mean discharges of a stream during a specific period, usually daily, monthly, or annually.

Membrane filter method A laboratory method used for coliform testing. The procedure uses an ultra-thin filter with a uniform pore size smaller than bacteria (less than a micron). After water is forced through the filter, the filter is incubated in a special media that promotes the growth of coliform bacteria. Bacterial colonies with a green-gold sheen indicate the presence of coliform bacteria.

Method detection limit The minimum concentration of a substance that can be accurately identified and measured with current lab technologies.

Midge A small fly in the family Chironomidae. The larval (juvenile) life stages are aquatic.

Minimum reporting level (MRL) The smallest measured concentration of a constituent that may be reliably reported using a given analytical method. In many cases, the MRL is used when documentation for the method detection limit is not available.

Mitigation Actions taken to avoid, reduce, or compensate for the effects of human-induced environmental damage.

Modes of transmission of disease The ways in which diseases spread from one person to another.

Monitoring Repeated observation, measurement, or sampling at a site, on a scheduled or event basis, for a particular purpose.

Monitoring well A well designed for measuring water levels and testing groundwater quality.

Multiple-tube fermentation method A laboratory method used for coliform testing, which uses a nutrient broth placed in a culture tubes. Gas production indicates the presence of coliform bacteria.

N

National Primary Drinking Water Regulations (NPDWRs) Regulations developed under the Safe Drinking Water Act, which establish maximum contaminant levels, monitoring requirements, and reporting procedures for contaminants in drinking water that endanger human health.

National Pollutant Discharge Elimination System (NPDES) A requirement of the CWA that discharges meet certain requirements prior to discharging waste to any water body. It sets the highest permissible effluent limits, by permit, prior to making any discharge.

Near Coastal Water Initiative This initiative was developed in 1985 to provide for the management of specific problems in waters near coastlines that are not dealt with in other programs.

Nitrate An ion consisting of nitrogen and oxygen (NO_3). Nitrate is a plant nutrient and is very mobile in soils.

Nonbiodegradable Substances that do not break down easily in the environment.

Nonpoint source A source (of any water-carried material) from a broad area, rather than from discrete points.

Nonpoint-source contaminant A substance that pollutes or degrades water that comes from lawn or cropland runoff, the atmosphere, roadways, and other diffuse sources.

Nonpoint-source water pollution Water contamination that originates from a broad area (such as leaching of agricultural chemicals from crop lad) and enters the water resource diffusely over a large area.

Nonpolar covalently bonded A molecule composed of atoms that share their electrons equally, resulting in a molecule that does not have polarity.

Nutrient Any inorganic or organic compound needed to sustain plant life.

O

Organic Containing carbon, but possibly also containing hydrogen, oxygen, chlorine, nitrogen, and other elements.

Organic chemical A chemical substance of animal or vegetable origin having carbon in its molecular structure.

Organic detritus Any loose organic material in streams—such as leaves, bark, or twigs—removed and transported by mechanical means, such as disintegration or abrasion.

Organic soil Soil that contains more than 20% organic matter in the upper 16 in.

Organochlorine compound Synthetic organic compounds containing chlorine. As generally used, this term refers to compounds containing mostly or exclusively carbon, hydrogen, and chlorine.

Outwash Soil material washed down a hillside by rainwater and deposited upon more gently sloping land.

Overland flow The flow of rainwater or snowbelt over the land surface toward stream channels.

Oxidation When a substance either gains oxygen or loses hydrogen or electrons in a chemical reaction. One of the chemical treatment methods.

Oxidizer A substance that oxidizes another substance.

P

Parts per million The number of weight or volume units of a constituent present with each one million units of the solution or mixture. Formerly used to express the results of most water and wastewater analyses, PPM is being replaced by milligrams per liter (mg/L). For drinking water analyses, concentration in parts per million and milligrams per liter are equivalent. A single PPM can be compared to a shot glass full of water inside a swimming pool.

Pathogens Types of microorganisms that can cause disease.

Perched groundwater Unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

Percolation The movement, under hydrostatic pressure, of water through interstices of a rock or soil (except the movement through large openings such as caves).

Perennial stream A stream that normally has water in its channel at all times.

Periphyton Microorganisms that coat rocks, plants, and other surfaces on lake bottoms.

Permeability The capacity of a rock for transmitting a fluid; a measure of the relative ease with which a porous medium can transmit a liquid.

pH A measure of the acidity (less than 7) or alkalinity (greater than 7) of a solution; a pH of 7 is considered neutral.

Phosphorus A nutrient essential for growth that can play a key role in stimulating aquatic growth in lakes and streams.

Photosynthesis The synthesis of compounds with the aid of light.

Physical treatment Any process that does not produce a new substance (e.g., screening, adsorption, aeration, sedimentation, and filtration).

Point source Originating at any discrete source.

Polar covalent bond The shared pair of electrons between two atoms are not equally held. Thus, one of the atoms becomes slightly positively charged and the other atom becomes slightly negatively charged.

Polar covalent molecule One or more polar covalent bonds result in a molecule that is polar covalent. Polar covalent molecules exhibit partial positive and negative poles, causing them to behave like tiny magnets. Water is the most common polar covalent substance.

Pollutant Any substance introduced into the environment that adversely affects the usefulness of the resource.

Pollution The presence of matter or energy whose nature, location, or quantity produces undesired environmental effects. Under the Clean Water Act, for example, the term is defined as a man-made or man-induced alteration of the physical, biological, and radiological integrity of water.

Polychlorinated biphenyls (PCBs) A mixture of chlorinated derivatives of biphenyl, marketed under the trade name Aroclor with a number designating the chlorine content (such as Aroclor 1260). PCBs were used in transformers and capacitors for insulating purposes and in gas pipeline systems as a lubricant. Further sale or new use was banned by law in 1979.

Polycyclic aromatic hydrocarbon (PAH) A class of organic compounds with a fused-ring aromatic structure. PAHs result from incomplete combustion of organic carbon (including wood), municipal solid waste, and fossil fuels, as well as from natural or anthropogenic introduction of uncombusted coal and oil. PAHs included benzo(a)pyrene, fluoranthene, and pyrene.

Population A collection of individuals of one species or mixed species making up the residents of a prescribed area.

Porosity The ratio of the volume of voids in a rock or soil to the total volume.

Potable water Water that is safe and palatable for human consumption.

Precipitation Any or all forms of water particles that fall from the atmosphere, such as rain, snow, hail, and sleet. The act or process of producing a solid phase within a liquid medium.

Pretreatment Any physical, chemical, or mechanical process used before the main water treatment processes. It can include screening, presedimentation, and chemical addition.

Primary Drinking Water Standards Regulations on drinking water quality (under SWDA) considered essential for preservation of public health.

Primary treatment The first step of treatment at a municipal wastewater treatment plant. It typically involves screening and sedimentation to remove materials that float or settle.

Public-supply withdrawals Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes such as domestic, commercial, industrial, and public water use.

Public water system As defined by the Safe Drinking Water Act, any system, publicly or privately owned, that serves at least 15 service connections 60 days out of the year or serves an average of 25 people at least 60 days out of the year.

Publicly Owned Treatment Works (POTW) A waste treatment works owned by a state, local government unit or Indian tribe, usually designed to treat domestic wastewaters.

R

Rain shadow A dry region on the leeward side of a topographic obstacle, usually a mountain range, where rainfall is noticeably less than on the windward side.

Reach A continuous part of a stream between two specified points.

Reaeration The replenishment of oxygen in water from which oxygen has been removed.

Receiving waters A river, lake, ocean, stream, or other water source into which wastewater or treated effluent is discharged.

Recharge The process by which water is added to a zone of saturation, usually by percolation from the soil surface.

Recharge area (groundwater) An area within which water infiltrates the ground and reaches the zone of saturation.

Reference dose (RfD) An estimate of the amount of a chemical that a person can be exposed to on a daily basis that is not anticipated to cause adverse systemic health effects over the person's lifetime.

Representative sample A sample containing all the constituents present in the water from which it was taken.

Return flow That part of irrigation water that is not consumed by evapotranspiration and that returns to its source or another body of water.

Reverse osmosis (RO) Solutions of differing ion concentration are separated by a semipermeable membrane. Typically, water flows from the chamber with lesser ion concentration into the chamber with the greater ion concentration, resulting in hydrostatic or osmotic pressure. In RO, enough external pressure is applied to overcome this hydrostatic pressure, thus reversing the flow of water. This results in the water on the other side of the membrane becoming depleted in ions and demineralized.

Riffle A shallow part of the stream where water flows swiftly over completely or partially submerged obstructions to produce surface agitation.

Riparian Pertaining to or situated on the bank of a natural body of flowing water.

Riparian rights A concept of water law under which authorization to use water in a stream is based on ownership of the land adjacent to the stream.

Riparian zone Pertaining to or located on the bank of a body of water, especially a stream.

Runoff That part of precipitation or snowmelt that appears in streams or surface-water bodies.

Rural withdrawals Water used in suburban or farm areas for domestic and livestock needs. The water generally is self-supplied and includes domestic use, drinking water for livestock, and other uses such as dairy sanitation, evaporation from stock-watering ponds, and cleaning and waste disposal.

S

Safe Drinking Water Act (SDWA) A federal law passed in 1974 with the goal of establishing federal standards for drinking water quality, protecting underground sources of water, and setting up a system of state and federal cooperation to ensure compliance with the law.

Saline water Water that is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids; generally expressed as milligrams per liter (mg/L) of dissolved solids; seawater is generally considered to contain more than 35,000 mg/L of dissolved solids. A general salinity scale is:

Concentration of dissolved solids in mg/L	
Slightly saline	1000–3000
Moderately saline	3000–10,000
Very saline	10,000–35,000
Brine	>35000

Saturated zone A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

Screening A pretreatment method that uses coarse screens to remove large debris from the water to prevent clogging of pipes or channels to the treatment plant.

Secondary Drinking Water Standards Regulations developed under the Safe Drinking Water Act that established maximum levels of substances affecting the aesthetic characteristics (taste, color, or odor) of drinking water.

Secondary maximum contaminant level (SMCL) The maximum level of a contaminant or undesirable constituent in public water systems that, in the judgment of USEPA, is required to protect the public welfare. SMCLs are secondary (nonenforceable) drinking water regulations established by the USEPA for contaminants that may adversely affect the odor or appearance of such water.

Secondary treatment The second step of treatment at a municipal wastewater treatment plant. This step uses growing numbers of microorganisms to digest organic matter and reduce the amount of organic waste. Water leaving this process is chlorinated to destroy any disease-causing microorganisms before its release.

Sedimentation A physical treatment method that involves reducing the velocity of water in basins so that the suspended material can settle out by gravity.

Seep A small area where water percolates slowly to the land surface.

Seiche A sudden oscillation of the water in a moderate-size body of water, caused by wind.

Sinuosity The ratio of the channel length between two points on a channel to the straight-line distance between the same two points; a measure of meandering.

Soil horizon A layer of soil that is distinguishable from adjacent layers by characteristic physical and chemical properties.

Soil moisture Water occurring in the pore spaces between the soil particles in the unsaturated zone from which water is discharged by the transpiration of plants or by evaporation from the soil.

Solution Formed when a solid, gas, or another liquid in contact with a liquid becomes dispersed homogeneously throughout the liquid. The substance, called a solute, is said to dissolve. The liquid is called the solvent.

Solvated When either a positive or negative ion becomes completely surrounded by polar solvent molecules.

Sorb To take up and hold either by absorption or adsorption.

Sorption General term for the interaction (binding or association) of a solute ion or molecule with a solid.

Specific yield The ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock.

Spring Place where a concentrated discharge of groundwater flows at the ground surface.

Surface runoff Runoff that travels over the land surface to the nearest stream channel.

Surface tension The attractive forces exerted by the molecules below the surface upon those at the surface, resulting in them crowding together and forming a higher density.

Surface water All water naturally open to the atmosphere, and all springs, wells, or other collectors that are directly influenced by surface water.

Surface Water Treatment Rule (SWTR) A federal regulation established by the USEPA under the Safe Drinking Water Act that imposes specific monitoring and treatment requirements on all public drinking water systems that draw water from a surface water source.

Suspended sediment Sediment that is transported in suspension by a stream.

Suspended solids Different from suspended sediment only in the way that the sample is collected and analyzed.

Synthetic organic chemicals (SOCs) Generally applied to manufactured chemicals that are not as volatile as volatile organic chemicals. Included are herbicides, pesticides, and chemicals widely used in industries.

T

Total head The height above a datum plane of a column of water. In a groundwater system, it is composed of elevation head and pressure head.

Total suspended solids (TSS) Solids present in wastewater.

Transpiration The process by which water passes through living organisms, primarily plants, into the atmosphere.

Trihalomethanes (THMs) A group of compounds formed when natural organic compounds from decaying vegetation and soil (such as humic and fulvic acids) react with chlorine.

Turbidity A measure of the cloudiness of water caused by the presence of suspended matter, which shelters harmful microorganisms and reduces the effectiveness of disinfecting compounds.

U

Unconfined aquifer An aquifer whose upper surface is a water table free to fluctuate under atmospheric pressure.

Unsaturated zone A subsurface zone above the water table in which the pore spaces may contain a combination of air and water.

V

Vehicle of disease transmission Any nonliving object or substance contaminated with pathogens.

Vernal pool A small lake or pond that is filled with water for only a short time during the spring.

W

Wastewater The spent or used water from individual homes, a community, a farm, or an industry that contains dissolved or suspended matter.

Water budget An accounting of the inflow to, outflow from, and storage changes of water in a hydrologic unit.

Water column An imaginary column extending through a water body from its floor to its surface.

Water demand Water requirements for a particular purpose, such as irrigation, power, municipal supply, plant transpiration, or storage.

Water table The top water surface of an unconfined aquifer at atmospheric pressure.

Waterborne disease Water is a potential vehicle of disease transmission, and waterborne disease is possibly one of the most preventable types of communicable illness. The application of basic sanitary principles and technology have virtually eliminated serious outbreaks of waterborne diseases in developed countries. The most prevalent waterborne diseases include typhoid fever, dysentery, cholera, infectious hepatitis, and gastroenteritis.

Water softening A chemical treatment method that uses either chemicals to precipitate or a zeolite to remove those metal ions (typically Ca^{2+}, Mg^{2+}, Fe^{3+}) responsible for hard water.

Watershed The land area that drains into a river, river system, or other body of water.

Wellhead protection The protection of the surface and subsurface areas surrounding a water well or well field supplying a public water system from contamination by human activity.

Y

Yield The mass of material or constituent transported by a river in a specified period of time divided by the drainage area of the river basin.

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