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Water Quality

Water is a primary component of the biosphere. The ability of the biosphere to support life as well as the health and enjoyment of that life depends on water quality. Adequate supplies of clean water are vital for agriculture, domestic use, recreation, wildlife, and thousands of manufacturing and mining processes. As competition for water grows, wise management and protection of that resource becomes increasingly important.

Historically, the primary objective of agricultural development has been production, i.e., maximizing arability and yields. Where production was the primary objective, environmental quality often suffered. Declines in natural habitat have spurred major changes in engineering and production practices. Environmental quality objectives now play a major role in development of designs and management strategies. Agriculture, forestry, construction, and other types of development are subject to federal and local regulations regarding water use, flow management, and associated transport of contaminants.

Many dramatic examples can be found throughout the world where production-oriented practices have resulted in environmental threats or actual degradation. The following are a few examples.

- In the San Joaquin Valley of California, selenium concentrations in the Kesterson Reservoir rose to levels that caused serious malformations in nesting birds. Naturally occurring selenium was leached from irrigated areas and carried by the San Luis Drain into the reservoir. Since the reservoir did not have an outlet, it acted as an evaporation basin, concentrating the solutes until toxic concentrations were reached. The drain and reservoir were ordered closed. The Department of the Interior eliminated discharges from the drain in 1986. Drainage for the San Luis Unit of the Central Valley is still unresolved.
- Intensive livestock production in some areas of the United States has created a nutrient imbalance where nutrients are imported in feed (and subsequently excreted as waste) in greater quantities than can be effectively utilized by local crops. Over-application of animal wastes to cropland has resulted in contamination of ground and surface waters. Feed additives such as copper and zinc can accumulate in the soil to the point of toxicity for some crops. Concerns are also growing about antibiotics and hormones added to feeds.
- A major irrigation project, started in the 1960s in the former Soviet Union, diverted much of the water from two rivers (Amu Darya and Syr Darya) that feed the Aral Sea on the Kazakhstan-Uzbekistan border. Evaporative losses now exceed inflows. By 2000, the surface area of the sea had been reduced by nearly half and the volume by about three-quarters, with the shoreline having receded

tens of kilometers. A sea that had been a productive fishery was reduced to concentrated brine where very little survives.

- Heavy withdrawals of water from the Colorado River in the western United States and Mexico are changing the ecology of the lower reaches of the Colorado and its delta on the Gulf of California. Withdrawals are for both irrigation and urban use. With these extractions, the Colorado River now reaches its outlet on the Gulf of California only in very wet years.
- Large feedlots in the central United States concentrate thousands of cattle on relatively small areas. Runoff from those feedlots is high in nutrients and can cause severe impacts if allowed to reach surface waters. Runoff collection and treatment facilities can greatly reduce the export of nutrients from feedlot operations.
- Many commonly used herbicides have been found in water supplies, sometimes at concentrations exceeding health advisory levels. Although normal usage is sometimes the source, careless handling of chemicals and equipment washwater is often to blame. Concerns have led to major changes in the types of chemicals permitted for use. Approved practices for mixing and rinsing have been developed to prevent direct contamination events.
- Many municipal waste treatment plants land-apply wastewater and sludge that contains trace amounts of heavy metals. The pH of the soils on the application sites must be carefully managed for many years so that the metals stay in insoluble, immobile forms. Failure to do so would allow the metals to leach into the groundwater.

These examples illustrate that well-intended practices can have unintended effects, often far beyond the area where the practices are implemented. The impacts of a particular practice on a small area may be insignificant, but the cumulative effects of regional implementation of that same practice can be devastating. Various agencies with responsibility for ecosystem management are now given authority to regulate practices on local, state, regional, and river-basin scales.

Human influence has changed many ecosystems and, in all likelihood, change will continue. The pressures of growing populations and desires for improved standards of living will continue to drive development. Engineers are in the middle of all this, charged with providing for society's needs while protecting society's interests in the quality of the environment and the long-term health of these resources. To meet these challenges, engineers must be aware of the effects of various practices and be able to select those that will maximize utility with minimal environmental impacts. They must be aware of the regulations that restrict, prohibit, or require certain practices. Competent engineers can be a voice of reason in the shaping of public policies and regulations.

Water Quality Issues

Direct measures of water quality are the concentrations of biological, chemical, and physical contaminants. Quality of aquatic habitat involves additional parameters such as temperature, channel characteristics, turbidity, and dissolved oxygen.

Water quality standards vary with the intended use. Standards and regulations have

been established for drinking water, discharge from industrial or municipal treatment plants, discharge or runoff from agricultural operations, runoff from forestry operations, and land application of wastewaters, to name a few. The primary regulatory agency in the United States is the Environmental Protection Agency (EPA), but various state and local authorities impose standards as well. Most agencies publish current standards via the Internet.

Many factors may be involved in any water quality situation: pH, alkalinity, temperature, dissolved oxygen, turbidity, sediment, macronutrients, other inorganic species, hardness, organic matter, salinity, pesticides, nonaqueous-phase liquids, or other contaminants resulting from human activity such as solvents, PCBs, and dioxin. In addressing any situation, consider, as appropriate:

- Cause or source. Natural, anthropogenic, or both? Magnitude or intensity of the source(s)?
- Concentrations that are (a) desirable, (b) tolerable, (c) toxic with chronic exposure, (d) toxic with acute exposure.
- Effects on soils, plants, or aquatic habitats.
- Solubility, volatility, density. Dominant physical/chemical forms.
- Transport mechanisms. Advection and/or diffusion.
- Reactions, biological or chemical, in groundwater or surface water. Rates.
- Partitioning of solutes between water and solids. Affinity for soil or organic matter.
- Persistence in the environment. Half-life. Daughter products. Modes of breakdown.
- Assessment methods. Can it be quantified? How is it measured? Standard analytical methods.
- Treatment and/or removal. Available methods. Efficacy. Cost. Practicality.
- Regulatory controls and requirements. Which agencies have authority?

Water quality issues are seldom easy. As the list above suggests, many factors—physical, chemical, biological, economic, social, and political—may be important. As an introduction to some of the issues in water quality, a number of major topic areas will be discussed briefly.

2.1 Trophic States

Waters may be classified according to trophic conditions (related to the availability of nutrients) or productivity. Trophic classification uses a continuous scale ranging from oligotrophic (relatively poor in nutrients and having low productivity) to mesotrophic (moderate nutrient availability and moderate productivity) to eutrophic (rich in nutrients and having high productivity). High productivity is not necessarily good. Many game fish do best in oligotrophic waters, which tend to be clear (Secchi disk depths averaging about 3 meters; see Figure 2.1). Eutrophic (and hypereutrophic) waters tend to be murky (Secchi disk depths averaging less than 1 meter). The high organic matter content of eutrophic systems (Figure 2.2) makes them more prone to becoming anoxic.

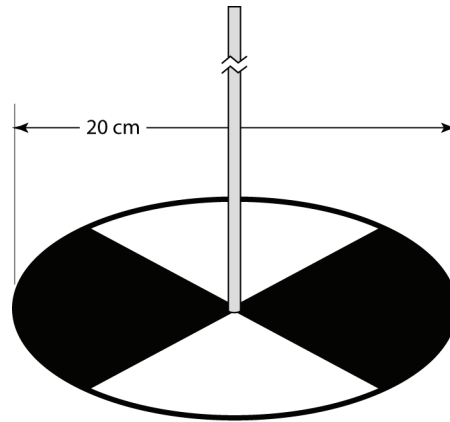


Figure 2.1—Secchi disk. The disk is lowered into a body of water until it is no longer visible. The depth is an index of the transparency of the water.

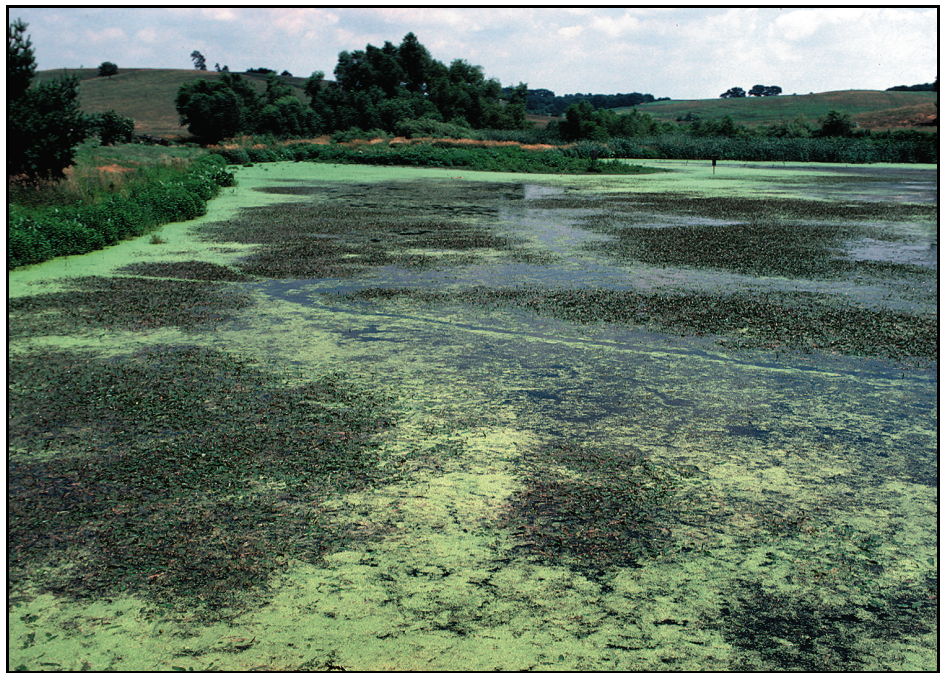


Figure 2.2—Algae in a lake in Iowa. (Photo by Lynn Betts, NRCS.)

In the course of natural aging, conditions in lakes change from oligotrophic to eutrophic as sediments and organic matter accumulate. This process normally takes thousands of years. Human influence can radically accelerate the process, but may be reversed somewhat through improved practices of nutrient management and erosion control (Chapters 7-10, 12-14).

Table 2.1 Trophic Status of Lakes

Trophic State	Secchi Depth (m)	Chlorophyll <i>a</i> (µg/L)	Total Phosphorus (µg/L)	TSI	Attributes
Oligotrophic	> 4.0	< 2.6	< 12	< 40	Clear water, oxygen throughout the year in the hypolimnion
Mesotrophic	2.0 to 4.0	2.6 to 7.2	12 to 24	40 to 50	Water moderately clear; increasing probability of hypolimnetic anoxia during summer
Eutrophic	0.5 to 2.0	7.2 to 55.5	24 to 96	50 to 70	Anoxic hypolimnia, macrophyte problems possible
Hypereutrophic	< 0.5	> 55.5	> 96	> 70	Light-limited productivity; dense algae and macrophytes

Sources: Carlson and Simpson (1996), Lee and Lin (2000).

The degree of eutrophication of a body of water can be quantified using a trophic state index that is based on measurements of Secchi disk depth (*SD*) in meters, chlorophyll *a* concentration (*CHL*) in micrograms per liter, or total phosphorus (*TP*) concentration in micrograms per liter (Carlson, 1977). Formulas for calculating the trophic state index (*TSI*) based on these measures are:

$$TSI = 60 - 14.4 \ln(SD) \quad (2.1)$$

$$TSI = 9.81 \ln(CHL) + 30.6 \quad (2.2)$$

$$TSI = 14.42 \ln(TP) + 4.15 \quad (2.3)$$

Table 2.1 shows attributes of the various trophic states along with *TSI* ranges and values of *SD*, *CHL*, and *TP* for lakes.

2.2 Dissolved Oxygen

The quality of natural waters as habitat for aquatic species is strongly related to the amount of oxygen available in those waters. With a free surface in contact with the atmosphere, the exchange of gases between air and water is usually adequate to support a wide range of species. Under some conditions, however, the gas exchange may not take place fast enough to supply all demands. Those organisms that can survive with lower oxygen concentrations will survive while those that require higher concentrations suffocate. Fish kills are the result of such competition.

The amount of dissolved oxygen (*DO*) naturally varies with depth in the water column. In swift or shallow streams, vertical mixing carries oxygen to the bottom. In slow streams and swamps, vertical mixing is weaker. In waters where oxygen demand is higher than the rate of supply by mixing and diffusion, the waters near the bottom may be anoxic.

2.3 Contaminant Sources

Any substance or organism that is present in an amount or concentration that is objectionable or harmful may be considered to be a contaminant. In some cases, contaminants are naturally occurring, but their release may be influenced by human activity, such as the problem with selenium in the Kesterson Reservoir cited earlier. More often, contaminants are directly produced and distributed by human activity. Countless agricultural, municipal, and industrial sources have contributed contaminants to both ground and surface waters.

Contaminant sources that are particularly important in rural areas include fertilizers, pesticides, septic tank effluent, animal wastes, and agricultural and municipal sludges. Particulate and gaseous emissions, such as smokestack or vehicle discharges, may be transported long distances through the atmosphere before eventual deposition in the landscape.

Biological Contaminants

Microorganisms in drinking water are a problem throughout the world. They include viruses, bacteria, algae, and protozoa. Although most microorganisms are harmless or beneficial, many are pathogens. The very young, very old, and immune-compromised are most susceptible to water-borne pathogens. The most common sources of these pathogens are human and animal wastes. Figure 2.3 shows the sizes of the biological contaminants discussed below.

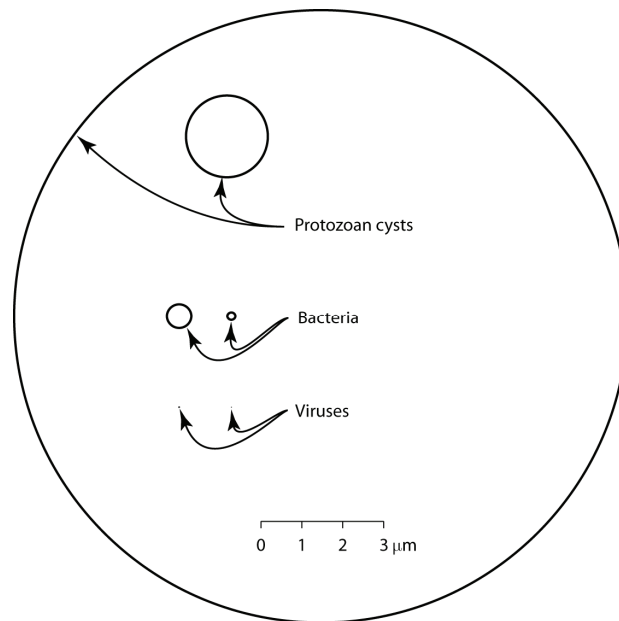


Figure 2.3—Relative sizes of biological contaminants.

2.4 Protozoa

Protozoan cysts range from 2 to 15 microns. The most common include *Giardia lamblia*, *Entamoeba histolytica*, and *Cryptosporidium*. These cause diarrhea and gastroenteritis. *Schistosomiasis* is found in stream banks in the tropics and is a major cause of disease in those regions (McCutcheon et al., 1992).

2.5 Bacteria

Bacteria range in size from 0.2 to 0.6 microns. They cause, for example, cholera (*Vibrio cholerae*), typhoid fever (*Salmonella* serogroup Typhi), and epidemic dysentery (*Shigella dysenteriae* type 1). Waterborne bacterial infections usually are associated with poor sanitation and hygiene. *Escherichia coli* include many coliform bacteria, mostly benign, that inhabit the intestines of warm-blooded animals. A test for fecal coliform is commonly used as an indicator of fecal contamination of a water supply. In recent decades, several toxic strains have been discovered that can cause diarrhea and even kidney failure (Mead and Griffin, 1998). Infection is usually via contaminated, uncooked, or undercooked foods or direct contact with infected individuals.

2.6 Viruses

Viruses are the smallest microorganisms, ranging from 0.01 to 0.03 microns. Enteric viruses infect the gastrointestinal tract of mammals and are excreted in feces. Where water supplies are contaminated by feces, there is the potential for transmission. Waterborne viruses of particular concern include hepatitis A, Norwalk-type viruses, rotaviruses, adenoviruses, enteroviruses, and reoviruses (AWWA, 1990), most of which infect the intestine and/or the upper respiratory tract. Viruses can also cause aseptic meningitis, encephalitis, poliomyelitis, and myocarditis. The most effective means of prevention are good sanitation and hygiene.

Chemical Contaminants

2.7 Concentration Units

There are several methods for expressing the amount of a solute in a given mass or volume of solution. Each has advantages for particular applications.

Molal concentration (molality) is the number of moles of solute per kilogram of solvent.

Molar concentration (molarity) is the number of moles of solute per liter of solution.

Normal concentration (normality) is the number of gram equivalent weights of solute per liter of solution. The gram equivalent weight is the gram molecular weight divided by the hydrogen equivalent (i.e., valence) of the substance.

Mass concentration is the mass of solute per unit volume of solution. Most water quality standards and laboratory reports express concentrations in mg/L or $\mu\text{g/L}$.

Equivalents per liter is the number of moles of solute multiplied by the hydrogen equivalent of the solute per liter of solution.

Parts per million (ppm) is the number of grams of solute per million grams of solution. Very small concentrations are often reported in parts per billion (ppb) or parts per trillion.

For a water solution, if the total solute concentration is less than 10 000 ppm and the solution temperature is near 4°C, molarity and molality may be considered equal and 1 ppm equals 1 mg/L. Likewise, 1 ppb equals 1 µg/L. For most practical purposes, these equivalencies may be used for total solutes less than 10 000 ppm and temperatures lower than 100°C. For higher concentrations, density corrections will be necessary (Freeze and Cherry, 1979).

Where concentrations reported in mg/L (or ppm) must be used in chemical computations, they can be converted to molarity or molality by:

$$\text{molarity} = \frac{\text{mg/L}}{1000 \times \text{formula weight}} \quad (2.4)$$

Example 2.1

Potassium bromide (KBr) is to be used in a tracer experiment. The KBr is to be applied using a sprayer calibrated to apply 200 L of water per hectare. To apply 8 g/ha of Br, how much 0.1N solution of KBr should be mixed with water to yield 200 L of solution for application?

Solution. A 0.1N solution contains 0.1 gram equivalent weight of solute per liter of solution. One gram equivalent weight of bromide is 79.9 g, so the solution contains $0.1 \times 79.9 = 7.99$ g Br per liter. To get 8 g Br, mix 1 L of 0.1N KBr with 199 L of water.

2.8 Macronutrients-Nitrogen and Phosphorus

Nitrogen (N) and phosphorus (P) are the primary macronutrients of concern with water quality. Both N and P are present in natural waters. Where significant N or P is added, algal blooms may occur. Algae compete very strongly for aquatic nutrients and respond very quickly to changes in trophic conditions. An abnormal abundance of nutrients permits rapid growth of algae (a bloom), which may cause offensive tastes or odors. As the algae die and decompose, dissolved oxygen can be depleted, killing fish and other aquatic fauna.

In freshwater systems, cyanobacteria (blue-green algae) are able to fix nitrogen from the atmosphere, so P is usually the limiting nutrient. In estuarine waters, N is usually limiting. Concentrations as low as 0.1 mg/L nitrate-nitrogen (NO₃-N) can be sufficient to trigger algal blooms in estuarine systems (Mallin, 1994).

Enrichment of rivers, lakes, estuaries, and coastal oceans with macronutrients from agricultural and urban sources has been clearly linked to eutrophication (Carpenter et

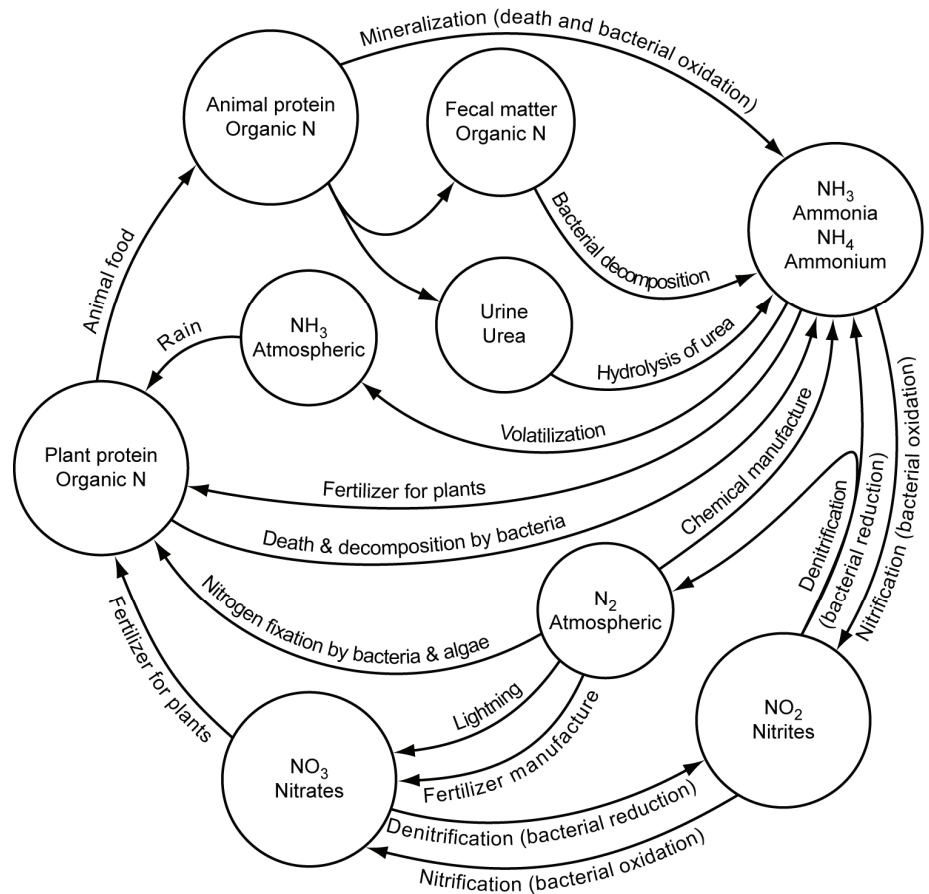


Figure 2.4–The nitrogen cycle. (Redrawn from SCS, 1992.)

al., 1998) and suggested as a cause of increases in populations of toxic microorganisms such as *Pfisteria piscicida* (Glasgow and Burkholder, 2000). More frequent occurrences of harmful algae blooms (often misnamed “red tides”) have been correlated with increases in pollution levels in many locations around the world, but there is still disagreement whether there is a causal link.

Nitrogen accounts for about 78% of the atmosphere, but the dominant gaseous form (N_2) cannot be used directly by most plants. To enhance plant growth, nitrogen is applied in chemical fertilizers (such as urea, $(NH_2)_2CO$; ammonium nitrate, NH_4NO_3 ; or anhydrous ammonia, NH_3) or in organic forms in sludges or animal and vegetable wastes. The inorganic forms become available as they dissolve in the soil water. The organic forms must first be mineralized (converted to inorganic forms). As the organic matter decomposes, ammonia(um) is released. Under anaerobic conditions, ammonia(um) may remain in solution or adsorbed to soil indefinitely. In aerobic conditions, with sufficient moisture and carbon, ammonia(um) can be quickly converted to nitrite

and then nitrate, an anionic form that is highly soluble and very mobile. N as nitrate is readily leached from the soil and can be a problem in groundwater. Nitrate can migrate for considerable distances in the groundwater without appreciable reduction in concentration. Riparian buffers can be effective for removing modest concentrations of nitrate from discharging groundwater (Gilliam et al., 1997). Water table management and controlled drainage (Chapter 14) can reduce nitrogen export in drainage waters from agricultural lands. Figure 2.4 depicts the nitrogen cycle.

Nitrate is the form of N most associated with health risks. High concentrations of nitrate in drinking water contribute to methemoglobinemia (blue baby syndrome), which primarily affects infants and has been associated with spontaneous abortions (both human and animal). The maximum contaminant level (MCL) established by the EPA is 10 mg/L nitrate-N. The MCL for nitrite-N is 1 mg/L, but high nitrite concentrations are very rare in nature because microbes in the soil rapidly convert nitrite to nitrate.

Nitrogen can also reach surface waters in airborne forms. Gaseous ammonia is released into the atmosphere from animal wastes. Oxides of nitrogen are produced by burning fossil fuels in power plants, waste incineration, and internal combustion engines. Atmospheric deposition is the return of these nitrogen compounds to land and water by either dry deposition or with precipitation. Nitrogen oxides and sulfur dioxide are the primary causes of acid rain.

Phosphorus occurs naturally in many mineral forms and is gradually released by chemical weathering. Phosphate-rich deposits are mined to produce fertilizers and other phosphate products. It is also found in organic matter. Phosphorus is applied to the land in both organic and chemical fertilizers (e.g., triple superphosphate $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$). Figure 2.5 presents an abbreviated phosphorus cycle specific to a waste application site. Soluble phosphate readily adsorbs onto soil solids or combines with iron or aluminum to form low-solubility compounds. Unless loading to the soil is so high that it overwhelms the immobilizing capacity of the soil, P will not migrate with soil water. The primary mode of transport is erosion by water, which carries P adsorbed to soil particles into surface waters. Erosion control practices (Chapters 7-10) and wetlands (Chapter 12) are very effective for limiting P in runoff.

If phosphorus-containing wastes are applied to the soil surface without incorporation, they may be easily detached and transported by water. Soluble P can enter surface waters this way.

There is no MCL for phosphorus in drinking water. Excess phosphorus is readily excreted and does not normally pose a health risk.

Potassium is usually grouped with N and P as a macronutrient, but it is not associated with health or water quality problems. There is no MCL for potassium in drinking water.

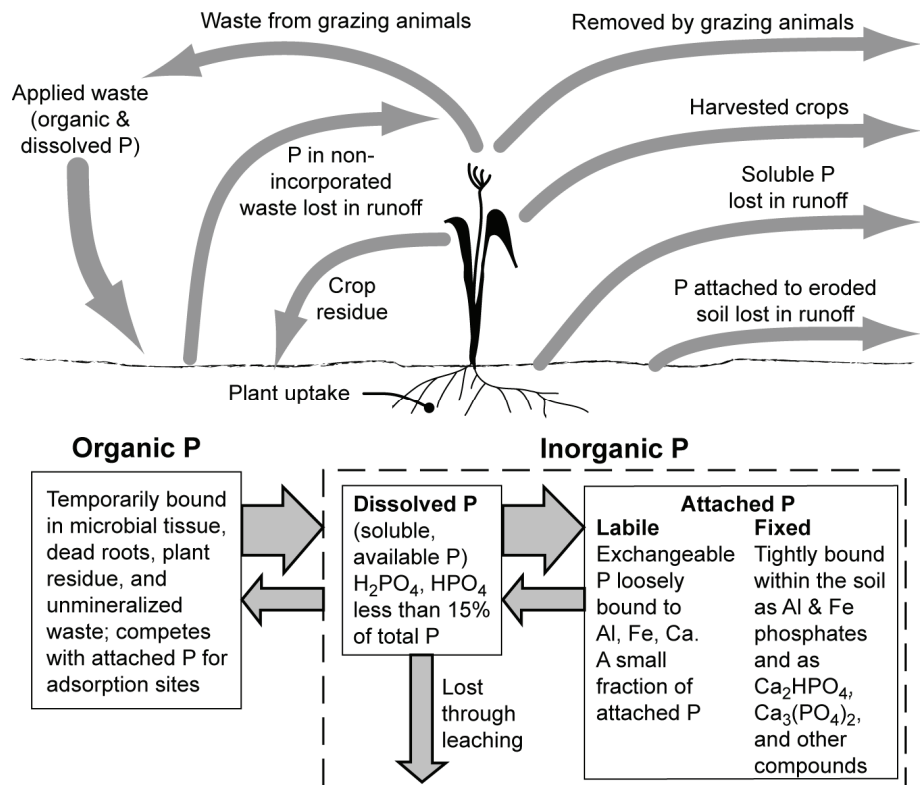


Figure 2.5—Phosphorus inputs and losses at a waste application site with transformations within the soil (abbreviated phosphorus cycle). (Redrawn from SCS, 1992.)

2.9 Inorganic Chemicals

There are thousands of chemicals that can be found in water. Solubility and toxicity vary widely. A few of the most common that are subject to federal regulation include: arsenic, barium, beryllium, cadmium, chromium, copper, cyanide, fluoride, lead, mercury, selenium, and thallium. Sources include discharge from metal and petroleum refineries, industrial discharges, and decaying piping systems. Natural mineral deposits may contribute to locally high concentrations. Some are present in fertilizers or are added to animal feeds.

The term heavy metals is variously used to refer to antimony, arsenic, cadmium, chromium, copper, lead, mercury, and zinc, among others. It has been defined to include all elements with atomic weights from that of copper to that of mercury (Kensh, 1992) or having a specific gravity greater than 4.0 (Connell and Miller, 1984). Many are essential trace nutrients. Non-essential elements may interfere with organisms by substituting for chemically similar elements. Several (e.g., arsenic, lead, and mercury) have been used in pesticides, but that practice has been largely discontinued due to the persistence of those elements and their concentration in the food chain.

Table 2.2 Water Hardness Classes

Description	Equivalent CaCO ₃ (mg/L)
Soft	0 to 60
Moderately hard	60 to 120
Hard	120 to 180
Very hard	> 180

Source: USGS (2011).

Heavy metals typically adsorb to soil minerals or organic matter, or form complexes or chelates. Dissolved concentrations are usually low. Increases in salinity, increases in oxygen availability, or decreases in pH tend to release metal ions into solution, where they are more mobile (Connell and Miller, 1984).

Inorganics also include compounds containing common ions such as sodium, calcium, magnesium, and chloride. Water hardness is often defined as the total concentration of the metallic cations (the most common are calcium and magnesium) in solution that react with sodium soaps to produce solids or scummy residue and which react with anions. Hardness is expressed as milligrams per liter equivalent CaCO₃. Table 2.2 shows concentration ranges corresponding to hardness classes used by the U.S. Geological Survey.

Hardness is a common problem in groundwater in areas underlain by carbonate rock such as limestone. Natural rainfall is slightly acidic and gradually dissolves these minerals as it percolates through them. Excessive hardness interferes with detergents and can cause scale deposits in heating systems or irrigation equipment. Excessive sodium (relative to calcium and magnesium) in soils tends to disperse clays, which restricts the movement of air and water through the soil profile. Chloride in excess of 250 mg/L, in the presence of sodium, gives water a salty taste. Crops have varying tolerances to salt concentrations in the soil water (Chapter 15).

Current MCLs for selected inorganics are presented in Table 2.3. Consult the EPA and regulatory agencies in your area for complete lists.

2.10 Organic Chemicals

Organic chemicals include thousands of compounds, both synthetic and natural. Those of greatest concern for water quality include pesticides (e.g., alachlor, atrazine, carbofuran, and lindane) and industrial chemicals, particularly solvents (e.g., benzene, toluene, xylene, and carbon tetrachloride). Many such organics are confirmed or suspected carcinogens.

The trend in pesticide development has been toward high specificity and short half-lives in the environment. This is a great improvement over persistent pesticides based on arsenic, mercury, and chlorinated hydrocarbons (e.g., DDT). Current MCLs for selected organics are presented in Table 2.3. Consult the EPA and regulatory agencies in your area for complete lists.

Many groundwater contamination incidents could be traced to operators who dumped unused pesticide mixes and equipment rinse water directly on the ground,

Table 2.3 Selected Drinking Water Quality Standards

Microorganisms	MCLG ^[a] (mg/L) ^[b]	MCL or TT ^[a] (mg/L) ^[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
<i>Cryptosporidium</i>	Zero	TT ^[c]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste
<i>Giardia lamblia</i>	Zero	TT ^[c]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste
<i>Legionella</i>	Zero	TT ^[c]	Legionnaire's Disease, commonly known as pneumonia	Found naturally in water; multiplies in heating systems
Total coliforms (including fecal coliform and <i>E. coli</i>)	Zero	5.0% ^[d]	Used as an indicator that other potentially harmful bacteria may be present ^[e]	Coliforms are naturally present in the environ- ment; fecal coliforms and <i>E. coli</i> come from human and animal fecal waste.
Viruses (enteric)	Zero	TT ^[c]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste
Disinfectants & Disinfection Byproducts	MCLG ^[a] (mg/L) ^[b]	MCL or TT ^[a] (mg/L) ^[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Chloramines (as Cl ₂)	MRDLG = 4 ^[a]	MRDL = 4.0 ^[a]	Eye/nose irritation; stom- ach discomfort, anemia	Water additive used to control microbes
Total Trihalomethanes (TTHMs)	n/a ^[f]	0.080	Liver, kidney or central nervous system prob- lems; increased risk of cancer	Byproduct of drinking water disinfection
Inorganic Chemicals	MCLG ^[a] (mg/L) ^[b]	MCL or TT ^[a] (mg/L) ^[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Asbestos (fiber >10 micrometers)	7 million fibers per liter	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Nitrate (measured as nitrogen)	10	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die; symptoms include shortness of breath and blue-baby syndrome	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits
Nitrite (measured as nitrogen)	1	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die; symptoms include short- ness of breath and blue- baby syndrome	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits

Table 2.3 (continued) Selected Drinking Water Quality Standards

Inorganic Chemicals	MCLG ^[a] (mg/L) ^[b]	MCL or TT ^[a] (mg/L) ^[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petro- leum refineries; erosion of natural deposits; discharge from mines
Organic Chemicals	MCLG ^[a] (mg/L) ^[b]	MCL or TT ^[a] (mg/L) ^[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Aalachlor	Zero	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system problems; reproductive difficulties	Runoff from herbicide used on row crops
Carbofuran	0.04	0.04	Problems with blood or nervous system; repro- ductive difficulties.	Leaching of soil fumigant used on rice and alfalfa
Chlordane	Zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Glyphosate	0.7	0.7	Kidney problems; repro- ductive difficulties	Runoff from herbicide use
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens
Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock
Picloram	0.5	0.5	Liver problems	Herbicide runoff
Polychlorinated biphenyls (PCBs)	Zero	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system diffi- culties; increased risk of cancer	Runoff from landfills; discharge of waste chem- icals
Simazine	0.004	0.004	Problems with blood	Herbicide runoff

Table 2.3 (continued) Selected Drinking Water Quality Standards

Source: Excerpted from EPA (2003).

^[a] Definitions:

Maximum Contaminant Level (MCL): The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.

Maximum Contaminant Level Goal (MCLG): The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.

Maximum Residual Disinfectant Level (MRDL): The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.

Maximum Residual Disinfectant Level Goal (MRDLG): The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.

Treatment Technique (TT): A required process intended to reduce the level of a contaminant in drinking water.

^[b] Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to parts per million (ppm).

^[c] EPA's surface water treatment rules require systems using surface water or ground water under the direct influence of surface water to (1) disinfect their water, and (2) filter their water or meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

- *Cryptosporidium*: (as of 1/1/02 for systems serving >10,000 and 1/14/05 for systems serving <10,000) 99% removal.
- *Giardia lamblia*: 99.9% removal/inactivation
- Viruses: 99.99% removal/inactivation
- *Legionella*: No limit, but EPA believes that if *Giardia* and viruses are removed/inactivated, *Legionella* will also be controlled.
- Turbidity: At no time can turbidity (cloudiness of water) go above 5 nephelometric turbidity units (NTU); systems that filter must ensure that the turbidity go no higher than 1 NTU (0.5 NTU for conventional or direct filtration) in at least 95% of the daily samples in any month. As of January 1, 2002, for systems servicing >10,000, and January 14, 2005, for systems servicing <10,000, turbidity may never exceed 1 NTU, and must not exceed 0.3 NTU in 95% of daily samples in any month.

^[d] No more than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-positive samples, and one is also positive for *E. coli* fecal coliforms, system has an acute MCL violation.

^[e] Fecal coliform and *E. coli* are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.

^[f] Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

- Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.3 mg/L)
- Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L)

often next to the well that supplied the water. Current best management practice requires a concrete pad with a sump—located some distance from the well—where chemical mixing and equipment cleaning are performed. Proper handling of the water collected in the sump prevents direct contamination of the soil and groundwater.

The great variety and complexity of organic materials found in water makes discrete analytical description impractical for many purposes. Organic materials can be quantified with collective parameters, such as chemical oxygen demand (COD), bio-

logical oxygen demand (BOD), dissolved organic carbon (DOC), and total organic carbon (TOC). COD is the equivalent amount of an oxidizing agent, such as permanganate, required for oxidation of the organic constituents; usually expressed as oxygen equivalents. BOD measures the amount of oxygen consumed in microbially mediated oxidation of the organic matter. TOC is a measure of the CO₂ produced in the oxidation or combustion of a water sample from which carbonate has been removed. These measures, especially BOD, are often used as indicators of the amount of oxygen that may be depleted from waters containing organics. The dependence of microbial activity on many other factors makes these measures difficult to apply in nature (Stumm and Morgan, 1996).

Physical Contaminants

2.11 Sediment

Particulate solids have various origins and effects on water quality. The most common contaminant and by far the largest (by mass) is sediment, i.e., soil particles that have become suspended either through erosion from upland areas (agricultural and other disturbed lands, Chapter 7), streambank erosion (Chapter 10), or detachment of streambed particles. The size and amount of sediment that can be transported depend on the energy of the flow: fast flowing streams have higher capacities for transport than do slow flowing streams (Chapters 6, 7, and 10). Vigorous flows can move boulders, whereas the quiet flows in lakes can transport only the finest silts and clays. Deposition of sediment can occur wherever flowing water slows (Chapters 7-9, and 12).

Sediment also includes carbonaceous materials, whether derived from geologic formations (such as coal) or modern plant detritus. Organic materials provide a food source for microbes and may harbor pathogens.

Carbonate and silica biocrystals are a minor source of sediment. Biocrystals are formed by organisms such as mollusks, foraminifers, sponges, and diatoms.

Excessive sediment can degrade aquatic habitat by restricting penetration of light, which affects photosynthetic activity and predator-prey relationships, and by altering benthic habitat (Wilber, 1983). Deposition of sediment in impoundments and channels also reduces capacity, increasing the frequency of flooding. Sediment from agricultural lands may carry nutrients or pesticides. Sediment can also change the benthic environment by filling in the spaces between rocks and gravel.

2.12 Turbidity

Turbidity refers to the murkiness of the water. It is quantified by measuring the degree to which light is scattered by suspended particulates (sediment and organic matter) in the water. The common unit is the Nephelometric Turbidity Unit (NTU). A number of sensors are commercially available for laboratory or field use. The Secchi disk (Figure 2.1) provides a method for quick evaluation of turbidity, although its visi-

bility is influenced by color of the water in addition to particulates.

Turbidity is not a health threat in itself. However, organic matter that contributes to turbidity can harbor pathogens and tends to deplete dissolved oxygen. Suspended solids increase treatment requirements.

Turbidity affects growth of phytoplankton, algae, and aquatic plants, generally favoring those organisms closest to the surface. Elevated turbidity places fish under stress, reducing feeding success, growth, and hatching rates. Benthic invertebrates may suffer from reduced oxygen levels. Particulates settling to the bottom can suffocate eggs and larvae.

Water Quality Regulations

In the United States, major water quality legislation began with the Federal Water Pollution Control Act of 1948. This authorized preparation of comprehensive programs for eliminating or reducing pollution of interstate waters and tributaries and improving sanitary conditions of surface and underground waters. This Act has been amended many times. The Reorganization Plan No. 3 of 1970 abolished the Federal Water Quality Administration in the Department of Interior and transferred its functions to the newly created EPA. The 1972 amendments included national objectives for restoration and maintenance of the chemical, physical, and biological integrity of the nation's waters. Limitations for point source discharges were to be determined.

The 1977 amendments renamed the legislation as the Clean Water Act (CWA) and authorized development of Best Management Practices (BMPs) and procedures for assumption of the regulatory programs by the states. The CWA was again amended by the Water Quality Act of 1987 that required states to develop strategies for toxics cleanup from waters where best available technology (BAT) discharge standards are inadequate. The act also authorized a \$400 million program for states to develop watershed-scale nonpoint source management and control programs under EPA oversight, and required EPA to study and monitor water quality effects attributable to dammed impoundments. Section 303(d) of the CWA requires states to identify pollutant-impaired waters and develop Total Maximum Daily Loads (TMDLs), which specify the amounts of various pollutants that can be tolerated from various sources in a watershed (Chapter 5). Section 319 established the Nonpoint Source Management Program, which provides grants to support demonstration projects, technical and financial assistance, education, training, and monitoring. Section 402 established the National Pollutant Discharge Elimination System (NPDES) to authorize EPA issuance of discharge permits. Section 404 gave the U.S. Army Corps of Engineers (COE) authority over discharge of dredged or fill materials into navigable waters.

The Safe Drinking Water Act (SDWA) of 1974 and its amendments in 1986 and 1996 were designed to protect public health by regulating drinking water supplies—rivers, lakes, reservoirs, springs, and wells (except private wells serving fewer than 25 persons). The SDWA authorized EPA to set health-based standards for both natural and man-made contaminants in drinking water. The original act focused on treatment, whereas the 1996 amendments added powers to protect sources and require operator training. To set a standard, the EPA first determines which contaminants may affect

public health, then establishes maximum contaminant level goals (MCLGs) below which there is no known or expected health hazard, and finally sets maximum contaminant levels (MCLs) as close to the MCLGs as considered feasible. An MCL is enforceable, whereas an MCLG is not.

The Wetlands Reserve Program (WRP) was established under the Food Security Act (FSA) of 1985 (as amended by the 1990 and 1996 Farm Bills). The WRP, a voluntary program that encourages restoration and protection of wetlands, is administered by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) in consultation with the Farm Service Agency. Landowners retain control of eligible lands, which may be used or leased for hunting, fishing, or other undeveloped recreational activities. Other wetlands legislation includes Sections 402 and 404 of the CWA. A 1990 Memorandum of Agreement (MOA) between the COE and EPA established the foundation for wetlands mitigation practices, including restoration of degraded wetlands or creation of new wetlands to compensate for unavoidable damage to existing wetlands. A 1994 multi-agency MOA established the NRCS as the lead agency for wetlands delineation on agricultural lands under both the CWA and FSA. (Chapter 12 discusses wetland processes and design.)

New legislation is introduced in each session of Congress. Current summaries of these acts and related regulations are available on the Internet from the U.S. EPA, the U.S. Army Corps of Engineers, USDA Natural Resources Conservation Service, U.S. Fish and Wildlife Service, and the U.S. Bureau of Reclamation.

Water Treatment

Whenever the quality of a water supply does not meet the standards for its intended use, some type of treatment will be necessary. Treatment processes vary in sophistication, but all add to the cost of the water. Application of best management practices can markedly improve the quality of the water supply, reducing treatment costs as well as providing environmental benefits.

This section briefly discusses major water treatment practices, their applicability, and efficacy. Treatment methods may include physical, chemical, and biological processes, either alone or in combination. A treatment method is selected to best fit the type of water quality problem, the intended use of the treated water, and the economics of the situation.

2.13 Clarification

Settling is often the first step in water treatment. Large or heavy particulates will fall to the bottom quickly in still water. Very fine suspended particulates can be made to settle more quickly by addition of flocculating agents, such as gypsum or polyacrylamide. Adjustment of pH may be needed. Flocs that do not settle may be removed by skimming, if they float, or by subsequent filtration.

2.14 Filtration

Filtration can be effective for removal of particulate contaminants. The size and amount of particulates present determines the type of filter that is appropriate.

Filters are needed with microirrigation systems (Chapter 18) to remove suspended particulates, which may include fine sands, silt, clay, or algae. They are also common in public and private water treatment systems. Sand filters have varying capacities and efficacies, depending on the size of the filter and the media used, and are easily regenerated by backwashing. Sand filters can remove most suspended materials, but are not effective with very fine particulates or bacteria.

Cartridge filters can be constructed with finer pores than sand filters. Materials include paper fiber, fiberglass, ceramics, and precision-etched polycarbonates. The finer pore structure requires more cross-sectional area than for a sand filter of equivalent capacity. Cartridge filters are most effective where the concentration of particulates is low, so that cleaning or replacement is required less frequently. Cartridge filters can remove bacteria, but should be regularly maintained in drinking water systems, as the cartridge itself could become a problem if bacteria accumulate and multiply. Some cartridge filters contain carbon, which can remove chlorine and some organic compounds.

For very demanding purposes, micro- (0.1-2 μm), ultra- (0.001-0.1 μm), and nanofiltration are available. Nanofiltration can remove organic compounds having molecular weights of 300 to 1000 and reject some salts.

2.15 Ion Exchange

The most familiar ion exchange treatment process is water softening. Sodium ions are stored in a filter bed of zeolite (an aluminosilicate resin). As hard water flows through the bed, sodium ions are exchanged for calcium and magnesium ions. The zeolite bed is periodically regenerated (charged with Na^+ and Cl^- ions) by flushing with brine.

Deionized water is produced in a similar process. Ions in the water are exchanged for H^+ and OH^- , which can then combine to form water. Deionization is used where extremely pure water is needed. Deionization will not generally remove nonionic compounds, organics, or pathogens.

Many other ion exchange processes have been developed. The reader should consult other texts or suppliers for additional information.

2.16 Disinfection

Chlorination is the most common method of disinfection. Chlorine gas is added to the water after pretreatments (clarification, filtration, etc.) to kill microbes. An excess of chlorine is added to provide a residual concentration (usually about 5 ppm) to control regrowth throughout the distribution system. If other organic compounds are present, chlorine tends to react with them first, forming chloramines or chlorinated hydrocarbons that may be carcinogens. This reaction also increases the amount of chlorine needed to achieve disinfection. Sodium hypochlorite and calcium hypochlorite are

alternative sources of chloride that are less dangerous to handle than chlorine gas. These are commonly used in small or private water systems or as algicides in microirrigation systems.

Ozonation uses ozone (O_3), a powerful oxidant, to kill pathogens. Unlike chlorine, ozone will not leave a lasting residual, so there is the possibility of subsequent re-growth of pathogens. Because of this, ozonation should not be used alone where water may reside in the system for extended periods before use.

Ionizing radiation, such as ultraviolet light, can kill many pathogens. Ultraviolet light can also break down low level organics. Like ozonation, it has no residual effect, which limits its application.

2.17 Reverse Osmosis

In reverse osmosis, a pressure difference on the order of 10 to 70 bars drives water across special membranes, rejecting nearly all organics and 90 to 99% of all ions. Over 99.9% of viruses and bacteria are also removed. A fraction of the source water, the concentrate or reject water, carries the rejected ions and other constituents to disposal. The fraction that passes through the membrane, the filtrate, is the desired product. Many types of membranes are commercially available to meet different permeate requirements.

2.18 Distillation

Distillation is the collection of condensed steam that is produced by boiling water. This can remove all types of impurities, though organics with boiling points near that of water require very close control and perhaps multiple distillations. Distillation is energy intensive, but can produce water with impurity concentrations as low as 10 parts per trillion.

Water Quality Modeling

Researchers and regulators make frequent use of computer models to study and predict behavior of systems from field to river basin scales. Models, however, can easily be misapplied and results can be misinterpreted or extrapolated beyond reason. Model users should have a thorough understanding of the physical processes of the system in question, the assumptions inherent in the conceptual model, and the limitations imposed by sparse or uncertain inputs.

Water quality modeling is, by nature, a problem with spatial aspects. Geographic information systems (GIS) are often used to manage the spatially distributed inputs and to store, manipulate, and display the model outputs.

Several good summaries of current models are available. The reader should consult sources such as the EPA, USGS, COE, NRCS, or Parsons et al. (2001). Many consulting groups provide programs, documentation, support, and training for water quality modeling.

Engineering in Water Quality

What is the engineer's role in protecting and improving water quality? What tools are needed? First, the engineer must thoroughly understand the physical processes involved (rainfall, runoff, infiltration, erosion, overland and channelized flow, etc.). Second, he or she must be able to adequately quantify those processes. Only then can the most appropriate management strategies, structures, and systems be selected to maximize the objectives of utility and environmental quality.

Water is absolutely essential to individuals, society, and wildlife. Conflicts over use and allocation will continue as opposing interests clash over a limited resource. Engineers, in cooperation with the physical and life sciences, must continually strive to discover and implement the most practical and economical solutions to these ever-changing challenges.

Internet Resources

U.S. Environmental Protection Agency (EPA):

www.epa.gov
www.epa.gov/ost/wqm
www.epa.gov/STORET/

U.S. Geological Survey (USGS):

water.usgs.gov/software/water_quality.html

USDA Natural Resources Conservation Service (NRCS):

www.nrcs.usda.gov
www.wsi.nrcs.usda.gov/W2Q/W2Q_home.html

U.S. Bureau of Reclamation (USBR):

www.usbr.gov

U.S. Army Corps of Engineers (COE):

www.usace.army.mil

U.S. Fish and Wildlife Service (FWS):

www.fws.gov

References

- AWWA (American Water Works Association). 1990. *Water Quality and Treatment: A Handbook of Community Water Supplies*, 4th ed. McGraw-Hill, New York.
- Carlson, R. E. 1977. A trophic state index for lakes. *Limnology and Oceanography* 22: 361-369.
- Carlson, R. E., and J. Simpson. 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society: Madison, Wisconsin.
- Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface water with phosphorus and nitrogen. *Ecological Applications* 8(3): 559-568.
- Connell, D. W., and G. J. Miller. 1984. *Chemistry and Ecotoxicology of Pollution*. John Wiley & Sons, New York.
- EPA (U.S. Environmental Protection Agency). 2003. *National Primary Drinking Water Standards*. EPA 816-F-03-016.
- Freeze, R. A., and J. A. Cherry. 1979. *Groundwater*. Prentice-Hall, Englewood Cliffs, New Jersey.

- Gilliam, J. W., J. E. Parsons, and R. L. Mikkelsen. 1997. Nitrogen dynamics and buffer zones. Pp. 54-61 in N. E. Haycock, T. P. Burt, K. W. T. Goulding, and G. Piney (eds.). *Buffer Zones: Their Processes and Potential and Water Protection*. Quest Environmental, Harpenden Herts, U.K.
- Glasgow, Jr., H. B., and J. M. Burkholder. 2000. Water quality trends and management implications from a five-year study of a eutrophic estuary. *Ecological Applications* 10(4):1024-1046.
- Kennish, M. J. 1992. *Ecology of Estuaries: Anthropogenic Effects*. CRC Press, Boca Raton, Florida.
- Lee, C. C., and S. D. Lin. 2000. *Handbook of Environmental Engineering Calculations*. McGraw-Hill, New York.
- Mallin, M. A. 1994. Phytoplankton ecology in North Carolina estuaries. *Estuaries* 17: 561-574.
- McCutcheon, S. C., J. L. Martin, and T. O. Barnwell, Jr. 1992. Water quality. In D. R. Maidment (ed.). *Handbook of Hydrology*. McGraw-Hill, New York.
- Mead, P. S., and P. M. Griffin. 1998. *Escherichia coli* O157:H7. *Lancet* 352(9135): 1207-1212.
- Parsons, J. E., D. L. Thomas, and R. L. Huffman, eds. 2001. *Agricultural Non-point Source Water Quality Models: Their Use and Application*. Southern Cooperative Series Bull. No. 398. Accessed June 2011 at s1004.okstate.edu/S1004/Regional-Bulletins/Modeling-Bulletin/.
- SCS (Soil Conservation Service). 1992. *National Engineering Handbook, Part 651: Agricultural Waste Management Field Handbook*. Accessed June 2011 at directives.sc.egov.usda.gov/.
- Stumm, W., and J. J. Morgan. 1996. *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters*, 3rd ed. J. W. Wiley & Sons, New York.
- USGS (U.S. Geological Survey). 2004. Explanation of hardness. Accessed June 2011 at water.usgs.gov/owq/hardness-alkalinity.html.
- Wilber, C. G. 1983. *Turbidity in the Aquatic Environment: An Environmental Factor in Fresh and Oceanic Waters*. Charles C. Thomas Publishers, Springfield, Illinois.

Problems

- 2.1 Research a current water problem in your area. Examine the history of the problem. How did it develop? What is being done about it?
- 2.2 Shock chlorination is a one-time method for disinfection of wells. Household bleach (5.25% NaOCl, by weight, specific gravity 1.08) is added to provide a chloride concentration of 100 ppm. Calculate the volume of bleach that must be added, per meter of water standing in the well, to 10-, 15-, and 25-cm diameter wells.
- 2.3 Choose a local water system (e.g., a municipal system) and determine the source of its water and all of the treatment processes it uses. Are the treatment processes dependent on the season of the year? If so, why and how?
- 2.4 The Secchi disk depth for a lake was measured at 1.8 m. What are the trophic status and the TSI for the lake?
- 2.5 Estimate the time required for sand (0.05-1 mm), silt (0.002-0.05 mm), and clay (<0.002 mm) particles to settle to the bottom of a 2-m deep settling basin. Use Stokes's Law (Equation 9.14), assuming spherical particles with the density of quartz (2.65 g/cm³).
- 2.6 Calculate the energy required per liter to distill water, assuming the source water is at 20°C and there is no energy recovery. Assuming an energy cost of \$0.10 per kilowatt-hour, estimate the daily cost for a household of four if it had to distill 1000 L/day for all of its domestic needs.
- 2.7 Search the EPA STORET database to find water quality data for your area. Report the location, types of data available, and periods of record.