

Introduction to Environmental Science & Engineering
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Chapter 4: Water Resources (pages 83 – 103)

4.1: The Hydrologic Cycle

Roughly one-fourth of the sun's energy that reaches the surface of the earth is used to evaporate water; propelling the Hydrologic Cycle. Water is evaporated from any wet surface and is also released by plants in considerable amounts into the atmosphere through their leaves during the transpiration process. This combination is called evapotranspiration, and occurs when water passes into the atmosphere and eventually returned as precipitation.

As water evaporates, most of the impurities are left behind (most notably being DDT), making the evaporative cycle one of nature's great water purifiers. Most of the world's water (about 94.2%) is contained in the oceans. Most of the accessible remainder (about 1.65%) is locked up in the icecaps and glaciers.

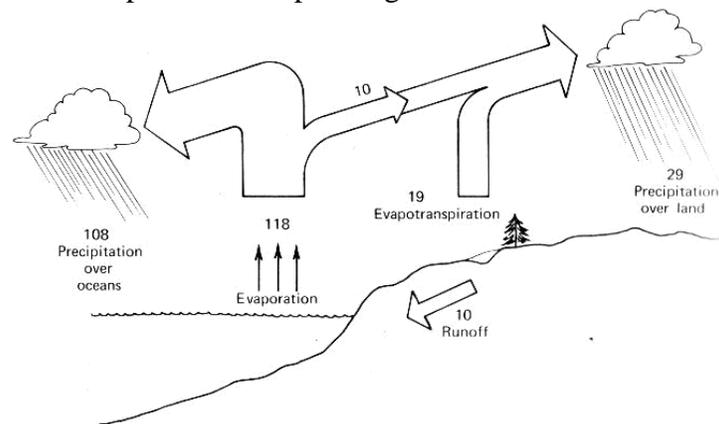


FIGURE 4.1 – World hydrologic cycle, units are 10^{15} gal/yr

TABLE 4.1 – Distribution of the Earth’s water Resource		
Location	Water volume, 10 ¹⁵ gal	Percent of total
World ocean	362,000	94.2
Glaciers	6,350	1.65
Lakes	60.5	0.016
Soil moisture	21.6	0.006
Atmospheric vapor	3.7	0.001
River (channel) waters	0.32	0.0001
Total groundwater	15,800	4.13
Groundwater less than .5 mi down	1,160	0.28

4.2: U.S. Water Resources and Uses

The average annual rainfall on the conterminous United States is about 30 inches, or a daily precipitation of 4200 billion gallons of water. Seventy percent of this (300 bgd, billion gallons per day) is lost to evapo-transpiration, leaving 1200 bgd as the daily runoff.

Figure 4.2 shows water usage in the US in 1970, indicating that the principal user of fresh water, both in terms of withdrawal (41%) and consumption (84%), was agriculture. Notice that lots of water, both fresh and saline, was withdrawn for cooling steam-electric power plants but that almost all of it was returned (albeit somewhat heated; an example of thermal pollution). This will increase in the future.

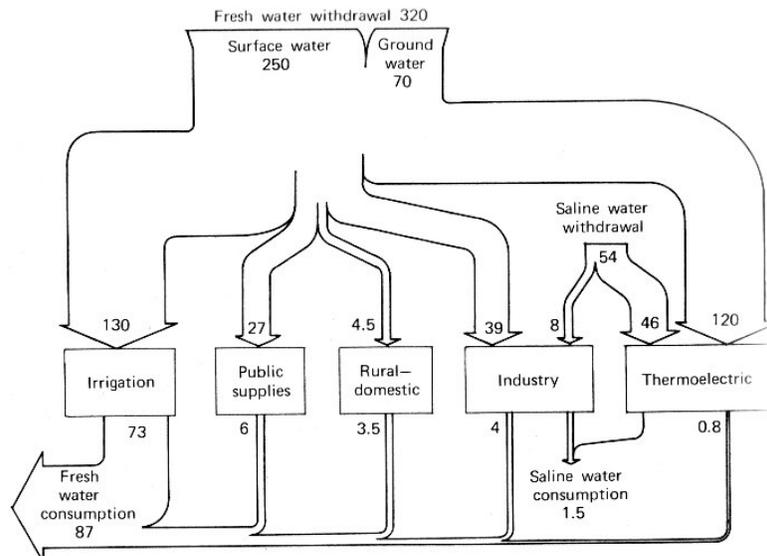


FIGURE 4.2 – Estimated water withdrawals and consumption in US in 1970: units are billions of gallons per day

4.3: Groundwater

About 70% of the rainfall in the US is lost to evaporation. Most of the rest runs off the surface into streams and lakes, and eventually returns to the sea. Some, however, slowly percolates down through the soil until it reaches a layer of impermeable rock. The water which builds up on the top of the impermeable rock fills all the openings, crevices, and pores in the overlying sand and rock, to a level called the *water table*. It then very slowly flows to the oceans. As shown in Figure 4.6, when the ground level drops below the water table, the groundwater helps supply streams and lakes giving a continuity of discharge they would not otherwise have. Groundwater resources are extremely important because they supply about 22% of present withdrawal. Difficulties exist with this in that the rate of replenishment of these supplies is so slow that they must be considered to be essentially nonrenewable resources.

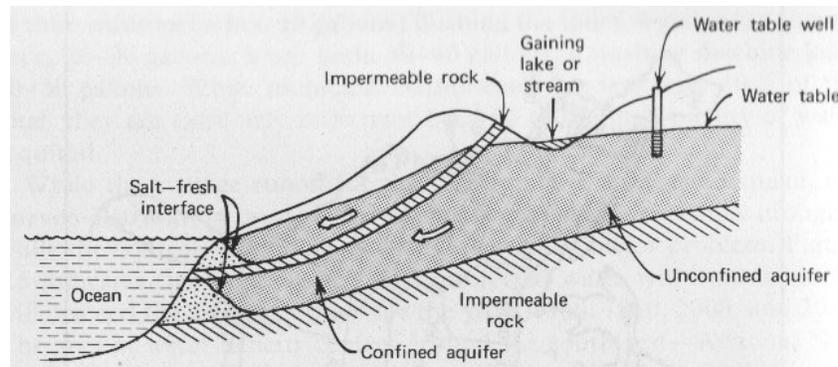


FIGURE 4.6 – Groundwater resources

One problem that can result from a drop in the water table is a corresponding sinking of the ground level in a process called *subsidence*. Another problem that can result from overexploitation of groundwater is that the water table can drop so low that it becomes uneconomical to pump it out. When this happens, the area involved may lose its principal water supply. Coastal areas face another sort of groundwater problem because of the close proximity of saline and fresh water. Under natural conditions there is a balance between the inflow of salt water and the outflow of fresh water, which establishes a boundary between the two regimes. However, as freshwater is pumped out of the area, the water table drops and the boundary moves inland. After a period of time, a coastal freshwater well may need to be abandoned because of this intrusion.

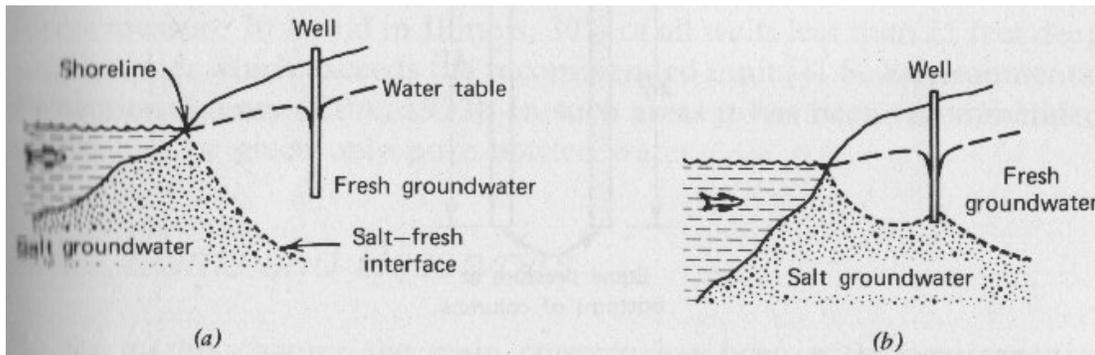


FIGURE 4.7 – Saltwater intrusion into a freshwater well due to over-pumping. (a) before, (b) after.

4.7: Conclusions

This chapter has pointed out the necessity to treat water-supply problems in terms of distribution and quality. The total quantity is adequate, providing the water is of sufficient quality after being use to enable it to be reused. There are major problems of distribution, especially in the southwestern US where present use patterns, which depend on exploitation of groundwater, cannot continue for long. The dropping water table is going to require major importations of water, strict water conservation measures, and very likely, increased construction and use of desalination facilities. Moreover, the overexploitation of the major rivers in the area has led to deteriorating relations with Mexico, as they are put on the receiving end of progressively poorer quality water.

Chapter 5: Water Pollutants (pages 105 – 122)

5.1: Types of Pollutants

There are several ways to categorize water pollutants, the following being ones which is used by the EPA:

1. *Oxygen-demanding wastes* are biodegradable organic compounds contained in domestic sewage or certain industrial effluents. When these compounds are decomposed by bacteria, oxygen is removed from the water. If the oxygen level drops low enough, the fish will die.
2. *Disease-causing agents* are various pathogenic microorganisms which usually enter the water with human sewage. Contact with these microbes can be made by drinking the water or through various water-contact activities.
3. *Synthetic organic compounds* include detergents and other household aids, pesticides, and various synthetic industrial chemicals. Many of these compounds are toxic to aquatic life and may be harmful to humans
4. *Plant nutrients* such as the nitrogen and phosphorus which drains from fertilized lands, as well as the effluent from most sewage treatment plants, stimulate the growth of algae and water weeds.
5. *Inorganic chemicals and mineral substances* includes the acids which form when water drains from abandoned mines, as well as the heavy metals such as mercury and cadmium.
6. *Sediments* are particles of soils, sands, and minerals washed from the land. They can smother bottom life such as shellfish and coral, as well as fill in reservoirs and harbors. Improper soil management leading to erosion is a major contributor.
7. *Radioactive substances* can enter the water from the mining and processing of radioactive ores, from various nuclear power operations, from medical facilities, and from nuclear weapons testing.
8. *Thermal discharges* from steam-electric power plants raise the temperature of the receiving water by as much as 20°F, resulting in various changes in the local ecosystem.

5.3: Dissolved Oxygen

The amount of dissolved oxygen (DO) in water is an important parameter of water quality. Fish, for example, require certain minimum amounts of DO depending upon their species, stage of development, level of activity, and the water temperature. For example, for a well-rounded, warm-water fish population, it is recommended that the DO

remain above 5 ppm for at least 16 hours of the day and during the other 8 hours it should not drop below 3 ppm.

There are four processes which affect the amount of oxygen in the water: reaeration, photosynthesis, respiration, and the oxidation of wastes. *Reaeration* is the process wherein oxygen enters the water through the contact the water surface makes with the atmosphere. The solubility of oxygen in fresh water, at a pressure of 1 atmosphere, decreases with temperature as shown in Figure 5.2. When the actual amount of oxygen in the water is less than the saturation value given in the figure, atmospheric oxygen passes into the water at a rate which is proportional to the deficit. By increasing the surface area in contact with the atmosphere the transfer of oxygen in contact with the atmosphere is increased, so a bubbling stream will pick up oxygen easier than a stagnant pond.

During photosynthesis, which of course occurs only during the daylight hours, oxygen is liberated, thereby increasing the DO level in the water. Respiration, however, is a process which continuously removes oxygen from the water. Combining the three effects of photosynthesis, respiration, and reaeration produces a diurnal variation of DO as shown in Figure 5.3. In this figure, photosynthesis is assumed to occur from 6 AM to 6 PM, bringing the DO level to slightly above saturation in the afternoon. While the water is supersaturated, oxygen diffuses out of the water instead of into it.

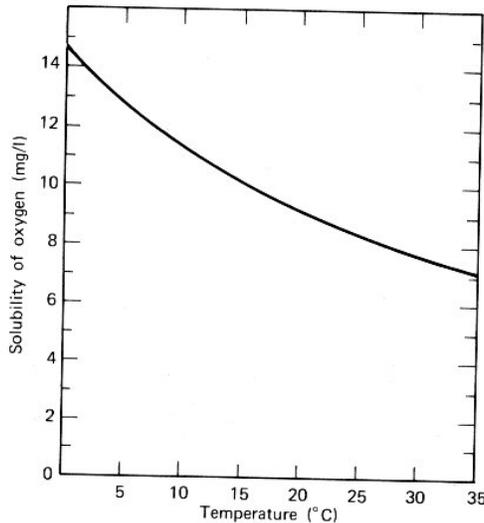


FIGURE 5.2 – Solubility of oxygen in fresh water exposed to water saturated air at 1 atmosphere pressure.

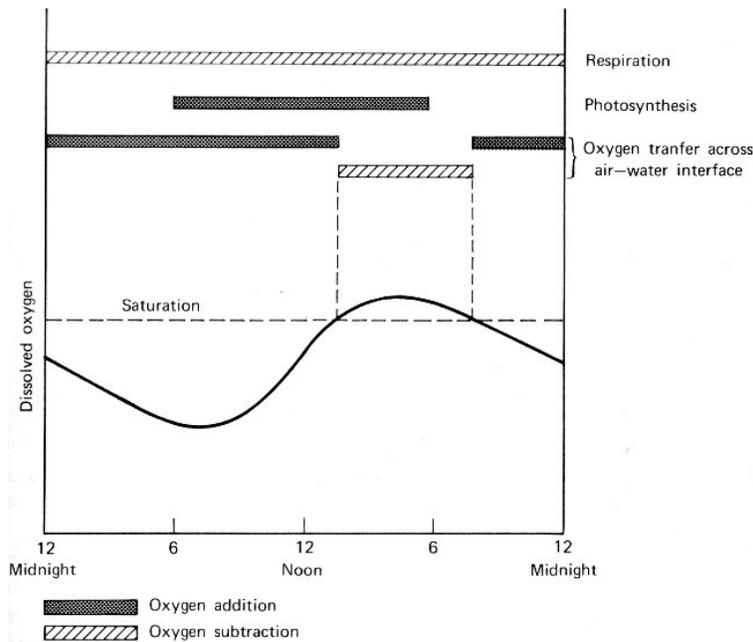
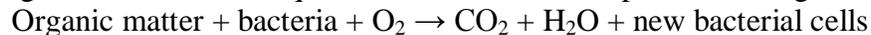


FIGURE 5.3 – Diurnal variation of DO assuming photosynthesis from 6 AM to 6 PM.

5.4: Decomposition

The fourth process which affects the amount of oxygen in the water is the oxidation of wastes. Microorganisms, especially bacteria, use organic wastes as food and in the process break down the complex organics into simple organic and inorganic materials. This decomposition may occur in the presence of oxygen, in which case it is called *aerobic* decomposition, or it may occur in the absence of oxygen in which it is called *anaerobic* decomposition.

The general form of the equation for aerobic decomposition of organic material is



The reaction of products from aerobic decomposition are not obnoxious, being simply carbon dioxide and water along with some sulfates and nitrates. The important point to notice is that during aerobic decomposition oxygen is removed from the water, resulting in a drop in DO.

If too much organic matter must be decomposed, the DO supply in the water may fall to zero. If this happens, not only will the oxygen-dependant aquatic life be killed, but the end products from the resulting anaerobic decomposition will be toxic and malodorous. Typical anaerobic decomposition reaction products include ammonia, methane, hydrogen sulfide, carbon dioxide, and water.

5.5: Biochemical Oxygen Demand

One of the most widely used measurements for estimating the water pollution potential of a given amount of organic waste is called the *biochemical oxygen demand*, or BOD. The BOD is a measure of the amount of oxygen required by bacteria to oxidize waste aerobically to carbon dioxide and water.

If we were to introduce an amount of organic matter into some water and monitor its decomposition, we would observe that the amount of organic material remaining would decrease exponentially with time. The amount of BOD which remains after some period of time is proportional to the remaining organic material, which results in a curve as shown in Figure 5.4. The initial value of BOD will of course be the total oxygen requirement to oxidize the organic material. This quantity is called the *ultimate BOD*, or BOD_L . An equation describing this curve is as follows:

$$BOD_{\text{remaining}} = BOD_L e^{-Kt} \quad (5-1)$$

Where K is a reaction-rate constant (which increases with temperature) and t is time.

Usually when curves of BOD versus time are drawn, they are actually made for BOD utilized and not BOD remaining. BOD utilized will be proportional to the amount of organic matter which has been oxidized and hence will have the shape shown in Figure 5.5. This distinction between BOD utilized and BOD remaining can cause confusion, so be aware of the difference.

The equation for BOD utilized is

$$BOD_{\text{utilized}} = BOD_L (1 - e^{-Kt}) \quad (5-2)$$

A standard way to measure BOD is to determine the amount of oxygen required by the bacteria during the first 5 days of decomposition (at 20°C). This is the 5-day BOD called BOD_5 , which is shown in Figure 5.5.

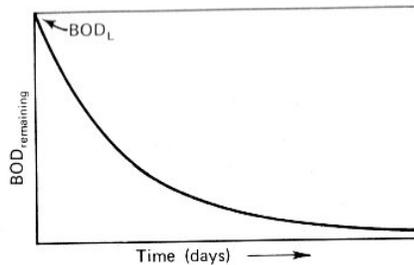


FIGURE 5.4 – BOD remaining as a function of time with initial value BOD_L .

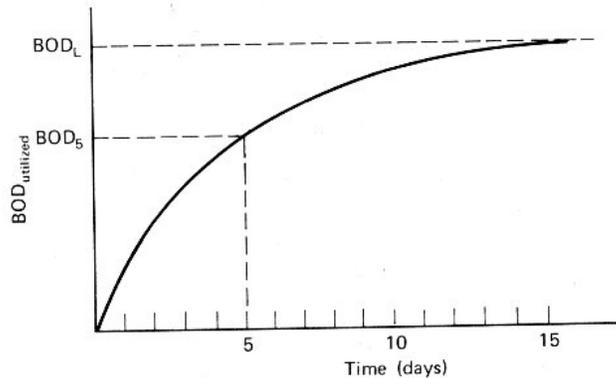
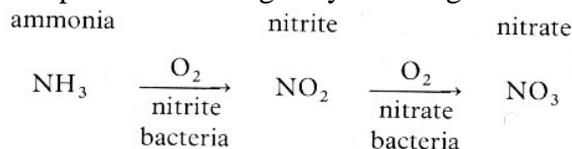


FIGURE 5.5 – This is the usual curve for BOD, and is actually BOD utilized. Also shown is the 5 day BOD.

The importance of the concept of BOD in water quality management must be emphasized. Consider that normal domestic sewage may have a 5-day BOD of around 200 mg/l and that industrial sewage may have a BOD of several thousands of milligrams per liter. Compare these requirements for oxygen to the amounts actually dissolved in water (e.g., from Figure 5.2, the saturation value at 20°C is only 9.2 mg/L). It is thus easy to anticipate the quick depletion of oxygen in any receiving water unless to anticipate the quick depletion of oxygen in any receiving water unless the dilution factor is quite high. Depleting the water of oxygen, remember, will kill the fish and the anaerobic decay products will be extremely objectionable.

It should be mentioned that there is a secondary effect which causes the demand for oxygen to suddenly increase after about 8-10 days. The organic nitrogen in the wastes is converted to ammonia during decomposition and the subsequent oxidation of the ammonia to nitrite (NO₂) and then nitrate (NO₃) requires oxygen. This process of *nitrification* was shown as part of the nitrogen cycle in Figure 1.7.



The total oxygen demand curve showing both the carbonaceous demand and the nitrification requirement is shown in Figure 5.6.

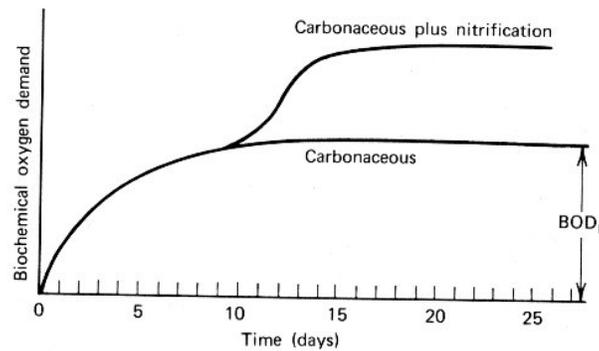


FIGURE 5.6 – The complete BOD curve includes the carbonaceous and nitrification demands

5.6: The Oxygen Sag Curve

We have seen that when wastes are discharged into a body of water, the amount of dissolved oxygen will decrease due to oxidation by bacteria. Opposing this drop in dissolved oxygen is reaeration which replaces oxygen through the surface, at a rate which is proportional to the depletion of oxygen below the saturation value. The simultaneous action of deoxygenation and reaeration produces what is called the *oxygen sag curve*, as shown in Figure 5.7. The DO curve initially drops as the wastes deplete the oxygen faster than it can be replaced. At the point where the DO is a minimum, the rate of reaeration becomes equal to the rate of oxygen utilization. Beyond that point the rate of reaeration exceeds the rate of utilization and the DO level eventually returns to normal. This sequence is referred to as the natural self-purification ability of water.

The horizontal axis of the oxygen sag curve may be either time or distance. If for example, a certain amount of waste is released all at one time into some impounded water, the DO level will be a function of time. If, however, there is a continuous discharge of wastes into a stream, then the oxygen sag curve will be a function of the distance downstream from the point of discharge.

As we move downstream from the point of discharge, and the dissolved oxygen begins to drop, there will be a corresponding change in the biota. Normal game fish will be replaced by fishes tolerant of the turbid, low DO waters. At the point downstream where the DO reaches its lowest value, conditions will be at their worst. If the stream goes anaerobic, there will be no fish and the only organisms present will be those able to obtain their oxygen from the surface, or those which are tolerant of low oxygen conditions.

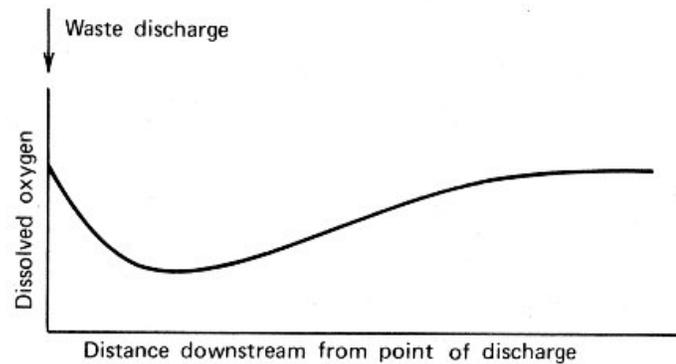


FIGURE 5.7 – The oxygen sag curve

5.9: Conclusions

The water-pollution examples of this chapter illustrate several important points. The biodegradable organic wastes are seen to be relatively harmless to an aquatic ecosystem providing the 'wastes are not so concentrated as to significantly decrease the dissolved oxygen level. Man, however, can easily overload these systems as he concentrates his numbers and activities, with the result that his wastes may be decomposed anaerobically. Anaerobic decay not only releases obnoxious reaction products, but it completely changes the character of the aquatic ecosystem. To avoid these problems, wastes may be treated before discharge to remove their oxygen demand, but, as we shall see in succeeding chapters, this is sometimes only a partial solution.

Chapter 7 – The treatment of Water and Wastes (pages 143 – 168)

There are many diseases which are associated with the contamination of water supplies by animal or human wastes. They include cholera, typhoid fever, paratyphoid fever, dysentery, tularemia, and infectious hepatitis. It has only been in the last century that these diseases have come under control in the developed world, largely by means of some relatively simple sanitation measures.

The basic sanitation techniques which are essential to the control of water-related diseases - the purification of water, and the treatment of sewage will be described in this chapter. We will see how the emphasis in water-quality control programs has shifted from the area of water-borne diseases, to control of oxygen-consuming wastes, and now to nutrient removal and water reclamation.

7.1: Biological Health Hazards

A simple way to categorize water-associated health hazards is according to whether they are communicable. Of the communicable water-associated diseases, those of most interest here are caused by the ingestion of biological agents. There are, however, other modes of transmission including simple water contact, as in the case of schistosomiasis, or insect vectors, as in the case of malaria, which are also important.

The contamination of water by sewage is the principal cause of waterborne diseases. Intestinal discharges of patients or carriers of such diseases contain the biological agents which are responsible for the disease's spread. A carrier may not even be aware that he is infected so it is essential that proper precautions be observed for all human wastes. The disease-causing organisms can be transferred from the excrement of an infected person into the mouths of healthy people by means of contaminated food or water. The spread of such infectious diseases can be controlled both by proper treatment and disposal of human wastes, and by purification of drinking water supplies.

The principal biological agents which are of concern in this context are pathogenic (disease-causing) bacteria, viruses, and parasites. Pathogenic bacteria are the causative agents of the great epidemic diseases cholera and typhoid - as well as bacillary dysentery, paratyphoid fever, and tularemia. Fortunately, intestinal bacteria that are discharged into natural waterways usually survive for only a matter of days. Figure 7.1 shows the rate at which fecal coliform bacteria (not pathogenic) die away. These bacteria exhibit an initial rapid decrease that results in about a 90% reduction in 2 days. However, thereafter the rate of decrease is considerably slower. It is interesting to note that this reduction is faster in warm, polluted water than in cold, clean water.

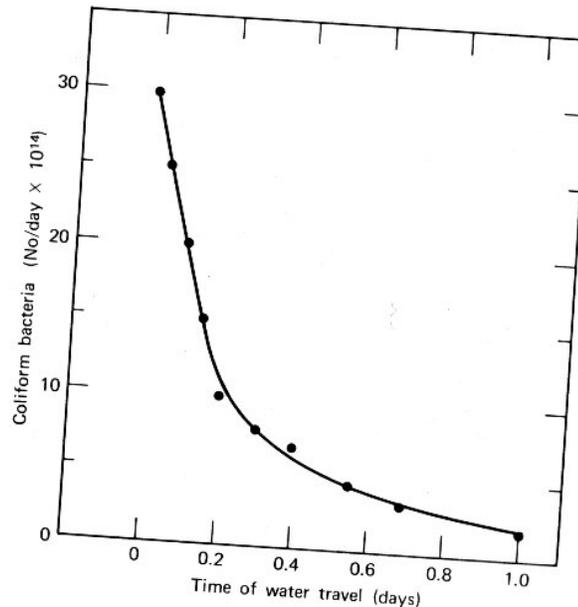


FIGURE 7.1 – Pattern of natural purification of coliform bacteria

The only viral disease that has been proven to be transmitted through drinking water is infectious hepatitis, although there are others for which transmission through water is theoretically possible. One of the particular difficulties with viruses is that some can survive the normal dosages of chlorine which are applied at water and sewage treatment plants to kill pathogens.

Among the parasites that may be ingested is the protozoa *Entamoeba histolytica*, which causes amebic dysentery. Another parasite is the guinea-worm which causes drantiasis, a common disease among the rural populations of many developing countries.

7.2: Urban Water and Sewage Systems

There are two convenient points to break the chain of events that can result in the spread of water-borne diseases. The first is the water treatment plant where drinking water must be made completely safe before being distributed. The second is the sewage treatment plant where wastes are processed before being released into the receiving water.

As shown in Figure 7.2, the increase in public water supplies and sewer stems in the U.S. is well correlated with the drop in typhoid fever deaths. These improvements are relatively recent, with the major drop in typhoid deaths having occurred in this century. Philadelphia, for example, began filtering its water supply in 1906 and began chlorination in 1913, with the result that the incidence of typhoid fever dropped by 98 % during the period 1906-1926 (Benarde 1970). A schematic version of a city water and sewer system is presented in Figure 7.3, along with some indications of potential trouble spots. Water, which may be withdrawn from various sources including rivers, reservoirs, and wells, is

transported to a water treatment plant for purification and perhaps fluoridation (to reduce dental caries). From the treatment plant it is passed to the distribution system of the city.

Waste water is shown being collected from sinks and toilets to be transported through sanitary lines to the sewage treatment plant. Many special precautions must be taken to prevent any kind of cross-connection between the water system carrying potable water and any other system carrying water of doubtful purity. If there are any pathways between the systems, and if there should be a loss of pressure in the potable water, impure water could be back-siphoned into the drinking water. Connections have been the most frequent source of water-borne outbreaks in the past.

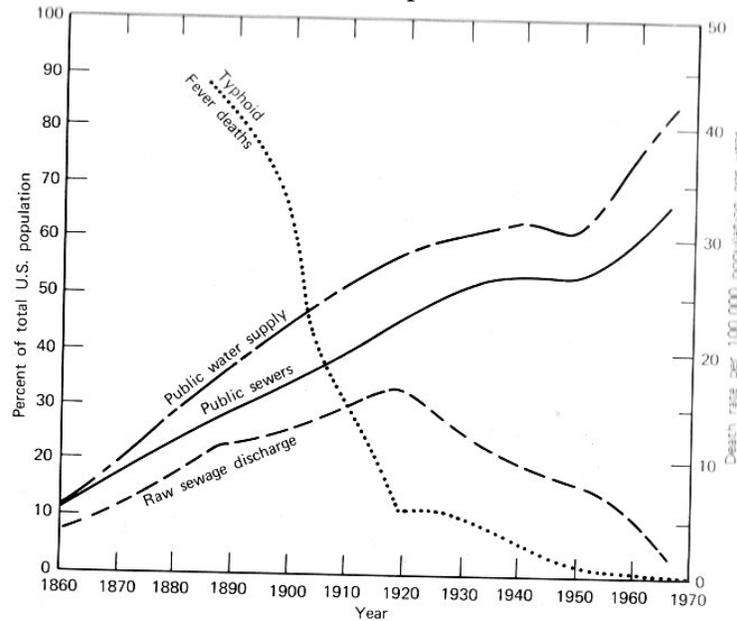


FIGURE 7.2 – Growth in the percentage of the US population serviced by public water and sewer systems is correlated with the drop in typhoid fever deaths.

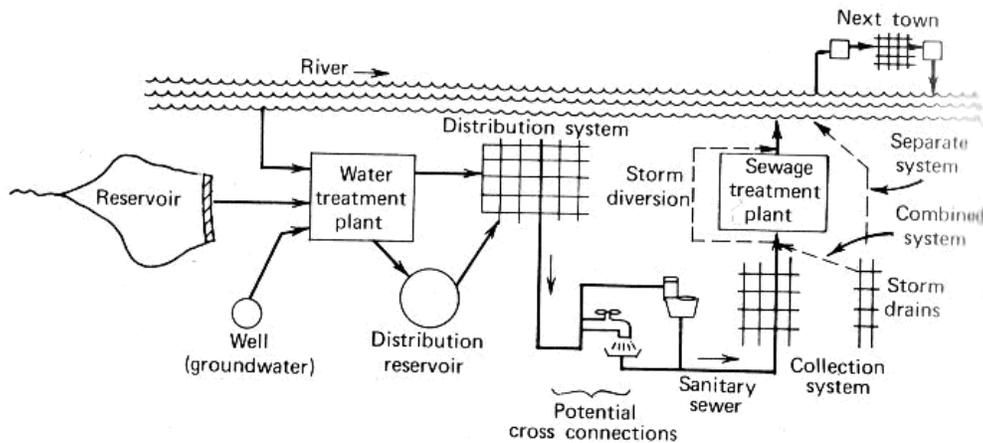


FIGURE 7.3 – Municipal water system including sources, treatment plant, distribution system, collection system, sewage plant, and disposal.

Also shown in the system is a storm sewer, which collects the runoff from the streets. Early sewer systems in this country simply *combined* storm runoff with the sanitary lines sending it all to the sewage treat plant. These combined sewer systems are unsatisfactory during periods of heavy rainfall because the sewage treatment plant can become overloaded, necessitating the diversion of large volumes of untreated directly into the receiving water. Newer cities have separate storm and sanitary sewers to avoid the overloading problem. Although separate systems are much better, they are still not perfect in that storm runoff is passed, untreated, back into the receiving water, though it may contain much objectionable material. The cost of separating existing combined systems would be extremely high, one estimate being \$48 billion (American Chemical Society 1969). In some areas it may be possible to avoid separation by temporarily storing storm runoff in large detention basins for treatment at a later time.

Notice in Figure 7.3 that the next town downstream is liable to be withdrawing water that has already been used upstream. At the bottom of a long river, such as the Mississippi, it is quite likely that a municipal water supply is distributing water that has already passed through another city's sewage system.

Many rural areas do not have any sewage treatment facilities at all, relying mainly on septic-tank systems of the type shown in Figure 4.10. In 1970 some 50 million people in the U.S. relied on these systems for sanitary services while another 10 million discharged their sewage *into* our waterways. When properly designed and maintained, septic tanks are adequate, but when they go bad they can be a health danger and an esthetic and olfactory nuisance.

7.3: Water Quality Criteria

Before going on to discuss techniques of water purification, it is worthwhile to briefly consider how water quality is evaluated. Water quality standards are of course dependent on how the water *is* to be used; for example, drinking water standards are more stringent than standards applicable to irrigation water.

The Federal Water Pollution Control Administration (FWPCA) in 1969 issued a set of criteria to be used by the states as guidelines in setting their own standards. They used the following water classifications: (a) Recreation and Aesthetics, (b) Public Water Supplies, (c) Fish, Other Aquatic Life, and Wildlife, (d) Agriculture, and (e) Industry. The Public Water Supplies category establishes criteria for the quality of water before being processed at a water treatment plant. The standards which states use to evaluate drinking water quality are based on U.S. Public Health Service (USPHS) standards.

The USPHS drinking water standards (1962) establish limits in four categories: (a) physical characteristics, (b) chemical characteristics, (c) radioactivity, and (d) bacteriological quality. In the category of physical characteristics it is specified that the water shall contain no impurity which would cause offense to the sense of sight, taste, or

smell. The recommended limits for chemical substances are presented in Table 7.1.

Of special interest here is the specification of bacteriological quality. It is very difficult to detect pathogenic microorganisms in a water supply; instead, the water is tested for *any* contamination by human or animal excreta by measuring coliform bacteria. There are literally hundreds of millions of harmless coliform bacteria (principally *Escherichia coli*) per gram of fecal material. In crude sewage there may be hundreds of thousands of fecal coliforms per cubic centimeter, but only a few pathogens. Therefore, the probability of there being any pathogens in a sample, without the accompanying fecal coliforms is essentially zero. On this basis, if a sample of drinking water is found to have no coliform bacteria, then it is reasonable to assume there are no pathogens either, and the water can be considered safe. Statistically, this is a good test, but as can be seen, it does not guarantee water purity.

It should be mentioned that the coliform group comprise not only fecal coliforms but also other coliforms which are principally found in soil and vegetation. It is possible to distinguish between fecal coliform and the other subgroups but there is no satisfactory way to differentiate between fecal coliforms of human and animal origin.

USPHS drinking water standards for coliform organisms involve considerable detail but roughly they specify that the most probable number (MPN) shall not exceed 1 coliform organism per 100 ml of water. For water-contact recreational activities, many states recommend a limit of 1000 coliform organisms per 100 ml. The coliform measurement is used as a criterion for closing a beach due to pollution.

TABLE 7.1 - USPHS Chemical Standards for Drinking Water (1962)

Substance	Recommended maximum concentration, milligrams per liter	Maximum permissible concentration, milligrams per liter
Alkyl benzene sulfonate (ABS)	0.5	-
Arsenic	0.01	0.05
Barium	-	1.0
Cadmium	-	0.01
Carbon chloroform extract	0.2	-
Chloride	250	-
Chromium	-	0.05
Copper	1.0	-
Cyanide	0.01	0.2
Iron	0.3	-
Lead	-	0.05
Manganese	0.05	-
Nitrate	45.0	-
Phenols	0.001	-
Selenium	-	0.01
Silver	-	0.05
Sulfate	250	-
Total Dissolved Solids	500	-
Zinc	5.0	-

7.4: Water Treatment Fundamentals

Water treatment plants are designed to bring raw water up to drinking water quality. A typical plant might include the following sequence of steps (Figure 7.4): mixing, coagulation, settling, filtration, and chlorination. Basically the idea is to coagulate the suspended particles which use turbidity, taste, odor, and color, so that they can be removed by settling and filtration.

In the mixer, a coagulant such as alum, $Al_2(SO_4)_3 \cdot 18H_2O$ is added the raw water and rapidly mixed. The coagulant enables colloidal particles to stick together when contact is made, thus forming a floc nucleus. It is essential at this stage to obtain rapid and uniform dispersion of the coagulant to assure complete reaction.

In the flocculation basin, gentle and prolonged agitation enables the submicroscopic coagulated particles to assemble into large, plainly visible, agglomerates. These particles are large enough to settle at a rapid rate, or be removed from suspension by filtration.

From the flocculator, the water is passed into a settling basin where it may typically be held for from 2 to 4 hours. Here the large floc particles are allowed to settle under the influence of gravity, whereupon they are collected as sludge and disposed of. The effluent from the settling basin then goes to the filtration unit.

One of the most widely used filtration units is called a rapid-sand filter, which consists of a layer of carefully sieved sand, 24-30 inches thick, on top of a 12-18 inch bed of graded gravels. The pore openings between grains of sand are often greater than the size of the floc particles that are to be removed; so much of the filtration is accomplished by means other than simple straining. Adsorption, continued flocculation, and sedimentation in the pore spaces are also important removal mechanisms. When the filter becomes clogged with particles, the inlet valve is closed and the filter is cleaned by backwashing for 3 or 4 minutes. During the coagulation, settling, and filtration, practically all of the suspended solids, most of the color, and about 98 % of the bacteria are removed. For safety, the effluent must be disinfected, usually by chlorination.

Chlorination, and perhaps fluoridation, are the final steps in water treatment before storage and distribution. Chlorine is particularly effective against pathogenic bacteria but its ability to destroy amoeba and viruses is questionable.

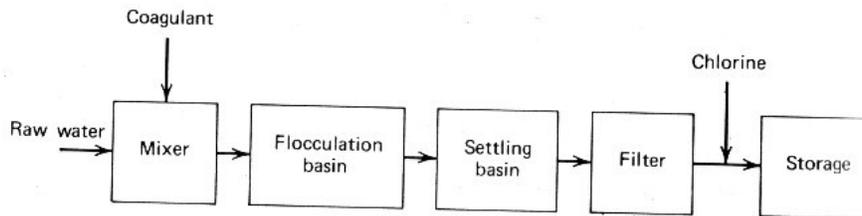


FIGURE 7.4 - Flow diagram for a water treatment plant.

7.5: Desalination

Table 7.1 indicates that the Public Health Service recommends 500 ppm as the maximum concentration of total dissolved solids (TDS) in drinking water. This concentration is regularly exceeded in many communities in the United States; in fact, over 3 million people in the U.S. receive water with a total dissolved solids concentration exceeding 1000 ppm (American Water Works Association 1971).

It has also been pointed out that as water evaporates, the salts are left behind so that many of man's uses of water (e.g., irrigation) have the effect of increasing the salt content (measured as total dissolved solids) of the return water. Conventional water treatment plants remove suspended and colloidal particles but are not effective in reducing the concentration of dissolved solids. There is, therefore, increasing interest being shown in desalination techniques not only for "brackish" water (roughly 1,000-10,000 ppm TDS) but also for seawater conversion (35,000 ppm TDS).

Desalination technology exists but is not commonly used except under special circumstances (e.g. on board ships or on islands). One factor which has been influential in restricting the proliferation of vast desalination projects is the requirement for large amounts of energy. From a relatively ample thermodynamic analysis (e.g., Spiegler 1962, or Harte and Socolow 1971), it can be shown that the theoretical minimum amount of energy required to desalt seawater, at 25°C, by any technique, is 2.65 kilowatt-hour (kWh) per

1000 U.S. gallons. An actual desalination plant would require considerably more energy than this theoretical minimum. Assuming a plant efficiency of 5 % (an average based on Table 10.1 in Spiegler 962) suggests that a value of 53 kWh per 1000 gallons is more realistic. To supply the U.S. average per capita water usage of 1600 gallons per day for all uses (including industry and agriculture) would therefore require close to 85 kWh of energy per person per day. For comparison, this is about one-third of the total amount of energy, per capita, consumed in the U.S., and is over three times the per capita consumption of electrical energy.

Though these amounts of energy are very large, it may be possible in the future to construct combined nuclear power plants and desalination facilities, with much of the energy for desalination coming from power plant waste heat. This makes desalination much more feasible than the above energy calculation might imply.

There are a number of techniques for desalinating water, including distillation, freezing, reverse osmosis, ion exchange, and electrodialysis. The particular technique which is most appropriate for a given area depends on such factors as the volume of water to be recovered, the salt concentration, and sources of energy available. We shall briefly describe two of the most frequently used processes: distillation and electrodialysis.

Distillation techniques are based on the fact that salts do not evaporate with water and hence if water is caused to vaporize and then to condense, the condensate will be pure water. Most of the world's seawater desalination uses some variation of this technique, which is schematically illustrated in Figure 7.5. Notice the incoming cold salt water is used to condense the steam. This serves the second purpose of warming the salt water so that less energy is required in the boiler, thus increasing the process efficiency. The efficiency is increased even more by connecting many stages, similar to those shown, in series, causing the incoming salt water temperature to gradually be raised as it passes from stage to stage.

The largest distillation plant in the U.S. is in Key West, Florida, and produces 2.6 million gallons per day (mgd). At current rates of municipal consumption, this could supply the needs of about 20,000 people. The cost of seawater desalting is currently about \$1 per 1000 gallons, but as Figure 7.6 indicates, as plant sizes increase in the future the cost is projected to decrease rapidly. For comparison, in 1965 the average cost to the consumer for water supplied by municipal systems was 29.2 cents per 1000 gallons (U.S. Water Resources Council 1968).

For brackish waters, a popular technique for desalination is *electrodialysis*. In electrodialysis the ions forming the salt are pulled out of solution by an electric field. Selective membranes, some of which pass only positively charged ions and some of which pass only negatively charged ions, make possible the separation of salt water from fresh, as shown in Figure 7.7. The two types of membranes are alternately spaced, so that when a voltage is applied to the electrodes the ions migrate into every other cell, leaving the alternate cells with fresh water. The energy requirements are dependent on the salinity of the water which makes these plants economical only for brackish water.

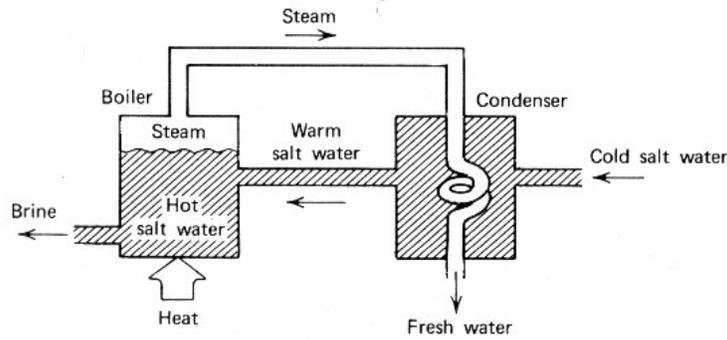


FIGURE 7.5 – Single-stage distillation

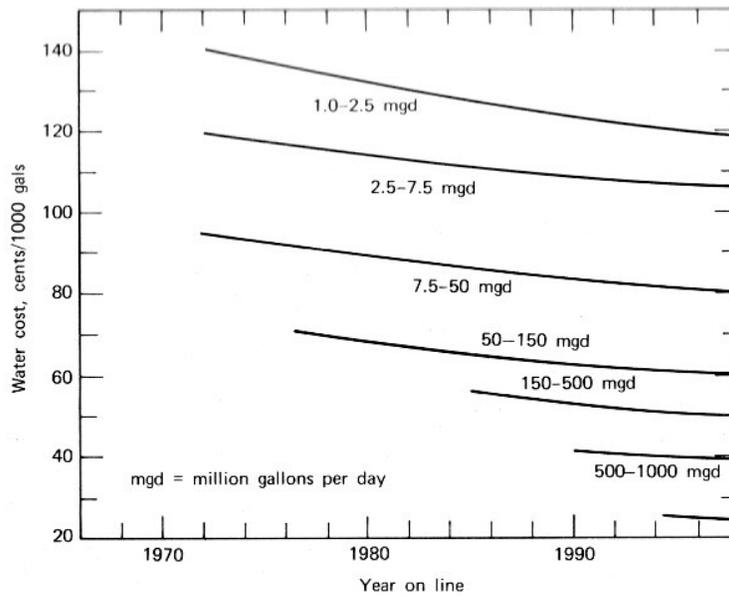


FIGURE 7.6 – Seawater desalting costs, distillation technology for a range of plant sizes

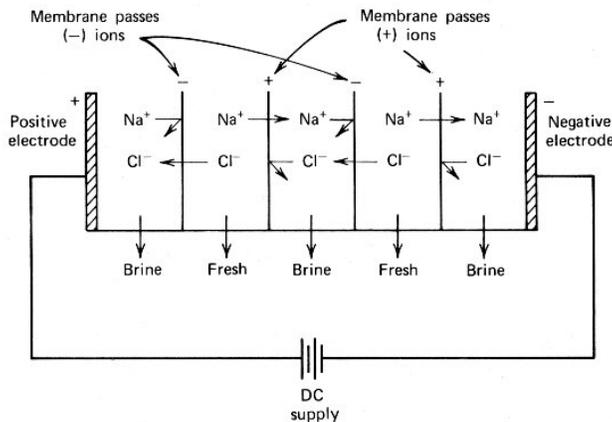


FIGURE 7.7 – Electrodialysis method of desalination. Selective membranes and electric field create alternate cells of fresh water and brine.

It is to be hoped that decreasing costs will make desalination competitive with the more environmentally disruptive techniques for acquiring fresh water such as were described in Section 4.6.

7.6: Sewage Treatment Fundamentals

In 1968 approximately 140 million people in the United States lived in communities served by sanitary sewer systems. That is very nearly twice as many as were so served in 1940. The number of people relying on cesspools and septic tanks has remained approximately the same during that period, being roughly 60 million. Our concern here is with the treatment and disposal of wastes collected in these sewered communities.

Municipal sewage is about 99.9% water and only about 0.03-0.06% solids. Typical values for BOD range from 75 to 276 mg/l and average flow rates in the U.S. are around 135 gallons per capita per day. The Composition of the sewage, of course, varies from city to city, being largely dependent on the inputs from industry. The sewage flows by gravity either to a sewage treatment plant or directly to the receiving water. The sewage of nearly 10 million people in the U.S. is discharged raw into our waterways (see Figure 7.8).

Sewage treatment plants are generally designated as supplying either primary, secondary, or tertiary treatment depending on the degree of purification. Primary treatment plants provide mechanical filtering and screening and the settleable solids are removed. This is followed by chlorination to disinfect the effluent which is then returned to the receiving body of water. Primary treatment typically removes about 35% of the BOD and 60% of the suspended solids. Obviously this is very minimal treatment but this is how the sewage of about 40 million people is treated. Very frequently if the effluent is to be released into the ocean, where there is plenty of dilution and no danger of depleting the DO, primary treatment is all that is used

Secondary treatment, which includes primary treatment (minus chlorination) as the first step, provides conditions for the biological oxidation of the organic wastes, much the same as would occur in nature. Secondary treatment removes about 90% of the BOD and 90% of the suspended solids. Most communities have this degree of treatment. The major complaint about secondary treatment though, is that while it does a good job of removing materials which would directly cause a drop in the DO of the receiving waters, it does a poor job of removing the nutrients such as nitrogen and phosphorus. "Typically only 5V" of the nitrogen and 30'7., of the phosphorus is removed. We have seen that these nutrients encourage the growth of nuisance algae which decrease the water quality and whose death and decay lead to a drop in DO.

Tertiary treatment is increasingly being recognized as an important part of any program to control eutrophication. Though most designs arc still in the development and testing stage, the effect of tertiary treatment is to greatly increase the removal efficiency

of nutrients and also improve the removal of BOD and suspended solids. In 1968 there were only ten tertiary treatment plants in the United States serving just over 325,000 people (USDI 1968b).

7.7: Primary and Secondary Treatment

When sewage first enters a treatment plant it is screened to remove large floating objects such as rags and sticks which might otherwise damage the pumps or clog small pipes. Screens vary, but typically might consist of parallel steel or iron bars spaced perhaps 1/2 inch apart. To avoid the disposal problem for material collected in the screens, some plants use a device called a comminuter. A comminuter grinds the coarse material into small enough particles that they can be left right in the sewage flow, to be removed later.

After screening, the sewage passes into a grit chamber where it is held for perhaps 1 minute. This allows sand, grit, and other heavy material to settle out. This material is usually nonoffensive after washing and is often disposed of as landfill.

From the grit chamber the sewage passes to a sedimentation tank where the speed of flow is reduced sufficiently to allow most of the suspended solids to settle out by gravity. Detention times of between 90 and 150 minutes are typical, resulting in a removal of from 50 to 65% of the suspended solids and from 25 to 40% of the 5 day BOD. The solids which settle out, called raw sludge are mechanically removed as are the grease and scum which float to the top. A simplified cross section of a rectangular sedimentation tank is shown in Figure 7.9; circular tanks are also common. As shown, an endless conveyor scrapes the floating material into a scum trough while it also pushes the settled solids into a sludge hopper.

If this is a primary treatment plant, the effluent at this point is chlorinated to destroy disease-causing bacteria and help control odors. Then it is released. Most modern sewage treatment plants follow primary treatment by biological, or secondary, treatment. Primary treatment removes the solids which settle easily, while secondary treatment is effective in removing most of the remaining organic matter by biological processes. Secondary treatment is very similar in concept to the processes of decomposition which occur in nature. Organic wastes are consumed by bacteria under controlled conditions, so that most of the BOD is removed in the treatment plant rather than in the receiving water.

Figure 7.10 shows a flow diagram for a secondary treatment plant which uses the activated-sludge process. After primary treatment (screen, grit chamber, primary settling), the effluent passes into an aeration tank here the organic matter is brought into contact with sludge which is sully laden with bacteria. To maintain aerobic conditions, air is pumped to the tank and the mixture is kept thoroughly agitated. The bacteria convert a portion of the organic waste into stabilized, low-energy compounds such as nitrates, sulfates, and carbon dioxide, but mostly new bacterial

cells are synthesized.

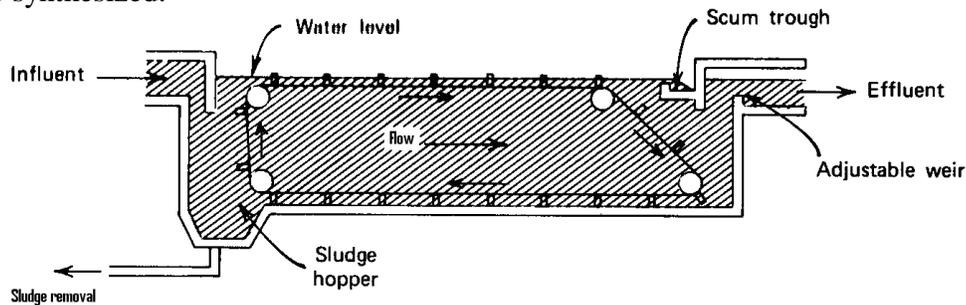


FIGURE 7.9 - Rectangular sedimentation tank.

After about 6 hours of aeration, the sewage (now referred to as the fixed liquor) passes on to a secondary settling tank where the solids (mostly bacterial masses) are separated from the liquid by subsidence. A portion of this activated sludge is recycled back to the aeration tank to maintain the proper level of biological activity there. The remainder of the sludge is removed for processing and disposal. The effluent from the secondary settling tank is then chlorinated and released.

Many biological treatment plants use a trickling filter instead of an aeration tank. The liquid effluent from the primary sedimentation tank is trickled over a bed of rocks which are covered by a layer of biological slime. The rock bed may be anywhere from about 3 to 8 feet in depth, with enough openings between rocks to allow air to easily circulate. As the waste water passes through the filter, the bacteria adsorb and consume the organic matter in much the same manner as occurs in the activated-sludge process. The biological community attached to the rocks is quite complex, consisting not only of various kinds of bacteria, but also fungi, algae, protozoa, worms, insect larvae, and snails. Periodically this biological slime is washed off of individual rocks by hydraulic action, to be later removed in the secondary settling tank.

Sludge which has been collected from the settling tanks is concentrated and sent to an anaerobic digester. Anaerobic decomposition in the digester is slow but has the advantage that only a small percentage of the wastes are converted into new bacterial cells. Most of it is converted into methane as an oxide. The remaining solids are well stabilized and can be dried and used for landfill or fertilizer. About 65-70% of sewage gas is methane (CH₄) which can be captured and used as a fuel for running blowers and boilers, pumping sewage, and generating electricity for the sewage plant. • On a daily per capita basis, a secondary sewage plant produces about 1.0 cubic foot of sewage gas, with a heating value of about 600 BTU (Metcalf and Eddy 1972). This amount of energy is about equal to the energy consumed by a 60 watt lightbulb burning for 3 hours.

There are other ways to treat sewage besides those mentioned here. Some communities use what are called stabilization or oxidation ponds which are large ponds, about 3 feet deep, with a surface area of about 1 acre for every 1000 people to be served. Oxygen is supplied to the ponds either by mechanical aeration or through the

photosynthetic activity of algae. The decomposition by bacteria is essentially the same as occurs in the activated-sludge process. Oxidation ponds may be used alone, in which case they may be as effective as secondary treatment, or as an addition to other waste treatment processes. At Santee, California, the effluent from a secondary treatment plant is kept in such a lagoon for 30 days. After chlorination, the lagoon water is allowed to trickle down through sandy soil into a lake which has such high quality water that it is used for swimming, boating, and fishing.

7.8: Tertiary Treatment

It has only been relatively recently that the processing of sewage beyond the secondary level has received much attention. Secondary treatment plants do a poor job of removing nutrients. Total nitrogen removal of from 25 to 55 %, and total phosphorus removal of from 10 to 30% are typical (McCarty 1970). As was discussed in Chapter 6, nutrient stimulation can lead to excessive growths of algae and other aquatic plants. There are so many techniques available for increasing the nutrient removal efficiencies of waste water treatment plants (see, for ample, Metcalf and Eddy 1972 Table 14.2), that it is convenient to classify them as being physical, chemical, or biological processes. Physical processes include filtration, distillation, and reverse osmosis; chemical processes include electro dialysis (Section 7.5), chemical precipitation, carbon adsorption, ammonia stripping, and ion exchange; biological processes include the harvesting of algae grown on the nutrients, bacterial assimilation, and bacterial nitrification and denitrification.

Obviously it would be impossible to discuss all of these techniques one short section so we shall instead describe the techniques which are in use at one of the nation's most advanced wastewater treatment plants - the 7.5 mgd South Tahoe facility in California. Effluent from the activated sludge secondary treatment portion of the plant is passed through the sequence of steps diagrammed in Figure 7.11.

The advanced treatment begins with the addition of lime which acts as coagulant (Section 7.4). The flocculated, high-pH water flows to the Chemical clarifier where suspended matter and most of the phosphates are settled out as a slime sludge. The effluent from the clarifier passes to the ammonia stripping tower for nitrogen removal. Ammonium ions in Waste water exist in equilibrium with ammonia and hydrogen ions according to the following equation:



At the high-pH levels created by the lime, the equilibrium is shifted far to the right so that the ammonia is virtually all present as a dissolved gas rather than as ammonium ion in solution. When the water is agitated in the presence of large amounts of air, the ammonia is liberated to the atmosphere. This happens in the 50 foot high, forced ventilation stripping tower, resulting in a removal of from 50 to 98% of the nitrogen.

The water leaving the tower is recarbonated to reduce the pH, using

carbon dioxide recovered from furnace stack gases. Filtration on a mixed media bed, consisting of coarse coal, medium-sized sand, and fine garnet, filters out remaining turbidity, phosphates, and calcium carbonate. The final step before chlorination is to pass the water through a column of granulated, activated carbon which removes color, odor, and almost all of the remaining organic material.

The effluent from the Tahoe plant is of very high quality. All of the suspended solids, 99.8% of the BOD, 94% of the phosphorus, and from 50 to 98 % of the nitrogen have been removed. The median coliform count is less than 2.2 per 100 ml (Culp and Moyer 1969). By law, all waste water must be removed from Tahoe basin, so the effluent is pumped over a ridge and released into a specially constructed reservoir at Indian Creek, 27 miles away.

7.9: The Cost of Water Pollution Control

It is important to at least briefly indicate the order-of-magnitude costs which are involved in water pollution control. Figure 7.12 indicates the economies of scale that can be achieved when large sewage treatment plants are built. For example, construction costs for an activated-sludge secondary treatment plant serving 5,000-10,000 people are about \$86 per capita, while the same facilities designed for a population of over 100,000 would cost only \$40 per capita. It is also indicated that the cost of constructing an activated-sludge plant is only about 30% more than the cost of simple primary treatment. For example, at the rates indicated in Figure 7.13, to construct an activated sludge plant for a city of 150,000 would cost roughly \$6 million, while primary treatment would cost \$4.5 million.

Construction costs are only one part of the total cost of a sewage treatment plant. Once installed, facilities must be operated and maintained. The Environmental Protection Agency (1972), for example, estimates that when the costs of industrial pollution control are calculated on an annualized basis, roughly one-fourth of the total is capital costs; operation and maintenance account for another 35 %; and interest payments make up the remaining 40 %.

Annual operation and maintenance costs for treatment plants show similar economies of scale as was indicated for capital costs, but the cost of running an activated-sludge plant is about double the cost of running a primary treatment plant. Tertiary treatment plants cost much more. Wollman (1971) suggests as a rule of thumb that total treatment costs are double for a tertiary treatment plant over a secondary plant.

As is always the case in pollution control, costs increase dramatically as higher levels of treatment are achieved. For example, a FWCPA study done on the Delaware Estuary (Figure 7.13) indicated that it would cost 12 times as much to assure a DO level of 5 mg/l as it would to provide 4 mg/l. To provide 6 mg/l increases the cost by about a factor of 4.

When water pollution control costs are considered on a national level, the necessary expenditures to achieve a reasonable level of water quality can be staggering. Table 7.2 summarizes some estimates reported by the Council on Environmental Quality in 1972. The data indicate the expenditures which would be required in the 1970's to bring water quality up to standards which were already law in mid-1972. The capital investment in treatment plants and the interceptor sewers, pumping stations, and outfalls associated with the plants would cost \$18.9 billion. Operating the plants would require another \$23.6 billion, for a total of \$42.5 billion. Expenditures required by the private sector, mostly manufacturing, are another \$40.9 billion. Total costs for the 10 year period are estimated at \$87.3 billion-excluding an estimated \$17-56 billion more which could be necessary if combined sewer systems were to be updated

TABLE 7.2 - The Costs of Water Pollution Control for the Years 1971-1980, Billions of 1971 Dollars

Sector	Cumulative requirements, 1971-1980		
	Capital investment	Operating costs	Cash flow
Public:	1.2	2.7	3.9
Federal			
State and local:	18.9	23.6	42.5
Treatment systems			
Combined sewers	(17-56)	n.a.	(17-56)
Private:	11.9	14.2	26.1
Manufacturing			
Utilities	4.5	4.2	8.7
Feed lots	1.9	1.8	3.7
Construction sediment	0.9	0.1	1.0
Vessels	0.9	0.5	1.4
Total	40.2	47.1	87.3

Congressional awareness of the water pollution problem resulted in passage of the Federal Water Pollution Control Act Amendments of 1972, which some consider to be the most comprehensive and expensive environmental legislation in the nation's history. The bill contains authorizations which total almost \$24.7 billion for fiscal years 1972-1975, including \$18 billion in contract authority for federal grants to the states for waste treatment facilities construction. It also requires municipal plants to provide secondary treatment by 1977.

The bill sets as a national *goal* the elimination of all pollutant discharges into U.S. waters by 1985, and as an interim goal, achievement of water quality safe for

fish, shellfish, wildlife and recreation by 1983. By July 1, 1977, all industries are required to use the "best practicable" technology for treatment of any discharges, and by *July 1, 1983*, they are required to install the "best available technology economically achievable."

7.10: Conclusions

It is interesting to note the historical shift in emphasis that has occurred in the water quality control programs of the United States. Initially, attention was focused on the need to control the dreadful outbreaks of water-borne diseases such as typhoid and cholera. The relatively simple techniques of filtration and chlorination of drinking water can be credited with saving many thousands of lives. It would in fact be possible to eliminate the majority of human disease in the world through the single step of supplying proper sanitation to all people.

Water-borne diseases however, are no longer the principal water pollution concern in this country. It will, of course, always be vitally important to diligently monitor our sanitation systems for pathogenic organisms, but after relative control was achieved, attention did shift to the control of oxygen-consuming wastes. Sewage treatment plants were designed to reduce the BOD load placed on receiving waters, and when properly operated, secondary treatment plants are quite satisfactory in this regard. Unfortunately, too many municipalities are still using inadequate primary treatment facilities.

More recently, water pollution problems have become more complex. Now it is necessary in some cases to be able to control the release of nutrients to slow the eutrophication of our lakes. Industry must also learn to do a better job of controlling the release of its many obnoxious effluents -mercury, cadmium, acid mine wastes, pesticides, heat, etc. The cost of the necessary programs is high, but not at all unreasonable in view of the danger involved in continuing to treat these problems lightly.