Chapter 3
Water Pollution

Although people now intuitively relate filth to disease, the transmission of disease by pathogenic organisms in polluted water was not recognized until the middle of the nineteenth century. The Broad Street pump handle incident demonstrated dramatically that water can carry diseases.

A British public health physician named John Snow, assigned to control the spread of cholera, noticed a curious concentration of cholera cases in one part of London. Almost all of the people affected drew their drinking water from a community pump in the middle of Broad Street. However, people who worked in an adjacent brewery were not affected. Snow recognized that the brewery workers' apparent immunity to cholera occurred because the brewery drew its water from a private well and not from the Broad Street pump (although the immunity might have been thought due to the health benefits of beer). Snow's evidence convinced the city council to ban the polluted water supply, which was done by removing the pump handle so that the pump was effectively unusable. The source of infection was cut off, the cholera epidemic subsided, and the public began to recognize the public health importance of drinking water supplies.

Until recently, polluted drinking water was seen primarily as a threat to public health because of the transmission of bacterial waterborne disease. In less developed countries, and in almost any country in time of war, it still is. In the United States and other developed countries, however, water treatment and distribution methods have almost eradicated bacterial contamination. Most surface water pollution is harmful to aquatic organisms and causes possible public health problems (primarily from contact with the water). Groundwater can be contaminated by various hazardous chemical compounds that can pose serious health risks. In this chapter we discuss the sources of water pollution and the effect of this pollution on streams, lakes, and oceans.

SOURCES OF WATER POLLUTION

Water pollutants are categorized as *point source* or *nonpoint source*, the former being identified as all dry weather pollutants that enter watercourses through pipes or channels. Storm drainage, even though the water may enter watercourses by way of pipes or channels, is considered nonpoint source pollution.

Other nonpoint source pollution comes from farm runoff, construction sites, and other land disturbances, discussed further in Chapter 10.

Point source pollution comes mainly from industrial facilities and municipal wastewater treatment plants. The range of pollutants is vast, depending only on what gets "thrown down the drain."

Oxygen-demanding substances, such as might be discharged from milk processing plants, breweries, or paper mills, as well as municipal wastewater treatment plants, make up one of the most important types of pollutant because these materials decompose in the watercourse and can deplete the water's oxygen and create anaerobic conditions. *Suspended solids* also contribute to oxygen depletion; in addition, they create unsightly conditions and can cause unpleasant odors. *Nutrients*, mainly nitrogen and phosphorus, can promote accelerated eutrophication, and some *bioconcentrated metals* can adversely affect aquatic ecosystems as well as make the water unusable for human contact or consumption.

Heat is also an industrial waste that is discharged into water; heated discharges may drastically alter the ecology of a stream or lake. Although local heating can have beneficial effects such as freeing harbors from ice, the primary effect is deleterious: lowering the solubility of oxygen in the water, because gas solubility in water is inversely proportional to temperature, and thereby reducing the amount of dissolved oxygen (DO) available to gill-breathing species. As the level of DO decreases, metabolic activity of aerobic aquatic species increases, thus increasing oxygen demand.

Municipal wastewater is as important a source of water pollution as industrial waste. A century ago, most discharges from municipalities received no treatment whatsoever. Since that time, the population and the pollution contributed by municipal discharge have both increased, but treatment has increased also. We define a *population equivalent* of municipal discharge as equivalent to the amount of untreated discharge contributed by a given number of people. For example, if a community of 20,000 people has 50% effective sewage treatment, the population equivalent is

$$(0.5)(20{,}000) = 10{,}000$$

Similarly, if each individual contributes 0.2 lb solids/day into wastewater, and an industry discharges 1000 lb/day, the industry has a population equivalent of 1000/0.2, or 5000 persons.

The sewerage systems in older U.S. cities have aggravated the wastewater discharge situation. When these cities were first built, engineers realized that sewers were necessary to carry off both stormwater and sanitary wastes, and they usually designed a single system to carry both discharges to the nearest appropriate body of water. Such systems are known as *combined sewers*. As years passed, city populations increased, and the need for sewage treatment became apparent, *separate sewer* systems were built: one system to carry sanitary sewage to the treatment facility and the other to carry off stormwater runoff.

Almost all of the cities with combined sewers have built treatment plants that can treat *dry weather flow*—the sanitary wastes when there is no stormwater runoff. As long as it does not rain, the plants can handle the flow and provide sufficient treatment; however, rain increases the flow to many times the dry weather flow, and most of it must be bypassed directly into a river, lake, or bay. The overflow will contain sewage as well as stormwater, and can be a significant pollutant to the receiving water. Attempts to capture and store the excess flow for subsequent treatment are expensive, but the cost of separating combined sewer systems is prohibitive.

Agricultural wastes, should they flow directly into surface waters, have a collective population equivalent of about 2 billion. Feedlots where large numbers of animals are penned in relatively small spaces provide an efficient way to raise animals for food. They are usually located near slaughterhouses and thus near cities. Feedlot drainage (and drainage from intensive poultry cultivation) creates an extremely high potential for water pollution. Aquaculture has a similar problem because wastes are concentrated in a relatively small space.

Sediment from land erosion may also be classified as a pollutant. Sediment consists of mostly inorganic material washed into a stream as a result of land cultivation, construction, demolition, and mining operations. Sediment interferes with fish spawning because it can cover gravel beds and block light penetration, making food harder to find. Sediment can also damage gill structures directly.

Pollution from petroleum compounds ("oil pollution") first came to public attention with the *Torrey Canyon* disaster in 1967. The huge tanker, loaded with crude oil, plowed into a reef in the English Channel, even though maps showed the submerged reefs. Despite British and French attempts to burn it, almost all of the oil leaked out and fouled French and English beaches. Eventually, straw to soak up the oil and detergents to disperse it helped remove the oil from the beaches, but the detergents were found to be the cleanup method more harmful to the coastal ecology.

By far the most notorious recent incident has been the *Exxon Valdez* spill in Prince William Sound in Alaska. Oil in Alaska is produced in the Prudhoe Bay region in northern Alaska and piped down to the tanker terminal in Valdez on the southern coast. On 24 March 1989, the *Exxon Valdez*, a huge oil tanker loaded with crude oil, veered off course and hit a submerged reef, spilling about 11 million gallons of oil into Prince William Sound, devastating the fragile ecology. About 40,000 birds died, including about 150 bald eagles. The final toll on wildlife will never be known, but the effect of the spill on the local fishing economy can be calculated, and it exceeds $100 million. The cleanup by Exxon cost about $2 billion.

While oil spills as large as the *Exxon Valdez* spill get a lot of publicity, it is estimated that there are about 10,000 serious oil spills in the United States every year, and many more minor spills from routine operations that do not make headlines. The effect of some of these spills may never be known.

The acute effect of oil on birds, fish, and microorganisms is well catalogued. The subtle effects of oil on other aquatic life is not so well understood and is potentially more harmful. For example, anadromous fish such as salmon, which find their home stream by the smell or taste of the water, can become so confused by the presence of strange hydrocarbons that they will refuse to enter their spawning stream.

Acid mine drainage has polluted surface waters since the beginning of ore mining. Sulfur-laden water leaches from mines, including old and abandoned mines as well as active ones, and contains sulfur compounds that oxidize to sulfuric acid on contact with air. The resulting acidity of the stream or lake into which this water drains is often high enough to kill the aquatic ecosystem.

The effects of water pollution can be best understood in the context of an aquatic ecosystem, by studying one or more specific interactions of pollutants with that ecosystem.

ELEMENTS OF AQUATIC ECOLOGY

Plants and animals in their physical environment make up an *ecosystem*. The study of ecosystems is *ecology*. Although we often draw lines around a specific ecosystem to be able to study it more fully (e.g., a farm pond) and thereby assume that the system is completely self-contained, this is obviously not true. One of the tenets of ecology is that "everything is connected with everything else."

Three categories of organism make up an ecosystem. The *producers* take energy from the sun and nutrients like nitrogen and phosphorus from the soil and produce high-energy chemical compounds by the process of photosynthesis. The energy from the sun is stored in the molecular structure of these compounds. Producers are often referred to as being in the first *trophic* (growth) level and are called *autotrophs* by the *heterotrophs*.

The second category of organism in an ecosystem is the *consumers*, who use the energy stored by photosynthesis by ingesting the high-energy compounds. Consumers in the second trophic level use the energy of the producers directly. There may be several more trophic levels of consumers, each using the level below it as an energy source. A simplified ecosystem showing various trophic levels is illustrated in Figure 3–1, which also shows the progressive use of energy through the trophic levels.

The third category of organism, the *decomposers* or decay organisms, use the energy in animal wastes and dead animals and plants, thereby converting the organic compounds to stable inorganic compounds. The residual inorganics (e.g., nitrates) are then nutrients for the producers, with the sun as the source of energy.

Ecosystems exhibit a flow of both energy and nutrients. Energy flow is in only one direction: from the sun and through each trophic level. Nutrient flow, on the other hand, is cyclic: Nutrients are used by plants to make high-energy molecules that are eventually decomposed to the original inorganic nutrients, ready to be used again.

The entire food web, or ecosystem, stays in dynamic balance, with adjustments being made as required. This balance is called *homeostasis*. For example, a drought may produce little grass, starving field mice and exposing them to predators like owls.

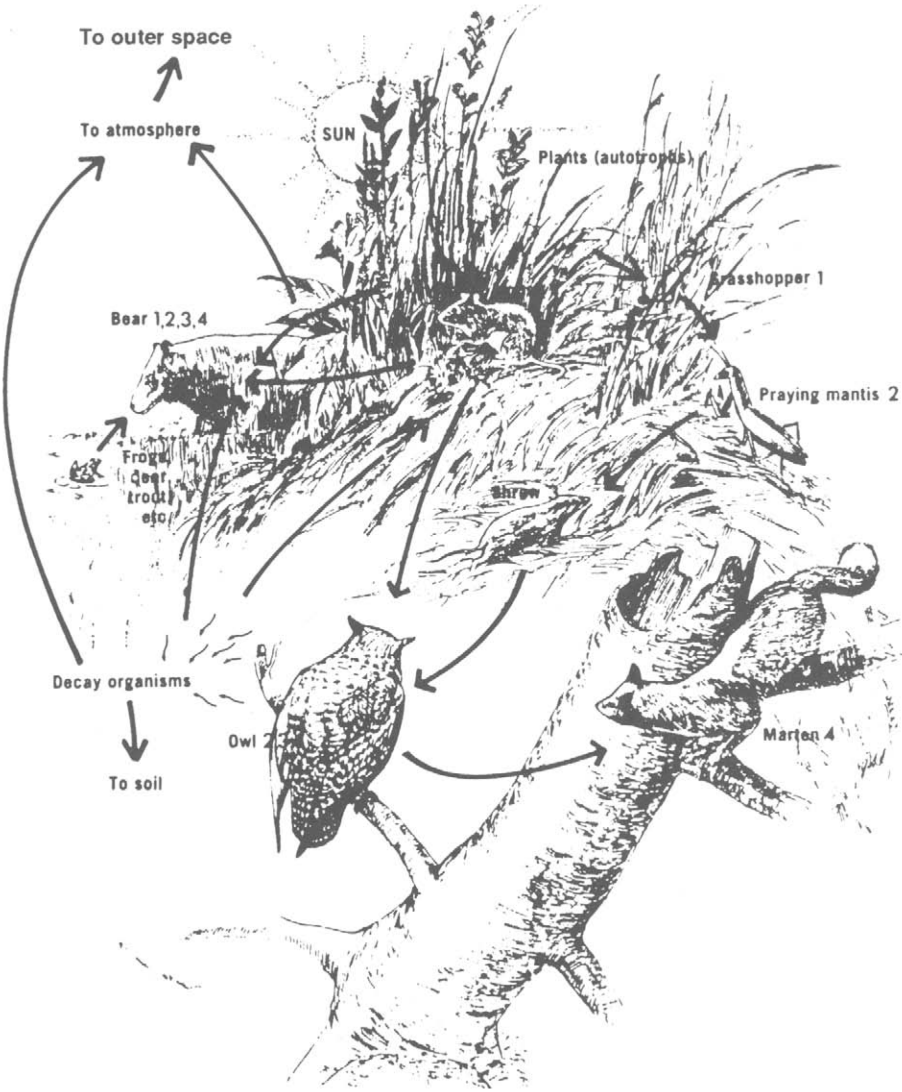

FIGURE 3–1. A typical terrestrial ecosystem. The numbers refer to trophic level above the autotrophic, and the arrows show progressive loss of energy. [From Turk, A., et al., *Environmental Science*, Philadelphia: W.B. Saunders (1974). Used with permission.]

The field mice spend more time inside their burrows, eat less, and thus allow the grass to reseed for the following year. External perturbations may upset and even destroy an ecosystem. In the previous example, use of a herbicide to kill the grass (instead of merely thinning it) might also destroy the field mouse population, since the mice would be more exposed to predatory attack.

Once the field mice, the source of food for the predatory owls, are gone, the owls eventually starve also and the ecosystem collapses.

Most ecosystems can absorb a certain amount of damage, but sufficiently large perturbations may cause irreversible damage. The ongoing attempt to limit the logging of old growth forests in the Pacific Northwest is an attempt to limit the damage to the forest ecosystem to what it can accommodate. The amount of perturbation a system can absorb is related to the concept of the *ecological niche*. The combination of function and habitat of an organism in an ecosystem is its niche. A niche is an organism's best accommodation to its environment. In the example given previously, if there are two types of grass that the mice could eat, and the herbicide destroys only one, the mice would still have food and shelter, and the ecosystem could survive. This simple example illustrates another important ecological principle: The stability of an ecosystem is proportional to the number of organisms capable of filling various niches. A jungle is a more stable ecosystem than the Alaskan tundra, which is very fragile. Another fragile system is that of the deep oceans, a fact that must be considered before the oceans are used as waste repositories.

Inland waterways tend to be fairly stable ecosystems, but are certainly not totally resistant to destruction by outside perturbations. Other than the direct effect of toxic materials like metals and refractory organic compounds, the most serious effect on inland waters is depletion of dissolved (free) oxygen (DO). All higher forms of aquatic life exist only in the presence of oxygen, and most desirable microbiologic life also requires oxygen. Natural streams and lakes are usually *aerobic* (containing DO). If a watercourse becomes *anaerobic* (absence of oxygen), the entire ecology changes and the water becomes unpleasant and unsafe. The DO concentration in waterways and the effect of pollutants are closely related to the concept of decomposition and biodegradation, part of the total energy transfer system that sustains life.

BIODEGRADATION

Plant growth, or photosynthesis, may be represented by the equation

$$CO_2 + H_2O \xrightarrow[\text{nutrients}]{\text{sunlight}} HCOH + O_2 \qquad (3.1)$$

In this representation formaldehyde (HCOH) and oxygen are produced from carbon dioxide and water, with sunlight as the source of energy and chlorophyll as a catalyst.[1] If the formaldehyde-oxygen mixture is ignited, it explodes, and the energy released in the explosion is the energy that was stored in the hydrogen-oxygen bonds of formaldehyde.

[1]Of course, formaldehyde is not the usual end product of photosynthesis, but is given here as an example of both how organic molecules are formed in photosynthesis and how the energy stored in it may be recovered.

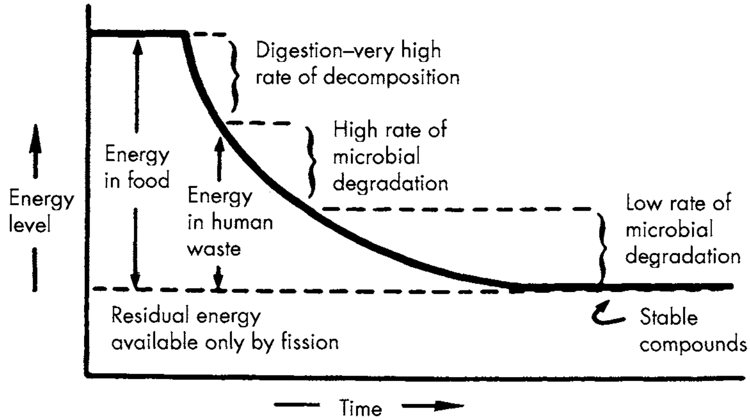

FIGURE 3–2. Energy loss in biodegradation. [Adapted from McGauhey, P.H., *Engineering Management of Water Quality*, New York: McGraw-Hill (1968).]

As discussed above, plants (producers) use inorganic chemicals as nutrients and, with sunlight as an energy source, build high-energy compounds. Consumers eat and metabolize (digest) these compounds, releasing some of the energy for the consumer to use. The end products of metabolism (excrement) become food for decomposers and are degraded further, but at a much slower rate than metabolism. After several such steps, very low energy compounds remain that can no longer be used by microorganism decomposers as food. Plants then use these compounds to build more high-energy compounds by photosynthesis, and the process starts over. The process is shown symbolically in Figure 3–2.

Many organic materials responsible for water pollution enter watercourses at a high energy level. The biodegradation, or gradual use of energy, of the compounds by a chain of organisms causes many water pollution problems.

AEROBIC AND ANAEROBIC DECOMPOSITION

Decomposition or biodegradation may take place in one of two distinctly different ways: aerobic (using free oxygen) and anaerobic (in the absence of free oxygen). If formaldehyde could decompose aerobically, the equation for decomposition would be the reverse of Equation 3.2, or

$$HCOH + O_2 \rightarrow CO_2 + H_2O + \text{energy} \qquad (3.2)$$

Generally, the basic equation for *aerobic decomposition* of complex organic compounds of the form $C_xH_yN_z$ is

$$\left(\frac{3x + y + z}{2}\right)O_2 + C_xH_yN_z \rightarrow xCO_2 + \frac{y}{2}H_2O + zNO + \text{products} \qquad (3.3)$$

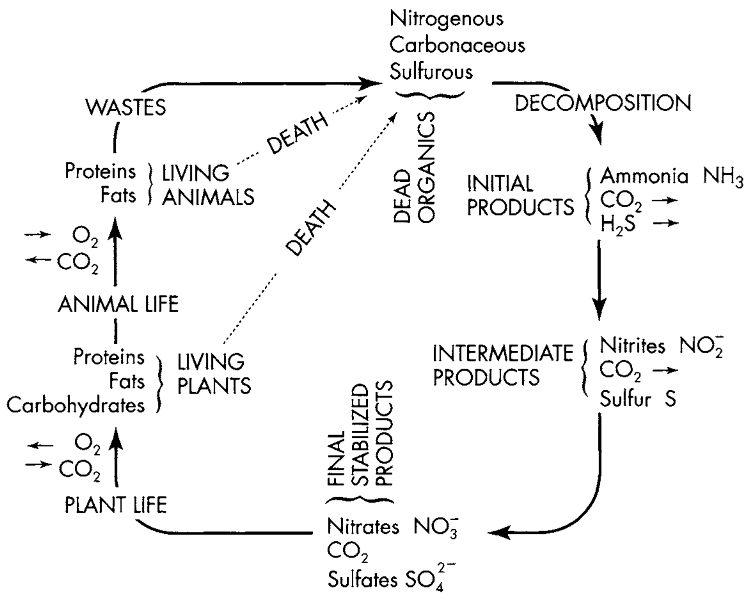

FIGURE 3–3. Aerobic nitrogen, carbon, and sulfur cycles. [Adapted from McGauhey, P.H., *Engineering Management of Water Quality*, New York: McGraw-Hill (1968).]

Carbon dioxide and water are always two of the end products of aerobic decomposition. Both are stable, low in energy, and used by plants in photosynthesis (plant photosynthesis is a major CO_2 sink for the earth). Sulfur compounds (like the mercaptans in mammal excrement) are oxidized to SO_4^{2-}, the sulfate ion, and phosphorus is oxidized to PO_4^{3-}, orthophosphate. Nitrogen is oxidized through a series of compounds ending in nitrate, in the progression

$$\text{Organic nitrogen} \rightarrow NH_3 \text{ (ammonia)} \rightarrow NO_2^- \text{ (nitrite)} \rightarrow NO_3^- \text{ (nitrate)}$$

Because of this distinctive progression, nitrogen has been, and still is, used as an indicator of water pollution. A schematic representation of the aerobic cycle for carbon, sulfur, and nitrogen is shown in Figure 3–3. This figure shows only the basic phenomena and greatly simplifies the actual steps and mechanisms.

Anaerobic decomposition is performed by a completely different set of microorganisms, to which oxygen is toxic. The basic equation for anaerobic biodegradation is

$$C_xH_yN_z \rightarrow CO_2 + CH_4 + NH_3 + \text{partly stable compounds} \tag{3.4}$$

Many of the end products of the reaction are biologically unstable. Methane (CH_4), for example, a high-energy gas commonly called marsh gas,[2] is physi-

[2]When methane is burned as a fossil fuel it is called "natural gas."

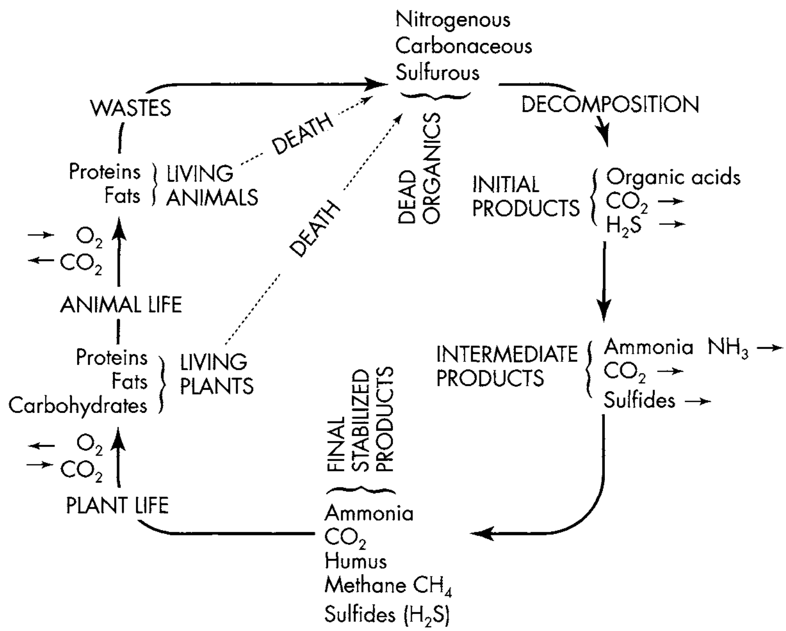

FIGURE 3–4. Anaerobic nitrogen, carbon, and sulfur cycles. [Adapted from McGauhey, P.H., *Engineering Management of Water Quality*, New York: McGraw-Hill (1968).]

cally stable but can be decomposed biologically. Ammonia (NH_3) can be oxidized, and sulfur is anaerobically biodegraded to evil-smelling sulfhydryl compounds like hydrogen sulfide (H_2S). Figure 3–4 is a schematic representation of anaerobic decomposition. Note that the left half of the cycle, photosynthesis by plants, is identical to the aerobic cycle.

Biologists often speak of certain compounds as hydrogen acceptors. When energy is released from high-energy compounds a C-H or N-H bond is broken and the freed hydrogen must be attached somewhere. In aerobic decomposition, oxygen serves the purpose of a hydrogen scavenger or hydrogen acceptor and forms water. In anaerobic decomposition, oxygen is not available. The next preferred hydrogen acceptor is NH_3, since in the absence of oxygen ammonia cannot be oxidized to nitrite or nitrate. If no appropriate nitrogen compound is available, sulfur accepts hydrogen to form H_2S, the compound responsible for the notorious rotten egg smell.

EFFECT OF POLLUTION ON STREAMS

When a high-energy organic material such as raw sewage is discharged to a stream, a number of changes occur downstream from the point of discharge. As the organic components of the sewage are oxidized, oxygen is used at a greater rate than upstream from the sewage discharge, and the DO in the stream decreases markedly. The rate of reaeration, or solution of oxygen from the air, also increases, but is often not great enough to prevent a total depletion of oxygen in the stream. When the stream DO is totally depleted, the stream is said to become anaerobic. Often, however, the DO does not drop to zero and the stream recovers without a period of anaerobiosis. Both of these situations are depicted graphically in Figure 3–5. The dip in DO is referred to as a *dissolved oxygen sag curve.*

The dissolved oxygen sag curve can be described mathematically as a dynamic balance between the use of oxygen by the microorganisms (deoxygenation) and the supply of oxygen from the atmosphere (reoxygenation). The mathematical derivation of the oxygen sag curve is included in the appendix to this chapter.

Stream flow is of course variable, and the critical DO levels can be expected to occur when the flow is the lowest. Accordingly, most state regulatory agencies base their calculations on a statistical low flow, such as a 7-day, 10-year low flow: the seven consecutive days of lowest flow that may be expected to occur once in ten years. This is calculated by first estimating the lowest 7-day flow for each year and then assigning ranks: m = 1 for the least flow (most severe) to m = n for the greatest flow (least severe), where n is the number of years considered. The probability of occurrence of a flow equal to or more than a particular low flow is

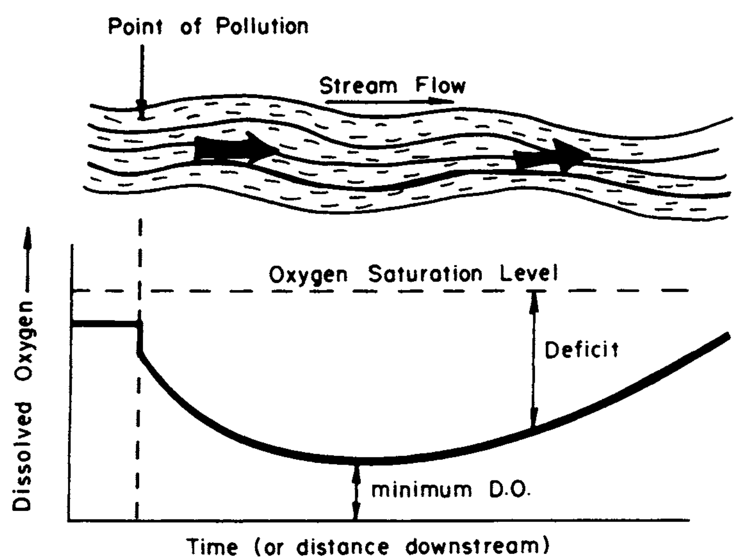

FIGURE 3–5. Dissolved oxygen downstream from a source of organic pollution. The curve shows a DO sag without anaerobic conditions.

$$P = \frac{m}{n + 1} \tag{3.5}$$

and is graphed against the flow. The 10-year low flow is then read from the graph at m/(n + 1) = 0.1.

Example 3.1

Calculate the 10-year, 7-day low flow given the data below.

Year	*Lowest Flow 7 Consecutive Days (m^3/s)*	*Ranking (m)*	*m/(n + 1)*	*Lowest Flow in Order of Severity (m^3/s)*
1965	1.2	1	1/14 = 0.071	0.4
1966	1.3	2	2/14 = 0.143	0.6
1967	0.8	3	3/14 = 0.214	0.6
1968	1.4	4	4/14 = 0.285	0.8
1969	0.6	5	5/14 = 0.357	0.8
1970	0.4	6	6/14 = 0.428	0.8
1971	0.8	7	7/14 = 0.500	0.9
1972	1.4	8	8/14 = 0.571	1.0
1973	1.2	9	9/14 = 0.642	1.2
1974	1.0	10	10/14 = 0.714	1.2
1975	0.6	11	11/14 = 0.786	1.3
1976	0.8	12	12/14 = 0.857	1.4
1977	0.9	13	13/14 = 0.928	1.4

These data are plotted in Figure 3–6, and the minimum 7-day, 10-year low flow is read at m/(n + 1) = 0.1 as 0.5 m^3/s.

When the rate of oxygen use overwhelms the rate of oxygen resupply, the stream may become anaerobic. An anaerobic stream is easily identifiable by the presence of floating sludge and bubbling gas. The gas is formed because oxygen is no longer available to act as the hydrogen acceptor, and ammonia, hydrogen sulfide, and other gases are formed. Some of the gases formed dissolve in water, but others can attach themselves as bubbles to sludge (solid black or dark benthic deposits) and buoy the sludge to the surface. In addition, the odor of H_2S will advertise the anaerobic condition for some distance, the water is usually black or dark, and fungus grows in long slimy filaments that cling to rocks and gracefully wave streamers downstream.

The outward evidence of an anaerobic stream is accompanied by adverse effects on aquatic life. Types and numbers of species change drastically downstream from the pollution discharge point. Increased turbidity, settled solid

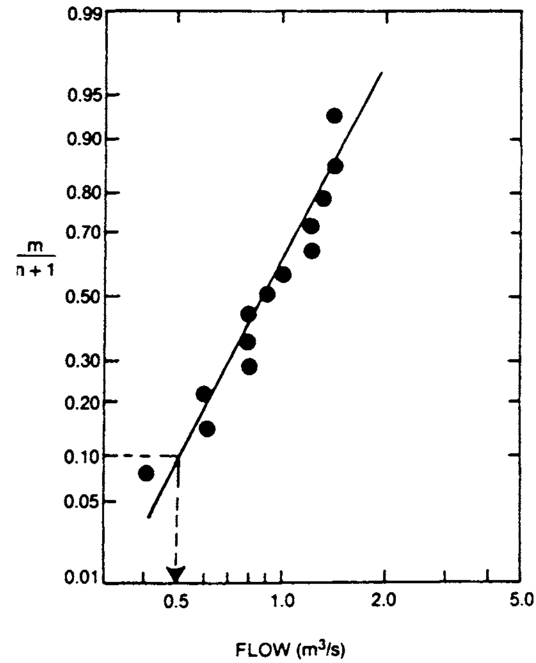

FIGURE 3–6.
Plot of 10-year, 7-day low flows for Example 3.1

matter, and low DO all contribute to a decrease in fish life. Fewer and fewer species of fish are able to survive, but those that do find food plentiful and often multiply in large numbers. Carp and catfish can survive in waters that are quite foul and can even gulp air from the surface. Trout, on the other hand, need very pure, cold, oxygen-saturated water and are notoriously intolerant of pollution.

Numbers of other aquatic species are also reduced, and the remaining species like sludge worms, bloodworms, and rat-tailed maggots abound, often in staggering numbers—as many as 50,000 sludge worms per square foot.

Figure 3–7 illustrates the distribution of both species and numbers of organisms downstream from a source of pollution. The diversity of species may be quantified by an index, such as

$$d = \sum_{i=1}^{S} \left(\frac{n_i}{n}\right) \log_{10}\left(\frac{n_i}{n}\right) \qquad (3.6)$$

where d = diversity index
n_i = number of individuals in the ith species
n = total number of individuals in all S species

Table 3–1 shows the results of a study in which the diversity index was calculated above and below a sewage outfall.

These reactions of a stream to pollution occur when a rapidly decomposable organic material is the waste. The stream will react much differently to in-

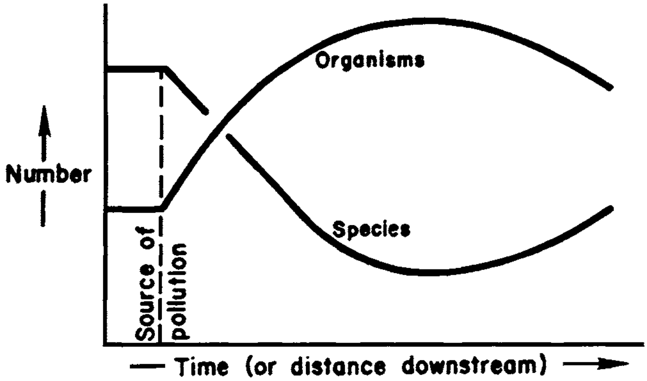

FIGURE 3–7. The number of species and the total number of organisms downstream from a point of organic pollution

TABLE 3–1. Diversity of Aquatic Organisms

Location	*Diversity Index (d)*
Above the outfall	2.75
Immediately below the outfall	0.94
Downstream	2.43
Further downstream	3.80

organic waste, as from a metal-plating plant. If the waste is toxic to aquatic life, both the kind and total number of organisms will decrease below the outfall. The DO will not fall and might even rise. There are many types of pollution, and a stream will react differently to each (Figure 3–8). When two or more wastes are involved the situation is even more complicated.

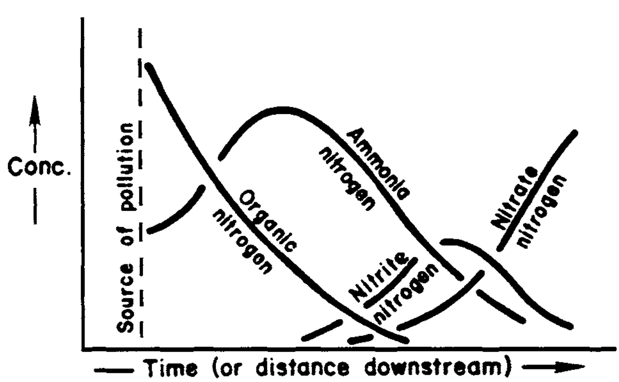

FIGURE 3–8
Typical variations in nitrogen compounds downstream from a point of organic pollution

EFFECT OF POLLUTION ON LAKES

The effect of pollution on lakes differs in several respects from the effect on streams. Light and temperature have significant influences on a lake, more so than on a stream, and must be included in any limnological[3] analysis. Light is the source of energy in the photosynthetic reaction, so that the penetration of light into the lake water is important. This penetration is logarithmic; for example, at a depth of 1 foot the light intensity may be 10,000 ft-candles (a measure of light intensity); at a depth of 2 feet, it might be 1000 ft-candles; at 3 feet, 100 ft-candles, and at 4 feet, 10 ft-candles. Light usually penetrates only the top two feet of a lake; hence, most photosynthetic reactions occur in that zone.

Temperature and heat can have a profound effect on a lake. Water is at a maximum density at 4°C; water both colder and warmer than this is less dense, and therefore ice floats. Water is also a poor conductor of heat and retains it quite well.

Lake water temperature usually varies seasonally. Figure 3–9 illustrates these temperature-depth relationships. During the winter, assuming that the lake does not freeze, the temperature is often constant with depth. As the weather warms in spring, the top layers begin to warm. Since warmer water is less dense, and water is a poor conductor of heat, a distinct temperature gradient known as *thermal stratification* is formed. These strata are often very stable and last through the summer months. The top layer is called the *epilimnion*; the middle, the *metalimnion*; and the bottom, the *hypolimnion*. The inflection point in the curve is called the *thermocline*. Circulation of water occurs only within a zone, and thus there is only limited transfer of biological or chemical material (including DO) across the boundaries. As the colder weather approaches, the top layers begin to cool, become more dense, and sink. This creates circulation within the lake, known as *fall turnover*. A spring turnover may also occur.

The biochemical reactions in a natural lake may be represented schematically as in Figure 3–10. A river feeding the lake would contribute carbon, phosphorus, and nitrogen, either as high-energy organics or as low-energy compounds. The *phytoplankton* or *algae* (microbial free-floating plants) take C, P, and N and, using sunlight as a source of energy, make high-energy compounds. Algae are eaten by *zooplankton* (tiny aquatic animals), which are in turn eaten by larger aquatic life such as fish. All of these life forms defecate, contributing a pool of *dissolved organic carbon*. This pool is further fed by the death of aquatic life. Bacteria use dissolved organic carbon and produce CO_2, in turn used by algae. CO_2 in addition to that dissolved directly is provided from the respiration of the fish and zooplankton, as well as the CO_2 dissolved directly from the air.

The supply of C, P, and N coming into an unpolluted lake is small enough to limit algae production, and productivity of the entire ecological system is limited. When large amounts of C, P, and N are introduced into the lake, however, they promote uncontrolled growth of algae in the epilimnion, since the algae can

[3]Limnology is the study of lakes.

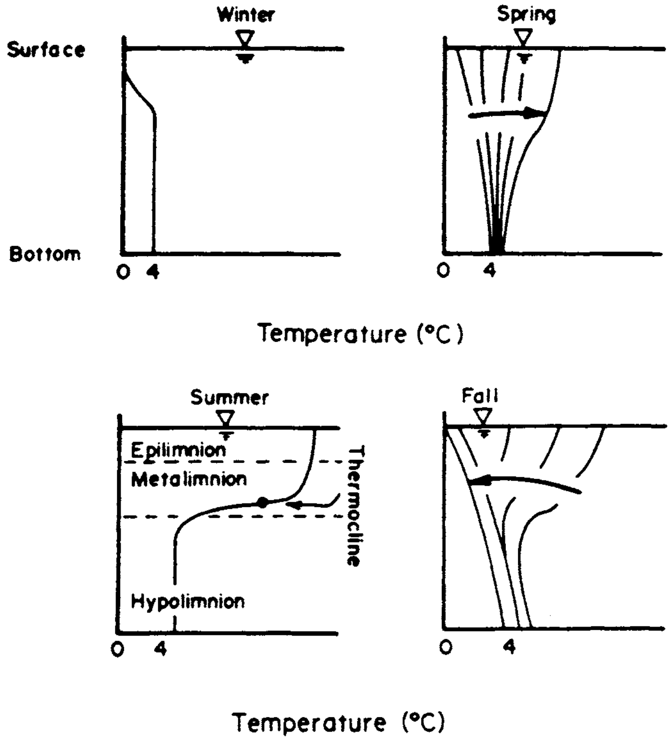

FIGURE 3–9. Typical temperature-depth relationships

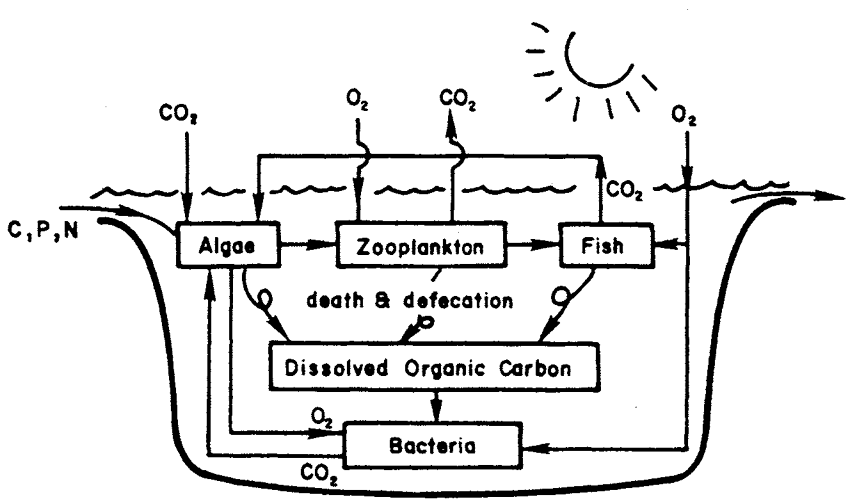

FIGURE 3-10. Schematic representation of lake ecology [Courtesy of Donald Francisco.]

assimilate nutrients very rapidly. When the algae die, they drop to the lake bottom (the hypolimnion) and become a source of carbon for decomposing bacteria. Aerobic bacteria will use all available DO in decomposing this material, and DO may thereby be depleted enough to cause the hypolimnion to become anaerobic. As more and more algae die, and more and more DO is used in their decomposition, the metalimnion may also become anaerobic, and aerobic biological activity would be concentrated in the upper few feet of the lake, the epilimnion.

The aerobic biological activity produces turbidity, decreasing light penetration and in turn limiting photosynthetic algal activity in the surface layers. The amount of DO contributed by the algae is therefore decreased. Eventually, the epilimnion also becomes anaerobic, all aerobic aquatic life disappears, and the algae concentrate on the lake surface because there is only enough light available for photosynthesis. The algal concentration forms large green mats, called *algal blooms*. When the algae in these blooms die and ultimately fill up the lake, a peat bog is formed.

The entire process is called *eutrophication*. It is the continually occurring natural process of lake aging and occurs in three stages:

- The *oligotrophic* stage, during which both the variety and number of species grow rapidly.
- The *mesotrophic* stage, during which a dynamic equilibrium exists among species in the lake.
- The *eutrophic* stage, during which less complex organisms take over and the lake appears to become gradually choked with weeds.

Natural eutrophication may take thousands of years. If enough nutrients are introduced into a lake system, as may happen as a result of human activity, the eutrophication process may be shortened to as little as a decade. The addition of phosphorus, in particular, can speed eutrophication, since phosphorus is often the *limiting nutrient* for algae: the particular nutrient that limits algal growth. The limiting nutrient for a system is that element the system requires the smallest amount of; consequently, growth depends directly on the amount of that nutrient.[4]

Where do these nutrients originate? One source is excrement, since all human and animal wastes contain C, N, and P. Synthetic detergents and fertilizers are a much greater source. About half of the phosphorus in U.S. lakes is estimated to come from agricultural runoff; about one-fourth, from detergents; and the remaining one-fourth, from all other sources. It seems unfortunate that the presence of phosphates in detergents has received so much unfavorable attention when runoff from fertilized land is a much more important source of P.

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[4]The addition of a limiting nutrient acts for algal growth much as stepping on the gas pedal limits the speed of your car. All of the components are available to make the car go faster, but it can't speed up until you "give it more gas." The gas pedal is a constraint, or limit, against higher speed. Dumping excess phosphorus into a lake is like floorboarding the gas pedal.