CHAPTER EIGHTEEN

WATER AND HEALTH

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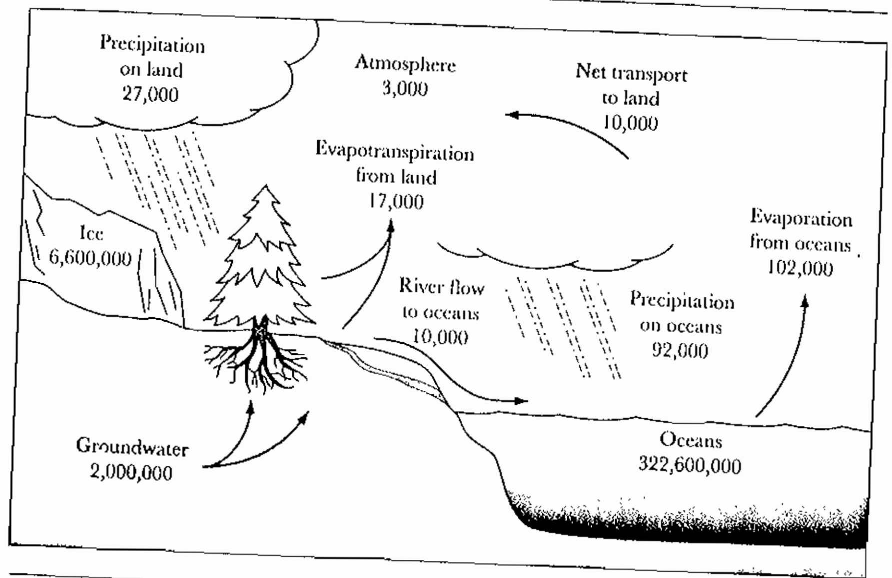
The existence of life, whether human, animal, avian, reptilian, amphibian, plant, or microbe, depends on water. The search for life (as we understand it) on other planets is always predicated on the search for evidence of water. Humans are approximately 60 percent water, and we cannot survive for more than a few days without it. It is therefore not surprising that human culture has been defined by water over the centuries. One has only to look at development along the major river systems of the world to realize how the water environment has dominated, and continues to dominate, human cultures.

The Hydrologic Cycle

Our planet would appear to have a surfeit of water, but most water is unavailable for human use. Over 97 percent of the world's water is salty, found in the oceans and (to a much lower extent) in inland seas and saltwater lakes. What remains is freshwater, but over two-thirds of this is locked in the Antarctic and Arctic ice caps. The freshwater that remains, in rivers and lakes, in the atmosphere, and within the ground, makes up less than 1 percent of the world's water. This is the supply potentially available for drinking, irrigating crops, and other uses.

Water is in continuous motion among these various locations, in a so-called hydrologic cycle that dominates the health of the planet. Without continuous

FIGURE 18.1. THE HYDROLOGIC CYCLE.



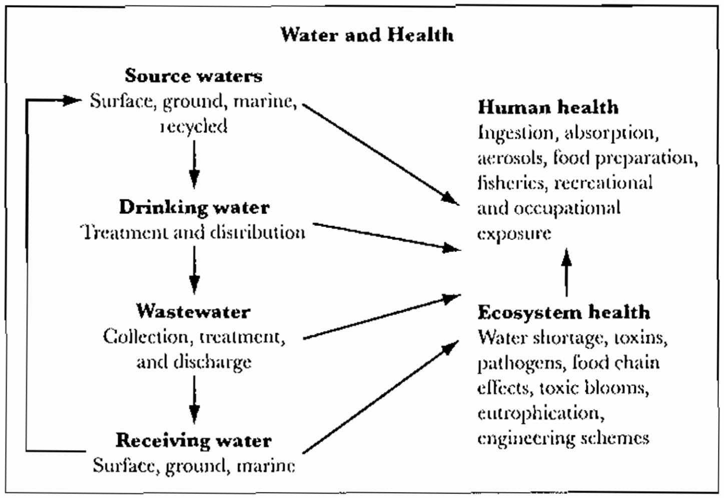
Note: Pools are in cubic miles; fluxes are in cubic miles per year.

Source: Redrawn from Winter, Harvey, Franke, and Alley, 2001. Originally modified from Schlesinger, W. H. *Biogeochemistry-An Analysis of Global Change.* San Diego: Academic Press, 1991, with permission from Elsevier.

evaporation from the oceans, precipitation on land, and runoff back to the oceans, no surface or groundwater recharge can take place, and we would eventually exhaust our available freshwater supplies. Figure 18.1 provides a diagrammatic overview of the hydrologic cycle—the dominant flows, or fluxes, and the critical reservoirs, or pools.

The hydrologic cycle teaches us to view water and health with a holistic perspective. The compartments of the hydrologic cycle are either directly or indirectly connected, and perturbation of one compartment is likely to affect all other compartments and therefore both human and ecological health. These interconnections are diagrammatically illustrated in Figure 18.2. This chapter explores these interconnections. It describes several processes that are crucially important to humans, including water consumption, waste production, waste treatment and discharge, and treatment for reuse, and outlines the multitude of health concerns at each step.

FIGURE 18.2. SCHEMATIC OF THE INTERCONNECTIONS BETWEEN WATER AND HEALTH.



Important Definitions

Available freshwater supplies are often conceptually divided into surface water and groundwater. The U.S. Environmental Protection Agency (EPA, 2004) defines these terms as follows:

- *Surface water:* all water naturally open to the atmosphere (rivers, lakes, reservoirs, ponds, streams, impoundments, seas, estuaries, and so forth)
- *Groundwater:* the supply of freshwater found beneath the earth's surface, usually in aquifers, which supplies wells and springs

Because surface water and groundwater are not independent of each other, an overlap category is also recognized. The EPA defines this as

- *Groundwater under the direct influence of surface water:* any water beneath the surface of the ground with: (1) significant occurrence of insects or other microorganisms, algae, or large-diameter pathogens; (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

These distinctions are important because they directly affect how we view the quality of a water resource and how we manage that resource. Ideally, water used as a drinking-water source (often called *source water*) should be of the highest quality, reducing the cost of water treatment and the risk of contamination. Groundwater has traditionally been considered a high-quality resource, because as rainfall and other surface waters percolate through soil into groundwater, they are cleaned by physical, chemical, and microbiological processes in the soil. However, the traditional confidence in groundwater may not always be well placed, as human activities such as land management practices can influence even relatively deep aquifers. Surface water, or groundwater under the direct influence of surface water (GWUDI), has traditionally been less favored as a source for drinking water. However, groundwater is not always available, and municipalities may have no choice but to implement extensive and costly surface water treatment. At present, just over half of Americans get their drinking water from surface sources.

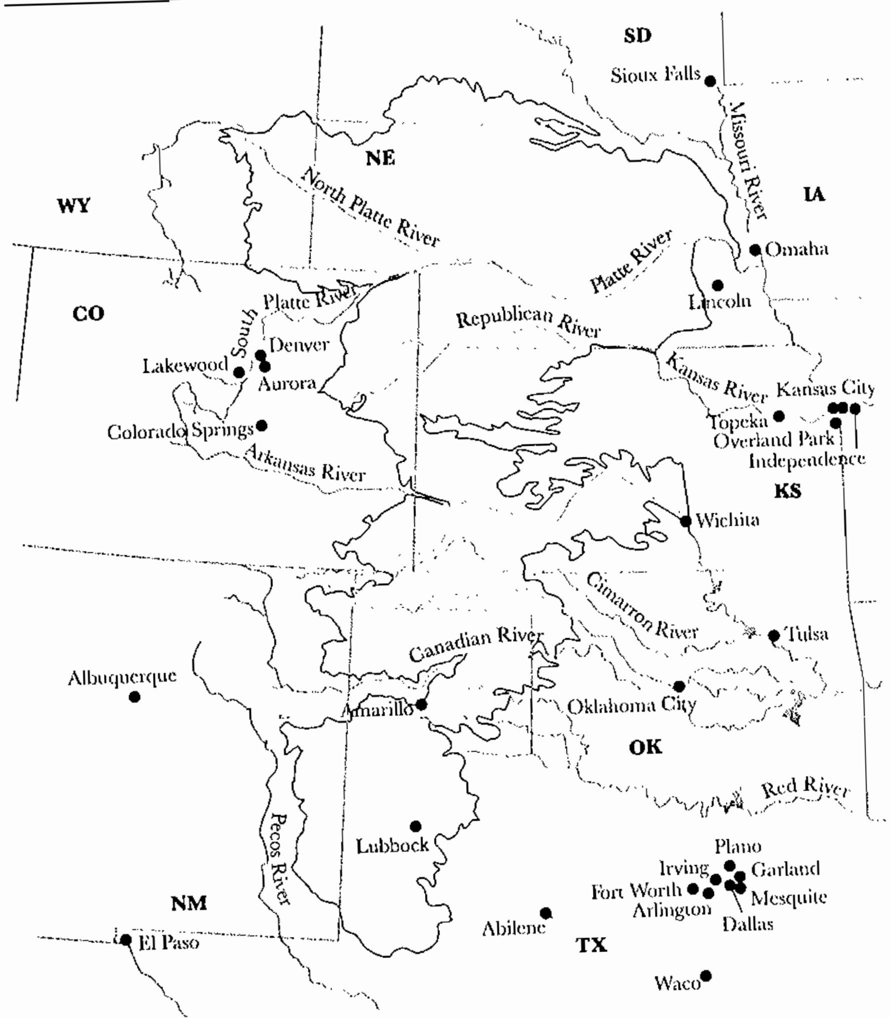
Surface and GWUDI water may be considered suitable for agricultural, industrial, or recreational uses with no or limited treatment. Different criteria are therefore developed and applied to source waters, depending on their ultimate use. Surface waters that are used as drinking-water sources are regulated by far stricter criteria, for example, than are waters used to irrigate crops. A fuller discussion of water regulations appears later in this chapter.

Water Use and Water Scarcity

Water scarcity may be one of the most critical health threats to human society today. In the long term, societies can survive only on renewable resources. When a resource is nonrenewable then it is available only in finite quantities, and when a resource is extracted faster than it can be renewed then eventually supply will not meet demand. Either pattern of use is nonsustainable. The most familiar examples of finite resources are fossil fuels. As explained in Chapter Fifteen, fossil fuel use is nonsustainable in the long term, leading to considerable pressure to develop alternative energy sources. Just as fossil fuels are mined, so is water. Technology has allowed us to extract more and more of the water trapped within the earth's crust. This has allowed human habitation, and agricultural and industrial development, to spread to arid areas of the planet that are poorly suited to sustain human life. Unfortunately, in arid regions aquifer recharge rates are low, and the deep aquifers laid down by countless ice ages are being gradually depleted. (Several books provide informative discussions of water use and water scarcity; see, for example, Gleick, 1993, 1998, 2000, 2002; Clarke, 1993; Postel, 1997.)

Figure 18.3 shows the Ogallala Aquifer, a groundwater resource so well known that it was highlighted in *National Geographic* magazine (Zwingle, 1993). This vast

FIGURE 18.3. THE OGALLALA AQUIFER.



Source: USGS High Plains Regional Ground-Water Quality Study (USGS, 2004).

aquifer underlies 174,000 square miles in parts of eight states from South Dakota to Texas, and provides an estimated 30 percent of all groundwater used for irrigation in the United States (U.S. Geological Survey [USGS], 2004) It was water from the Ogallala that helped convert the central plains of North America from a dust bowl to an agriculturally rich region. However, the Ogallala is a finite resource. It consists of *fossil water,* water sequestered underground for thousands of years, and the current rate of water extraction far exceeds the rate at which it is replenished. For some states, groundwater supplies are expected to be depleted in the next twenty to thirty years. Already, farmers in the region are having to drill much deeper wells or rely on surface water instead, which has lowered farm yield in the region substantially. In addition to water scarcity, water quality in parts of the aquifer may have been compromised by agricultural practices.

Population and Water Scarcity

The adequacy of the water supply reflects a balance among water availability, population, and the ways in which people use water. In many parts of the world, as described in Chapter Ten, population pressure places a severe strain on water resources. According to the U.S.-based Population Action International, by 2025 27 percent of nations will face *water stress* (defined as a water supply at or below 1,700 m^3 per person per year), and an additional 11 percent of nations will face *water scarcity* (defined as a water supply at or below 1,000 m^3 per person per year) (Engelman and others, 2004). These numbers reflect all domestic, industrial, and agricultural water use for a region. They are based on conservative projections of population growth; if population growth is higher than anticipated, then water will be relatively more scarce. Although some countries have enormous supplies of water (Greenland, the world's leader, has more than 10 million m^3 per capita per year), others are arid. At the extreme limit of water availability, the West Bank and the Seychelles have zero per capita water availability and are entirely dependent on other countries for their water supply.

Water use varies not only with population but with level of development and affluence. At one extreme, people in wealthy countries with ample water supplies are relatively profligate users of water. In the United States, for example, where the supply of renewable freshwater is estimated to be 10,800 m^3 per person per year (not including Alaska or Hawaii) (United Nations Educational, Cultural and Scientific Organization [UNESCO], 2003), the estimated annual per capita withdrawal is 1,688 m^3. Of this, 12 percent is used in homes, 46 percent in industry, and 42 percent in agriculture (Pacific Institute, 2003). The 12 percent used in homes represents 555 liters per person per day, of which less than 0.2 percent is required for drinking (based on EPA's estimated daily water consumption of 927 ml per person per day (EPA, 2000). Advanced sanitation (including flush toilets) is the norm in the United States and requires large amounts of domestic water use.

In contrast, Somalia's supply of renewable freshwater is far lower, an estimated 1,538 m^3 per person per year. The per capita withdrawal is also far lower than that in the United States, an estimated 70 m^3 per year, of which 3 percent is used in homes, a negligible amount is used in industry, and 97 percent is used for agriculture. In this case, domestic water use represents 5.75 liters per person per day, of which close to 20 percent is required for consumption. There is little margin of safety in this situation, and a temporary disruption of the water supply, such as a drought, can be devastating.

Agriculture and Water Scarcity

The division of water use in Somalia is typical for many of the less developed countries and reflects the enormous amount of water that is needed to grow food. In fact, on a global scale, agriculture accounts for almost 70 percent of water withdrawal (UNESCO, 2003). Many Web sites list water-related facts, and one much-quoted figure, taken from the Web site of Brita (2005), a major manufacturer of household drinking water filters, is that approximately 6,800 gallons of water are required to grow a day's food for a family of four. Another oft-quoted figure is that 1,000 tons of water are required to produce 1 ton of wheat (Postel, 1999). Nonedible crops such as cotton also require large amounts of water; the decimation of the Aral Sea is attributed to cotton irrigation (Ellis, 1990). As a result, it is not surprising that agricultural uses of water are the greatest global contributors to water scarcity and to depletion of aquifers. Considerable efforts have been made over the past decade to replace conventional irrigation with methods that minimize water wastage, such as drip or other micro-irrigation techniques. (The irrigation "crisis" is described in detail in Postel, 1999.)

Political Implications

The dependence of food production on irrigation links freshwater use with food security and therefore with human nutrition and well-being. Accordingly, the political implications of water scarcity are enormous. Most of the major rivers and aquifers of the world cross international or at least state borders. Any use of water by one nation or state affects all downstream users. Impoundments (dams) are particularly damaging to downstream users, as they dramatically reduce water flow for these communities, particularly during dry seasons. There are numerous examples of national and international crises emerging from shared water resources (as shown in Table 18.1). In the extreme, these crises may erupt into what has been called *resource wars* (Klare, 2001). (More detailed discussions can be found in Chapter Twelve of this volume; Clarke, 1993; Gleick, 1993, 1998.)

TABLE 18.1. HOT SPOTS: PAST AND POTENTIAL FUTURE WATER RESOURCE CONFLICTS.

River Basin	Length (km)	Countries	Source of Conflict
Nile	6,693	Tanzania, Kenya, Zaire, Burundi, Rwanda, Ethiopia, Uganda, Sudan, and Egypt	Irrigation
Tigris/Euphrates	1,840/2,700	Turkey, Syria, Iraq, and Iran	Hydroelectric projects; irrigation
Indus/Beas/Sutlej/Ravi	2,896 (Indus)	India, Pakistan, and Tibet	Diversions; Sikh versus Hindu
Ganges/Brahmaputra	2,414/2,896	India, Bangladesh, Nepal, and Bhutan	Deforestation and siltation; diversions
Jordan	93	Israel, Jordan, Lebanon, and Syria	Diversions (arguably the underlying cause of Arab-Israeli conflicts)
Parana/Paraguay	3,998 (Parana)	Brazil, Paraguay, Bolivia, Argentina, and Uruguay	Dams (hydroelectric)
Rio Grande	3,057	United States and Mexico	Development; irrigation
Colorado	2,336	United States and Mexico	Development; irrigation

Climate Change and Water

Global climate change is discussed in detail in Chapter Eleven. Here, we consider the effect of climate change on water. Warming global temperatures will result in increased evaporation from the oceans, an increase in water vapor in the atmosphere, and increasing precipitation, including more severe weather events (Easterling and others, 2000). There is also a positive feedback loop involved, because more water vapor in the atmosphere will exacerbate the greenhouse effect. Weather changes are expected to be complex, with precipitation increasing in some regions and decreasing in others. The burden of water scarcity may shift. For example, on the one hand, increases in rainfall could benefit arid regions.

On the other hand, mountainous regions that depend primarily on snowpack for their water may experience shortages if warmer temperatures prevent snow accumulation. Although climate models are filled with uncertainty and predictions must be viewed with extreme caution, it appears likely that the hydrologic cycle as we now know it will change in coming decades and that in some regions water scarcity may substantially worsen.

Human Impacts on Aquatic Systems

Not only do water quantity and quality affect human health but human activities affect every aspect of aquatic ecosystems. Hydrodynamics—the way water moves—is dramatically altered by projects such as dams, levies, canals, channelization, concretization, and extraction. In turn, fundamental nutrient cycles are altered in ways that completely change the biology and chemistry of a system. In extreme cases this can lead to eutrophication (when high nutrient loads stimulate blooms of algae in the water, in turn stimulating microbial activity). Oxygen is used up and massive fish kills may result. As shown in Table 18.2,

TABLE 18.2. EXAMPLES OF HEALTH CONSEQUENCES OF ENGINEERING SCHEMES.

Engineering Scheme	Examples	Environmental Consequences	Health Effects
Dams and irrigation projects	Aswan High Dam, Egypt; Sennâr Dam, Sudan; Akosombo Dam, West Africa	Created habitat for snails that carry the schistosome parasite	Dramatic increases in schistosomiasis
Hydroelectric projects	James Bay	Conditions created for methylation of mercury in sediments and subsequent accumulation through the food chain	Levels of mercury in Inuit that exceed WHO health guidelines
Channelization	Mississippi River	Exacerbated extreme Midwest flooding events	Huge economic consequences, loss of property, and loss of livestock; depression
Channelization, intensive draining, diking, and developing	Florida's Kissimmee River, Lake Okeechobee, and the Everglades	Destroyed habitat for wildfowl and fish nurseries; caused lake eutrophication, algal blooms, and fish kills; reduced groundwater recharge, and dramatically changed the Everglades ecosystem	Primarily ecological and economic; long-term effects on human health of changes to Florida's hydrological cycle as yet unknown

changes such as these can directly affect health, completing a cycle of humans to water to humans.

Water contaminants fall into two general categories, chemical and biological. Chemical contaminants, such as arsenic, may occur naturally or may be discharged into water through industrial, agricultural, municipal, and recreational activity. Biological contaminants include bacteria, viruses, and protozoans; these originate from many sources, including human and animal wastes. The next two sections of this chapter present information on these two categories of contaminants.

Chemical Contaminants

A wide variety of chemicals can contaminate water, as shown in Table 18.3. These contaminants may originate from either point sources or nonpoint sources, which are defined as follows (EPA, 2004).

- *Point source:* a stationary location or fixed facility from which pollutants are discharged; any single identifiable source of pollution; for example, a pipe, ditch, ship, ore pit, factory smokestack.
- *Nonpoint sources:* diffuse pollution sources (that is, the pollutants do not have a single point of origin or are not introduced into a receiving stream from a specific outlet; for example, they are pollutants carried off the land by stormwater). Common nonpoint sources are agriculture, forestry, urban, mining, construction, dams, channels, land disposal, saltwater intrusion, and city streets.

Examples of point source chemical releases include discharges of mercury, solvents, or polychlorinated biphenyls (PCBs) from industrial drainpipes, and leakage of MTBE and petrochemicals from corroding underground gasoline tanks. A major example of a nonpoint source is agricultural runoff containing pesticides and nutrients. City streets and parking lots are important nonpoint sources; these sources can result in massive contamination of surface and groundwaters, as the impermeable surfaces accumulate high concentrations of street contaminants such as oils and household wastes that then run off during heavy rainfall. Some contaminants, such as toxic metals and acidity in mine drainage, can arise from both point and nonpoint sources. Other sources of anthropogenic contaminants include deep injection of wastes into groundwater, lead leaching from older drinking-water distribution pipes, and the vast quantities of pharmaceuticals that are released in human sewage and from agriculture and aquaculture.

TABLE 18.3. CLASSES OF CHEMICAL CONTAMINANTS IN WATER.

	Classes	Examples
Petroleum and coal hydrocarbons	Crude oil	Alkanes, heterocyclics, aromatics
	Refined oil	Gasoline, diesel, heating fuels
	Combustion or conversion products	Polycyclic aromatic hydrocarbon (PAHs), synfuels, by-products
Synthetic organics	Halogenated hydrocarbons	Polychlorinated biphenyls (PCBs), chlorofluorocarbons (CFCs), pesticides, solvents
	Plasticizers, phthalic acid esters	Polyvinyl chloride (PVC), DEHP
	Others	Surfactants, organophosphate pesticides, synthetic pyrethrinoids, fuel additives (MBTE)
Metals	Cadmium, mercury, lead, silver, zinc, copper, chromium, nickel, arsenic	
Radionuclides	Transuranics	Plutonium, americium, curium
	Fission products	Cesium-137, strontium-90
	Activation products	Cobalt-60, manganese-54, zinc-65, chromium-51
	Natural	U-Th decay series
Disinfection by-products	Chlorination, chloramination, and ozonation by-products	Chloroform, trichloroacetic acids, chlorinated furanones, bromate
Industrial wastes	Process by-products, from mining, dredging, and other resource extraction processes	Many of the chemicals already named, plus acids, ash, desalination brines, heat (from cooling water), anticorrosion chemicals, cyanide, and so forth
Municipal and agricultural wastes (not including pathogens)	Nutrients, range of household and agricultural chemicals, including those suspected to cause endocrine disruption	Phosphorus, nitrogen, carbon, silicon, antibiotics, disinfectants, pesticides, fluoride, nonylphenol ethoxylates,[a] and so forth

[a]Of recent concern are the nonylphenol ethoxylates, chemicals that have been used extensively—as detergents, emulsifiers, wetting agents and dispersing agents—in a wide range of industrial processes and consumer products. These compounds and their degradation products are thought to have estrogenic properties with profound consequences for aquatic biota (disrupting or preventing reproduction) and may also be a human health concern.

Source: Adapted in part from Capone and Bauer, 1992.

Naturally Occurring Chemical Contaminants

Many naturally occurring chemicals are toxic to humans. In most cases these result from nonpoint sources. Chemicals that naturally occur in the earth's soils and rocks, for example, can readily diffuse into ground or surface waters. As a result, water may be naturally enriched with fluoride, selenium, arsenic, and a variety of other chemicals. Nitrogen contamination of ground and surface waters is often attributed to wastewater discharge or excessive addition of fertilizers. However, leguminous plants, such as soybeans and alfalfa, which have a symbiotic relationship with bacteria that fix atmospheric nitrogen, may also contribute to nitrate enrichment of ground and surface waters (Cox and Kahle, 1999).

Arsenic is an important example of a naturally occurring toxic contaminant of water. Very high levels of arsenic exist in groundwater in Bangladesh and West Bengal. To reduce risks of epidemic cholera and other diarrheal diseases, the United Nations Children's Fund (UNICEF) began a program in the 1970s to install tube wells throughout these regions. The consequent exposure to arsenic in drinking water (described in greater detail in Chapter Thirteen, Box 13.3), is considered one of the greatest environmental disasters in history. However, even lower levels of arsenic contamination, as occur in many parts of the United States, are cause for concern, as there is strong evidence linking these exposures to skin disease and cancer. Stricter regulations have met political barriers due to the fact that arsenic is a naturally occurring compound that is expensive to remove from drinking water. Many medium, small, and very small water systems (defined as serving 3,301 to 10,000, 501 to 3,300, and 25 to 500 people, respectively) use source water contaminated with arsenic, at concentrations that barely met the old standard of 50 μg/l. To meet the new recommended standard of 10 μg/l, many of these systems require technologies far beyond their limited operating budgets (Ford and others, 2005). For some water systems, meeting these standards may result in generation of large volumes of arsenic-contaminated wastes. This in itself could present an environmental health risk, as disposal practices have not yet been fully established or their safety tested.

An increasingly recognized natural source of chemical contaminants is toxins produced primarily by algae and cyanobacteria. Human activity can promote the production of these toxins through nutrient loading and resulting eutrophication. From the perspective of drinking water and recreational use of freshwaters, cyanobacterial blooms are of particular concern.

Cyanobacteria, sometimes imprecisely called *blue-green algae,* are simple photosynthetic organisms closely related to bacteria, found in water bodies throughout the world. Water bodies that are rich in nutrients, such as eutrophic lakes, agricultural ponds, or catch basins, may support proliferation of cyanobacteria. In some cases a body of clear water can become turbid, discolored (green, blue-green, or reddish-brown) and covered with a film, or scum, in just a few days. Several genera of cyanobacteria, including *Microcystis*, *Anabaena*, and *Aphanizomenon*, release a wide range of low molecular weight chemicals that include neurotoxins, hepatotoxins, skin and gastrointestinal irritants, enzyme inhibitors, and compounds that create taste and odor problems, such as geosmin. People who drink or swim in contaminated waters may be at risk, as are livestock and wildlife. Numerous fatalities have been reported (Bartram and Chorus, 1999; Metcalf and Codd, 2004).

In addition to the cyanobacteria, many species of planktonic algae produce toxins that accumulate in shellfish or finfish, resulting in poisonings. These include paralytic shellfish poisoning (PSP, caused by saxitoxins), diarrheic shellfish poisoning (DSP, caused by okadaic acid), amnesic shellfish poisoning (ASP, caused by domoic acid), neurotoxic shellfish poisoning (NSP, caused by brevetoxins), and ciguatera fish poisoning (CFP, caused by ciguatoxin or maitotoxin). A number of these poisonings are life threatening and constitute major public health threats worldwide, with enormous economic implications due to fisheries closures. (Many resources on this topic are available through the Woods Hole Oceanographic Institution, 2005.)

Anthropogenic Chemical Contaminants

Industrialization has left an enormous legacy of contamination. Exploitation of the earth's resources has resulted in ground and surface waters contaminated with heavy metals and hydrocarbons. Uncontrolled industrial discharges, military activities, landfills, leaking underground storage tanks, agricultural activities, and many other human activities have and continue to contaminate ground and surface waters.

Anthropogenic chemicals can be divided into a number of classes, as described in Table 18.3. However, in terms of broad categories, they can be thought of as organic, inorganic, or a combination of the two, as in the case of methylmercury. The environmental fate and transport of a contaminant chemical is a direct function of its chemistry (discussed later in this section). For example, the organic contaminants popularly known as persistent organic pollutants (POPs) are so named because their chemistry dictates that they are degraded at negligible or only very slow rates by naturally occurring microbes, are rapidly partitioned into soils or sediments, and consequently are present in the environment for very long periods of time. PCBs, the classic example of a POP, persist for decades at multiple hazardous waste sites throughout the United States and globally (see the section on environmental reservoirs later in this chapter).

It is sobering to think about the number of chemicals dispersed into the environment. The USGS (2000) estimates that about 1 billion pounds of pesticides are used in the United States every year, with about 80 percent used in agriculture. As part of its National Water Quality Assessment Program (NAWQA), the USGS is conducting the Pesticide National Synthesis Project to obtain an assessment of pesticides in the streams, rivers, and groundwater of the United States. For a wealth of information on pesticide contamination, see USGS, 2000; for discussion of a variety of additional water quality issues in the United States, see NAWQA, 2005.) (An interesting example of this information is a report on the pesticides used on golf courses and detected in groundwater beneath those sites (USGS, 1998), which lists no fewer than thirty-nine herbicides, thirty insecticides, thirty-two fungicides, four nematicides, three adjuvants (chemicals added to pesticide formulations to increase efficiency), and seven growth hormones. Golf courses in New Jersey alone are credited with twenty-eight herbicides, fifteen insecticides, twenty-five fungicides, one nematicide, and seven growth hormones. Very few of these chemicals have been rigorously tested for aquatic toxicity but may be considered POPs that will remain in sediments and soils for many years, decades, or even centuries (see the section on storage later in this chapter).

Transformations

Once contaminants are released into the aquatic environment, they have considerable potential for both chemical and biological transformation to more or less toxic forms, analogous to the human biotransformation described in Chapter Two. As a result, although water may contain parent molecules such as pesticides and herbicides, a range of degradation products may also be present. Remediation, whether chemical or biological, attempts to replicate some of these changes, reducing toxic chemicals to nontoxic degradation products such as CO_2, CH_4, H_2O, or, in the case of metals, insoluble or otherwise nonbioavailable forms. Unfortunately, transformations in the natural environment frequently result in more toxic or increasingly bioavailable forms. For example, in the presence of oxygen (aerobic conditions), many groups of organisms are capable of breaking down trichloroethylene, a commonly used solvent that frequently ends up in groundwater. One end product is vinyl chloride, a known carcinogen that cannot be further degraded under aerobic conditions.

Biological Transformations. For almost every organic contaminant released to the aquatic environment, there appears to be a microbe that can employ the compound as an energy or carbon source, or simply assist in its degradation through the process of cometabolism, where enzymes that evolved for another substrate fortuitously degrade the contaminant with no benefit to the microbe. As with organic contaminants, reduced forms of certain metals can be used as energy sources (electron donors) and oxidized forms can be used as energy sinks (electron acceptors). (Many textbooks discuss microbial metabolism and pollutant interactions, for example, Mitchell, 1992; Madigan, Martinko, and Parker, 2004.)

One other major interaction between microbes and contaminants results from detoxification mechanisms. The methylation of mercury may be one such mechanism, although the specific benefits of this process to the microbe are currently unknown. The case of the James Bay poisonings mentioned in Table 18.2 provides a good example of the process. Impoundments built for hydroelectricity in the James Bay region of Quebec resulted in extensive flooding of forested lands. Organic matter degradation by microbes resulted in consumption of oxygen, anoxic conditions at the sediment water interface, and ideal conditions for growth of anaerobic sulfate-reducing bacteria (SRB). SRB are known to convert inorganic mercury, either naturally occurring in soils or from atmospheric deposition, to methylmercury, which is highly lipid soluble and rapidly accumulates through the food chain. Contaminated fish were then eaten by Inuit communities, resulting in concentrations of mercury in people that exceeded World Health Organization (WHO) guidelines (Calow and Petts, 1992).

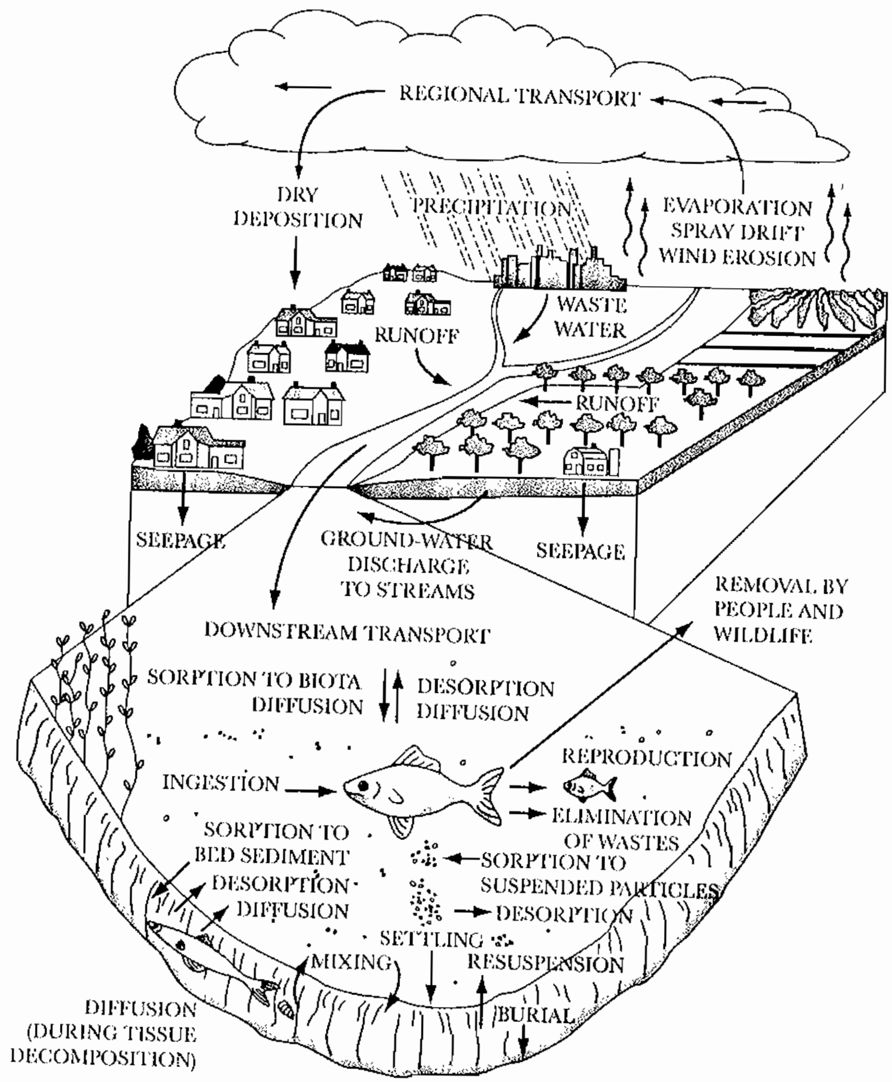
Chemical Transformations. A leading example of chemical transformations is the formation of disinfection by-products (DBPs). When chlorine is added to drinking water as part of the disinfection process, it reacts with naturally occurring organic compounds present in source and distributed waters. The result is potentially toxic chlorinated-by-products. Examples of these compounds include halomethanes such as chloroform, bromoform, dichloromethane, and dibromomethane. Similarly, ozone reacts with natnrally occurring bromine to form toxic bromates. DBPs are discussed in more detail later in this chapter.

Deposition, Storage, and Bioconcentration

For many years it was thought that chemicals discharged into receiving waters would simply be diluted to the point that they could be ignored. In recent years it has become abundantly clear that dilution is no longer sufficient. Chapter Two described how chemicals move through the body in predictable ways, a keystone of toxicology; the same is true for chemicals in ecosystems, including hydrologic cycles, as demonstrated in Figure 18.4.

The fate of a given chemical in receiving waters is a function of both its physical and chemical nature. The degree to which a chemical may partition into sediments or into the biota depends to some degree on its partition coefficient, a measure of its relative affinity for an organic solvent (octanol) and water. This in turn depends to some degree on measures of solubility and hydrophobicity.

FIGURE 18.4. PESTICIDE MOVEMENT IN THE HYDROLOGIC CYCLE, INCLUDING PESTICIDE MOVEMENT TO AND FROM SEDIMENT AND AQUATIC BIOTA WITHIN THE STREAM.



Source: USGS, 2000, as modified from Majewski and Capel, 1995.

In turn, each of these parameters affects the bioavailability and subsequent toxicity of a given chemical.

Bioavailability. An insoluble metal salt such as cadmium, lead, or copper sulfide, or an organic contaminant that is tightly adsorbed to sediment particles, is unlikely to be taken up by an organism. Conversely, other substances are physically and chemically available to be taken up, and they are known as *bioavailable.* This concept requires careful definition. Although contaminants resting in undisturbed sediments may not pose an immediate health threat, their chemical characteristics may predispose them to accumulate in biological tissues. Such organic or organometallic compounds are generally nonpolar (*hydrophobic,* or water fearing) as opposed to polar (*hydrophilic,* or water-loving). They are relatively insoluble in water, but once ingested—for example, by benthic invertebrates that burrow in the sediments—they may accumulate through the food chain, as they are readily soluble in lipids. (Excellent textbooks are available to further an understanding of the complexities of chemical partitioning in sediments, water, and the biota, for example, Schwarzenbach, Gschwend, and Imboden, 1993; Morel and Hering, 1993; Stumm and Morgan, 1996.)

Environmental Reservoirs. Many environments therefore represent potential reservoirs of contaminants. The group of organic compounds that degrade slowly in the environment, known as persistent organic pollutants (POPs), includes many of the synthetic organic chemicals mentioned in Table 18.3. Because they generally have low solubility, they tend to partition to sediments, particulate material, or the biota in aquatic systems, where they have been considered no longer bioavailable. One group of POPs that has received attention over the last two decades has been the polychlorinated biphenyls (PCBs). Originally considered inert, PCBs were used extensively in the electronics industry as dielectric material in capacitors and transformers and as binding or insulating materials for a wide range of applications, including building materials. As a result of past disposal practices, numerous sites now exist in the United States and globally where concentrations of PCBs reach levels in the tens of thousands of parts per million. The Hudson River in New York and New Bedford Harbor in Massachusetts are two of the better-known PCB-contaminated Superfund sites in the United States.

Unfortunately, evidence is now accruing that PCBs cause cancer and other health effects in animals (Agency for Toxic Substances and Disease Registry, 2000) and are therefore potentially of concern to human health. PCBs are broken down at extremely slow rates by sediment bacteria. Anaerobic organisms can initially remove chlorine atoms from highly chlorinated PCBs, but the resulting molecules resist further degradation unless exposed to aerobic conditions where other groups

of bacteria continue the degradation process. Although considerable research has been undertaken to find ways to accelerate biodegradation *in situ,* to date these biological processes are so slow that several decades to centuries may be needed to demonstrate substantial levels of degradation. Short of extensive dredging, sediments remain reservoirs of PCBs and sources of exposure through the food chain for the foreseeable future.

Health Effects

A vast number of potentially toxic chemicals have been discharged into or formed in waterways and can potentially end up in surface water and groundwater. Evidence suggests multiple health effects, ranging from birth defects to cancer (Table 18.4). However, the links between waterborne chemical exposures and

TABLE 18.4. EXAMPLES OF STUDIES LINKING EXPOSURE TO CHEMICALS IN DRINKING WATER WITH INCREASED HEALTH RISK.

Place	Contaminant	Source	Health Effect	Certainty?	Useful Reference
Cape Cod, Massachusetts	Perchloroethylene (PCE)	Leachate from vinyl lining of water pipes	Breast cancer	Small to moderate increased risk	Aschengrau, Rogers, and Ozonoff, 2003
Churchill County, Nevada	Tungsten and arsenic	Unknown	Leukemia	Speculative	CDC, 2003
Woburn, Massachusetts	Solvents including trichloroethylene (TCE)	Chemical manufacturing wastes	Childhood leukemia	Probable, with caution	Costas, Knorr, and Condon, 2002
Bergen, Essex, Morris, and Passaic Counties, New Jersey	TCE and PCE	Not specified	Leukemia and non-Hodgkins lymphoma	Link with exposure suggested	Cohn and others, 1994
Gassim Region, Saudi Arabia	Petroleum oils	Refineries?	Carcinoma of the esophagus	Speculative	Amer, El-Yazigi, Hannan, and Mohamed, 1990
Northwestern Illinois	TCE, PCE, and other solvents	Landfill?	Bladder cancer	Speculative	Mallin, 1990

health outcomes have been difficult to prove conclusively. Epidemiological studies face several challenges: exposures that are relatively low and difficult to measure, exposures to the chemicals of concern through routes other than water, and confounding by competing causes of diseases of interest. These challenges are more fully explained in Chapter Three.

Microbiological Contaminants

After considering the sources of microbiological contaminants and how they may be used to indicate water quality, this section describes some specific environmental pathogens of concern and the transformation, deposition, storage, and bioconcentration of microbiological contaminants in the water supply.

Sources

Since ancient times, people have recognized that human and animal wastes can contaminate water and threaten health. A great many pathogenic organisms can be found in water. Many of these are shown in Table 18.5, together with their infectious dose and the diseases they cause. Like chemical contaminants, biological contaminants can come from point sources such as leaking septic systems or nonpoint sources such as runoff from city streets.

Because most (but not all) biological contaminants result from human or animal wastes, waste treatment practices play a major role in water contamination. Sewage is managed in many ways, from the primitive to the highly technical, as illustrated in Figure 18.5. Human waste can be discharged directly to receiving waters through surface water runoff from open defecation sites, a common occurrence in many developing countries, or processed in ways ranging from a simple shallow pit to a larger community sewage system. These latter systems require large volumes of water for efficient operation, so large amounts of wastewater are generated, requiring subsequent treatment before release to receiving waters. Wastewater treatment and discharge can place a heavy burden on receiving waters in terms of pathogens, nutrients, and toxic chemicals. For some river systems, wastewater makes up the primary flow during dry seasons. Groundwater can also be contaminated with human pathogens from leaking septic systems, contaminated runoff infiltrating wellheads, and seepage from animal feedlots.

An idealized wastewater treatment process is shown in Figure 18.6, which is loosely based on Boston's Deer Island treatment plant (Massachusetts Water

TABLE 18.5. PATHOGENS IN DRINKING WATER: INFECTIOUS DOSES, DISEASES, AND ADDITIONAL COMMENTS.

Pathogen	Infectious Dose[a]	Disease(s)	Comments
Bacteria			
Vibrio cholerae	10^8	Cholera	New toxigenic serogroups with antibiotic resistance
Salmonella spp.	10^{6-7}	Salmonellosis	Antibiotic resistance
Shigella spp.	10^2	Shigellosis	Antibiotic resistance
Toxigenic *E. coli*	10^{2-9}	Diarrheal diseases	Major identified cause of diarrheal disease
For example, *E. coli* O157		Hemolytic-uremic syndrome	Enteropathogenic, enterotoxigenic, and enterohemorrhagic strains identified including multiple antibiotic resistant strains
Campylobacter spp.	10^6	Campylobacteriosis	Antibiotic resistance
Leptospira spp.	3	Leptospirosis	Increases with flooding events
Francisella tularensis	10	Tularemia	Significance in drinking water unknown
Yersinia enterocolitica	10^9	Yersiniosis	Significance in drinking water unknown
Aeromonas spp.	10^8	Skin and respiratory infections	Gastritis?
Helicobacter pylori	?	Gastric ulcers or cancer	Exposure route unknown
Legionella pneumophila	>10	Legionellosis, Pontiac fever	Underestimated cause of pneumonia
Mycobacterium avium	?	Disseminated infections	Increasing in healthy populations
Protozoa			
Giardia lamblia	1–10	Giardiasis	Underdiagnosed
Cryptosporidium parvum	1–30	Cryptosporidiosis	Underdiagnosed, extreme chlorine resistance
Naegleria fowleri	High?	Primary amoebic meningoencephalitis	Disease very rare, yet exposures common
Acanthamoeba spp.	?	Encephalitis and others	Transmission of bacterial pathogens?
Entamoeba histolica	10–100	Dysentery	High rates of infection and associated mortality
Cyclospora cayetanensis	?	Cyclosporidiosis	Most outbreaks associated with contaminated produce
Isospora belli	?		Significance in drinking water unknown
Microsporidia	?	Microsporidiosis	May be widespread
Balantidium coli	25–100		Significance in drinking water unknown
Toxoplasma gondii	?	Toxoplasmosis	Significance in drinking water unknown
Viruses[b]	1–10	Diarrheal disease, meningitis, heart disease, liver disease, and so forth	Incidence probably dramatically underestimated; many viruses may remain to be discovered

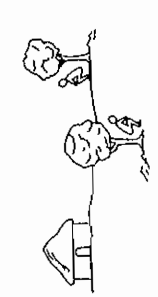
Note: Data compiled from WHO, 1993; Hazen and Toranzos, 1990; Geldreich, 1996.

[a]Infectious dose is the number of infectious agents that produce infection (asymptomatic or symptomatic) in 50 percent of tested volunteers and is therefore not useful for risk estimates for disease.

[b]Viruses include caliciviruses (especially Norovirus), Poliovirus, Coxsachievirus, Echovirus, Reovirus, Adenovirus, Hepatitis A, Hepatitis E, Rotavirus, Astrovirus, Coronavirus, and others to be identified.

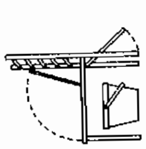
Source: Reproduced from Ford, 2004.

FIGURE 18.5. SANITATION OPTIONS.

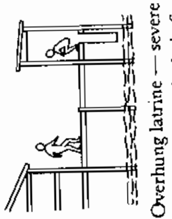


Open defecation — obvious health risks, particularly in built-up areas

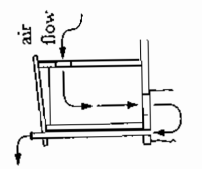
Shallow pit — flies and hookworm problems.



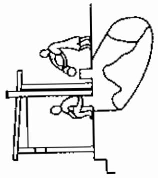
Bucket latrine — odor, flies, excreta disposal (known as "nightsoil").



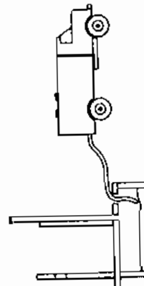
Overhung latrine — severe health risks, particularly for downstream users



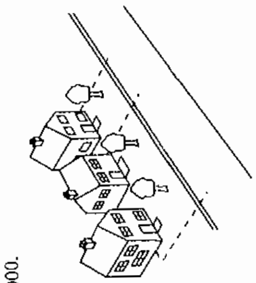
Pit latrine. There are many versions of the pit latrine: simple, borehole, ventilated (shown here), double-pit, pour-flush and off-set pour-flush (both have water traps to prevent flies and odor); each has its own set of advantages and disadvantages, detailed in Franceys, Pickford, and Reed, 1992.



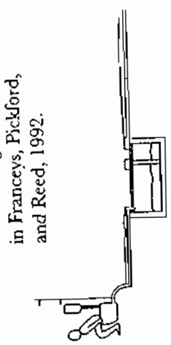
Composting latrine — needs careful operation and separate urine collection. However, composting toilet systems and other similar wastewater management methods — where waste is turned into humus — are increasingly considered the ecological alternative; see Del Porto and Steinfeld, 2000.



Vaults and cesspits — high cost and need for reliable collection service.



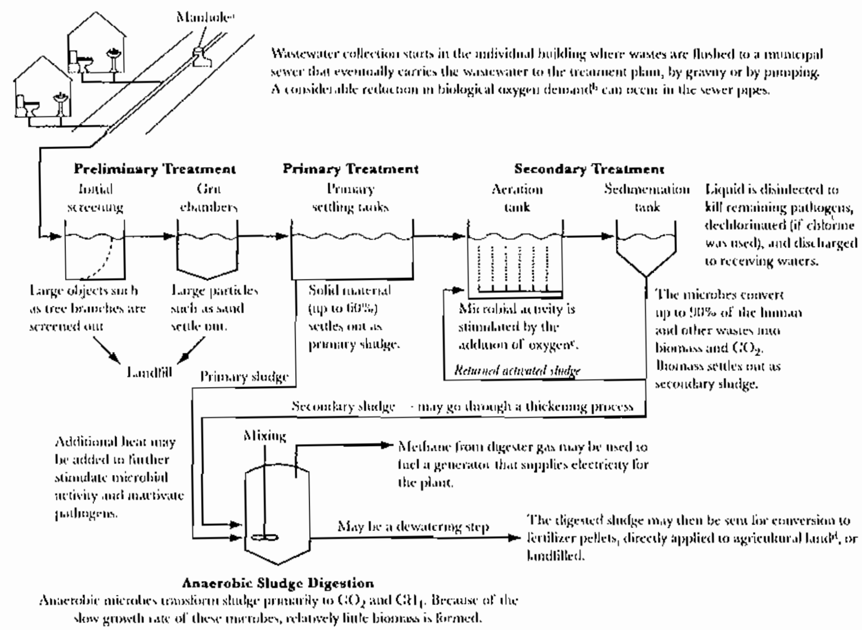
Sewerage — although the solution of choice for most municipalities, the system requires large volumes of water for efficient operation and the collected wastewater needs extensive treatment before discharge to receiving waters.



Septic tank – the septic tank (and its smaller version the Aqua-privy) relies on separation of solids (sludge), liquid, and scum. The liquid and scum flow out to an absorption field, and the sludge requires regular mechanical removal. A major concern is the soil type and siting of the absorption field, particularly in relation to drinking-water wells.

Source: Diagrams reproduced from Franceys and others, 1992. © World Health Organization.

FIGURE 18.6. AN IDEALIZED WASTEWATER TREATMENT SYSTEM, BASED ON BOSTON'S DEER ISLAND SYSTEM.



Note: Most municipal wastewater can be treated using this or a similar treatment train. However, if industrial or other sources of toxic chemicals are present, wastes may need to undergo far more technologically sophisticated and expensive tertiary treatment. Further discussion of wastewater treatment is beyond the scope of this chapter and many excellent texts are available to the reader (for example, Bitton, 1999).

[a]Manholes give access from the street to the main sewer for maintenance. However, there may also be direct connections to street drains in the case of a combined sewer system. This may dramatically increase the volume of wastewater that the treatment plant has to process, often overwhelming the system and allowing untreated wastewater to be released to receiving waters.

[b]*Biological oxygen demand*, or BOD, is a measure of the readily assimilable organic carbon present in wastewater. BOD is defined as the amount of oxygen used by microorganisms in the aerobic degradation of organic wastes over a set time period and temperature (usually five days at 20°C).

[c]Secondary treatment can range from an energy-intensive activated sludge system, where oxygen is added to accelerate microbial activity, to simple aeration ponds, which rely on the action of wind, algae, and macrophytes to facilitate oxygen transfer.

[d]Land application of sewage sludge is facing increasingly stringent regulations due to concerns about pathogens and toxic chemicals in the food chain and about potential contamination of ground and surface waters.

Resources Authority, n.d.). Systems such as this are expensive to build and maintain, and in general only the wealthiest municipalities can afford such extensive systems.

In recent years waterborne disease outbreaks in North America have been linked to exceptionally heavy rainfall and resultant flooding. This is not surprising given the increased emphasis on high-density farming practices and their proximity to water supplies. Two outbreaks are illustrative: the outbreak of cryptosporidiosis in Milwaukee in 1993 and the outbreak of *E. coli* O157 in Walkerton, Ontario, in 2000. (These and other outbreaks are discussed in detail by Hrudey and Hrudey, 2004.)

The Milwaukee outbreak was the largest documented waterborne disease outbreak in the United States. An estimated 400,000 people became ill, and there were more than 50 associated deaths. In this outbreak, water underwent complete treatment (coagulation, sedimentation, rapid sand filtration, and chlorination), disinfection (1.5 mg/L chlorine) was not deficient or interrupted, and standards for coliforms (<1/100 ml) and turbidity (<1 NTU [nephelometric turbidity unit]) were met. Operational lapses were identified, including poor mixing during coagulation and restarting of dirty filters without backwashing. However, the root cause was presumably massive numbers of *C. parvum* oocysts being washed into Milwaukee's source water, Lake Michigan, close to the city's water intakes. A number of sources of contamination were suspected, including runoff from farms, sewage treatment, or other unidentified sources during the heavy rainfalls that preceded the outbreak (Mac Kenzie and others, 1994). Archived stool samples subsequently showed that the *C. parvum* were all the human genotype (type 1), strongly suggesting that human sewage was in fact the source (Sulaiman and others, 1998).

The 2000 outbreak of *E. coli* O157 in Walkerton, Ontario, sickened hundreds of people and caused seven deaths. In this case the indicator organism, *E. coli*, was measured in drinking water, but no action was immediately taken. The root cause was presumably *E. coli* O157 and other pathogens, such as *Campylobacter*, contaminating a shallow well that was sited inappropriately close to an adjacent cattle farm. Retrospective studies established *E. coli* O157:H7 and *Campylobacter* as the primary agents of the outbreak, with strains matched between stool samples, water samples, and manure samples by molecular typing methods (discussed in Hrudey and Hrudey, 2004). Box 18.1 provides a chronology of the outbreak. However, the reader is also referred to the Report of the Walkerton Commission of Inquiry (O'Connor, 2002) for fascinating insights into this tragic event, the lessons learned, and the political ramifications from waterborne disease deaths that few would think could happen in developed countries.

Box 18.1. Chronology of Events During the Walkerton, Ontario, *E. coli* O157 Outbreak in 2000

Preamble. The town of Walkerton, Ontario, was taking part of its source water from a well adjacent to a local farming operation. Problems began around May 2000.

- May 12: Heavy rains sustained for several days are thought to have caused pathogens in cattle manure either to infiltrate the wellhead or to contaminate the aquifer through seepage.
- May 17: Tests of the drinking water indicate the presence of coliforms and *E. coli* in samples taken on May 15. However, the general manager of the Public Utilities Commission fails to notify appropriate health officials.
- May 18: Walkerton residents begin to report symptoms of gastrointestinal illness; two children with bloody diarrhea are hospitalized.
- May 19: Health officials contact the Public Utilities Commission and are assured that the water is safe.
- May 20–21: The number of illnesses continues to rise. The government health officer orders a "boil water" advisory, despite continued assurances from the utility personnel.
- May 22: First person dies.
- May 23: Independent tests show that *E. coli* O157:H7 is present in the drinking water. Hundreds of people complain of symptoms, more than 150 people seek hospital treatment, and a two-year-old girl dies.
- May 24: Two more deaths.
- May 25: Fifth death, and four children listed as critical.
- May 29: Sixth death.
- May 30: Seventh death.
- May 31: Public inquiry ordered.

Outcome. The utility had been falsifying records for some time, and the chlorination system had not been working properly. The utility operator "did not like the taste of chlorine." Class action suits and criminal investigations have followed, but the real outcome of this tragedy is the implementation of far stricter regulations for Ontario's drinking water—and the realization that proper operator training is critical.

Source: Adapted from Ford and others, 2005.

The Indicator Concept

To monitor the microbiological quality of water, measurable indicators are needed. Although many microbial species could be chosen for this purpose (see Table 18.6), the traditional indicator has been the coliform group. The premise has been that the concentration of coliform organisms reflects the overall microbial quality of water.

TABLE 18.6. THE INDICATOR APPROACH.

Indicator	What Does It Indicate	Limitations
Coliforms	Presence of the coliform group of bacteria, many of which are present in human or animal fecal material.	Certain coliforms grow naturally in drinking water biofilms, particularly at warmer temperatures. Not indicative of protozoa or viruses.
E. coli	Presence of *E. coli*; strong indication of fecal contamination.	Inactivated more rapidly than other pathogens. Not indicative of protozoa or viruses.
Coliphage	Indicative of the presence of viruses specific to *E. coli*	May or may not be indicative of viral pathogens. Not indicative of protozoa or bacteria.
Enterococci	May be indicative of presence of animal wastes as well as human waste.	Not indicative of protozoa or viruses.
Clostridium	Spore-forming bacteria; anaerobes; protozoa.	Not indicative of viruses.
Pseudomonos	Survives in drinking water biofilms; may indicate presence of bacterial pathogens that are more persistent than the coliforms.	Not indicative of protozoa or viruses.
Aeromonads	Survives in drinking water biofilms; may indicate presence of bacterial pathogens that are more persistent than the coliforms.	Not indicative of protozoa or viruses.
Human-specific *Bacteroides fragilis* bacteriophage	Indicative of the presence of viruses specific to *B. fragilis*; may be present when coliphage is absent.	May or may not be indicative of viral pathogens. Not indicative of protozoa or bacteria.
Turbidity	May indicate that the water exceeds turbidity regulations. Some studies show increased risk for waterborne disease at high turbidity (pathogens adhere to particles).	Only measures turbidity; cannot be directly correlated to pathogen loading.
Residual chlorine	Measures the disinfectant residual at the tap. Absence of residual chlorine has been shown in some studies to be consistent with waterborne disease.	Only measures residual chlorine; cannot be directly correlated to pathogen loading.

Methods to detect and quantify coliform counts have become increasingly sophisticated. In the early 1900s, growth of bacteria on a nutrient agar plate at ~37°C was thought to be indicative of possible contamination by enteric organisms (reviewed in Payment, Sartory, and Reasoner, 2003). In more recent decades, coliform bacteria were enumerated in selective liquid culture media, using a technique known as the *most probable number* method. The *membrane filtration* technique has now gained in popularity, and currently, *enzyme-specific assays*, which are accurate and can be easily conducted by water utility personnel, have gained favor. (Geldreich, 1996, provides a good discussion of these tests.)

However, the indicator concept with its reliance on total coliform counts has recently been challenged. Once human pathogens have contaminated ground and surface waters, their fate is very much organism specific. In fact, the coliform group is inactivated relatively rapidly, whereas other human pathogens can survive for extended periods. This is particularly true for the pathogenic protozoa that form highly resistant cysts or oocysts and the viruses that appear to survive adsorbed to particulate material. As a result, a reassuringly low coliform count could belie a dangerous level of other organisms. Alternative approaches to monitoring water quality might include measuring *E. coli* rather than total coliforms as the primary indicator of fecal contamination and using additional indicators of viral and protozoan contamination. (The advantages and shortcomings of the indicator approach have been discussed extensively in the literature; useful references are available on the American Academy for Microbiology Web site: Ford and Colwell, 1995; Rose and Grimes, 2001.)

Environmental Pathogens

There is also a wide range of environmental pathogens—organisms that although they may be discharged in human sewage are distinguished by their ability not only to persist in the environment but also to grow and proliferate. Two of the better-known examples of this type of pathogen are *Legionella pneumophila* and the environmental mycobacteria.

As with exposure to chemicals, exposure to waterborne pathogens can occur through multiple transmission routes. Some are obvious, such as ingestion of contaminated water or exposure through recreational use, either through unintended ingestion or through skin abrasions or alternative *portals of entry* (eye, ear, anal, urogenital). Other, perhaps less obvious, routes of exposure include breathing contaminated aerosols from showers, toilet flushing, dish washing, garden hoses, fountains, waterfalls, and cooling towers and from air conditioner, humidifier, and refrigerator drip pans. Many infectious agents are also transmitted through the use of hot tubs and whirlpool spas (see Box 18.2).

Box 18.2. The Hidden Hazards of Hot Tubs

When you next decide to bathe in a hot tub, indoor swimming pool, or even your shower, you will not be alone! Many bacteria find these environments ideal for survival and proliferation. In particular the environmental mycobacteria have been implicated in a number of outbreaks of the pulmonary disease known as *hot tub lung*. *Legionella pneumophila* has caused outbreaks of legionellosis and Pontiac fever and *Pseudomonas aeruginosa* has been implicated in outbreaks of folliculitis. In addition, *lifeguard lung*, a form of hypersensitivity pneumonitis, is associated with frequent exposure to pool aerosols containing endotoxin, a cell wall component of gram-negative bacteria. In fact bacteria thrive in these environments, particularly in piping systems where water remains stagnant for much of the time, and are probably associated with biofilms (discussed under *storage*).

Transformations

Like chemical contaminants, microbial contaminants can be transformed once they are discharged into receiving waters. Often these changes result in less risk to humans. Environmental stress can rapidly inactivate a number of pathogenic organisms, or at least create a viable but nonculturable (Colwell and others, 1985) or *injured* (Singh and McFeters, 1990) state. However, those same stress factors might also increase an organism's virulence. One way in which this could occur is through adaptation to intracellular survival and growth. Recent research suggests that some pathogens can survive, resist chlorine, and even grow within protozoan *hosts*. Examples include species of *Escherichia, Citrobacter, Enterobacter, Klebsiella, Salmonella, Yersinia, Shigella, Legionella,* and *Campylobacter* (King, Shotts, Wooley, and Porter, 1988). More recently, some environmental mycobacteria have been shown to survive in protozoan hosts (reviewed in Pedley and others, 2004). At least in the case of *Legionella* and the mycobacteria, adaptation to the protozoan host may be a mechanism that allows the pathogens to elude the human immune system through intracellular survival and growth in macrophages (reviewed in Samrakandi, Ridenour, Yan, and Cirillo, 2002).

Vibrio cholerae, the organism that causes cholera, presents a special case of an interaction between a pathogen and plankton, one that can be viewed as an environmental transformation. The *Vibrio* associates with plankton, particularly zooplankton such as copepods, a strategy that appears to allow it to multiply and concentrate to infectious doses. Although this may not directly increase virulence, it seems to play a role in initiating the cycle of epidemic cholera transmission (Colwell, 1996).

Large quantities of antibiotics are discharged to receiving waters through wastewater discharge, agriculture, and aquaculture practices. The likely consequence of these discharges is increased antibiotic resistance among naturally occurring microbes, with the potential for transfer of resistance factors to human pathogens (Levy, 1998). This transformation can lead to increasing numbers of pathogens in the environment that resist antibiotic treatment, and therefore represent an increased threat to human health (Levy, 1998; Shea, 2003).

Deposition, Storage, and Bioconcentration

Just as chemicals may accumulate in higher organisms, a number of different pathogens can become concentrated in organisms. The best-known example is filter feeding shellfish, such as oysters and clams. Outbreaks of food poisoning often occur as the result of consumption of shellfish that have concentrated planktonic algae, viruses, bacteria, or even protozoa. Infectious disease outcomes from eating contaminated shellfish, crustacea, and fish that have concentrated fecal wastes include hepatitis A, norovirus, campylobacteriosis, salmonellosis, cryptosporidiosis, and *Vibrio*-related diseases including cholera. In fact any infectious disease agent transmissible by water could potentially be concentrated in aquatic organisms.

What about storage reservoirs for pathogens? Early studies showed that the fecal coliform indicator organisms (Table 18.6) were concentrated 100- to 1,000-fold more in bottom sediments than they were in overlying waters (Van Donsel and Geldreich, 1971). Similarly, *Salmonella* and other pathogens have been shown to survive in sediments for extended periods. Recent research suggests that *Salmonella* may even be transmitted from contaminated sediments via chironomid (midge) larvae (Moore, Martinez, Gay, and Rice, 2003).

Biofilms. An important *storage area* is the biofilm, or slime, that forms on any surface in contact with water but is of particular concern in drinking-water pipes. Biofilms provide protective environments that may allow microbes to survive chemical stressors such as disinfectants in the overlying water and may even allow certain pathogens to proliferate (for example, *Legionella,* the mycobacteria, and others). Biofilms are also known to contribute to pipeline degradation, "dirty water," odor, and blockage (Ford, 1993). They are also nutrient-rich environments that potentially provide ideal conditions for gene transfer (virulence factors, antibiotic resistance factors) between microbes that are in close proximity to each other.

Wildlife and Wildfowl. Another major environmental reservoir for pathogens is wildlife and wildfowl. Many enteric pathogens such as *Salmonella* species are natural inhabitants of the intestinal tracts of both warm- and cold-bloodied animals. Others may be fortuitously carried through the intestinal tracts of wildlife and wildfowl due to their presence in human and animal garbage. Wildfowl have emerged as a particular concern for protected watersheds. However well the perimeter of a surface water is fenced, only the smallest areas can be effectively covered. Scavenger birds such as gulls may be a particular problem, as they are attracted to human garbage. A recent USGS report (Converse, Wolcott, Docherty, and Cole, 2001) reviewed studies that showed that *Campylobacter, Listeria, Salmonella, Escherichia coli, Cryptosporidium, Chlamydia,* Rotavirus, and other potentially pathogenic microbes have been isolated from feces of wildfowl, including gulls, Canada Geese, and ducks.

The Global Burden of Waterborne Disease

The primary source of information on the global burden of disease is the World Health Organization. Each year, WHO publishes the World Health Report (see, for example, WHO, 2003c), with a series of annexes that describe mortality and morbidity (reported as disability-adjusted life years, or DALYs, to express both the severity of disease and years lost through premature death). This information is reported for the preceding year through national registries that are estimated to represent about 30 percent of the global burden of disease. Although waterborne disease is not specifically identified, the category *diarrheal disease* is always included, as are malaria and a number of other tropical diseases related to water. In the case of diarrheal disease, multiple routes of exposure to infectious (and chemical) causes exist, including water, food, and person-to-person transmission. However, it is virtually impossible to distinguish these routes clearly, as the spread of diarrheal disease within a population can be dominated by *secondary transmission.* In other words, an initial infection caused by consumption of contaminated drinking water may then rapidly spread through person-to-person transmission or through food contaminated by the water itself or by the infected individual.

A commonly quoted estimate of the impact of waterborne diseases is between 2 and 3 million deaths in children under the age of five each year (for example, Ford and Colwell, 1995). The official WHO figures for morbidity and mortality from diarrheal diseases for 2002 are approximately 1.8 million deaths and 61.1 million DALYs (WHO, 2003b). This burden is comparable to the mortality and morbidity figures for other leading infectious diseases: 2.8 million deaths and 86.1 million DALYs for HIV/AIDS; 1.6 million deaths and 35.4 million DALYs for tuberculosis; and 1.2 million deaths and 44.7 million DALYs for malaria. When examining the global burden of waterborne disease, several considerations are important:

- WHO figures are based on numbers reported by individual member states and undoubtedly underestimate the burden of diarrheal disease. Questionnaire-based studies to examine community incidence of gastrointestinal disease suggest that officially reported figures may underestimate actual incidence by several hundredfold (reviewed in Ford, 1999).
- *The World Health Report for 1996* suggests that 70 percent of diarrheal episodes are caused by contaminated foods (WHO, 1996). However, water may play a role in this pathway, as contaminated water may have been used in food preparation.
- Diarrheal disease is not the only outcome from waterborne disease (discussed in Ford and Colwell, 1995).
- WHO figures may understate the importance of waterborne diseases. Patients with HIV/AIDs often die of opportunistic infections, including waterborne diseases such as cryptosporidiosis and disseminated infections from environmental mycobacteria. Therefore, some deaths attributed to HIV/AIDS may also be attributable to waterborne diseases.
- Malaria is considered a water-related disease, and anthropogenic changes to the watershed may increase the habitat for mosquitoes that carry the protozoan pathogen.

Vector-Borne Diseases

Some of the most prevalent and deadly infectious diseases in the world are transmitted by vectors that are related to water (see Table 18.7). In fact, water plays a critical role in vector-borne disease transmission. The 2003 WHO mortality and morbidity figures for malaria reflect a slight increase from 2001. Clearly, the global burden of suffering from malaria remains vast. Other major vector-borne diseases whose life cycles are associated with water include those caused by blood, liver, lung, and gastrointestinal flukes, hemorrhagic viruses, hemoflagellate protozoa, blood and tissue nematodes, and tapeworms. Their vectors include mosquitoes, blackflies, crustacea, and fish.

Waterborne diseases may be controlled, and in some cases eliminated, through changes in water sources, water quality, and human behavior, offering enormous prospects for public health advances. The effort to control dracunculiasis is perhaps the best example of a successful eradication program (aside from the program that eradicated smallpox). Dracunculiasis is an extremely debilitating disease caused by ingestion of copepods carrying the guinea worm. The disease causes extraordinary suffering to people in poorer nations who depend on poor-quality water sources. Essentially through hygiene education and water source protection, a disease that previously infected millions of people every year was reduced to about 75,000 cases in 2000, with 73 percent in the Sudan and the remainder in sub-Saharan Africa. (For further information on dracunculiasis and the eradication program, see WHO, 2004.) Box 18.3 illustrates the rapid decline in dracunculiasis cases and the measures that are currently being undertaken to eradicate this disease.

TABLE 18.7. EXAMPLES OF VECTOR-BORNE DISEASES WITH RISK FACTORS ASSOCIATED WITH WATER.

Disease	Pathogen	Vector	Risk Factors	Control Strategies
Malaria	*Plasmodium falciparum, P. vivax, P. malariae,* and *P. ovale* (protozoa)	Anopheles mosquitoes	Standing water (mosquito breeding sites); being outdoors in malaria endemic areas, particularly in the evenings; no prior exposures	Removal of standing water; chemoprophylaxis; bed nets; behavior modification; insecticide sprays
Onchocerciasis (river blindness)	*Onchocerca volvulus* (nematode)	*Simulium* spp. (blackflies)	Flowing streams with vegetation	Avoid endemic areas
Schistosomiasis	*Schistosoma mansoni, S. japonicum,* and *S. haematobium* (trematodes)	Snails	Flooding; damming; creation of irrigation ditches	Destruction of snails or habitat; avoiding contact with water in endemic areas; proper disposal of human waste
Dracunculiasis	*Dracunculus medinensis* (Guinea worm—nematode)	Copepod	Contaminated drinking water	Provision of disinfected drinking water; prevention of source water contamination
West Nile encephalitis	West Nile Virus (flavivirus)	Culex mosquitoes	Standing water; vegetation; discarded tires (hold stagnant water)	Removal of standing water; screens; behavior modification; insecticide sprays
Fish tapeworm	*Diphyllobothrium* spp. (cestoda)	Copepods and fish	Ingestion of undercooked or raw fish	Thorough cooking

Box 18.3. Dracunculiasis Eradication

In the 1980s, millions of people were infected with dracunculiasis (guinea worm disease), and hundreds of millions were considered at risk from contaminated water. The guinea worm's larvae live in copepods in water. When a person drinks the contaminated water, the ingested larvae begin to burrow into surrounding tissues and mate. The males die, but the females may grow to a meter in length and contain millions of embryos. The female eventually migrates to the skin surface and breaks through, causing intense pain and high risk of secondary infection of the ulcerated tissue. Before the female breaks through the skin, approximately one year after initial infection, the victim may be unaware of the infection. He or she typically bathes the infected ulcer in water, and this releases larvae, which subsequently mature in the copepod host to complete the cycle. In 1986 and again in 1991, the World Health Organization established the Dracunculiasis Eradication Program, effectively reducing incidence of the disease by 95 percent (WHO data reported in Spearman, 1998) Since then, progress has been continuing, and each year new countries report the successful elimination of the disease. Today, dracunculiasis remains in the poorest countries, where people lack access to clean water. The Sudan has clearly been one of the major problem areas.

In fact, eradication of the disease is relatively straightforward—stopping the transmission cycle. Since there is no treatment for the disease, programs focus first on identifying infected individuals and preventing them from recontaminating water sources and, second on educating people to filter or boil drinking water (relatively coarse filtration material can remove the copepods) or treating selected water sources to kill the copepods.

Together with UNICEF, CDC, and Global 2000, WHO has adopted the following strategy (WHO, 2004):

- implement effective case containment measures in all endemic villages,
- establish a community-based surveillance system in every known endemic village with monthly reporting of cases, supervision, and integration of surveillance for other major preventable diseases,
- target specific interventions (provision of safe water, health education, community mobilization, filter distribution, and treatment of selected water sources with temephos (Abate®),
- map all endemic villages and maintain global and national dracunculiasis databases for monitoring of the epidemiological situation,
- sustain advocacy for eradication of the disease, and
- certify dracunculiasis eradication country by country world-wide.

Waterborne Diseases

Although a wide range of diseases is caused by waterborne pathogens (Table 18.6), the most common outcome, and the one that most frequently remains undiagnosed, is acute gastrointestinal infection (AGI). AGI can be caused by viruses, bacteria, or protozoa. In addition, symptoms similar to AGI may be caused by chemical contaminants. The etiology of waterborne disease is strongly affected by the sources of the infectious agents. For example, *Shigella* species are primarily human pathogens, and shigellosis outbreaks can usually be associated with contamination from human sewage. *E. coli*, *Campylobacter*, *Salmonella*, and many of the protozoan and viral pathogens are zoonotic. In other words, they are also associated with livestock, wildlife, and wildfowl. Hence fecal contamination of water from any of these sources can result in a waterborne disease outbreak, which is why there is increasing concern about high-density animal husbandry practices, particularly in areas prone to flooding (Wing, Freedman, and Band, 2002).

Viral Diseases. Viruses are increasingly implicated as major causative agents of AGI. In the United States alone, it has been estimated that 80 percent of the 38.6 million annual cases of gastroenteritis are caused by viruses (Mead and others, 1999). Of well over 100 known viruses that can potentially be transmitted in drinking water, the caliciviruses and rotaviruses are most commonly diagnosed. However, types of Poliovirus, Coxsachievirus, Echovirus, Reovirus, Adenovirus, Hepatitis A, Astrovirus, Coronavirus, and Hepatitis E have been implicated in waterborne outbreaks, and there may be many further, as yet uncharacterized, groups of viruses that could cause AGI and other disease manifestations.

Scientific understanding of the role of viruses in waterborne diarrhea has been limited by the difficulties inherent both in their specific diagnosis and in measurement of the agents in drinking water and food. For example, the caliciviruses are now thought to be the major causes of both food and waterborne illness worldwide, but research has been limited by the fact that they cannot be cultured. This fascinating family of viruses first came to light in 1972 after electron microscopists identified small round particles in samples from an outbreak of AGI that had occurred in Norwalk, Ohio, four years earlier, when 50 percent of children and teachers at an elementary school became sick. Analysis of surveillance data between 1995 and 2000 in Europe suggested that this specific group of caliciviruses (one of potentially four different Calicivirus genera), now known as noroviruses, accounts for more than 85 percent of all nonbacterial outbreaks of gastroenteritis (Lopman and others, 2003). In the United States, Mead and others (1999) estimated that noroviruses caused 23 million cases of gastroenteritis each year.

A recent review describes three distinct groups pathogenic to humans that have now been identified using molecular epidemiology techniques (Lopman, Brown, and Koopmans, 2002). This approach amplifies and "fingerprints" genetic material (in this case RNA), so researchers can compare potential sources of infection with clinical samples. Using these techniques it has been shown that

caliciviruses are transmitted through drinking water, shellfish, uncooked foods such as salads and fruits, food handling, environmental exposures (bathing, contaminated surfaces, and so forth), and person to person. In fact, person to person transmission is thought to be the major route of infection, including infection through aerosol formation caused by the *projectile vomiting* characteristic of these infections. Further advances in molecular epidemiology may also show that animals are a source of infection, as they have been shown to be infected by strains of Calicivirus that are quite similar to the three human pathogen groups. The clinical and public health significance of human caliciviruses is considerable, particularly as there appears to be no long-term immunity to these agents in humans.

Bacterial Diseases. Of the bacterial diseases, campylobacteriosis remains the most common form of bacterial dysentery, followed by pathogenic *E. coli*, salmonellosis, and shigellosis. The global incidence of these diseases is difficult to estimate. In the United States, Morris and Levin (1995) estimated that water causes 35,000 case of shigellosis, 59,000 cases of salmonellosis, 150,000 cases of *E. coli* infection, and 320,000 cases of campylobacteriosis each year. These diseases are of course prevalent worldwide, but many other infectious agents that are relatively under control in developed countries remain epidemic in other countries. Cholera (caused by *Vibrio cholerae*) and typhoid (caused by *Salmonella typhi*) are perhaps the best-known examples of waterborne disease that have caused global pandemics in the past. Typhoid tends to emerge in less developed countries in epidemic proportions where sanitation is compromised. This happened in Chile during the 1980s and was attributed, at least in part, to irrigation of vegetables with wastewater, increased rainfall, inadequate water treatment, and a deteriorating economy (Cabello and Springer, 1997).

On a global basis morbidity and mortality from *E. coli* infections are today thought to exceed those of cholera and other identified waterborne disease. The *E. coli* strains that produce enterotoxin (enterotoxigenic *E. coli*, or ETEC), can also be enteropathogenic or enterohemorrhagic, as in the notorius *E. coli* O157-H7 outbreak in Walkerton (Box 18.1). Estimates of morbidity and mortality from cholera are in the tens of thousands per year. In contrast, ETEC are estimated to cause approximatly 400 million diarreal episodes, with 700,000 deaths among children less than five years old each year (reported in Chakraborty and others, 2001).

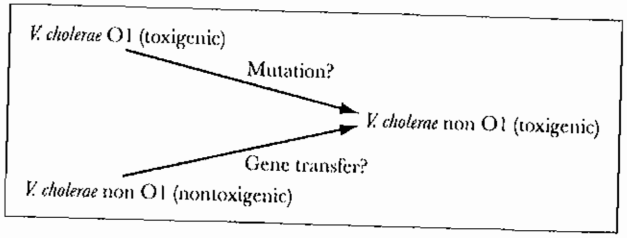
Many opportunistic pathogens can also be transmitted through water. These include species of *Aeromonas*, *Pseudomonas*, *Klebsiella*, and others. It is extremely difficult to estimate the contributions of these agents to morbidity and mortality through consumption of drinking water. Certainly they are a major cause of hospital-acquired infections with high associated mortality risks. Other opportunistic pathogens of interest include *Legionella*, the nontuberculous mycobacteria, and

Helicobacter pylori. Legionella and the nontuberculous mycobacteria occupy a unique niche in their ability to proliferate in hot-water systems, their environmental ubiquity, and their resistance to disinfection. In the case of *Legionella*, the global burden of disease is thought to exceed reported numbers by a wide margin. In the United States it has been estimated that *Legionella* causes at least 13,000 cases of bacterial pneumonia per year (Breiman and Butler, 1998). Researchers are divided on whether water is a significant route for dissemination of *Helicobacter pylori*.

Cholera remains both epidemic and pandemic (affecting multiple countries) due in part to its ability to survive and multiply in the environment associated with plankton and other aquatic organisms (Colwell, 1996). There have now been seven pandemics of cholera since 1817, the most recent of which reached South America in 1991 and had reportedly caused more than a million cases and 10,000 deaths by 1994 (Pan American Health Organization, 1995). There are several possible theories to account for cholera's arrival in South America, including transport in a ship's bilge water (associated with plankton), transport in infected individuals, or transport in imported foods. Alternatively, it could have been endemic, surviving in the environment and only emerging with compromised sanitation after the continent had been free of epidemic cholera for more than 100 years. The truth may never be known. Cholera may emerge when sanitation practices break down, but blooms of aquatic organisms have also been associated with cholera outbreaks in Bangladesh (Colwell and Huq, 1994). The ecological linkages are fascinating, and the reader is encouraged to examine the growing literature on this topic.

Cholera is of particular interest because there is evidence that it is beginning to change. The causative agent of the past seven pandemics has been *V. cholerae*, serogroup O1. In the early 1990s, *V. cholerae*, serogroup O139, emerged in India in epidemic form, the first time that a non-O1 serogroup of *V. cholerae* was shown to cause epidemic cholera. There is now molecular evidence that O139 strains were derived from O1 strains through genetic modification (Faruque, Albert, and Mekalanos, 1998). It is important to learn more about the conditions that resulted in emergence of the toxigenic O139 serogroups and that could therefore result in many more, perhaps environmentally hardier, serogroups of this pathogen. The emergence of epidemic strains could occur through mutation of existing strains or through gene transfer. This is diagramatically represented in Figure 18.7. Although the example is *V. cholerae*, the principle illustrated could apply equally to other pathogens, such as the toxigenic *E. coli*. In the case of gene transfer, virulence factors could also be transferred between species. Both mutation and gene transfer would appear possible within the drinking-water distribution system, where organisms are likely to be exposed to a variety of stressors such as chlorine and metal ions (Ford, 1993).

FIGURE 18.7. EMERGENCE OF NEW EPIDEMIC SEROGROUPS OF *VIBRIO CHOLERAE*.



Source: Reproduced from Ford, 2005.

Protozoal Diseases. Protozoa receive considerable media attention due to the size of recent outbreaks, which are partially due to low infectious doses and high resistance to water treatment. *Cryptosporidium parvum* has attracted most attention, with *C. parvum* replacing *Giardia lamblia* as the most common cause of waterborne disease outbreaks in the U.K., and the second most common cause in the United States. In the case of *Cryptosporidium*, its global distribution is far broader than reported, due in part to misdiagnosis. For example, in Russia where monitoring for the pathogen has been introduced only in the last few years, recent seroprevalence studies (studies that examine the presence of antibodies to a specific pathogen in blood samples) suggest that almost 90 percent of the population sampled had been exposed to *Cryptosporidium* infection (Egorov and others, 2004). Studies by the same authors found *Cryptosporidium* oocysts in most source waters tested and in stool samples of approximately 7 percent of people with diarrhea (Egorov and others, 2002).

Additional protozoa of current interest include *Cyclospora* and *Toxoplasma*, although a waterborne ronte of transmission is far from proven. A third group of protozoans, the microsporidia, are smaller than other protozoans and are increasingly recognized as causative agents of both human and animal diseases. They are also more likely to penetrate filtration systems than the larger protozoa are, so it is reasonable to suspect a waterborne route of exposure. (A number of publications provide useful in-depth reviews of the protozoan pathogens; see, for example, Marshall, Naumovitz, Ortega, and Sterling, 1997; Hunter, 1997.)

Fungal Diseases. Recent studies have suggested that fungal species, including *Aspergillus, Cladosporium, Epicoccum, Penicillium*, and *Trichoderma*, are frequently isolated from treated drinking water (Arvanitidou, Kanellou, Constantinides, and Katsouyannopoulos, 1999). *Candida* yeasts are also occasionally isolated from drinking water and apparently correlate with the indicator organisms, total and fecal coliforms. A number of fungi and yeasts isolated from drinking water are potential pathogens, or at least can produce toxic metabolites and readily spoil foods.

Viroids and Prions. To date there is no direct evidence of transmission of viroids through water. Viroids, single stranded RNA, are thought to cause only plant diseases. Like similar infectious agents known as satellite RNAs, which are dependent on a helper virus for replication, these agents are unlikely to pose a serious threat to human health through drinking water. Of course the absence of any information linking these agents to human disease does not mean that in future linkages will not emerge. For example, the Hepatitis Delta agent is essentially a viroid encapsulated in a hepatitis B coat.

In contrast, prions, infectious proteinaceous material, have risen to prominence following the devastating economic threat and perceived human health threat from the bovine spongiform encephalopathy (BSE) outbreak in the U.K. (The BSE Inquiry, 2000). Although prions have not been isolated from drinking waters, it is reasonable to consider the risks of contamination from, for example, rendering wastes, abattoirs, and landfills.

Safe Drinking Water

Ensuring the safety of drinking water extends from the source to the faucet: protection of water sources from contamination, water treatment to remove contaminants, and protection of water from recontamination during distribution.

Source Protection

Probably the most important consideration for protection of human health in relation to potable water supplies is provision of high-quality source water. Watershed protection is critical to this process but often comes into direct conflict with development and with recreational uses of watersheds. In many metropolitan areas development has dramatically outstripped the availability of high-quality source water. Inevitably, many municipalities are dependent today on surface waters that may receive wastewaters, both treated and untreated. Protection of source waters involves maintaining generous buffers, limiting access for recreational purposes, and preventing agricultural and industrial uses. Many would argue that all wildlife and wildfowl should be prevented from accessing source water, however impractical this may be. New York City has gone to extraordinary lengths to protect upstate source water, as described in Box 18.4. This approach turned out to be more cost effective than treating water arriving from contaminated sources.

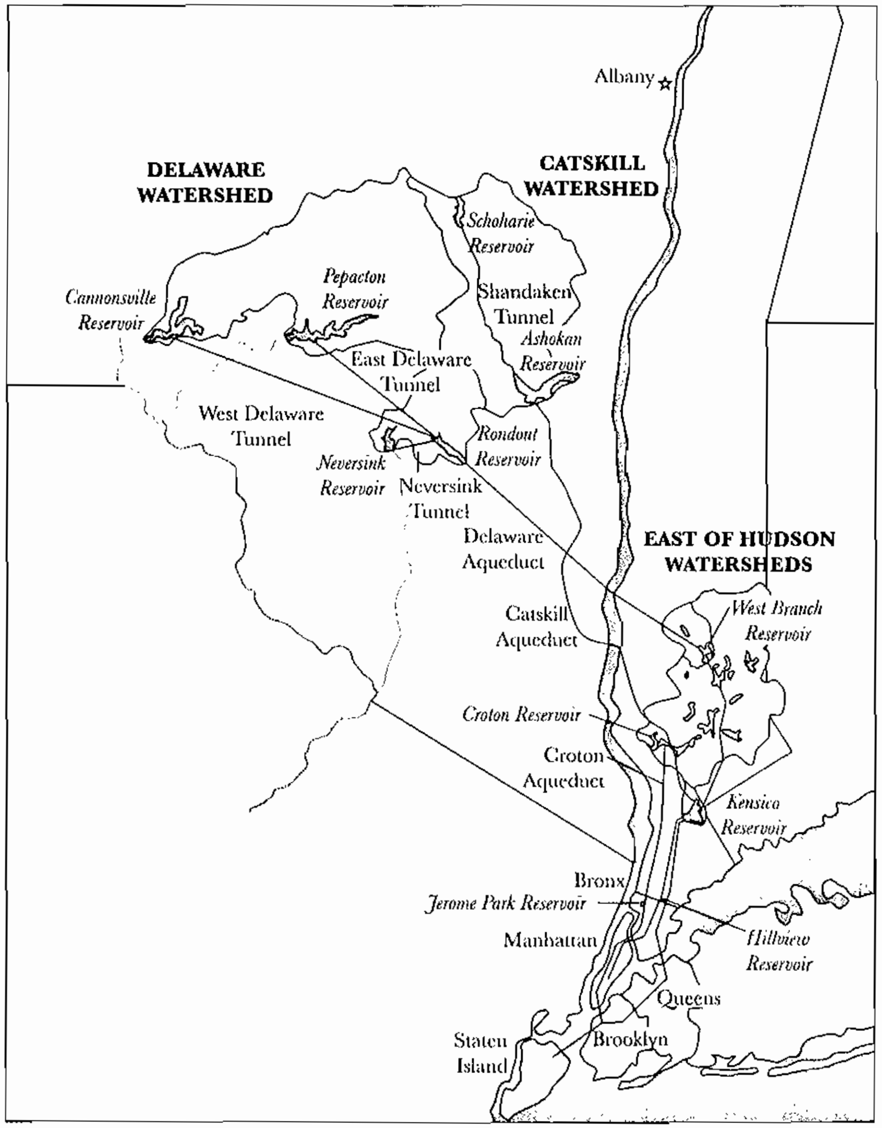
Box 18.4. Protecting Source Water for New York City

Early settlers in what is now New York obtained water from shallow wells. The chronology of subsequent water source development for New York City, adapted from the history of the New York City Water System (New York City Department of Environmental Protection, 2002), is presented in the following list:

1677	The first public well is dug.
1776	A local reservoir is constructed to serve a population of approximately 22,000. Water is distributed through hollow logs.
Early 1800s	Local wells and reservoirs become polluted and the supply is insufficient. The decision is made to extract water from the Croton River through construction of a reservoir and aqueduct (see Figure 18.8).
1842	The "old Croton Reservoir" and the "old Croton Aqueduct" are put in service. Water is conveyed to storage reservoirs in the city prior to distribution, primarily through cast-iron pipes.
1890	A second aqueduct (the "new Croton Aqueduct") is put in service to convey more water from the Croton watershed.
1905	The Board of Water Supply is created and the decision is taken to develop the Catskill watershed.
1915	The Ashokan Reservoir and Catskill Aqueduct are completed.
1928	Development of the Catskill system is completed, including the Schoharie Reservoir and the Shandaken Tunnel.
1927	Plans are submitted to develop the Rondout watershed and Delaware River tributaries within the State of New York.
1937	In spite of legal action brought by the State of New Jersey, construction of the "Delaware system" is begun.
1944	Completion of the Delaware Aqueduct; 1950, completion of the Rondout Reservoir; 1954, completion of the Neversink Reservoir; 1955, completion of the Pepacton Reservoir; 1964, completion of the Cannonsville Reservoir.

New York City's water supply is specifically designed so that reservoirs have interconnections that allow flexibility and virtually ensure that effects of localized droughts are minimized. The system delivers water to the city primarily by gravity and is therefore relatively economical. However, development of these watersheds is not without political implications. The Delaware River basin includes parts of Delaware, New Jersey, New York, and Pennsylvania. Each state relies in part on the basin for water for drinking or industrial uses. However, as the upstream user,

FIGURE 18.8. NEW YORK CITY'S WATER SUPPLY SYSTEM.



Source: The Catskill Center for Conservation and Development, n.d.

New York's development of this water supply can potentially affect the three downstream users. The Croton, Catskill, and Delaware watersheds include prime recreational and agricultural lands. In addition, the many upstream communities that have developed in these watersheds resent the fact that they cannot fully use these resources that must be protected to serve a population some 100 miles downstream.

For New York, as for other major municipalities in the United States without filtration (including Boston, Portland, and Seattle), the rules changed in 1989. As part of the Safe Drinking Water Act, in this year the EPA promulgated the Surface Water Treatment Rule (SWTR). The SWTR requires filtration of all public water supply systems supplied by unfiltered surface water unless a series of criteria, referred to as the *filtration avoidance criteria*, are met. New York City has published these criteria on its Web site (New York City Department of Environmental Protection, 1997):

- Objective Water Quality Criteria—the water supply must meet certain levels for specified constituents including coliforms, turbidity and disinfection by-products.
- Operational Criteria—a system must demonstrate compliance with certain disinfection requirements for inactivation of *Giardia* and viruses; maintain a minimum chlorine residual entering and throughout the distribution system; provide uninterrupted disinfection with redundancy; and undergo an annual on-site inspection by the primacy agency to review the condition of disinfection equipment.
- Watershed Control Criteria—a system must establish and maintain an effective watershed control program to minimize the potential for contamination of source waters by *Giardia* and viruses.

The City of New York faces billions of dollars in costs to implement filtration of its drinking water and hence has gone to exceptional lengths to prove that it can meet these criteria. In addition to programs to purchase land in the watersheds, the New York City Department of Environmental Protection published *Final Rules and Regulations for the Protection from Contamination, Degradation and Pollution of the New York City Water Supply and Its Sources* (1997). This 122-page document provides a regulatory framework for the following potential watershed contaminants: "hazardous substances and hazardous wastes, radioactive materials, petroleum products, human excreta, wastewater treatment plants, sewerage systems, service connections and discharges to sewerage systems, subsurface sewerage treatment systems, storm water pollution prevention plans and impervious surfaces, miscellaneous point sources, solid waste, agricultural activities, pesticides, fertilizers and snow disposal and storage and use of winter highway maintenance materials" (New York City Department of Environmental Protection, 1997).

Water Treatment

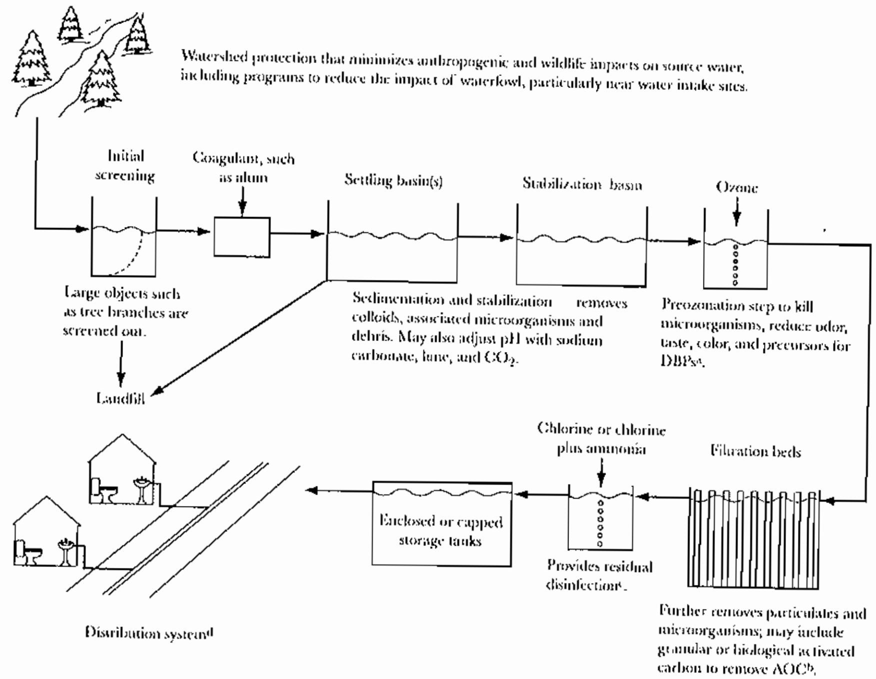
Given that many source waters are of poor quality, and that even high-quality source water can become contaminated, some level of water treatment is considered essential. Arguably, the water treatment train begins with conveyance of water from the source to the plant. Prevention of contamination during conveyance, which in certain cases could be hundreds of miles of pipeline, aqueduct, or even open ditches, is clearly important.

Water treatment consists of several sequential steps (see Figure 18.9). Water entering the treatment plant may undergo coarse filtration to remove vegetation, trash, dead animals, and other large solids. Chemicals may be added for specific purposes; for example, potassium permanganate may be added to oxidize soluble iron and manganese, making them easier to remove. (These metals, when present, discolor water and stain clothing and plumbing fixtures.) The next step is coagulation and precipitation. In this step a chemical such as aluminum sulfate is added, together with lime and sodium bicarbonate, which causes suspended solids, bacteria, and other particles to clump together into *floc*. The floc is then allowed to settle out, removing these materials from the water. Filtration comes next, although in some plants a disinfecting step, such as ozonation, is added to reduce microbial counts and prevent excessive microbial growth on filter materials. Filtration methods range from simple, time-honored techniques such as slow sand filtration to sophisticated technologies such as nanofiltration, depending on the resources available and the size of the population served.

The final step is postfiltration disinfection. Since the early twentieth century, chlorination has been the most widely used form of disinfection. Chlorine and chlorine compounds are thought to act as disinfectants by denaturing enzymes. Chlorine has the advantage of forming a residual in water as it flows from the treatment plant through the pipes of the distribution system to faucets. This helps prevent regrowth of microorganisms in the distribution system (although biofilms impede this goal). More recently, with concerns about the potential toxicity of chlorination by-products, alternative forms of disinfection such as ozonation and pulsed UV have been gaining popularity. Table 18.8 compares alternative forms of disinfection with chlorination.

Disinfection Resistance. One reason for exploring alternatives to chlorination is the growing realization that a number of microbes are apparently capable of surviving at the "safe" chlorination levels typically maintained in drinking water. Mechanisms of survival vary from a relatively resistant cell wall to intracellular survival. One of the most resistant microorganisms is the protozoan *Cryptosporidium parvum*, mentioned earlier. *C. parvum* forms extremely environmentally resistant oocysts that allow the organism to resist chlorine concentrations at levels that far

FIGURE 18.9. A MULTIBARRIER APPROACH TO MAXIMIZE THE MICROBIOLOGICAL QUALITY OF WATER.



Note: This presumes a treatment system that has sufficient capacity to maintain adequate pressure throughout the distribution system for twenty-four hours per day and that minimizes opportunities for microbial colonization of the pipelines.

[a]Disinfection by-products are formed by ozonation of source waters, including aldehydes and brominated by-products (discussed in Boorman and others, 1999). UV disinfection, used extensively in wastewater treatment, is rapidly gaining acceptance as an alternative to ozonation.

[b]AOC = assimilable organic carbon—carbon that can be readily used by microorganisms and therefore stimulates their growth.

[c]Residual disinfection requires a chemical that will not be rapidly broken down in the distribution system so that it retains some disinfecting activity at point of use (the tap). To date the only practical chemicals appear to be chlorine or chloramines. Chloramination may be preferable to using chlorine, as it is believed that chloramines penetrate biofilms more effectively than chlorine alone. They also reduce DBP formation and are more effective at a high pH (a high pH is often necessary for corrosion control). Where chloramination is used, intermittent chlorination and system flushing is recommended, as chlorine is the more powerful oxidizing agent.

[d]A rigorous program is necessary to upgrade distribution system networks and to prevent interconnections through leakage, backflushing, improper hydrant use, and so forth.

TABLE 18.8. APPROACHES TO DISINFECTION.

Disinfectant	Benefits	Concerns	Cost
Chlorine	Retains a residual; strong disinfectant	Taste and odor; toxicity of by-products; some microbes are resistant; not effective at high pH	Moderate
Chloramination	Retains a residual; used for a wider range of pHs; may penetrate biofilms more effectively than free chlorine	Weaker disinfectant; some by-products formed but less than with free chlorine	Moderate
Chlorine dioxide	Powerful disinfectant; no by-products formed	Toxic; cannot be stored; chemically unstable; no residual	Expensive
Ozone	Powerful disinfectant; can be effective against chlorine-resistant microbes	Must be generated on site; can increase assimilable organic carbon; forms bromates	Expensive, but can be economical with a large operation
UV (pulsed)	Short contact time; no toxic by-products; not influenced by pH or temperature	No residual; not effective with high-turbidity water	Increasingly competitive and gaining in popularity

exceed those considered safe for drinking water treatment. Ozonation is thought to be marginally more effective against *C. parvum*, but does tend to be more expensive and does not provide a residual in the distribution system. There appears to be no alternative to chlorination for maintaining a residual, although addition of ammonia with chlorine to form chloramines is an alternative, particularly if a high pH is maintained as part of a corrosion control strategy. Disinfection resistant strategies can be summarized as follows (Ford, 1999):

- Cyst formation (protozoans); spore formation (for example, *Bacillus* sp.)
- Resistant cell wall (for example, mycobacteria)
- Viable but nonculturable (many bacterial species); injured (for example, indicator species); dwarf forms (for example, *Vibrio* sp.)
- Biofilm associated (for example, *Legionella pneumophila, Pseudomonas aeruginosa*, and many others); particle associated (for example, viruses)
- Intracellular survival (for example *Legionella pneumophila, Mycobacterium avium*, and so forth)

Disinfection By-Product Toxicity. Given the necessity for residual disinfection in distributed water, some chlorine (or chloramines) must be added posttreatment. However, chlorine compounds react with naturally occurring organic matter to form *disinfection by-products* (DBPs). The best-recognized DBPs are trihalomethanes such as chloroform and trichloroacetic acid. However, the range of disinfection by-products is enormous given the range of chemical precursors that can occur in source water. There has been some recent focus on a chlorinated furanone, 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone, known as mutagen X. A laboratory in Finland has estimated that this compound may be greater than 100-fold more mutagenic than chloroform. However, it is present at much lower concentrations than chloroform (Boorman and others, 1999).

There is accumulating evidence that many of these chlorinated organic compounds are carcinogenic. Much of this evidence comes from animal experiments using high-dose exposures. Human exposures through drinking water are typically orders of magnitude lower, and the extent of risk to humans has been difficult to quantify. Moreover, although toxicological data are available for the trihalomethanes and haloacetates, little information is available on other DBPs. Hence, there is great uncertainty about the overall risk of DBPs. One estimate is that DBPs are responsible for 4,200 cases of bladder cancer and 6,500 cases of rectal cancer in the United States each year (Morris and others, 1992), and DBPs have been estimated to cause approximately three additional cancer deaths per 10,000 population in Taiwan (Yang, Chiu, Cheng, and Tsai, 1998).

The risk levels associated with DBPs are of concern, but they are substantially lower than the risks associated with contaminated water, especially in developing nations. In Africa, infant mortality rates from inadequate and unsafe water are between 2 and 5 percent annually (Taylor, 1993). In Latin America, in 1990, several million cases of diarrheal disease were reported, with an estimated 300,000 deaths (de Macedo, 1993). And in the United States, 5,000 deaths are attributed to foodborne illness each year (Mead and others, 1999), of which some proportion is very likely due to preparation of food with contaminated water.

In many settings, then, the risk of microbiological contamination of water eclipses the risk of DBPs. Many water experts conclude that the microbiological quality of drinking water should never be compromised for ill-defined health risks from DBPs. However, once tap water is confirmed to be free of infectious doses of pathogens, it is reasonable to explore ways to reduce the potential toxicity from DBPs. In the United States and other developed countries, this has involved examination of alternative forms of disinfection (Clark and Boutin, 2001). However, for many countries, economic reality makes these technologies and their continued maintenance an unrealistic solution and chlorine remains the most practical effective way to reduce waterborne disease.

Water Distribution

Water distribution is a critical step, and its failure has been implicated in many cases of drinking water contamination and waterborne disease outbreaks. Water, generally containing a disinfectant residual, may be distributed through hundreds of miles of pipeline throughout a major city. In addition to the major distribution lines, the water also flows through building pipelines. All these pipes are potential sites for cross-contamination through a variety of processes. Metal pipes are susceptible to corrosion and through time can develop holes that may cause external sources of water to enter the pipes during periods of low pressure. This happens, for example, when hydrants are extensively used during firefighting. Low pressure in the drinking water system can also cause back siphonage from pipes or tubing left hanging in sinks or other water or waste storage. This is a particular issue in high-rise buildings, where distribution system pressure may be insufficient to maintain supply to top floors throughout a twenty-four-hour period. Where this is the case, there is a tendency for residents to fill bathtubs and other vessels to provide a reserve. In the absence of external contamination, regrowth of microorganisms in distribution lines is a very real problem. This is particularly true at dead end sites such as fire hydrants. Water remains essentially stagnant at these sites, and any residual chlorine in the system is rapidly combined with organic matter, allowing microbes to grow and proliferate (Ford, 1993).

Point-of-Use Treatment and Bottled Water

An alternative to direct consumption of tap water that consumers increasingly consider is a point-of-use treatment device or bottled water for their potable water supply. These are certainly viable options, but it is necessary to maintain a point-of-use device properly to avoid exacerbating water quality problems by, in effect, providing a "biofilm reactor" that encourages microbial growth. Bottled water places the consumer at the mercy of the manufacturer, as bottled water is not currently as rigorously regulated as municipal water. In addition, there is a compelling argument that if the money people are willing to pay for point-of-use filters and bottled water were invested in municipal treatment and distribution, many current health risks (real and perceived) could be mitigated.

Regulatory Framework

Water quality monitoring regulations are well developed for a vast suite of chemicals, driven primarily by the increasingly sensitive technologies that can be used for measuring trace levels of contaminants. Unfortunately, the same is not true for microbial contaminants. The indicator approach (Table 18.6) remains the primary method for assessing microbiological quality of drinking water, despite the fact that many pathogens survive for extended periods in drinking water in the absence of these indicators. Indeed, a number of environmental pathogens may be present in drinking water in the complete absence of any contamination source.

The Safe Drinking Water Act

In the Safe Drinking Water Act (SDWA) (EPA, 2005), passed in 1974 and amended in 1986 and 1996, the U.S. Congress mandated the Environmental Protection Agency to regulate contaminants in drinking water that might pose a risk to human health. This complex piece of legislation has a number of important provisions.

A central strategy of the SDWA is to set permissible levels of contaminants in drinking water provided by public drinking-water utilities. EPA establishes two sets of benchmarks, one based on ideal health goals and the other based on feasibility. In the first set, known as Maximum Contaminant Level Goals (MCLGs), a goal is defined as the "level of a contaminant in drinking water below which there is no known or expected risk to health" after drinking two liters of water each day for seventy years. These levels are set to include a margin of safety. For many contaminants, such as carcinogens, lead, and some pathogens, MCLGs are set at zero. MCLGs are public health goals, not enforceable standards. In contrast, Maximum Contaminant Levels (MCLs) are legal limits. They are set as close to MCLGs as possible, taking into account both technological feasibility and cost.

The National Primary Drinking Water Regulations (NPDWR) promulgated by the EPA are based on these benchmarks. These regulations now extend to fifty-three organic compounds, sixteen inorganic compounds, four classes of radionuclides, four types of disinfection by-products, and three disinfectants. In terms of microbial contaminants, *Cryptosporidium*, *Giardia lamblia*, *Legionella*, and viruses are regulated, but only in terms of percentage of removal or inactivation by treatment. Heterotrophic plate counts (a measure of microbial load), turbidity, and total coliform levels (including fecal coliforms and *E. coli*) are also regulated and can be directly measured, but as discussed earlier, these indicators are imperfect markers of the presence of pathogens. The EPA also publishes National Secondary Drinking Water Regulations (NSDWR), which are nonenforceable guidelines for contaminants that cause cosmetic or aesthetic problems in drinking water.

The SDWA includes additional regulatory requirements. For example, EPA has established monitoring schedules, monitoring methods, and acceptable treatment technologies. Also, as discussed in Box 18.4, the Surface Water Treatment Rule governs filtration of public water supply systems.

As a requirement of the 1996 Amendment to the SDWA, EPA is required to publish, every five years, a list of contaminants that are not subject to regulation at the time of publication but that are anticipated to occur in drinking water and may require future regulation. Known as the Contaminant Candidate List (CCL), the latest iteration, CCL 2, includes forty-two chemical and nine microbiological contaminants. The CCL helps guide the EPA's research agenda. Chemicals on the list undergo extensive toxicity assessments, and risks of exposure through drinking water are characterized to the degree that current methodologies allow. The CCL 2 includes the following microbiological contaminants:

- Viruses:—adenoviruses, caliciviruses, coxsackieviruses, and echoviruses
- Bacteria: *Aeromonas hydrophila, Helicobacter pylori, Mycobacterium avium intracellulare* (MAC), cyanobacteria, and their toxins
- Protozoa:—*Microsporidia* (*Enterocytozoon* and *Septata*)
- Algae: freshwater algae and their toxins

With the possible exception of *A. hydrophila,* these contaminants are unlikely to be regulated in the near future. However, the CCL provides an important indication of contaminants that will receive growing public health attention.

Total Coliform Rule

In 1989, the EPA finalized the Total Coliform Rule. This rule is currently the driving force behind drinking water safety and frequently serves as the first indication (other than turbidity) of potential contamination. The rule requires a water system to establish a regular coliform sampling plan, with sample sites that accurately represent water quality throughout the distribution system. Any sample that is positive for total coliforms requires repeat samples and must be tested for fecal coliforms or *E. coli*. Specific requirements vary somewhat depending on the population served; however, for a large municipality, having more than 5 percent of samples test positive for total coliforms in a month constitutes a monthly Maximum Contaminant Level violation that must be reported to the municipality's respective state by the end of the next business day and the public must be notified within thirty days. Acute MCL violations result from any repeat fecal coliform or *E. coli* positive sample, or any routine fecal coliform or *E. coli* positive sample followed by a repeat total coliform sample. In the case of an acute violation the state must be notified by the end of the next business day and the public must be notified within twenty-four hours.

An additional component of the Total Coliform Rule that is designed to protect smaller public water systems is the Sanitary Survey. Every system collecting

fewer than five samples per month is required to have regular Sanitary Surveys, usually every five years. This survey is designed to evaluate the entire water system, its operations, and its maintenance in order to ensure public health. (The EPA Web site provides numerous resources for conducting Sanitary Surveys, including a guidance manual; see EPA, 1999.)

Consumer Confidence Reports

An important outcome of the 1996 Amendment to the SDWA has been the requirement for utilities to provide Consumer Confidence Reports. The requirement was finalized in 1998 and is designed to "enable Americans to make practical, knowledgeable decisions about their health and their environment." In addition to carrying out rapid notification when coliform counts are high, water systems are required, at a minimum, to inform consumers annually of (EPA, 1998)

- the lake, river, aquifer, or other source of the drinking water;
- an explanation of the susceptibility to contamination of the local drinking water source;
- how to get a copy of the water system's complete source water assessment
- the level of any contaminant found in local drinking water, as well as EPA's MCL for comparison;
- the likely source of that contaminant;
- the potential health effects of any contaminant detected in violation of an EPA health standard;
- an explanation of the system's actions to address any contaminant and restore safe drinking water;
- the water system's compliance with other drinking water-related rules;
- an educational statement for vulnerable populations about avoiding *Cryptosporidium;*
- educational information on nitrate, arsenic, or lead in areas where these contaminants are detected above 50 percent of EPA's standard; and
- phone numbers of additional sources of information, including the water system and EPA's Safe Drinking Water Hotline (800-426-4791).

Recreational Water Standards

The EPA and state agencies also regulate recreational waters. For example, swimming advisories are posted where indicator organisms exceed recommended levels. For freshwater, current standards are 126 *E. coli* per 100 ml or 33 enterococci per 100 ml. The regulations state that only one of these two indicator organisms should be used. For seawater, the standard is set at 35 enterococci per 100 ml. (For further information on recreational water safety and on the rationale for standards, see EPA, 2003; Bartram and Rees, 2000; WHO, 2003a.)

Conclusion

Finally, a few new issues deserve some attention: How should we be assessing current water safety risks? How should we be dealing with the appearance of new diseases that may be transmitted by means of water? What use can we make of molecular epidemiology in assessing water quality? And what is the potential for wastewater reuse?

Risk Characterization for Water Contaminants

Risk assessment is the process used to prioritize interventions and to reduce human exposure to environmental sources of chemicals and pathogens, as described in Chapter Thirty-Two. However, microbiological risk assessment raises some additional considerations. These involve exposure assessment, variability, and complexity.

To identify microbial hazards, *spot* samples are generally taken from finished water at the treatment plant, and occasionally at conveniently accessible sites in the distribution system. However, distribution of pathogens is extremely heterogeneous in drinking water. Most consumers will not ingest an infectious dose of a pathogen, and measurements of water samples will frequently be zero. However, a few individuals may consume a large number of infectious microbes. Moreover, as previously discussed, most pathogens are poorly indicated by the presence of the routinely monitored coliform group. Utilities expect that major contamination events in a watershed will be recognized from turbidity spikes; however, this is not always the case. Turbidity spikes were not excessive for the contamination event in Milwaukee in 1993 (Mac Kenzie and others, 1994). An event of far smaller magnitude may not result in elevated turbidity, or minor spikes may be missed. Although a rare event, a *plug* of infectious oocysts, cysts, or viruses could enter the distribution system and be very easily missed by a spot sampling program, yet contain sufficient numbers to virtually ensure that ingestion will result in infection (Gale, 2001). Exposure assessment therefore remains a challenge in microbial risk assessment.

Similarly, variability is a key challenge. People vary in the doses of pathogens they sustain, an outcome related both to variation across the drinking-water system and to variation in individuals' consumption of water. People also vary in their responses to a specific infectious dose, depending on individual susceptibility (age, health, and other factors), prior exposure (immunity), and the degree of virulence of the pathogen itself (affected by numerous environmental factors).

Infectious agents themselves vary. Organisms may lose virulence and even infectivity in the distribution system or after exposure to disinfection. Conversely, organisms may increase or change in virulence and in their ability to resist antibiotics following environmental exposures.

Complexity arises in numerous ways. To begin with, water is a complex environment. It may be contaminated by both chemicals and microbes, and these two classes of contaminants interact. Some chemicals of concern are actually bacterial, fungal, or algal toxins. Some may be produced within the distribution system pipeline by the action of certain groups of organisms; the sulfate-reducing bacteria produce sulfides and other sulfur-containing chemicals, nitrifying bacteria produce nitrites and nitrates from ammonia compounds (either in source water or from chloramination). And some chemicals—the disinfection by-products—result from water treatment practices to minimize microbial contamination.

Partly for these reasons, the health risks associated with drinking water are still not fully defined and quantified. The World Health Organization publishes drinking water quality standards that are internationally recognized. In some cases, such as the WHO's current standard for arsenic, these standards are more stringent than those of the U.S. EPA. It is likely that health risks are minimal for individuals without predisposing factors—in developed nations individuals with predisposing factors would be the very young, the elderly, the pregnant, and those with compromised immune function. However, on the global scale, susceptible individuals may be as common as the nonsusceptible. Malnutrition, stress, concomitant diseases, and socioeconomic deprivation increase susceptibility. The global risk from contaminated water may be enormous.

Despite this risk, people in areas with contaminated water may, paradoxically, be protected by immunity resulting from multiple prior exposures. By all the criteria just mentioned, these populations are highly susceptible, yet immunity results in lower than expected incidence of many waterborne diseases. This immunity must come at some cost to the individual, but there is not yet a robust approach to estimate the burden of disease from exposure to multiple infectious agents (and toxins). This complexity—like the complexity within water itself—continues to challenge microbial risk assessment efforts (Gale, 2001; Fewtrell and Bartram, 2001).

The Phenomenon of New Disease

Many factors can promote the real or apparent emergence of a new disease. New ecological niches, such as the hot-water systems that support growth of *Legionella*, may contribute. Factors such as population density and increasing numbers of susceptible individuals (the very young, the elderly, pregnant women, and the immunocompromised) could provide an extensive human reservoir for opportunistic pathogens and promote changes in virulence patterns, even in developed countries. Increased adaptation to the human host might be responsible for increased infection rates in populations with no underlying susceptibility (for example, mycobacterial diseases).

Legionella pneumophila, E. coli O157, *Vibrio cholerae* O139, *Helicobacter pylori, Cryptosporidium parvum,* and *Hepatitis E,* are all examples of microorganisms categorized as "new" or "newly recognized" pathogens. Well-established pathogens should arguably be added to this list as they develop antibiotic resistance and can change virulence patterns (Ford, 1999). Research is clearly needed to understand better the ecology of the water environment that may promote new disease emergence. One research priority is biofilms, the microbial films that form on the surfaces of pipe material, which may provide an opportunity for horizontal gene transfer both within and between species. The biofilm environment may also promote expression of plasmids through exposure to chemical stressors such as metals. An increasing body of research links metal resistance with multiple antibiotic resistance determinants, presumably expressed on the same plasmids (discussed in Ford, 1993).

Molecular Epidemiology

Gene chips are tiny devices whose surfaces contain arrays of DNA or RNA fragments. When water comes into contact with the gene chip, biological materials in the sample could potentially be identified through fluorescent labeling This emerging technology may one day play a role in monitoring water quality. A recent American Academy for Microbiology report begins with the imagined scenario that a gene chip placed in the flow of water will one day detect each pathogen, with the fluorescence response triggering an alarm that prompts an appropriate treatment response (Rose and Grimes, 2001).

At present, however, the role of gene chip technology is limited by the inability to analyze and interpret accurately the vast amounts of data generated. There are also at least two major technical challenges. First, in order for a gene chip to be developed and its results understood, the target organisms must be characterized and a highly specific gene segment recognized. However, most organisms in drinking water have yet to be characterized. Second, the organism's genetic material must come in contact with the chip surface in order to hybridize to the probe. However, the heterogeneous distribution of microbes in drinking water and the need to lyse the cell are barriers that dramatically reduce the potential sensitivity of the technique. Nevertheless,

gene chip technology is likely to play an increasing role in identifying water contaminants.

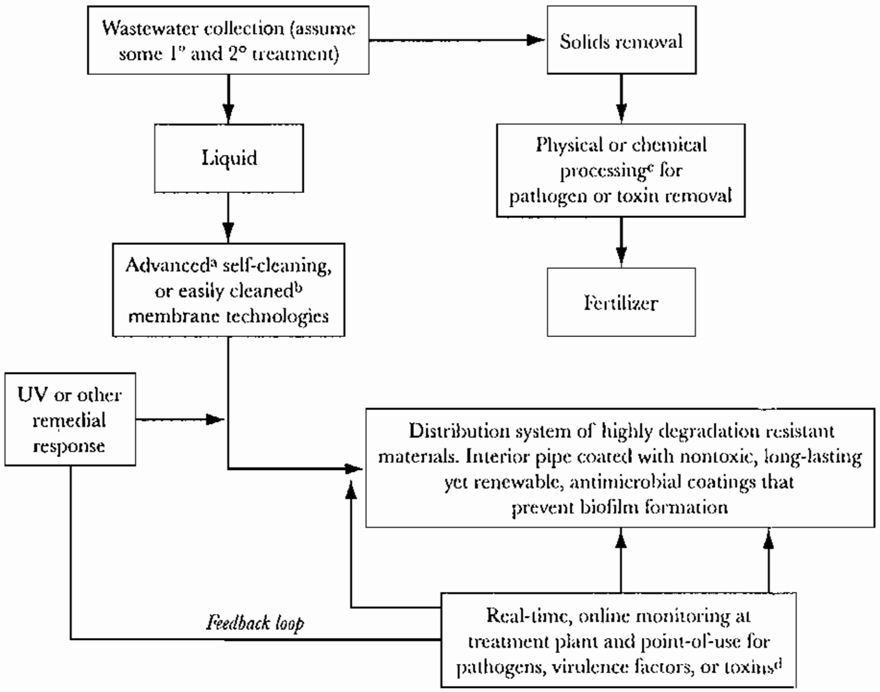
Wastewater Reuse

This discussion would not be complete without returning to the topic of wastewater. A vital step in providing adequate, safe drinking water is to understand that wastewater is a valuable resource. Today, water reuse programs are increasingly encouraged in the more arid states in the United States, primarily for nonpotable uses. This involves separate collection of black water (primarily toilet wastes, although it may also include other wastewater rich in organics, such as the effluent from a garbage disposal system) and gray water (other sources of wastewater such as bath and shower water). The gray water can then be used to irrigate nonedible plants and in some cases can also be used for toilet flushing.

The simplest use of gray water is direct discharge from the house to the landscape. However, there are understandable health concerns as bath and shower water may contain potential pathogens. A wide range of gray water treatment systems is available. These systems may be sufficiently sophisticated (and expensive) to remove both chemical and biological contaminants and essentially to mimic the water treatment process (Figure 18.9) on a small scale. The use of recycled wastewater to augment diminishing supplies of drinking water is just beginning. The barriers to wastewater recycling are probably issues of public perception more than cost. Just as many arid nations increasingly rely on desalination to supply drinking water, treatment technologies are more than capable of recycling wastewater to a potable quality. The predicted increase in the number of water-scarce countries during the twenty-first century makes education in this area critical. However, water recycling alone will not be sufficient without a concerted effort to conserve the available remaining resources. Figure 18.10 shows an idealized scheme for future provision of safe drinking water. Although this process would be expensive, it is increasingly recognized that water is dramatically undervalued and should be appropriately priced. It is often stated that water is a human right (WHO, 2003b). Certainly, like food, it is a human necessity. However, as mentioned earlier, people are willing to purchase bottled water at considerable expense because of their real and perceived concerns for the quality of water at the tap. There is no question that the true cost of water should be subsidized for those who cannot afford it, but realistic pricing for those who can afford to pay could dramatically improve the safety of drinking water for everyone.

However, a word of caution is necessary. How safe should our drinking water be? Arguably, for the immunocompromised it can never be too safe. Filtration technologies may one day provide water, at least at the level of the treatment plant, that is 100 percent free not only of infectious agents but also of all microorganisms.

FIGURE 18.10. IDEALIZED SCHEME FOR SAFE DRINKING WATER.



[a]Many companies now invest heavily in microfiltration, ultrafiltration, nanofiltration, and reverse osmosis membrane technologies. Hollow-fiber filtration technologies, for example, are allowing filtration capacities adequate for municipal water systems.
[b]For example, patented gas backwash systems for USFilter's Memcor® microfiltration systems.
[c]There is currently considerable debate on appropriate criteria for land application of sewage sludges, known as *biosolids*. Treatment produces biosolids that range from Class B biosolids, with a consequent risk to surface waters, to Class A biosolids, which are essentially pathogen free.
[d]The ideal monitoring tool depicted in a recent American Academy of Microbiology report (Rose and Grimes, 2001).

Source: Reproduced from Ford, 2005.

Perhaps distribution pipes will eventually be lined with materials that effectively prevent biofilm buildup. However, is this in fact optimal for the immunocompetent? Some waterborne exposure to microorganisms may be important in developing and maintaining healthy immune systems.

Thought Questions

1. Global warming may bring increasing temperatures over the next twenty years. What might be the potential consequences for waterborne and water-related diseases? Choose a specific disease, and discuss how it may be affected.
2. Almost every city has a deteriorating water distribution system. As a result, municipalities lose between 30 and 50 percent of distributed water. Imagine yourself to be the manager of a municipal water facility, and discuss options for reducing water loss. What are the alternatives, if any, to distributed water, and what would be the health risks associated with each alternative?
3. Given the number of options for water treatment available today, what would your recommendations need to take into account if you were involved in installing a new water treatment plant in a developing country with high rates of enteric diseases?
4. *The coliform group has been used for most of the past century as an indicator of fecal pollution. However, directly monitoring for pathogens such as* Vibrio cholerae *would be far more protective of public health.* Please agree or disagree with this statement, and give your reasons.
5. Describe the Aral Sea disaster. Discuss health consequences to the local communities and the long-term fate of this ecosystem.
6. *The answer to a waterborne disease outbreak is to "shock" chlorinate.* Explore this statement and the health risks that would be mitigated. What new health risks might emerge from the application of large doses of chlorine?
7. What health concerns arise from reuse of wastewater? What exposure pathways to pathogens might occur from land application of sewage sludge, reuse of wastewater for irrigation of garden plants, and toilet flushing?
8. *Relative to developing countries, waterborne disease in the United States is a nonissue. The CDC reports very few deaths from waterborne disease outbreaks, and we therefore have no reason to worry.* Identify and discuss the potential fallacies in this statement.

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For Further Information

The American Water Works Association (AWWA) provides consumer information on drinking water and many other water-related topics. It also provides useful links to a number of sites, including a link to a unique site for physicians

to help them improve "recognition of waterborne disease and health effects of water pollution":

American Water Works Association. Homepage. [http://www.awwa.org]. 2005.
Meinhardt, P. "Recognizing Waterborne Disease and The Health Effects of Water Pollution." [http://www.waterhealthconnection.org/index.asp] 2005

The Web site of the British Geological Survey provides information on the greatest mass poisoning from contaminated water ever recorded, the arsenic crisis in Bangladesh:

British Geological Survey. "Arsenic Contamination of Groundwater" [http://www.bgs.ac.uk/arsenic]. 2004.

The *Morbidity and Mortality Weekly Report* (MMWR) of the Centers for Disease Control and Prevention is the authoritative source on outbreaks of infectious disease in the United States. However, at least for waterborne disease, reports likely underestimate by orders of magnitude the actual incidence. Another useful CDC site provides information on drinking water, diarrheal disease, and recreational water quality.

Centers for Disease Control and Prevention. *Morbidity and Mortality Weekly Report.* [http://www.cdc.gov/mmwr]. (Weekly.)
Centers for Disease Control and Prevention, Division of Parasitic Diseases. "Parasitic Disease Information: Waterborne Illnesses." [http://www.cdc.gov/ncidod/dpd/parasites/waterborne/default.htm]. 2000.

The U.S. Environmental Protection Agency Web offers numerous useful resources related to water and health; see, for example:

U.S. Environmental Protection Agency. "Ground Water and Drinking Water." [http://www.epa.gov/safewater]. 2005.
U.S. Environmental Protection Agency. Homepage. [http://www.epa.gov]. 2005.
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The Pacific Institute is "an independent, nonpartisan think tank studying issues at the intersection of development, environment, and security." Its Web site has links to a selection of publications on water that form a considerable database on, for example, global water availability and water use, as well as many other critical water issues:

Pacific Institute. Homepage. [http://www.pacinst.org]. 2005.

The United Nations offers a number of water-related Web sites; see, for example:

United Nations Children's Fund. "Water, Environment and Sanitation." [http://www.unicef.org/wes/index.html]. 2005.
United Nations Development Programme. "Water." [http://www.undp org/water]. 2005.
United Nations Educational, Scientific and Cultural Organization. "Water." [http://www.unesco.org/water]. 2005.
United Nations Environment Programme. "Freshwater." [http://freshwater.unep.net]. 2005
United Nations. Homepage. [http://www.un.org]. 2005.

The U.S. Geological Survey maintains an extremely useful resource with current assessments of ground and surface water quality in many U.S. river basins and aquifers:

U.S. Geological Survey. "National Water Quality Assessment Program." [http://water.usgs.gov/nawqa]. 2005.

The Water and Sanitation Program describes itself as "an integrated partnership to help the poor gain sustained access to improved water and sanitation":

Water and Sanitation Program. Homepage. [http://www.wsp.org]. 2005.

The Water Environment Federation (WEF) describes itself as a "technical and educational organization with members from varied disciplines who work toward the WEF vision of preservation and enhancement of the global water environment":

Water Environment Federation. Homepage. [http://www.wef.org]. 2005.

The Water Environment Research Foundation funds research to "address water quality issues as they impact water resources, the atmosphere, the lands, and quality of life." For examples of research projects on water and health, see

Water Environment Research Foundation. "News Highlights." [http://www.werf.org/index.cfm]. 2005.

The World Bank Web site provides links to major World Bank-funded projects; see, for example:

World Bank. Homepage. [http://www.worldbank.org]. 2005.
World Bank. "Water Resources Management." [http://lnweb18 worldbank.org/ESSD/ardext.nsf/18ParentDoc/WaterResourcesManagement?Opendocument]. 2004.
World Bank. "Water Supply and Sanitation." [http://www.worldbank.org/watsan]. 2005.

The Woods Hole Oceanographic Research Institution offers probably the best maintained source of on-line information on toxic algal blooms:

Woods Hole Oceanographic Research Institution. "Harmful Algae." [http://www.whoi.edu/redtide]. 2005.

The World Health Organization is arguably the leading source of information for internationally accepted statistics on human health, including water and health; see, for example:

World Health Organization. Homepage. [http://www.who.int/en]. 2005.
World Health Organization. "WHO Guidelines for Drinking Water Quality." [http://www.who.int/water_sanitation_health/dwq/guidelines/en]. 2005.
World Health Organization. "WHO Infectious Disease Index" (providing links to pages on diarrheal disease, cholera, dracunculiasis, malaria, and so forth). [http://www.who int/health-topics/idindex.htm]. 2005.
World Health Organization "Water, Sanitation and Health." [http://www.who.int/water_sanitation_health/en]. 2005
World Health Organization "WHO Weekly Epidemiological Record." [http.//www.who.int/wer/en]. (Weekly.)
World Health Organization. "WHO World Health Report" (links to annual reports with data on the global burden of disease). [http://www.who.int/whr/en]. 2005.

The World Water Council, an "international water policy think tank," offers many articles on water policies and the barriers to and solutions for effective management of the world's water resources:

World Water Council. Homepage. [http://www.worldwatercouncil.org]. 2005.