

## Chapter 4 Water Quality Engineering

The uses we make of water in lakes, rivers, ponds, and streams are greatly influenced by the quality of the water found in them. Activities such as fishing, swimming, boating, shipping, and waste disposal have very different requirements for water quality. In many parts of the world, the introduction of pollutants from human has seriously degraded water quality even to the extent of turning pristine trout streams into foul open sewers with few life forms and fewer beneficial uses.

Water quality management is concerned with the control of pollution from human activities so that the water is not degraded to the point that it is no longer suitable for intended uses. In water quality management it's also important to know how much is too much for a particular water body.

To know how much waste can be tolerated (the technical term is *assimilated*) by a water body, we must know the type of pollutants discharged and the manner in which they affect water quality. We must also know how water quality is affected by natural factors such as the mineral heritage of the watershed, the geometry of the terrain, and the climate of the region.

### 4.1. Water pollutants and their sources

**Point Sources.** The wide range of pollutants discharged to surface waters can be grouped into broad classes, as shown in Table 4-1. Domestic sewage and industrial wastes are called point sources because they are generally collected by a network of pipes or channels and conveyed to a single point of discharge into the receiving water. In general, point source pollution can be reduced or eliminated through waste minimization and proper wastewater treatment prior to discharge to a natural body.

**Table 4-1** Major pollutant categories and principal sources of pollutants

Pollutant category	Point sources		Non-point sources	
	Domestic sewage	Industrial wastes	Agricultural runoff	Urban runoff
Oxygen-demanding material	X	X	X	X
nutrients	X	X	X	X
Pathogens	X	X	X	X
Suspended solids/sediments	X	X	X	X
Salts		X	X	X
Toxic metals		X		X
Toxic organic chemicals		X	X	
Endocrine-disrupting chemicals	X	X	X	
Heat		X		

**Non-Point Sources.** Urban and agricultural runoff are characterized by multiple discharge points. These are called non-point sources. Often the polluted water flows over the surface of the land or along natural drainage channels to the nearest water body.

Runoff from agricultural land is a significant non-point source. Fertilizer, whether in the form of manure or commercial fertilizer, contributes nutrients. Agricultural runoff carries toxic organic compounds in the form of pesticides. Soil erosion contributes suspended solids. Implementation of *Best Management Practices* (BMP) to reduce excess application of fertilizer and pesticides along with erosion control programs conserves the farmers economic investment while protecting the river.

**Oxygen-Demanding Material.** Anything that can be oxidized in the receiving water with the consumption of dissolved oxygen is termed oxygen demanding material. The consumption of dissolved oxygen, DO, poses a threat to fish and other higher forms of aquatic life that must have oxygen to live. Oxygen-demanding materials in domestic sewage come primarily from human waste and food residue. Particularly noteworthy among the many industries that produce oxygen-demanding wastes are the food processing and paper industries.

**Nutrients.** Nitrogen and phosphorus, two nutrients of primary concern, are considered pollutants because they are too much of a good thing. All living things require these nutrients for growth. Thus, they must be present in rivers and lakes to support the natural food chain. Problems arise when nutrient levels become excessive and the food web is grossly disturbed, which causes some organisms to proliferate at the expense of others. As will be discussed in a later section, excessive nutrients often lead to large growths of algae, which in turn become oxygen-demanding material when they die and settle to the bottom. Some major sources of nutrients are phosphorus based detergents, fertilizers, and food-processing wastes.

**Pathogenic Organisms.** Microorganisms found in wastewater include bacteria, viruses, and protozoa excreted by diseased persons or animals. When discharged into surface waters, they make the water unfit for drinking. If the concentration of pathogens is sufficiently high, the water may also be unsafe for swimming and fishing. Certain shellfish can be toxic because they concentrate pathogenic organisms in their tissues, making the toxicity levels in the shellfish much greater than the levels in the surrounding water.

**Suspended Solids.** Organic and inorganic particles that are carried by the wastewater into a receiving water are termed suspended solids (SS). When the speed of the water is reduced by flowing into a pool or a lake, many of these particles settle to the bottom as sediment. Organic suspended solids may also exert an oxygen demand. Inorganic suspended solids are discharged by some industries but result mostly from soil erosion. Deposition of excessive sediment loads into lakes and reservoirs reduces the usefulness of the water and also will destroy ecological habitats.

## 4.2. Water quality management in Rivers

The objective of water quality management is simple to state: to control the discharge of pollutants so that water quality is not degraded to an unacceptable extent below the natural background level. however to control we must be able to measure the pollutants, predict the impact of the pollutants on water quality, determine the background water quality which would

be present without human intervention, and decide the levels acceptable for intended uses of the water.

The impact of pollution on a river depends both on the nature of the pollutant and the unique characteristics of the individual river. Some of the most important characteristics include the volume and speed of water flowing in the river, the river's depth, the type of bottom, and the surrounding vegetation. Other factors include the climate of the region, the mineral heritage of the watershed, land use patterns, and the types of aquatic life in the river. Water quality management for a particular river must consider all these factors.

we can control the pollution of a river by specifying total maximum daily loads (TMDL). A TMDL specifies the maximum amount of pollutant that a water body can receive and still meet water quality standards.

#### 4.2.1. Effects of Oxygen-Demanding Wastes on Rivers

To predict the extent of oxygen depletion, it is necessary to know how much waste is being discharged and how much oxygen will be required to degrade the waste. However, because oxygen is continuously being replenished from the atmosphere and from photosynthesis by algae and aquatic plants, as well as being consumed by organisms, the concentration of oxygen in the rivers is determined by the relative rates of these competing processes.

##### Biochemical Oxygen Demand

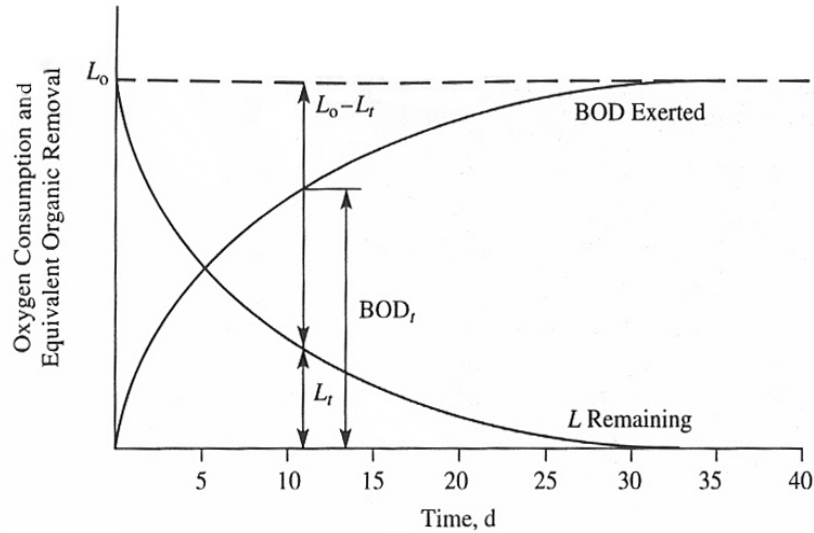
The amount of oxygen required to oxidize a substance to carbon dioxide and water may be calculated by stoichiometry if the chemical composition of the substance is known. This amount of oxygen is known as the *theoretical oxygen demand* (ThOD).

**Example 4-1.** Compute the ThOD of 108.75 mg/L of glucose ( $C_6H_{12}O_6$ ).

In contrast to the ThOD, the *chemical oxygen demand*, COD, is a measured quantity that does not depend on knowledge of the chemical composition of the substances in the water. In the COD test, a strong chemical oxidizing agent (chromic acid) is mixed with a water sample and then boiled. The difference between the amount of oxidizing agent at the beginning of the test and that remaining at the end of the test is used to calculate the COD.

If the oxidation of an organic compound is carried out by microorganisms using the organic matter as a food source, the oxygen consumed is known as *biological oxygen demand*, or BOD. The actual BOD is less than the ThOD due to the incorporation of some of the carbon into new bacterial cells. The test is a bioassay that utilizes microorganisms in conditions similar to those in natural water to measure indirectly amount of biodegradable organic matter present. *Bioassay* means to measure by biological means. A water sample is inoculated with bacteria that consume the biodegradable organic matter to obtain energy for their life processes. Because the organisms also utilize oxygen in the process of consuming the waste, the process is called *aerobic* decomposition. This oxygen consumption is easily measured. The greater the amount of organic matter present, the greater the amount of oxygen utilized. The BOD test is an indirect measurement of organic matter because we actually measure only the change in dissolved oxygen concentration caused by the microorganisms as they degrade the organic matter.

When a water sample containing degradable organic matter is placed in a closed container and



**Figure 4-1** BOD curve

inoculated with bacteria, the oxygen consumption typically follows the pattern shown in Figure 4-1. It is generally assumed the rate at which oxygen is consumed is directly proportional to the concentration degradable organic matter remaining at any time. As a result, the BOD curve Figure 4-1 can be described mathematically as a first-order reaction. Using our definition of reaction rate and reaction order from Chapter 3, this may be expressed as,

$$\frac{dL_t}{dt} = -r_A \quad (4-1)$$

where  $L_t$  = oxygen equivalent of the organics remaining at time  $t$ , mg/L

$$-r_A = -kL_t$$

$k$  = reaction rate constant,  $d^{-1}$

Rearranging Equation 4-1 and integrating yields:

$$\frac{dL_t}{L_t} = -k dt$$

$$\int_{L_0}^{L_t} \frac{dL_t}{L_t} = -k \int_0^t dt$$

$$\ln \frac{L_t}{L_0} = -kt$$

or

$$L_t = L_o e^{-kt}$$

Where  $L_o$  = oxygen equivalent of organic compounds at time  $t=0$

Rather than  $L_t$  our interest is in the amount of oxygen used in the consumption of the organics ( $BOD_t$ ). From Figure 4-1, it is obvious that  $BOD_t$  is the difference between the initial value of  $L_o$  and  $L_t$  so

$$\begin{aligned} BOD_t &= L_o - L_t \\ &= L_o - L_o e^{-kt} \\ &= L_o(1 - e^{-kt}) \end{aligned} \quad (4-2)$$

$L_o$  is often referred to as the ultimate BOD, that is, the maximum oxygen consumption possible when the waste has been completely degraded. Equation 4-2 is called the BOD rate equation and is often written in base 10:

$$= L_o(1 - 10^{-Kt}) \quad (4-3)$$

Note that lower case  $k$  is used for the reaction rate constant in base  $e$  and that capital  $K$  is used for the constant in base 10. They are related:  $k = 2.303(K)$ .

Oxygen depletion is related to both the ultimate BOD and the BOD rate constant ( $k$ ), while the ultimate BOD increases in direct proportion to the concentration of degradable organic matter, the numerical value of the rate constant is dependent on the following:

1. The nature of the waste
2. The ability of the organisms in the system to utilize the waste
3. The temperature: Laboratory test is done at a standard temperature of 20°C, and the BOD rate constant is adjusted to the receiving water temperature using the following expression:

$$k_T = k_{20}(\theta)^{T-20} \quad (4-4)$$

where  $T$  = temperature of interest, °C

$k_T$  = BOD rate constant at the temperature of interest,  $d^{-1}$

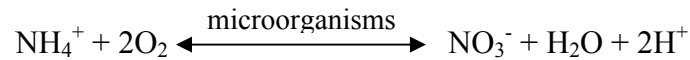
$k_{20}$  = BOD rate constant determined at 20°C,  $d^{-1}$

$\theta$  = temperature coefficient. This has a value of 1.135 temperatures between 4 and 20°C and 1.056 for temperatures between 20 and 30°C

## Nitrogen Oxidation

Many organic compounds, such as proteins, contain nitrogen that can be oxidized with the consumption of molecular oxygen. But, the organisms and rates of nitrogen oxidation are distinctly different from those of carbon oxidation. Logically, oxygen consumption due to oxidation of carbon is called *carbonaceous BOD* (CBOD), while that due to nitrogen oxidation is called *nitrogenous BOD* (NBOD).

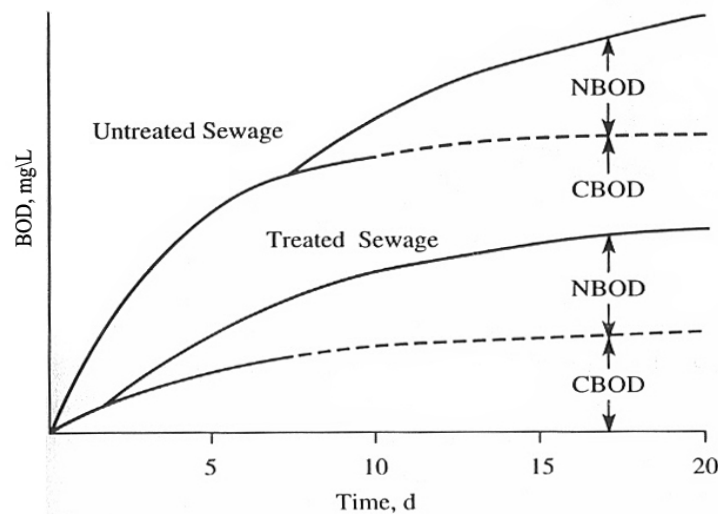
Nitrogen is released into the surrounding water as ammonia ( $\text{NH}_3$ ) from different organic compounds plus that from other sources such as industrial wastes and agricultural runoff, and it's usually found as ammonium cation ( $\text{NH}_4^+$ ). The ammonia is then oxidized to nitrate ( $\text{NO}_3^-$ ) by a special group of nitrifying bacteria as their source of energy in a process called nitrification. The overall reaction for ammonia oxidation is



From this reaction the theoretical NBOD can be calculated as follows:

$$\text{NBOD} = \frac{\text{grams of oxygen used}}{\text{grams of nitrogen oxidized}} = \frac{4 \times 16}{14} = 4.57 \frac{\text{g O}_2}{\text{g N}}$$

When samples of untreated and treated sewage are subjected to the BOD test, oxygen consumption follows the pattern shown in figure 4-2.

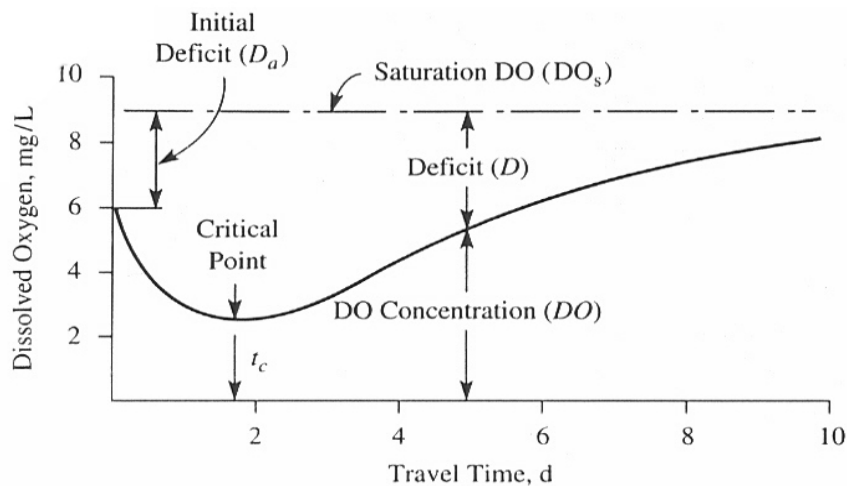


**Figure 4-2** BOD curve showing both carbonaceous and nitrogenous BOD

### DO Sag Curve

The concentration of dissolved oxygen in a river is an indicator of the general health of the river. All rivers have some capacity of self-purification. As the amount of waste increases, the self-purification capacity can be exceeded, causing detrimental changes in plant and animal life. When the DO drops below about 4 to 5 mg/L, most game fish will have been driven out. If the DO is completely removed, fish and other higher animals are killed or driven out and extremely noxious conditions result. The water becomes blackish and foul smelling as the sewage and dead animal life decompose under anaerobic conditions.

One of the most major tools of water quality management in rivers is the ability to assess the capability of a stream to absorb a waste load. This is done by determining the profile of DO concentration downstream from a waste discharge. This profile is called the DO sag curve (see figure 4-3). As depicted in figure 4-5, the biota of the stream are often a reflection of the dissolved oxygen conditions in the stream.



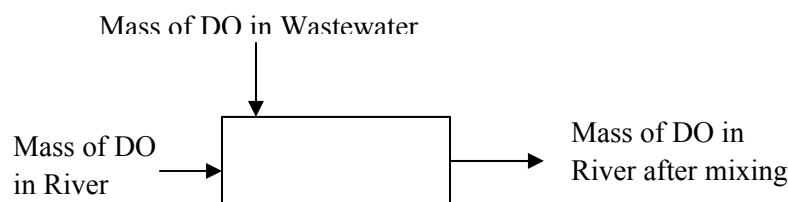
**Figure 4-3** Typical DO sag curve

To develop a mathematical expression for the DO sag curve, the sources of oxygen and the factor affecting oxygen depletion must be identified and quantified. The only significant sources of oxygen are reaeration from the atmosphere and photosynthesis of aquatic plants. Oxygen depletion is caused by the following factors:

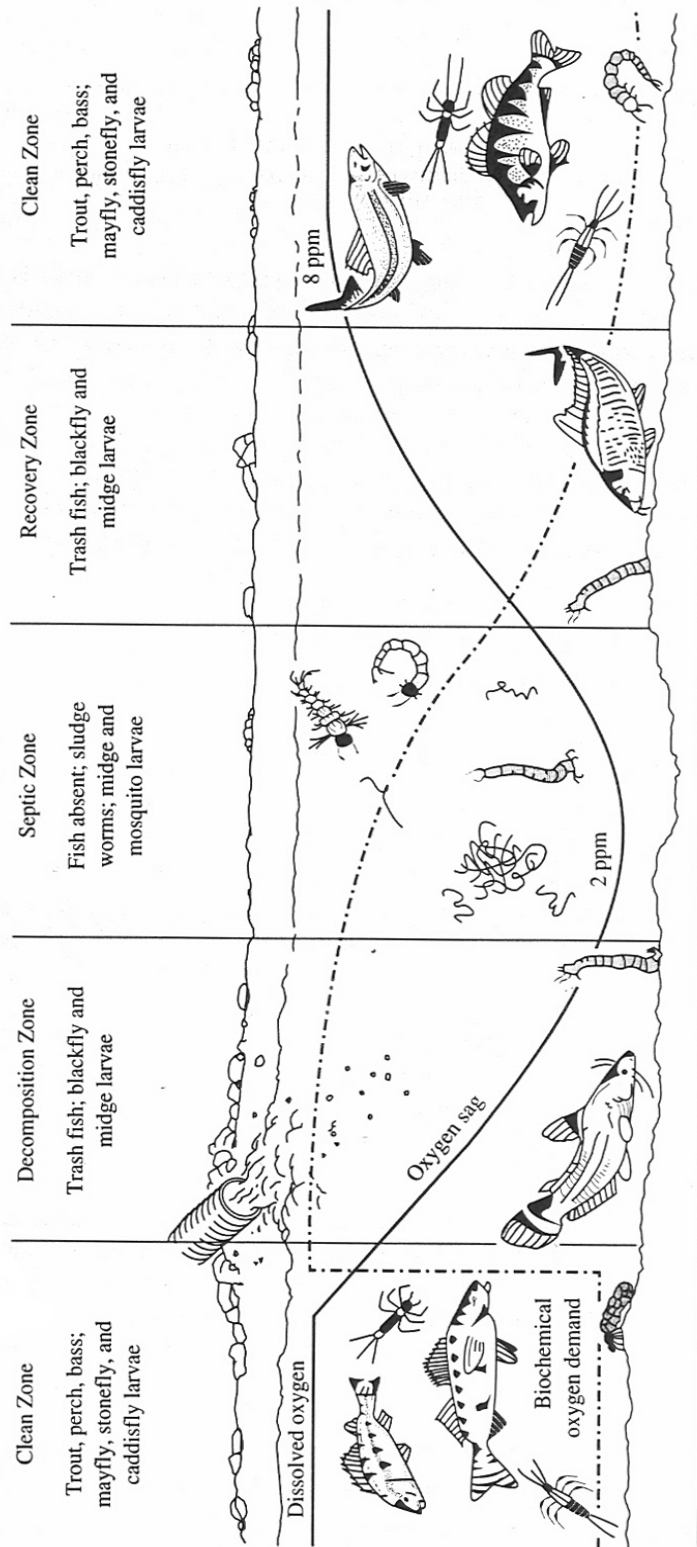
- Carbonaceous and nitrogenous BOD of waste discharged and the BOD in the upstream the river from the waste discharge point.
- The DO in the waste discharge which is usually less than that in the river. Thus, the DO in the river is lowered as soon as the waste is added.
- Non-point source pollution, the respiration of living organisms in the sediments, and the respiration of aquatic plants

The most commonly used equation for DO sag curve is known as *Streeter-Phelps Equation*, which is developed by considering only initial DO reduction, CBOD, and reaeration from the atmosphere.

**Mass-Balance Approach.** Three conservative mass balances may be used to account for initial mixing of the waste stream and the river. DO, CBOD, and temperature all change as the result of mixing of the waste stream and the river. Once these are accounted for, the DO sag curve may be viewed as a nonconservative mass balance, that is, one with reaction.



**Figure 4-4** Conservative mass balance diagram for DO mixing.



**Figure 4-5** Oxygen sag downstream of a biodegradable organic chemical source.



The concentrations of DO and BOD after mixing (see figure 4-5) are the respective masses per unit time divided by the total flow rate:

$$DO = \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r} \quad (4-5)$$

$$L_a = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r} \quad (4-6)$$

Where  $Q_w$  = volumetric flow rate of wastewater,  $m^3/s$

$Q_r$  = volumetric flow rate of river,  $m^3/s$

$DO_w$  = dissolved oxygen concentration in the wastewater,  $g/m^3$

$DO_r$  = dissolved oxygen concentration in the river,  $g/m^3$

$L_w$  = ultimate BOD of the wastewater,  $mg/L$

$L_r$  = ultimate BOD of the river,  $mg/L$

$L_a$  = initial ultimate BOD after mixing  $mg/L$

---

**Example 4-2.** A certain college discharges  $17,360 m^3/d$  of treated wastewater into a nearby river. The treated wastewater has a  $BOD_5$  of  $12 mg/L$  and  $k$  of  $0.12 d^{-1}$  at  $20^\circ C$ . The river has a flow rate of  $0.43 m^3/s$  and an ultimate BOD of  $5.0 mg/L$ . The DO of the river is  $6.5 mg/L$  and the DO of the wastewater is  $1.0 mg/L$ . Compute the DO and initial ultimate BOD after mixing.

---

The temperature after mixing is found by solving a heat balance equation rather than a mass balance (Loss of heat by hot bodies = gain of heat by cold bodies). The final river temperature after mixing is thus calculated as:

$$T_f = \frac{Q_w T_w + Q_r T_r}{Q_w + Q_r} \quad (4-7)$$

**Oxygen Deficit.** The oxygen deficit is the amount by which the actual dissolved oxygen concentration is less than the saturated value with respect to oxygen in the air:

$$D = DO_s - DO \quad (4-8)$$

Where  $D$  = oxygen deficit,  $mg/L$

$DO_s$  = saturation concentration of dissolved oxygen at the temperature of the river after mixing,  $mg/L$

$DO$  = actual dissolved oxygen concentration,  $mg/L$

**Initial Deficit ( $D_a$ ).** The initial deficit is calculated as the difference between saturated DO and the concentration of the DO after mixing (Equation 4-5):

$$D_a = DO_s - \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r} \quad (4-9)$$

---

**Example 4-3.** Calculate the initial deficit of the river after mixing with the wastewater from the college (Example 4-2). The stream temperature is  $10^\circ C$  and the wastewater temperature is  $10^\circ C$ .

---

**DO Sag Equation.** After doing a mass balance analysis of DO in a small reach (stretch) river we can develop Streeter-Phelps equation. The oxygen deficit can then be expressed as a function of oxygen utilization and reaeration from the atmosphere:

$$\frac{dD}{dt} = k_d L - k_r D \quad (4-10)$$

where  $\frac{dD}{dt}$  = the change in oxygen deficit (D) per unit time, mg/L.d

$k_d$  = deoxygenation rate constant,  $d^{-1}$

$k_r$  = reaeration rate constant,  $d^{-1}$

L = ultimate BOD of river water, mg/L

D = oxygen deficit in river water, mg/L

By integrating Eq. 4-10, and using the initial conditions (at  $t = 0$ ,  $D = D_a$ ) we obtain the DO sag equation:

$$D = \frac{k_d L_a}{k_d - k_r} (e^{-k_d t} - e^{-k_r t}) + D_a (e^{-k_r t}) \quad (4 - 11)$$

where D = oxygen deficit in river water after exertion of BOD for time, t, mg/L

$L_a$  = initial ultimate BOD after river and wastewater have mixed (Eq 4-6), mg/L

t = time of travel of wastewater discharge downstream, d

When  $k_d = k_r$ , Equation 4-11 reduces to:

$$D = (k_d t L_a + D_a) (e^{-k_d t}) \quad (4 - 12)$$

**Deoxygenation Rate Constant.** The deoxygenation rate constant difference from the BOD rate constant because there are physical and biological differences between a river and a BOD bottle. The following formula can be used to estimate  $k_d$  from  $k$  using characteristics of the stream.

$$k_d = k + \frac{v}{H} \eta \quad (4 - 13)$$

Where  $k_d$  = deoxygenation rate constant at 20°C,  $d^{-1}$

$v$  = average speed of stream flow, m/s

$k$  = BOD rate constant determined in laboratory at 20°C,  $d^{-1}$

H = average depth of stream, m

$\eta$  = bed-activity coefficient

The bed-activity coefficient may vary from 0.1 for stagnant or deep water to 0.6 or more for more rapidly flowing streams.

---

**Example 4-4** Determine the deoxygenation rate constant for the reach of the river (Example 4-2, 4-3) below the wastewater outfall (discharge pipe). The average speed of the stream flow in the river is 0.03 m/s. The depth is 5.0 m and the bed-activity coefficient is 0.35.

---

**Reaeration.** The value of  $k_r$  depends on the degree of turbulent mixing, which is related to stream velocity, and on the amount of water surface exposed to the atmosphere compared to the volume of water in the river. A narrow, deep river will have a much lower  $k_r$  than a wide, shallow river. A generalized empirical equation to estimate the reaeration constant based on the characteristics of the stream and the molecular diffusion of oxygen into water is given below:

$$k_r = \frac{3.9v^{0.5}}{H^{1.5}} \quad (4 - 14)$$

where  $k_r$  = reaeration rate constant at 20°C, day<sup>-1</sup>  
 $v$  = average stream velocity, m/s  
 $H$  = average depth, m

Note that it is physically impossible for the DO to be less than zero. If the deficit calculated is greater than the saturation DO, then all the oxygen is depleted at some earlier time and the DO is zero. If the result of your calculation yields a negative DO, report it as zero because it cannot be less than zero!

The lowest point on the DO sag curve, which is called the critical point, is of major interest since it indicates the worst conditions in the river. The time to the critical point ( $t_c$ ) can be found by differentiating Equation 4-11, setting it equal to zero, and solving for  $t$  using base  $e$  values for  $k_r$  and  $k_d$ .

$$t_c = \frac{1}{k_r - k_d} \ln \left[ \frac{k_r}{k_d} \left( 1 - D_a \frac{k_r - k_d}{k_d L_a} \right) \right] \quad (4 - 15)$$

or when  $k_d = k_r$ :

$$t_c = \frac{1}{k_d} \left( 1 - \frac{D_a}{L_a} \right) \quad (4 - 16)$$

The critical deficit ( $D_c$ ) is then found by using this critical time in Equation 4-11.

---

**Example 4-5.** Determine the DO concentration at a point 5 km downstream from the college discharge into the river (Example 4-2, 4-3, and 4-4). Also determine the critical DO and the distance downstream at which it occurs.

---