Chapter 2

Water Pollution:

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.

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, water-borne diseases remain a major public health threat.

In the developed countries, however, water treatment and distribution methods have almost eradicated microbial contamination in drinking water.

Now, 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 will 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.

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 the rapid biological 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 that increase the stream temperatures due to solar radiation.

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. 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 x 20,000. 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.

In past, almost all of the cities with combined sewers have treatment plants that can only handle dry weather flow (i.e., no storm water runoff). When it rains, the flow in the combined sewer system increases to many times the dry weather flow and most of it must be bypassed directly into a river, lake, or bay.

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 storm water runoff. This change improved the overall treatment of sewage by decreasing the frequency of bypasses and allowing additional levels of sewage treatment, such as phosphorus removal, to be added at the wastewater treatment plant. It left unresolved the treatment of storm water runoff, which is now one of the major sources of water pollution.

**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, and fecal coliform bacteria (bacteria that normally live in the intestinal tract of warm-blooded animals and indicate contamination by animal wastes).

Both surface and groundwater pollution are common in agricultural regions because of the extensiveness of fertilizer and pesticide application.

**Pollution from petroleum compounds** Petroleum hydrocarbons from atmospheric sources (e.g., automobile exhaust fumes) are deposited daily on road surfaces. When it rains, these oily deposits wash into nearby streams and lakes.

The acute effect of oil on birds, fish, and other aquatic organisms is well cataloged; the subtle effects of oil on aquatic life is not so well understood and is potentially more harmful. For example, anadromous fish that 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.

**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 prevents them from reproducing.

Acid mine drainage has polluted surface waters.
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.

**ELEMENTS OF AQUATIC ECOLOGY**

Plants and animals in their physical and chemical environment make up an ecosystem. The study of ecosystems is termed *ecology*.

One of the tenets of ecology is that “everything is connected with everything else.”

Three categories of organisms make up an ecosystem. The producers use energy from the sun and nutrients like nitrogen and phosphorus from the soil to 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*.

The second category of organisms in an ecosystem includes the consumers, who use the energy stored during 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.

The third category of organisms, the decomposers or decay organisms, use the energy in animal wastes, along with dead animals and plants, converting the organic compounds to stable inorganic compounds (e.g., nitrate) that can be used as nutrients by the producers.

Ecosystems exhibit a flow of both energy and nutrients. The original energy source for nearly all ecosystems is the sun. *Energy flows 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.

A simplified ecosystem showing various trophic levels is illustrated in the Fig.
A typical terrestrial ecosystem. The numbers refer to trophic level above the autotrophic, and the arrows show progressive loss of energy.

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. If a watercourse becomes anaerobic, the entire ecology changes and the water becomes unpleasant and unsafe. The dissolved oxygen 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:

\[ 6\text{CO}_2 + 12\text{H}_2\text{O} + \text{light} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{H}_2\text{O} + 6\text{O}_2 \]

In this simplified example, glucose (C\(_6\)H\(_{12}\)O\(_6\)), water (H\(_2\)O), and oxygen (O\(_2\)) are produced from carbon dioxide (CO\(_2\)) and water, with sunlight as the source of energy and chlorophyll as a catalyst.

Photosynthesis is basically a redox reaction.

In addition to sunlight, CO\(_2\), and H\(_2\)O, plants require inorganic nutrients, particularly nitrogen and phosphorous, to grow.

The following equation shows that production of algal protoplasm (the living portion of an algae cell) requires a ratio of 106 units of carbon and 16 units of nitrogen for every unit of phosphorus:

\[ 106\text{CO}_2 + 16\text{NO}_3^- + \text{HPO}_4^{2-} + 122\text{H}_2\text{O} + 18\text{H}^+ \rightarrow [(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}(\text{H}_3\text{PO}_4)] \]

(algal protoplasm)

Plants (producers) use inorganic nutrients and sunlight as an energy source to build high-energy compounds.

Consumers eat and metabolize these compounds, releasing some of the energy for the consumer to use.

The end product of metabolism (excrement) becomes food for decomposers and is degraded further, but at a much slower rate because many of the readily digestible compounds have already been consumed.

After several such steps, only very low-energy compounds remain, and decomposers can no longer use the residue 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 the Fig.
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).

The basic equation for *aerobic decomposition* of complex organic compounds is:

\[
\text{HCOH} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy}
\]

The biological decomposition of glucose under aerobic conditions would result in the release of \(\text{CO}_2\), \(\text{H}_2\text{O}\), and energy that can be used for metabolism:

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{H}_2\text{O} + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 12\text{H}_2\text{O} + \text{energy}
\]

Carbon dioxide and water are always two of the end products of aerobic decomposition.

Nitrogen, phosphorus, and sulfur compounds are often included in the general discussion of decomposition because the breakdown and release of these compounds during decomposition of organic matter can contribute to water quality problems.

In aerobic environments, sulfur compounds are oxidized to the sulfate ion (\(\text{SO}_4^{2-}\)) and phosphorus is oxidized to phosphate (\(\text{PO}_4^{3-}\)).
Any phosphate not rapidly taken up by microorganisms is bound by physical or chemical attraction to suspended sediments and metal ions, making it unavailable to most aquatic organisms.

Nitrogen is oxidized through a series of steps in the progression:

$$\text{Organic N} \rightarrow \text{NH}_3(\text{ammonia}) \rightarrow \text{NO}_2^-(\text{nitrite}) \rightarrow \text{NO}_3^- (\text{nitrate})$$

Because of this distinctive progression, various forms of nitrogen are used as indicators of water pollution. A schematic representation of the aerobic cycle for carbon, nitrogen, sulfur, and phosphorus is shown in the Fig.

Aerobic carbon, nitrogen, phosphorus, and sulfur cycles.

**Anaerobic decomposition** is usually performed by a completely different set of microorganisms, to which oxygen may even be toxic. The basic equation for anaerobic biodegradation is:

$$2\text{HCOH} \rightarrow \text{CH}_4 + \text{CO}_2 + \text{energy}$$

The following Figure is a schematic representation of anaerobic decomposition. Note that the left half of the cycle, photosynthesis by plants, is identical to the aerobic cycle.
Many of the end products of anaerobic decomposition are biologically unstable. Methane (CH$_4$), for example, is a high-energy gas commonly called “marsh gas” (or “natural gas” when burned as fuel).

Although methane is physically stable, it can be oxidized and used as an energy source (food) by a variety of aerobic bacteria.

Ammonia (NH$_3$) can also be oxidized by aerobic bacteria or used by plants as a nutrient.

**Sulfur** is anaerobically biodegraded to evil smelling sulphydryl compounds like hydrogen sulfide (H$_2$S), and can be used as an energy source by aerobic bacteria.

Phosphates released during anaerobic decomposition are very soluble in water and do not bind to metal ions or sediments. Soluble phosphate is easily taken up by plants and used as a nutrient.
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).

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 coliform.

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 re-aeration 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.

Both of these situations are depicted graphically in the Fig.

Dissolved oxygen downstream from a source of organic pollution.

Curve A depicts an oxygen sag 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 $D_s$ 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 $k_1'$:

$$\left( \frac{d}{dt} z(t) \right) = k_1' z(t).$$

This differential equation has a simple solution:

$$z(t) = L_0 e^{-k_1' t},$$

where $L_0$ 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 following Fig. for various values of $k_1'$, and with $L_0 = 30$ mg/L

Amount of oxygen required at any time $t(z(t))$ for various deoxygenation constants ($k_1'$) when the ultimate carbonaceous oxygen demand ($L_0$) is 30 mg/L.

Since the ultimate oxygen requirement is $L_0$ and the amount of oxygen still needed at any given time is $z$, the amount of oxygen used after time $t$, the biochemical oxygen demand (BOD), is simply the difference between $L_0$ and $z(t)$:
BOD (t) = L_0 - z (t) = L_0(1 - e^{-k_2' t}).

This relationship is plotted in the following Fig. and it can be seen that the BOD asymptotically approaches L_0 as time passes.

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_0).

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

$$\frac{d}{dt} d(t) = k_2'(d_s - d(t)) = k_2' D(t)$$

where D(t) is the oxygen deficit at time t, in milligrams per liter (mg/L), and k_2' 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 may be used

$$k_2' = \frac{3.9v^{1/2}\sqrt{(1.037)(T-20)}}{H^{3/2}}$$

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 the following Table.
Reaeration Constants

<table>
<thead>
<tr>
<th>Type of watercourse</th>
<th>$k_2$ at $20^\circ\text{C}^a$ (days$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small ponds or backwaters</td>
<td>0.10–0.23</td>
</tr>
<tr>
<td>Sluggish streams</td>
<td>0.23–0.35</td>
</tr>
<tr>
<td>Large streams, low velocity</td>
<td>0.35–0.46</td>
</tr>
<tr>
<td>Large streams, normal velocity</td>
<td>0.46–0.69</td>
</tr>
<tr>
<td>Swift streams</td>
<td>0.69–1.15</td>
</tr>
<tr>
<td>Rapids</td>
<td>$&gt;$1.15</td>
</tr>
</tbody>
</table>

*aFor temperatures other than $20^\circ\text{C}$, $k_2(T) = k_2(20^\circ\text{C})(1.024)^{T-20}$.

Immediately downstream from a source of organic pollution the rate of use will often exceed the reaeration 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.

This may be expressed mathematically as:

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

which can be solved to give:

$$D(t) = \frac{k'_1 L_0}{k'_2 - k'_1} (e^{-k'_1 t} - e^{-k'_2 t}) + D_0 e^{-k'_2 t}$$

where $D_0$ 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:

$$D = \frac{k_1 L_0}{k_2 - k_1} (10^{-k_1 t} - 10^{-k_2 t}) + D_0 10^{-k_2 t}$$

since:

$$e^{-k't} = 10^{-kt} \text{ when } k = 0.43 k'$$

The initial oxygen deficit ($D_0$) is calculated as a flow-weighted proportion of the initial stream oxygen deficit and the wastewater oxygen deficit:

$$D_0 = \frac{D_s Q_s + D_p Q_p}{Q_s + Q_p}$$
where $D_s$ is the oxygen deficit in the stream directly upstream from the point of discharge, in milligrams per liter.

$Q_s$ is the stream flow upstream from the wastewater discharge, in cubic meters per second (m³/s).

$D_p$ is the oxygen deficit in the wastewater being added to the stream, in milligrams per liter.

and $Q_p$ is the flow rate of wastewater, in cubic meters per second.

Similarly, the ultimate carbonaceous BOD ($L_o$) is:

$$L_0 = \frac{L_s Q_s + L_p Q_p}{Q_s + Q_p}$$

where $L_s$, is the ultimate BOD in the stream immediately upstream from the point of wastewater discharge, in milligrams per liter.

$Q_s$ is the stream flow upstream from the wastewater discharge, in cubic meters per second.

$L_p$, is the ultimate BOD of the wastewater, in milligrams per liter.

and $Q_p$ is the flow rate of the wastewater, in cubic meters per second.

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

$$t_c = \frac{1}{k_2' - k_1'} \ln \left[ \frac{k_2'}{k_1'} \left( 1 - \frac{D_0 (k_2' - k_1')}{k_1' L_0} \right) \right]$$

where $t_c$ is the time downstream when the dissolved oxygen concentration is the lowest.

An actual dissolved oxygen sag curve is shown in the following Fig. Note that the stream becomes anaerobic at about mile 3.5, recovers, then drops back to 0 after receiving effluents from a city and a paper mill. Also shown in the figure is the expected dissolved oxygen sag if 95% of the demand for oxygen is removed from all discharges.
EXAMP1: Assume that a large stream has a reoxygenation constant $k'_2$ 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?

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 $Do = 0$ because the stream is saturated.

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

The dissolved oxygen 30 miles downstream will be the saturation level minus the deficit, or $10 - 1.0 = 9.0 \text{ mg/L}$.
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 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:

\[
P = \frac{m}{n + 1}
\]

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 the following Example are plotted in the following Fig. the minimum 7-day, 10-year low flow is estimated to be 0.5 m³/s.
EXAMPL 2: Calculate the 7-day, 10-year low flow given the data below.

<table>
<thead>
<tr>
<th>Year</th>
<th>Lowest flow 7 consecutive days (m³/s)</th>
<th>Ranking (m)</th>
<th>m/(n + 1)</th>
<th>Lowest flow in order of severity (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>1.2</td>
<td>1</td>
<td>1/14 = 0.071</td>
<td>0.4</td>
</tr>
<tr>
<td>1966</td>
<td>1.3</td>
<td>2</td>
<td>2/14 = 0.143</td>
<td>0.6</td>
</tr>
<tr>
<td>1967</td>
<td>0.8</td>
<td>3</td>
<td>3/14 = 0.214</td>
<td>0.6</td>
</tr>
<tr>
<td>1968</td>
<td>1.4</td>
<td>4</td>
<td>4/14 = 0.285</td>
<td>0.8</td>
</tr>
<tr>
<td>1969</td>
<td>0.6</td>
<td>5</td>
<td>5/14 = 0.357</td>
<td>0.8</td>
</tr>
<tr>
<td>1970</td>
<td>0.4</td>
<td>6</td>
<td>6/14 = 0.428</td>
<td>0.8</td>
</tr>
<tr>
<td>1971</td>
<td>0.8</td>
<td>7</td>
<td>7/14 = 0.500</td>
<td>0.9</td>
</tr>
<tr>
<td>1972</td>
<td>1.4</td>
<td>8</td>
<td>8/14 = 0.571</td>
<td>1.0</td>
</tr>
<tr>
<td>1973</td>
<td>1.2</td>
<td>9</td>
<td>9/14 = 0.642</td>
<td>1.2</td>
</tr>
<tr>
<td>1974</td>
<td>1.0</td>
<td>10</td>
<td>10/14 = 0.714</td>
<td>1.2</td>
</tr>
<tr>
<td>1975</td>
<td>0.6</td>
<td>11</td>
<td>11/14 = 0.786</td>
<td>1.3</td>
</tr>
<tr>
<td>1976</td>
<td>0.8</td>
<td>12</td>
<td>12/14 = 0.857</td>
<td>1.4</td>
</tr>
<tr>
<td>1977</td>
<td>0.9</td>
<td>13</td>
<td>13/14 = 0.928</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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 NH₃, H₂S, and other gases are formed.

Some of the gases dissolve in water, but others can attach themselves as bubbles to sludge and buoy the sludge to the surface. In addition, the odor of H₂S will advertise the anaerobic condition for some distance, the water is usually black or dark.

Other adverse effects on aquatic life accompany the unpleasant physical appearance of an anaerobic stream.

Increased turbidity, settled solid matter, and low dissolved oxygen all contribute to a decrease in fish life.

The numbers of other aquatic species are also reduced under anaerobic conditions, as shown in the following Fig.
The number of species and the total number of organisms downstream from a point of organic pollution.

The diversity of species may be quantified by using an index, such as the Shannon-Weaver diversity index:

\[ H' = \sum_{i=1}^{S} \left( \frac{n_i}{n} \right) \ln \left( \frac{n_i}{n} \right) \]

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 \( J \):

\[ J = \frac{H'}{\ln S} \]

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.
The following Table shows a simplified example of biotic diversity and equitability upstream and downstream from a pollution outfall.

### Diversity and Equitability of Aquatic Organisms

<table>
<thead>
<tr>
<th>Species</th>
<th>Pollution tolerance</th>
<th>No. of individuals in sample</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upstream</td>
<td>Downstream</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>from</td>
<td>from</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>outfall</td>
<td>outfall</td>
</tr>
<tr>
<td>Mayflies</td>
<td>Intolerant</td>
<td>20</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Rat-tailed</td>
<td>Tolerant</td>
<td>0</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>maggots</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trout</td>
<td>Intolerant</td>
<td>5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Carp</td>
<td>Tolerant</td>
<td>1</td>
<td>20</td>
<td></td>
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<tr>
<td>$H'$ diversity</td>
<td></td>
<td>0.96</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>$J$</td>
<td></td>
<td>0.87</td>
<td>0.20</td>
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</table>

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 the following Fig.

![Diagram](image_url)

Typical variations in nitrogen compounds downstream from a point of organic pollution.
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.

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.

**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.

The presence of large amounts of organic matter causes 90-99% of all wavelengths to be absorbed within the first meter. Because of this, algal growth is concentrated near the surface of a lake.

**Temperature and heat** often have a profound effect on a lake. Water is at a maximum density at 4°C; warmer or colder water is less dense, and will float.
Water is also a poor conductor of heat and retains heat quite well.

Lake water temperature usually varies seasonally as shown in the Figure.

![Diagram of typical temperature depth relationships in lakes.](image)

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.
The biochemical reactions in a natural lake are represented schematically in the following Fig. 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.

![Schematic representation of lake ecology.](image)

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.

The growth of algae in most lakes is limited by the availability of phosphorus; if phosphorus is insufficient supply, nitrogen is usually the next limiting nutrient.

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 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 aerobic 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.

**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 a result of human activity, the eutrophication process may be shortened to as little as a decade.

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 a river 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.

**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.

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.

**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 thus fragile 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 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.

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.

Most sewage effluents receive only secondary treatment which is not effective at removing certain types of pollutants, including phosphorus.
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.

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.

Heavy metals, copper in particular, may be toxic to aquatic species as well as harmful to human health.

A considerable number of incidents of surface water contamination by hazardous and carcinogenic organic compounds. The sources of these include effluent from petrochemical industries and agricultural runoff, which contains both pesticide and fertilizer residues.

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.

PROBLEMS