Chapter 2

WATER POLLUTION

2.1 Introduction

Although people 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 could carry diseases. In 1854, a public health physician named John Snow, assigned to try 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 understand the importance of having clean drinking water supplies.

Until recently, water pollution was viewed primarily as a threat to human health because of the transmission of bacterial and viral waterborne diseases. In less developed countries, and in almost any country in time of war, waterborne diseases remain a major public health threat. In the United States and other developed countries, however, water treatment and distribution methods have almost eradicated microbial contamination in drinking water. We now recognize that water pollution constitutes a much broader threat and continues to pose serious health risks to the public as well as aquatic life. In this chapter we discuss the sources of water pollution and the effect of this pollution on streams, lakes and oceans.

2.2 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 agricultural runoff, construction sites, and other land disturbances. 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, compose one of the most important types of pollutants because these materials decompose in the watercourse and can deplete the water of dissolved oxygen.
- Sediments and suspended solids may also be classified as a pollutant. Sediments consists of mostly inorganic material washed into a stream as a result of land cultivation, construction, demolition, and mining operations. Sediments interfere with fish spawning because they can cover gravel beds and block light penetration, making food harder to find. Sediments can also damage gill structures directly, smothering aquatic insects and fishes. Organic sediments can deplete the water of oxygen, creating anaerobic (without oxygen) conditions, and may create unsightly conditions and cause unpleasant odors.
- Nutrients, mainly nitrogen and phosphorus, can promote accelerated eutrophication, or the rapid biological "aging" of lakes, streams, and estuaries. Phosphorus and nitrogen are common pollutants in residential and agricultural runoff, and are usually associated with plant debris, animal wastes, or fertilizer. Phosphorus and nitrogen are also common pollutants in municipal wastewater discharges, even if the wastewater has received conventional treatment. Phosphorus adheres to inorganic sediments and is transported with sediments in storm runoff. Nitrogen tends to move with organic matter or is leached from soils and moves with groundwater.
- Heat may be classified as a water pollutant when it is caused by heated industrial effluents or from anthropogenic (human) alterations of stream bank vegetation that increase the stream temperatures due to solar radiation. Heated discharges may drastically alter the ecology of a stream or lake. Although localized heating can have beneficial effects like freeing harbors from ice, the ecological effects are generally deleterious. Heated effluents lower the solubility of oxygen in the water because gas solubility in water is inversely proportional to temperature, thereby reducing the amount of dissolved oxygen available to aerobic (oxygen-dependent) species. Heat also increases the metabolic rate of aquatic organisms (unless the water temperature gets too high and kills the organism), which further reduces the amount of dissolved oxygen because respiration increases.

- Municipal wastewater often contains high concentrations of organic carbon, phosphorus, and nitrogen, and may contain pesticides, toxic chemicals, salts, inorganic solids (e.g., silt), and pathogenic bacteria and viruses. 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 of 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 or 10,000. Similarly, if each individual contributes 0.2 lb of solids per day into wastewater, and an industry discharges 1,000 lb/day, the industry has a population equivalent of 1,000/0.2, or 5,000.
- Agricultural wastes that flow directly into surface waters have a collective population equivalent of about two billion. Agricultural wastes are typically high in nutrients (phosphorus and nitrogen), biodegradable organic carbon, pesticide residues, andfecal coliform bacteria (bacteria that normally live in the intestinal tract of warm-blooded animals and indicate contamination by animal wastes). Feedlots where large numbers of animals are penned into 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. Even relatively low densities of animals can significantly degrade water quality if the animals are allowed to trample the stream bank, or runoff from manure-holding ponds is allowed to overflow into nearby waterways. Both surface and groundwater pollution are common in agricultural regions because of the extensiveness of fertilizer and pesticide application.
- 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. Despite British and French attempts to burn the oil, almost all of it leaked out and fouled French and English beaches. Eventually, straw was used to soak up the oil and detergents were applied to disperse the oil (detergents were later found to be harmful to the coastal ecology).

- Acids and bases from industrial and mining activities can alter the water quality in a stream or lake to the extent that it kills the aquatic organisms living there, or prevent them from reproducing. Acid mine drainage has polluted surface waters since the beginning of ore mining. Sulfur-laden water leached from mines, including old and abandoned mines as well as active ones, contains compounds that oxidize to sulfuric acid on contact with air. Deposition of atmospheric acids originating in industrial regions has caused Lake Acidification throughout vast areas of Canada, Europe, and Scandinavia.

Synthetic organics and pesticides can adversely affect aquatic ecosystems as well as making the water unusable for human contact or consumption. These compounds may come from point source industrial effluents or from nonpoint source agricultural and urban runoff. 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.

2.3 Effect of Pollution on Streams

The effect of pollution on streams depends on the type of pollutant. Some compounds are acutely toxic to aquatic life (e.g., heavy metals), and will cause dead zones downstream from the pollutant source. Some types of pollutants are health concerns to humans, but have little impact on stream communities. For example, coliform bacteria are an indicator of animal waste contamination, and are therefore an important human health concern, but most aquatic organisms are not harmed by the presence of coliforms. One of the most common types of stream pollutants is the introduction of biodegradable organic material. When a high-energy organic material such as raw sewage is discharged into 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 rate greater than that upstream from the sewage discharge, and the dissolved oxygen in the stream decreases markedly. The rate of reaeration, or solution of oxygen from the air, also increases, but is often not enough to prevent total depletion of oxygen in the stream. If the dissolved oxygen is totally depleted, the stream becomes anaerobic. Often, however, the dissolved oxygen does not drop to 0 and the stream recovers without a period of anaerobiosis. Both of these situations are depicted graphically in Figure 2.1. The dip in dissolved oxygen is referred to as a dissolved oxygen sag curve. In the Figure 2.1, curve *A* depicts an oxygen sag

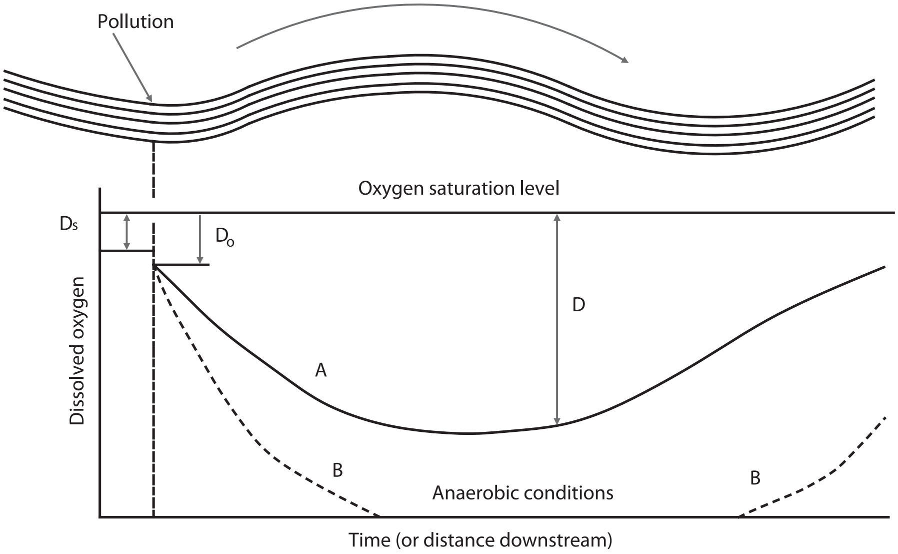

Figure 2.1: **Dissolved oxygen downstream from a source of organic pollution**

without anaerobic conditions; curve B shows an oxygen sag curve when pollution is concentrated enough to create anaerobic conditions, D_o is the oxygen deficit in the stream after the stream has mixed with the pollutant, and D, is the oxygen deficit of the upstream water.

The effect of a biodegradable organic waste on a stream's oxygen level may be estimated mathematically. Let $z(t)$ = the amount of oxygen still required at time t, in milligrams per liter (mg/L), and k'_1 = the deoxygenation constant, in days^{-1}.

The deoxygenation constant k_1' will depend on the type of waste, the temperature, the stream velocity, etc. The rate of change of z over time is proportional to k_1':

$$\frac{d}{dt} z(t) = k'_1 \, z(t) \tag{2.1}$$

This differential equation has a simple solution:

$$z(t) = L_o e^{-k'_1 t} \tag{2.2}$$

where L_o is the ultimate carbonaceous oxygen demand, in milligrams per liter (mg/L), or the amount of oxygen needed to degrade the carbonaceous organic material in the wastewater at the point where the effluent first enters into and mixes with the stream. This equation is plotted in Figure. 2.2 for various values of k_1', and with L_0 = 30 mg/L. Since the ultimate oxygen requirement is L_o and the amount of oxygen still needed at any given time is *z*,

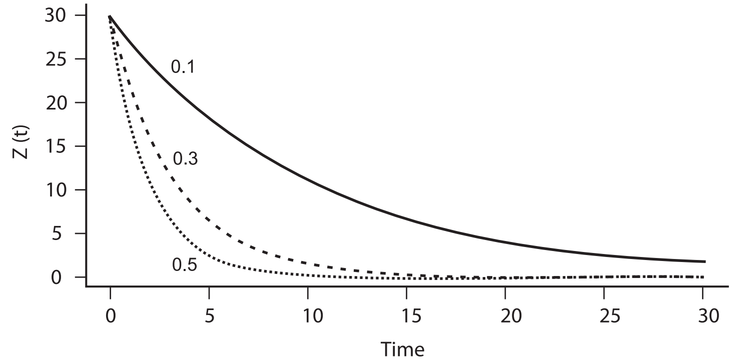

Figure 2.2: Amount of oxygen required at any time t(z(t)) for various deoxygenation constants (q) when the ultimate carbonaceous oxygen demand (L_o) is 30 mg/L

the amount of oxygen used after time *t*, the biochemical oxygen demnd (BOD), is simply the difference between L_0 and $z(t)$:

$$BOD(t) = L_o - z(t) = L_o(1 - e^{-k'_1 t}) \qquad 2.3$$

This relationship is plotted in Figure 2.3, and it can be seen that the BOD asymptotically approaches *Lo* as time passes. Contrasting with this increase in BOD over time is the reoxygenation of the stream by natural forces. This will depend on the difference between the current amount of dissolved oxygen, and the maximum amount of oxygen the water can hold at saturation. In other words, if *d* is the actual amount of dissolved oxygen in the water, and d_s is the amount of dissolved oxygen at saturation, then *d*

$$\frac{d}{dt} d(t) = k'_2(d_s - d(t)) = k'_2\, D(t) \qquad 2.4$$

where *D (t)* is the oxygen deficit at time *t*, in milligrams per liter (mg/L), and k_1' is the reoxygenation constant, in days^{-1}.

The value of k_2' is obtained by studying the stream using a tracer. If this cannot be done, a generalized expression (O'Connor 1966) may be used

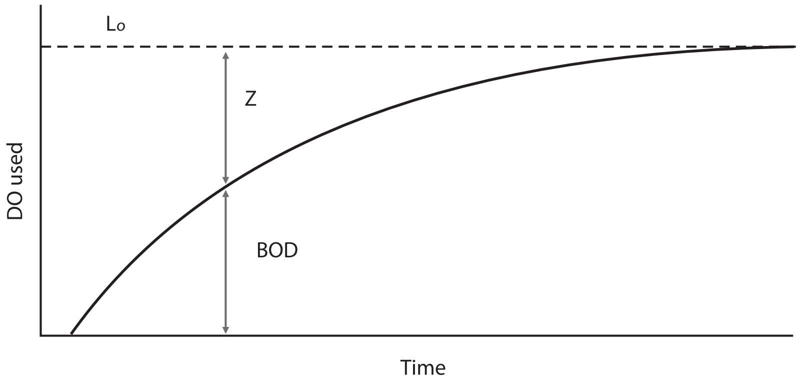

Figure 2.3: Dissolved oxygen used (BOD) at any time *t* plus the dissolved oxygen still needed at time *t(z(t))* is equal to the ultimate oxygen demand (L_o)

$$k'_2 = \frac{3.9v^{1/2}\sqrt{(1.037)^{(T-20)}}}{H^{3/2}} \tag{2.5}$$

where, T is the temperature of the water in degrees Celsius, H is the average depth of flow in meters, and v is the mean stream velocity in meters per second (m/s). Alternatively, k_2' values may be estimated from a table like Table 2.1. For a stream loaded with organic material, the simultaneous deoxygenation and reoxygenation of the water forms the dissolved oxygen sag curve, first developed by Streeter and Phelps in 1925 (Streeter and Phelps 1925). The shape of the oxygen sag curve, as shown in Figure 2.4, is the sum of the rate of oxygen use and the rate of oxygen supply. Immediately, downstream from a source of organic pollution the rate of use will often exceed the rearation rate and the dissolved oxygen concentration will fall sharply. As the discharged organic matter is oxidized, and fewer high-energy organic compounds are left, the rate of use will decrease, the supply will begin to catch up with the use, and the dissolved oxygen will once again reach saturation.

Table 2.1: Reaeration constants

Type of watercourse	k_2' at 20° C[a] (days^{-1})
Small ponds or backwaters	0.10-0.23
Sluggish streams	0.23-0.35
Large streams, low velocity	0.35-0.46
Large streams, normal velocity	0.46-0.69
Swift streams	0.69-1.15
Rapids	>1.15

[a] For temperatures other than 20°C, $k_2'(T) = k_2'(20°C)(1.024)^{T-20}$.

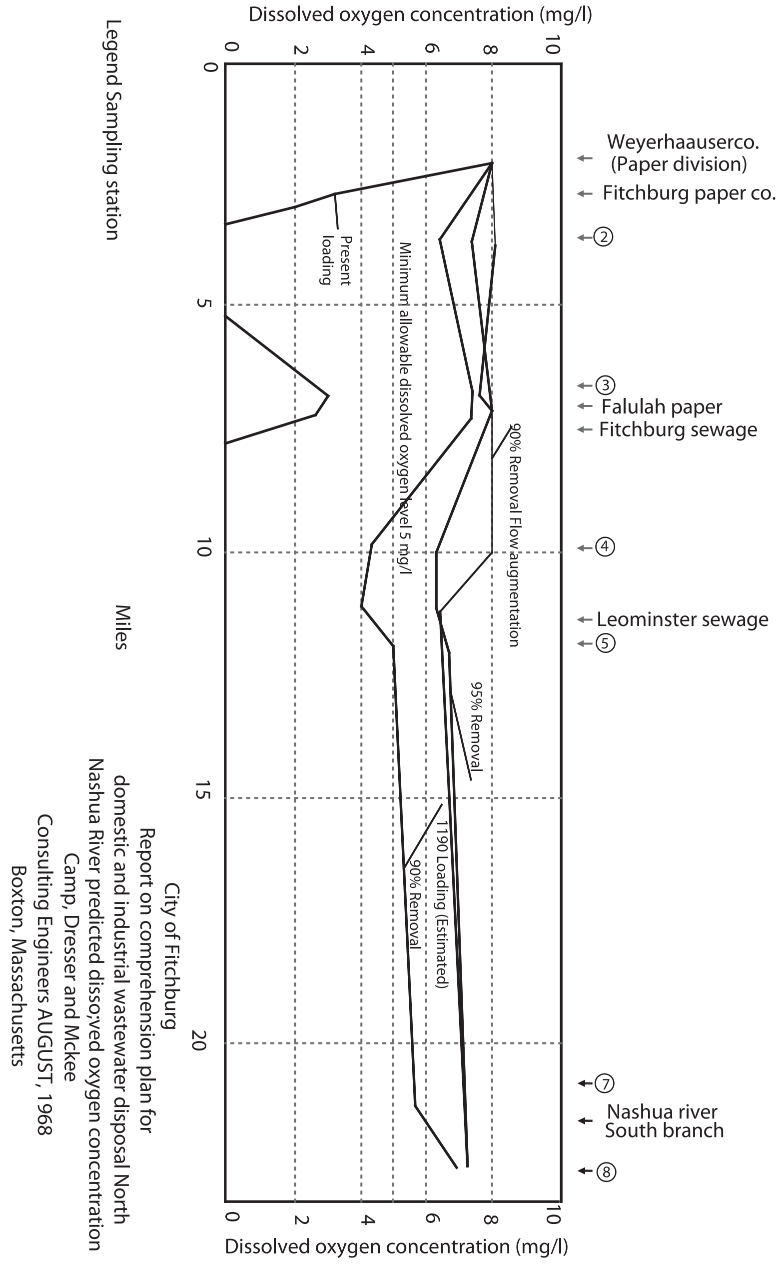

Figure 2.4: **Example of dissolved oxygen sag (going to 0; anaerobic conditions) and the projected dissolved oxygen sag if various types of wastewater treatment are provided.**

Source: Adapted from E.C. (1975)

This may be expressed mathematically as:

$$\frac{d}{dt}D(t) = k'_1\, z(t) - k'_2\, D(t) \qquad 2.6$$

which can be solved to give:

$$D(t) = \frac{k'_1 L_o}{k'_2 - k'_1}\left(e^{-k'_1 t} - e^{-k'_2 t}\right) + D_o\, e^{-k'_2 t} \qquad 2.7$$

Where D_o is the initial oxygen deficit in the stream at the point of wastewater discharge, after the stream flow has mixed with the wastewater, in milligrams per liter (mg/L).

The deficit equation can also be expressed in common logarithms:

$$D = \frac{k_1 L_o}{k_2 - k_1}\left(10^{-k_1 t} - 10^{-k_2 t}\right) + D_o 10^{-k_2 t} \qquad 2.8$$

Since:

$e^{-k't} = 10^{-kt}$ when $k = 0.043k'$

The initial oxygen deficit (Do) is calculated as a flow-weighted proportion of the initial stream oxygen deficit and the wastewater oxygen deficit:

$$D_o = \frac{D_s Q_s + D_p Q_p}{Q_s + Q_P} \qquad 2.9$$

where D_s is the oxygen deficit in the stream directly upstream from the point of discharge, in milligrams per liter (mg/L); Q_s is the stream flow upstream from the wastewater discharge, in cubic meters per second (m^3/s); D_p is the oxygen deficit in the wastewater being added to the stream, in milligrams per liter (mg/L); and Q_p is the flow rate of wastewater, in cubic meters per second (m^3/s). Similarly, the ultimate carbonaceous BOD (L_0) is:

$$L_o = \frac{L_s Q_s + L_p Q_p}{Q_s + Q_P} \qquad 2.10$$

where L_s is the ultimate BOD in the stream immediately upstream from the point of wastewater discharge, in milligrams per liter (mg/L); Q_s is the stream flow upstream from the wastewater discharge, in cubic meters per second (m^3/s); L_p is the ultimate BOD of the wastewater, in milligrams per liter (mg/L); and Q_p is the flow rate of the wastewater, in cubic meters per second (m^3/s). The most serious water quality concern is the downstream location where the oxygen deficit will be the greatest, or where the dissolved oxygen concentration is the lowest. By setting $dD/dt = 0$, we can solve for the time when this minimum dissolved oxygen occurs, the critical time, as

$$t_c = \frac{1}{k'_2 - k'_1} \ln\left[\frac{k'_2}{k'_1}\left(1 - \frac{D_o(k'_2 - k'_1)}{k'_1 L_o}\right)\right] \qquad 2.11$$

Where t_c is the time downstream when the dissolved oxygen concentration is the lowest. An example of dissolved oxygen sag curve is shown in Figure. 2.4. Note that the stream becomes anaerobic at about mile 3.5, recovers, and then drops back to 0 after receiving effluents from a city and a paper mill.

Example 2.1: Assume that a large stream has a reoxygenation constant k_1' of 0.4/day, a flow velocity of 5 miles/h, and at the point of pollutant discharge, the stream is saturated with oxygen at 10 mg/L. The wastewater flow rate is very small compared with the stream flow, so the mixture is assumed to be saturated with dissolved oxygen and to have an oxygen demand of 20 mg/L. The deoxygenation constant k_1' is 0.2/day. What is the dissolved oxygen level 30 miles downstream?

Solution:

Stream velocity = 5 miles/h, hence it takes 30/5 or 6 h to travel 30 miles. Therefore, t = 6 h/24 h/day = 0.25 day, and $D_o = 0$ because the stream is saturated.

$$D = \frac{(0.2)(20)}{0.4 - 0.2}\left(e^{-(0.2)(0.25)} - e^{-(0.4)(0.25)}\right) = 1.0 mg / L$$

The dissolved oxygen 30 miles downstream will be the saturation level minus the deficit, or 10 - 1.0 = 9.0 mg/L

Stream flow is variable, of course, and the critical dissolved oxygen levels can be expected to occur when the flow is the lowest. Accordingly, most regulatory agencies base their calculations on a statistical low flow, such as a 7-day, 10-year low flow: the 7 consecutive days of lowest flow that may be expected to occur once in 10 years. This is calculated by first estimating the lowest 7-day flow for each year, 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 greater than or equal to a particular low flow is

$$P = \frac{m}{n+1} \qquad 2.12$$

Example 2.2:

Calculate the 7-day, 10-year 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 serverity (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

Solution:

When P is graphed against the flow using probability paper, the result is often a straight line (log-probability sometimes gives a better fit). The 10-year low flow can be estimated from the graph at $m/(n + 1) = 0.1$ (or 1 year in 10). The data from Example 2.2 are plotted in Figure 2.5; the minimum 7-day, 10-year low flow is estimated to be 0.5 m^3/s

When the rate of oxygen use overwhelms the rate of oxygen reaeration, the stream may become anaerobic. An anaerobic stream is easily identifiable by the presence of floating sludge, bubbling gas, and a foul smell. The gas is formed because oxygen is no longer available to act as the hydrogen acceptor, and NH_3, H_2S, and other gases are formed. Some of the gases dissolve in water, but others

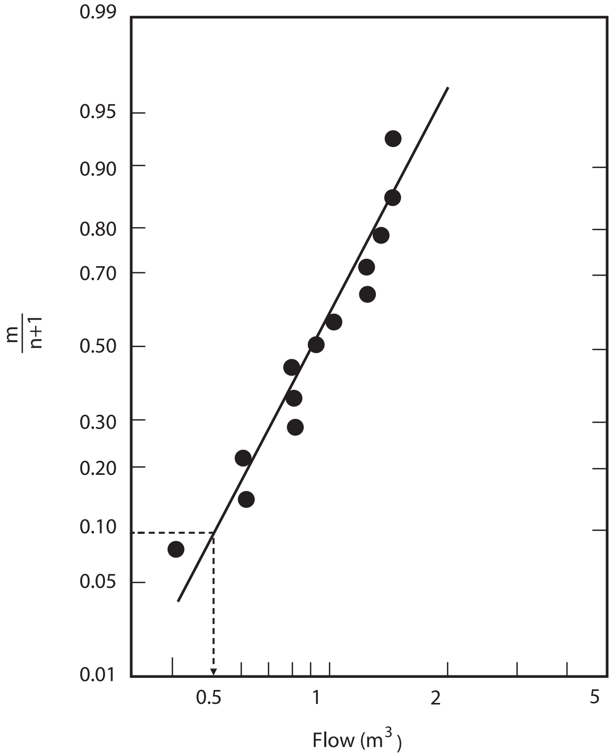

Figure 2.5: Plot of 7-day, 10-year low flows, for Example 2.2.

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 filamentous bacteria (sewage "fungus") grow in long slimy filaments that cling to rocks and wave graceful streamers downstream.

Other adverse effects on aquatic life accompany the unpleasant physical appearance of an anaerobic stream. The types and numbers of species change drastically downstream from the pollution discharge point. Increased turbidity, settled solid matter, and low dissolved oxygen all contribute to a decrease in fish life. Fewer and fewer species of fish are able to survive, but those species that do survive find food plentiful, and often multiply in large numbers. Carp and catfish can survive in water that is 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. The numbers of other aquatic species are also reduced under anaerobic conditions, as shown in Figure 2.6. 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. The diversity of species may be quantified by using an index, such as the Shannon-Weaver diversity index (Shannon and Weaver 1949).

$$H' = \sum_{i=1}^{s} \left(\frac{n_i}{n}\right) \times \ln\left(\frac{n_i}{n}\right) \qquad 2.13$$

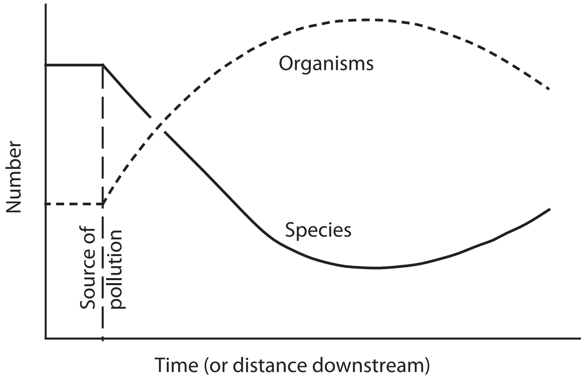

Figure 2.6: **The number of species and the total number of organisms downstream from a point of organic pollution.**

where H' is the diversity index, n_i is the number of individuals in the i_{th} species, and n is the total number of individuals in all S species. Diversity indices can be quite difficult to interpret because they are composed of two different measurements: species richness (how many different kinds of organisms are present?) and species equitability (how evenly are the individuals distributed among the species?). One way to overcome this problem is to convert the diversity index into an equitability index, such as Pielou's J (E.C 1975):

$$J = \frac{H'}{\ln S} \qquad 2.14$$

Pielou's J is a measure of how close H' is to its maximum value for any given sample, approaching 1.0 at maximum equitability. Although still widely used for general comparisons, both H' and J have been replaced with more complex indices that take into account the relative abundance of pollution-tolerant or intolerant species. Table 2.2 shows a simplified example of biotic diversity and

Table 2.2: **Diversity and equitability of aquatic organisms**

Species	**Pollution tolerance**	**No. of individuals in samples**	
		Upstream from outfall	**Downstream from outfall**
Mayfiles	Intolerant	20	5
Rat-tailed maggots	Tolerant	0	500
Trout	Intolerant	5	0
Crap	Tolerant	1	20
	Diversity (H') =	0.96	0.22
	Equitability (J) =	0.87	0.20

equitability upstream and downstream from a pollution outfall. As mentioned earlier, nitrogen compounds may be used as indicators of pollution. The changes in the various forms of nitrogen with distance downstream are shown in Figure 2.7. The first transformation, in both aerobic and anaerobic decomposition, is the formation of ammonia; thus the concentration of ammonia increases as organic nitrogen decreases. As long as the stream remains aerobic, the concentration of nitrate will increase to become the dominant form of nitrogen.

These reactions of a stream to pollution occur when a rapidly decomposable organic material is the waste. The stream will react much differently to inorganic 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 downstream from the outfall.

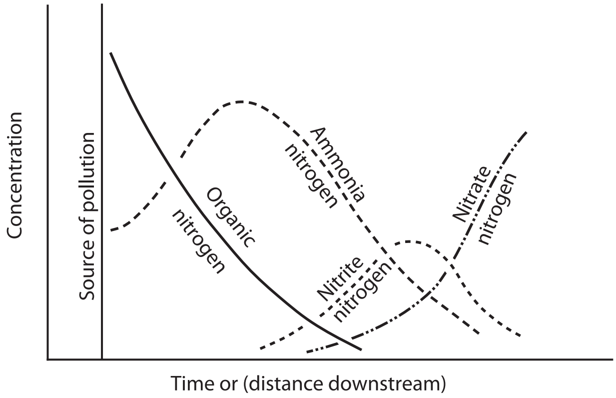

Figure 2.7: **Typical variations in nitrogen compounds downstream from a point of organic pollution.**

The dissolved oxygen will not fall, and might even rise. There are many types of pollution, and a stream will react differently to each. When two or more wastes are involved, the situation is even more complicated.

Box 2.1

River pollution of Bangladesh

River water is considered polluted when it is altered from the natural state in its physical, chemical and microbiological composition and when its suitability for any safe and beneficial use becomes questionable. The signs of physical water contamination may become obvious through bad taste, offensive odours, unchecked growth of aquatic weeds, decrease in the number of aquatic animals, floating of oil and grease, colouration of water and so on. However, more intensive laboratory testing is required to determine the chemical and microbiological water quality parameters such as pH (to measure the level of acidity or alkalinity), dissolved oxygen, biological and/or chemical oxygen demand, phosphorus and nitrogen ion concentration, dissolved solids, heavy metals, salinity, coliform bacteria count and so forth.

Generally, our rivers are being polluted by the discharge of untreated industrial effluent and urban wastewater, agrochemicals, sewage water, storm runoff, solid waste dumping, oil spillage, sedimentation and encroachment. The water quality also depends on effluent types and discharge quantity from different types of industries, types of agrochemicals used in agriculture, and seasonal water flow and dilution capability by the river system. The river Buriganga is a typical example of serious surface water pollution in our country. In the present scenario this river carries only wastewater during the months (November to April) of the dry season becoming toxic during this period. The level of pollution is so high that no aquatic species can survive in it and the situation is getting worse day by day. Test results during the dry season at eight points along the river found the level of dissolved oxygen within 0.6 to 1.8 mg/l at five points and zero at other points. The requisite level of oxygen is more than 5 mg/l for the survival of aquatic lives. In fact, the Buriganga has become a dumping ground of all kinds of solid, liquid and chemical wastes which are generated by the activities in and around the river. Studies show that up to 18,500 cubic metres of liquid wastes, 19,000 kilograms of solid wastes and 17,600 kilograms of biological oxygen demand load go into the Buriganga each day from these sources. The Bangladesh

Inland Water Transport Authority sources confirmed that huge quantities of discarded polythene deposits are unearthed near Sadarghat area during dredging.

The pollution problem of our rivers have become complex because of its multidimensional nature. There are social, economic, political and environmental dimensions to this issue which need to be addressed simultaneously while attempting a sustainable solution to the problem. It is a mammoth challenge for developing countries like Bangladesh where a speedy economic growth is requisite without compromising with the conservation of the natural environment or endangering the livelihood of a particular community such as the fishermen or the farmers.

Source: Adpated from (EnergyBangla 2011)

2.4 Effect of Pollution on Lakes

The effect of pollution on lakes differs in several respects from the effect on streams. Water movement in lakes is slower than in streams, so reaeration is more of a problem in lakes than streams. Because of the slow movement of water in a lake, sediments, and pollutants bound to sediments, tend to settle out of the water column rather than being transported downstream. Light and temperature have important influences on a lake, and must be included in any *limnological* analysis (limnology is the study of lakes). Light is the source of energy in the photosynthetic reaction, so the penetration of light into the lake water determines the amount of photosynthesis that can occur at various depths in the lake. Light penetration is logarithmic and a function of wavelength. Short wavelengths (blue, ultraviolet) penetrate farther than long wavelengths (red, infrared). Light penetration at all wavelengths is less in lakes with high concentrations of dissolved organic matter. In pristine lakes, 60-80% of the incident blue/UV light, and 10-50% of the red/IR may penetrate beyond the first 3 ft; in *humic* (boggy) lakes, the presence of large amounts of organic matter causes 90-99% of all wavelengths to be absorbed within the first 3 ft. Because of this, algal growth is concentrated near the surface of a lake, in the photic zone, which is limited to the maximum depth where there is still enough light to support photosynthesis. Temperature and heat often have a profound effect on a lake. Water is at a maximum density at 4°C; warmer or colder water (including ice) is less dense, and will float. Water is also a poor conductor of heat and retains heat quite well.

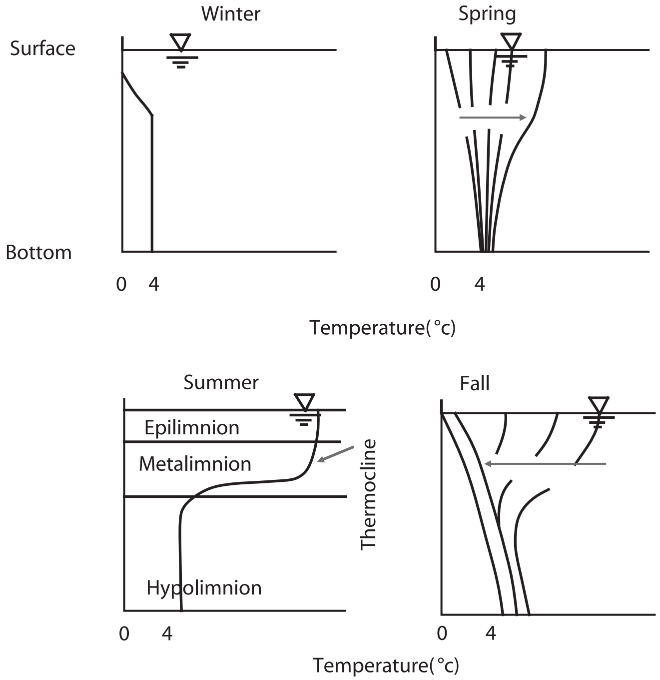

Figure 2.8: **Typical temperature depth relationships in lakes**

Lake water temperature usually varies seasonally (Figure 2.8). During the winter, if the lake does not freeze, the temperature is relatively constant with depth. As the weather warms in the spring the top layers of water begin to warm. Since wanner water is less dense, and water is a poor conductor of heat, the lake eventually stratifies into a warm, less dense, surface layer called the *epilimnion* and a cooler, denser, bottom layer, the *hypolimnion*. A thermal gradient, the *metalimnion*, is present between these two layers. The inflection point in the temperature gradient is called the *thermocline* (early limnologists used "thermocline" to describe the entire thermal gradient). Circulation of water occurs only within a stratum, and thus there is only limited transfer of biological or chemical material (including dissolved oxygen) between the *epilimnion* and the *hypolimnion*. As colder weather approaches, the top layer cools, becomes denser, and sinks. This creates circulation within the lake, known as fall turnover. If the lake freezes over in the winter, the lake surface temperature will be less than 4°C, and the ice will float on top of the slightly denser (but still cold) underlying water. When spring comes, the lake surface will warm slightly and there will be a spring turnover as the ice thaws. The biochemical reactions in a natural lake are represented schematically in Figure 2.9. A river feeding the lake would contribute carbon, phosphorus, and nitrogen, either as high-energy organics or as low-energy compounds. The phytoplankton (free-floating algae) take carbon, phosphorus and nitrogen and using sunlight as an energy source, 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 or excrete waste products, contributing a pool of dissolved organic carbon. This pool is further fed by the death of aquatic life and by the near-constant leakage of soluble organic compounds from algae into the water. Bacteria use dissolved organic carbon and produce carbon dioxide, which is in turn used by algae. Carbon dioxide is also provided by respiration of fish and zooplankton, as well as dissolving into the water directly from the air.

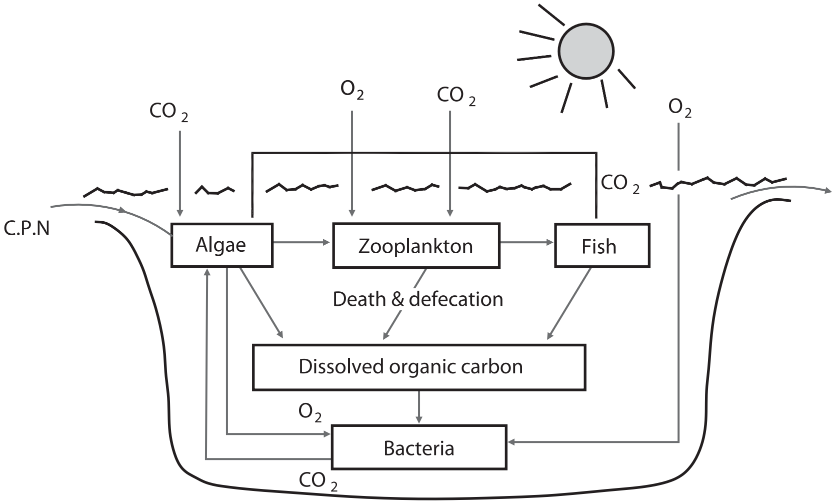

Figure 2.9: **Schematic representation of lake ecology.**

The growth of algae in most lakes is limited by the availability of phosphorus; if phosphorus is in sufficient supply, nitrogen is usually the next limiting *nutrient*. (A limiting nutrient is an essential element or compound that controls the rate of algal growth because the nutrient is not readily available.) Some algal species have special growth requirements that result in co-limitation by other nutrients (e.g., silica is required for diatom growth). When phosphorus and nitrogen are introduced into the lake, either naturally from storm runoff, or from a pollution source, the nutrients promote rapid growth of algae in the epilimnion. 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 dissolved oxygen in the process of decomposing this material, and the dissolved oxygen may be depleted enough to cause the hypolimnion to become anaerobic. As more and more algae die, and more and more dissolved oxygen is used in their decomposition, the metalimnion may also become anaerobic. When this occurs arobic biological activity is restricted to the epilimnion. The increasing frequency of this condition over the years is called eutrophication. Eutrophication is the continually occurring natural process of lake aging and occurs in three stages:

- the oligotrophic stage, which is characterized by low levels of biological productivity and high levels of oxygen in the hypolimnion;
- the mesotrophic stage, which is characterized by moderate levels of biological productivity and the beginnings of declining oxygen levels following lake stratification; and
- the eutrophic stage, at which point the lake is very productive, with extensive algal blooms, and increasingly anaerobic conditions in the hypolimnion.

Natural eutrophication may take thousands of years. If enough nutrients are introduced into a lake system, as may happen as aresult of human activity, the eutrophication process may be shortened to as little as a decade. Because phosphorus is usually the nutrient that limits algal growth in lakes, the addition of phosphorus, in particular, can speed eutrophication. If only phosphorus is introduced into a lake, it will cause some increase in algal growth, but nitrogen quickly becomes a limiting factor for most species of algae. One group of photosynthetic organisms, however, is uniquely adapted to take advantage of high phosphorus concentrations: the *cyanobacteria*, or blue green "algae." Cyanobacteria are autotrophic bacteria that can store excess phosphorus inside their cells in a process called *luxury consumption*. The bacteria use the excess phosphorus to support future cell growth (up to about 20 cell divisions). The cyanobacteria also have the ability to use dissolved N_2 gas as a nitrogen source, which is rapidly replenished by atmospheric N_2. Most other aquatic autotrophs cannot use N_2 as a nitrogen source. As a result, cyanobacteria thrive in environments where nitrogen has become limiting to other algae, and can sustain their growth using cellular phosphorus for long periods of time. Not surprisingly, cyanobacteria are often water quality indicators of phosphorus pollution.

Where do these nutrients originate? One source is excrement, since all human and animal wastes contain organic carbon, nitrogen, and phosphorus. 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. Phosphate concentrations between 0.01 and 0.1 mg/L appear to be enough to accelerate eutrophication. Sewage treatment plant effluents may contain 5-10 mg/L of phosphorus as phosphate, and ariver draining farm country may carry 1-4 mg/L. Residential and urban runoff may carry up to 1 mg/L, mostly from pet wastes, detergents, and fertilizer. In moving water, the effects of elevated phosphorus are usually not apparent because the algae are continually flushed out and do not accumulate. Eutrophication occurs mainly in lakes, ponds, estuaries, and sometimes in very sluggish rivers.

Typical profiles in a lake for a number of parameters are shown in Figure 2.10. It is found that a lake is warmer on top than at lower depths, how dissolved oxygen can drop to 0, and nitrogen and phosphorus are highly concentrated in the lake depths while algae bloom on the surface.

2.5 Effect of Pollution on Groundwater

A popular misconception is that all water that moves through the soil will be purified "naturally" and will emerge from the ground in a pristine condition. Unfortunately, there are limits to what soil can remove, and groundwater pollution is becoming an increasing concern throughout the world.

Many soils do have the ability to remove certain types of pollutants, including phosphorus, heavy metals, bacteria, and suspended solids. Pollutants that dissolve in water, like nitrate and ammonia, may pass through soils into the groundwater. In agricultural regions, the nitrogen and other soluble chemicals in fertilizers or animal wastes can seep into the groundwater and show up in alarmingly high concentrations in local drinking water wells. Recent study of the Abbotsford/Sumas aquifer (a water bearing zone of rock, sand, gravel, etc.), which supplies water to more than 100,000 people in the western portion of Canada and Washington, indicated that 40% of the wells tested had nitrate levels above 10 mg/L (EPA maximum recommended drinking water level), and 60% had nitrate levels above 3 mg/L (a general warning level for nitrate in drinking water). The agricultural community is becoming more aware of the connection between agricultural practices and groundwater pollution. Many countries have begun working with dairy owners and farmers to develop farm management

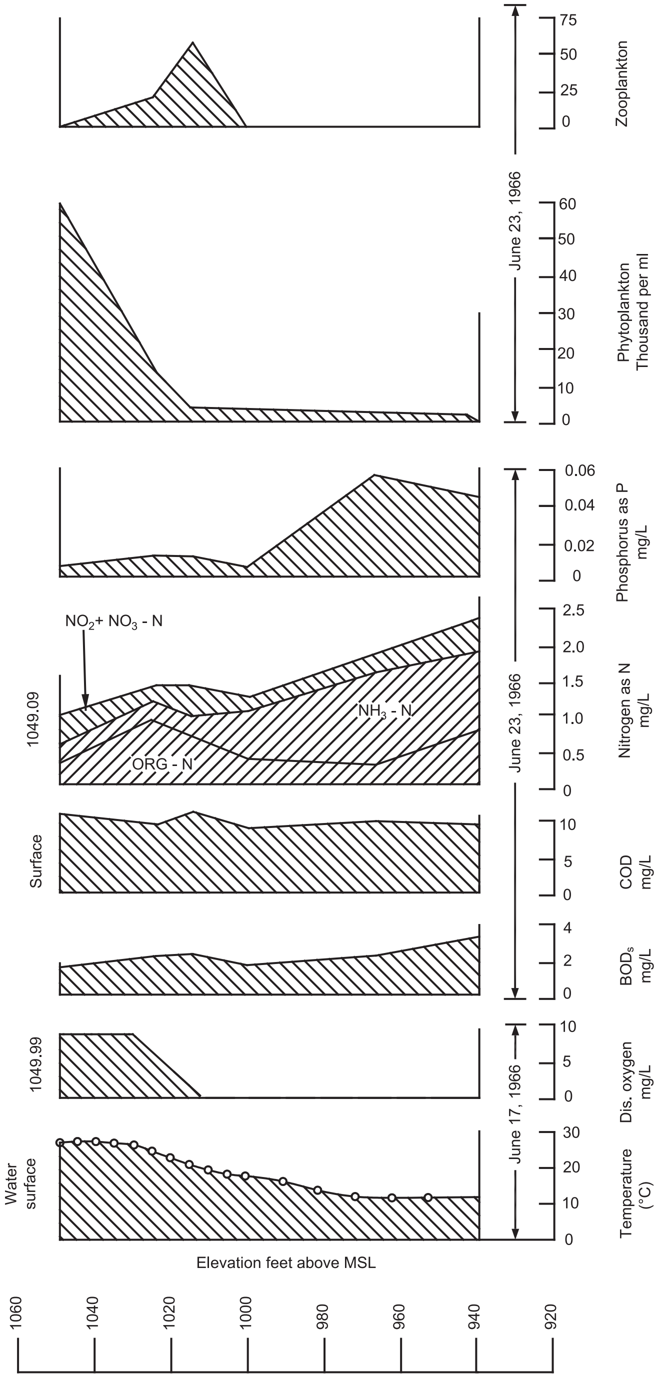

Figure 2.10: Water quality profiles for a water supply reservoir. (P. and Rudd. 1977)

plans that restrict fertilizer applications to periods of active plant growth, which helps prevent groundwater pollution by sequestering nitrate into growing vegetation. These farm plans also include surface water pollution prevention techniques such as restricting animal access to stream banks, setting maximum animal density goals, requiring manure-holding ponds, and revegetating riparian (stream side) areas. Other potential sources of groundwater pollution include leaking underground storage tanks, solid waste landfills, improperly stored hazardous waste, careless disposal of solvents and hazardous chemicals on ground surfaces, and road salts and deicing compounds.

2.6 Effect of Pollution on Oceans

Not many years ago, the oceans were considered infinite sinks; the immensity of the seas and oceans seemed impervious to assault. Now we know that the seas and oceans are fragile environments and we are able to measure detrimental effects. Ocean water is a complicated chemical solution, and appears to have changed very little over millions of years. Because of this constancy, however, marine organisms have become specialized and intolerant to environmental change. Oceans are thusfragile ecosystems, quite susceptible to pollution. A relief map of the ocean bottom reveals two major areas: the continental shelf and the deep oceans. The continental shelf, especially near major estuaries, is the most productive in terms of food supply. Because of its proximity to human activity, it receives the greatest pollution load. Many estuaries have become so badly polluted that they are closed to commercial fishing. The Baltic and Mediterranean Seas are in danger of becoming permanently damaged.

Ocean disposal of untreated wastewater is severely restricted in the United States, but many major cities all over the world still discharge untreated sewage into the ocean. Although the sewage is carried a considerable distance from shore by pipeline and discharged through diffusers to achieve maximum dilution, the practice remains controversial, and the long-term consequences are much in doubt. Even in the United States, most sewage effluents receive only secondary treatment, which is not effective at removing certain types of pollutants, including phosphorus.

Box 2.2

The Deepwater Horizon oil spill in the Gulf of Mexico

The Deepwater Horizon oil spill (also referred to as the BP oil spill, the Gulf of Mexico oil spill, the BP oil disaster, or the Macondo blowout) is an oil spill in the Gulf of Mexico which flowed for three months in 2010. It is the largest accidental marine oil spill in the history of the petroleum industry. The spill stemmed from a sea-floor oil gusher that resulted from the April 20, 2010, explosion of Deepwater Horizon.

The spill caused extensive damage to marine and wildlife habitats and to the Gulf's fishing and tourism industries. In late November 2010, 4,200 square miles (11,000 km^2) of the Gulf were re-closed to shrimping after tar balls were found in shrimpers' nets. The amount of Louisiana shoreline affected by oil grew from 287 miles (462 km) in July to 320 miles (510 km) in late November 2010. In January 2011, an oil spill commissioner reported that tar balls continue to wash up, oil sheen trails are seen in the wake of fishing boats, wetlands marsh grass remains fouled and dying, and that crude oil lies offshore in deep water and in fine silts and sands onshore. A research team found oil on the bottom of the seafloor in late February 2011 that did not seem to be degrading. Skimmer ships, floating containment booms, anchored barriers, sand-filled barricades along shorelines, and dispersants were used in an attempt to protect hundreds of miles of beaches, wetlands, and estuaries from the spreading oil. Scientists have also reported immense underwater plumes of dissolved oil not visible at the surface as well as an 80-square-mile (210 km^2) "kill zone" surrounding the blown well.

2.7 Heavy Metals and Toxic Substances

In 1970, Barry Commoner and other scientists alerted the nation to the growing problem of mercury contamination of lakes, streams, and marine waters. The manufacture of chlorine and lye from brine, called the chlor-alkali process, was identified as a major source of mercury contamination. Elemental mercury is methylated by aquatic organisms (usually anaerobic bacteria), and methylated mercury finds its way into fish and shellfish and thus into the human food chain. Methylmercury is a powerful neurological poison. Methylmercury poisoning was first identified in Japan in the 1950s as “Minamata disease.” Mercury-containing effluent from the Minamata Chemical Company was found to be the source of mercury in food fish. Mercury contamination in oceanic fishes is currently widespread, and of sufficient concern that the U.S. Food and Drug Administration issued a consumer alert on March 9, 2001, advising that pregnant women, women of childbearing age, nursing mothers, and young children should avoid eating shark, swordfish, king mackerel, and tilefish. Many states in the United States have issued similar warnings about potentially hazardous levels of mercury or other bioaccumulated toxins in freshwater sport fish. Arsenic, copper, lead, and cadmium are often deposited in lakes and streams from the air near emitting facilities. These substances may also enter waterways from runoff from slag piles, mine drainage, and industrial effluent. Effluents from electroplating contain a number of heavy metal constituents. Heavy metals, copper in particular, may be toxic to aquatic species as well as harmful to human health.

In the past quarter century, a considerable number of incidents of surface water contamination by hazardous and carcinogenic organic compounds were reported in the United States. The sources of these include effluent from petrochemical industries and agricultural runoff, which contains both pesticide and fertilizer residues. Trace quantities of chlorinated hydrocarbon compounds in drinking water may also be attributed to the chlorination of organic residues by chlorine added as a disinfectant. The production of these disinfection by-products is difficult to eliminate in the drinking water treatment process, but maintaining clean, unpolluted, source water is the first step.

Box 2.3

Contamination of Heavy Metal in Gulshan-Baridhara Lake, Dhaka

Water pollution by heavy metals due to human activities is causing serious ecological problems in many regions of the world. Metals which are discharged into natural waters at increased concentrations in sewage, industrial effluents or from mining operations can have severe toxicological effects on humans and aquatic ecosystems.

Gulshan-Baridhara lake is an artificial lake of Dhaka Metropolis. It is located 23°48' N and 90°25' E of Dhaka city. The length of the lake is 3.8 km which covers an area of 0.0160 km^2. It has an average depth of 2.5 m, and a volume of 12 ×10^5/m^3. As a part of the natural drainage system this lake still plays an important role and simultaneously the lake is also one of the major sources of water to recharge the ground water. Bangladesh Government has declared it as an "Ecologically Critical Area" in 2001 under the Environment Preservation Act and Environment Preservation Rules. The lake is a channel-like elongated water body which is located in the northern fringe of the main part of Dhaka city. Mohuya et al. (2010) did some intensive research on the heavy metal pollution of the lake during summer and monsoon and they determined the concentrations of cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), and lead (Pb) in the pelagic water of Gulshan-Baridhara Lake.

- The concentrations of Cd, Cr, Cu, Ni and Pb in the lake water varied from 0.068 - 0.091, 0.048 - 0.225, 0 - 6.135, 0 - 0.062 and 0.023 - 0.067 mg/l during the summer season, respectively. Mean values of the contaminants of Cd, Cr, Cu, Ni and Pb in summer were 0.083, 0.100, 2.336, 0.074, and 0.046 mg/l, respectively.
- In monsoon the concentration of above mentioned heavy metals varied from 0.016 - 0.019 mg Cd/l, 0.005 - 0.035 mg Cr/l, 0.002 - 0.018 mg Cu/l, 0.007 - 0.159 mg Ni/l, and 0.052 - 0.151 mg Pb/l. Mean values of these heavy metals in monsoon were 0.018, 0.018, 0.011, 0.037 and 0.093, mg/l, respectively.

The research results revealed that among the heavy metals only Pb concentration exceeded the standard level during the monsoon, otherwise concentrations of all other four heavy metals (Cd, Cr, Cu and Ni) exceeded the standard level of drinking, fishing and surface water as set up by World Health Organization (WHO), Government of Bangladesh (GOB), United States Environmental Protection Agency (USEPA), Department of Environment (DOE) and Federation Water Pollution Control Administration (FWPCA) of US, for the summer period. Therefore, the lake water was found highly polluted in the summer season when the rainfall was comparatively low.But during the monsoon the values were in general low and fall within various standard levels. This adjustment might have occurred because of rainfall and dilution. Only in the cases of Pb, concentration level was found high during the monsoon. It might be due to the high percentage of lead in Dhaka's air in recent time, which mixed up with rain water during monsoon and finally reached to the water bodies through precipitation.

Adapted from Mohuya et. al 2010

2.8 Conclusion

Water pollution stems from many sources and causes, only a few of which are discussed here. Rivers and streams demonstrate some capacity to recover from the effects of certain pollutants, but lakes, bays, ponds, sluggish rivers, and oceans have little resistance to the effects of water pollution. We have a long history of introducing pollutants into aquatic environments, and have had only partial success at repairing the damage that has already been done and curbing the activities that result in environmental degradation. Nonpoint source pollution continues to be a serious threat to receiving waters, as does the continued release of sewage and industrial effluents throughout the world. As we have seen with mercury contamination in fishes, environmental pollution can have widespread and lasting consequences.

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