# Water Pollution and Control

**PDH: 4.0 Hours**
**Dr. M. A. Karim, P.E., F.ASCE**

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## 1. Introduction

The course presents the Introduction, Water Pollutants and Their Sources, Water Pollution in Rivers that includes Total maximum daily load (TMDL), Effect of Oxygen Demanding Wastes on Rivers, Biochemical Oxygen Demand (BOD), Graphical Determination of BOD Constants, Laboratory Measurements of BOD, DO Sag Curve, and Effects of Nutrients on Water Quality in Rivers. This course is suggested for civil engineers, environmental engineers, and water and wastewater treatment plant managers and operators.

In this course we define water pollution, TMDL, BOD, COD and discuss the pertinent regulations and permitting requirements of NPDES permit, types of water pollutants and their sources, Effect of Oxygen Demanding Wastes on Rivers, Biochemical Oxygen Demand (BOD), Graphical Determination of BOD Constants, Laboratory Measurements of BOD, DO Sag Curve, and Effects of Nutrients on Water Quality in Rivers. We also discuss how we can control the water pollution, what are the effects of water pollution, and how we can stop the water pollution.

## 2. Learning Objectives

Upon successful completion of this course, the participants will be able to:

- Identify water pollutants and their sources.
- Defines TMDL, BOD, and COD.
- Model BOD and calculate $BOD_5$ and $BOD_u$.
- Determine BOD rate constants graphically.
- Develop DO Sag Curve (Model).
- Solve problems using BOD model and DO Sag curve equations.
- Explain the effects of nutrients of nutrients on water quality in rivers.

## 3. Water Pollution

Water is typically referred to as polluted when it is impaired by anthropogenic contaminants and either does not support a human use, such as drinking water, or undergoes a marked shift in its ability to support its constituent biotic communities, such as fish. Natural phenomena such as volcanoes, algae blooms, storms, and earthquakes also cause major changes in water quality and the ecological status of water.

Water pollution is a major global problem which requires ongoing evaluation and revision of water resource policy at all levels (international down to individual aquifers and wells). It has been suggested that water pollution is the leading worldwide cause of deaths and diseases[1,2] and that it accounts for the deaths of more than 14,000 people daily.[2] An estimated 580 people in India die of water pollution related illness every day.[3]

A polluted river draining an abandoned copper mine

Raw sewage and industrial waste discharging in a river

The uses of water in rivers, lakes, ponds, and streams is greatly influenced by the quality of water found in them. The following are the major usages that must be considered in water pollution:

- Fishing, swimming, boating, shipping, and waste disposal have very different requirements for water quality
- Water quality management in concerned with the control of pollution from human activity so that the water is not degraded to the point that is no longer suitable for intended uses.
- How much waste can be tolerated or assimilated by a water body, type of pollutants discharged, and the manner in which they affect water quality must be known.
- Originally, the intent of water quality management was to protect the intended uses of a water body while using water as an economic means of waste disposal within the constraints of its assimilated capacity.
- In 1972, the Congress established that it was the national interest to "restore the chemical, physical, and biological integrity of the nation's waters".
- In addition to making the water safe to drink, the Congress also established a goal of "**water quality which provides for the protection and propagation of fish, shellfish, and wildlife, and provides for recreation in and on the water**."
- By understanding the impact of pollutants on water quality, the environmental engineer can properly design the treatment facility to remove these pollutants to acceptable levels.

## 4. Water Pollutants and their Sources

The major water Pollutants are:

- Oxygen demanding materials
  - Biochemical Oxygen Demand (BOD)
  - Chemical Oxygen Demand (COD)
- Nutrients
  - Phosphorus
  - Nitrogen
- Pathogens
- Suspended solids

The wide range of pollutants discharged to surface water can be grouped into broad classes as point sources and non-point sources. Domestic sewage and industrial wastes are called point sources because they are generally collected by a network of pipes of channels and conveyed to a single point of discharge into the receiving water. Domestic sewage consists of wastes from homes, schools, office buildings, and stores. In general, point source pollution can be reduced or eliminated through waste minimization and proper wastewater treatment prior to discharge to a natural water body. Urban and agricultural runoff are characterized by multiple discharge points and these are called ***non-point source***. Much of the non-point source pollution occurs during rainstorms or spring snowmelt resulting from large flow-rates that make treatment even more difficult. Non-point pollution from urban storm water, and, in particular, storm water collected in ***combined sewers*** that carry both storm water and municipal sewage. Elimination of ***Combined Sewer Overflow* (CSO)** may minimize non-point source pollution. Major pollutant categories and principal sources of pollutants. Table 1 provides a list of water pollutants and the sources where they come from.

**Table 1: List of water pollutants and their sources[4]**

| Pollutant Category | Point Source | | Non-Point Source | |
|---|---|---|---|---|
| | **Domestic Sewage** | **Industrial Sewage** | **Agricultural runoff** | **Urban runoff** |
| Oxygen demanding materials | 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 | |
| Heat | | X | | |
| | | | | |

## 5. Water Pollution in Rivers

- Major Pollutants Affecting Rivers are:
  - BOD
  - Ammonia($NH_3$)
- Adverse Effects of $NH_3$ are:
  - Toxic to fish
  - Oxygen demand
  - Nutrient for algal growth

- The objective of water quality management is simply to control the discharge of pollutants so that water quality is not degraded to an unacceptable extent below the natural background level.
- The impact of pollution on a river depends both on the nature of the pollutant and the unique characteristics of the individual river such as volume, speed of water flowing, river's depth, type of bottom, and the surrounding vegetation.
- Other factors include the climate of the region, the mineral heritage of the watershed, land use pattern, and types of aquatic life in the river.
- Some pollutants, particularly oxygen-demanding wastes and nutrients are so common and have such a profound impact on almost all types of rivers that they deserve special emphasis.

## 6. Total Maximum Daily Load (TMDL)

A **TMDL** specifies the maximum amount of pollutant that a water body can receive and still meet the water quality standards. Under Section **303(d) of the 1972 Clean Water Act**, states, territories, and authorized tribes are required to develop list of impaired waters. Impaired waters are those that do not meet water quality standards that the states, territories, and authorized tribes have established. The law requires that these jurisdictions (states, territories, and authorized tribes) establish priority ranking of waters on the lists and develop a **TMDL** for these waters. In addition, **TMDL** allocates loadings (i.e., mass of pollutants expressed as lbs/day instead of mg/L: 1 mg/L = 8.34 lb/MG) that may be contributed among point and non-point sources. The **TMDL** is computed on pollutant by pollutant basis for a list of pollutants similar to those in **Table 1**.

The **TMDL** is computed as:

$$TMDL = \sum WLA + \sum LA + MOS \quad \text{......(1)}$$

where, *WLA* = waste load allocation (i.e., portion of the TMDL assigned to existing and future point sources)

*LA* = loading allocation (i.e., portions of the TMDL assigned to existing and non-point sources)

*MOS* = margin of safety

In 1956 Congress enacted the Federal Water Pollution Control Act (Public Law 92-500). Under 1972 amendments to the **Federal Water Pollution Control Act and Clear Water Act** (Public Law 94-

217), established the **National Pollutant Discharge Elimination System (NPDES),** which calls for limitation on the amount or quality of effluent and requires all municipal and industrial discharges to obtain permits. This permit is called **NPDES permit**.

## 7. Effect of Oxygen-Demanding Wastes on Rivers

Oxygen-demanding materials as either organic or inorganic cause depletion of the dissolved oxygen in the water. This poses a threat to fish and other higher forms of aquatic life if the concentration of dissolved oxygen falls below a critical point. To predict the extent of oxygen depletion, it is necessary to know how much waste is being discharged and how much oxygen is required to degrade the waste. Because oxygen is continuously being replenished from the atmosphere and from photosynthesis by algal 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. Organic oxygen-demanding materials are commonly measured by determining the amount of oxygen consumed during degradation in a manner approximating degradation in natural waters.

## 8. Biochemical Oxygen Demand (BOD)

**BOD** is the amount of oxygen consumed by microorganisms as they consume biodegradable organic matter. The amount of oxygen required to oxidize a substance to carbon dioxide and water may be calculated **by stochiometry** if the chemical composition of the substance is known. This amount of oxygen is known as the Theoretical Oxygen Demand (**ThOD**).

**Example 1:** Compute the ThOD of 100 mg/L of an organic compound whose chemical formula is $C_6H_{12}O_6$ (glucose)[6].

**Solutions:**

The balance chemical equation of $C_6H_{12}O_6$ when oxidized with $O_2$ is:

$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O$ …………………………………. (2)

12x6+1x12+16x6 + 6x16x2 = 6(12+16x2) + 6(1x2+16)

[*Gram atomic weight (GAW) of C = 12, GAW of H = 1,* and *GAW of O = 16*]

= 180 + 192 = 264 + 108

Thus, it takes 192 grams of oxygen to oxidize 180 grams of $C_6H_{12}O_6$ to $CO_2$ and $H_2O$

$$\text{ThOD of 100 mg/L of } C_6H_{12}O_6 = \frac{192 \text{ gram of } O_2}{180 \text{ gram of } C_6H_{12}O_6} \times 100 \text{ mg/L of } C_6H_{12}O_6$$

= 106.67 mg/L of $O_2$ ≈ **107 mg/L of $O_2$. Ans.**

Although ultimate BOD (designated as BODu or $L_0$) is the representation of the organic strength of wastewater, the 5-day BOD (designated as $BOD_5$) is used as an industry standard since ultimate BOD may take up to 120 days to determine. Therefore, $BOD_5$ is determined by laboratory experiment. The

BOD model can help find the ultimate BOD to understand the highest organic strength of water and wastewater.

## 9. Chemical Oxygen Demand (COD)

COD is the amount of oxygen required to oxidize the organic matter by strong oxidizing chemicals(potassium dichromate) under acidic conditions. During the determination of ***COD***, organic matter is converted to carbon dioxide and water regardless of the biological assimilability of the substance. One of the chief limitations of ***COD*** test is its inability to differentiate between biologically oxidizable and biologically inert organic matter. In addition, it does not provide any evidence of the rate at which the biologically active material would be stabilized under conditions that exist in nature. The major advantage of *COD* test is the short time required for evaluation. The determination can be made in about 3 hours rather than the 5-day required for the measurement of *BOD*. For this reason, it is used as a substitute for the *BOD* test in many instances.

- Applications of COD Data:
  - The COD test is used extensively in the analysis of industrial wastes. It is particularly valuable in surveys designed to determine and control losses to sewer system.
  - Results may be obtained within a relatively short time and measure taken to correct errors on the day they occur.
  - In conjunction with the BOD test, the COD test is helpful in indicating toxic conditions and presence of biologically resistant organic substances.
  - The test is widely used in the operation of treatment facilities because of the speed with which results can be obtained.

## 10. Modeling BOD

It is often assumed that the rate of decomposition of organic waste is proportional to the amount of waste available. If $L_t$ represents the amount of oxygen demand left after time $t$, then, assuming a **first order reaction**, we can write,

$$\frac{dL_t}{dt} = -kL_t \quad \text{......(3)}$$

where, $k$ = *BOD* reaction rate constant (time$^{-1}$). Negative sign indicates the reduction of organics in the waste. Rearranging the above equation and integrating,

$$\frac{dL_t}{L_t} = -kdt \quad \Rightarrow \int_{L_o}^{L_t} \frac{dL_t}{L_t} = -k\int_0^t dt$$

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

$$\Rightarrow L_t = L_0 e^{-kt} \quad \text{......(4)}$$

where, $L_o$ is the ultimate carbonaceous oxygen demand, which is the total amount of oxygen required by microorganisms to oxidize the carbonaceous portion of the waste. $L_o$ is also referred to as the ultimate *BOD* ($BOD_u$) at $t = 0$.

Now, $L_o = BOD_t + L_t$ and combining, we get,

$BOD_t = L_o - L_t = L_o - L_o e^{-kt} = L_o (1 - e^{-kt})$

$\mathbf{BOD_t = y_t = L_o (1 - e^{-kt})}$ ………..…………………………………….………(5)

In *e base*, $BOD_t = y_t = L_o (1 - e^{-kt})$

In *10 base*, $BOD_t = y_t = L_o (1 - 10^{-Kt})$

- [$\log_e 10 = 1/\log_{10} e = 2.303$]

$k = (2.303)K$ and $k_T = k_{20}(\theta)^{T-20}$ ……………………………..……….. (6)

$k_T$ = *BOD rate constant at temperature,* $T^oC$

$k_{20}$ = *BOD rate constant at temperature,* $20^oC$

$\theta$ = *temperature coefficient* = 1.135 *for* 4-20$^oC$ = 1.056 *for* 20-30$^oC$

*Usually* $\theta$ = 1.047 *may be used for any temperature range*

Figures plots Eq.(4) and Eq.(5) that shows BOD and oxygen equivalent relationships. Table 2 shows the typical values of ***k*** for different types of waste.

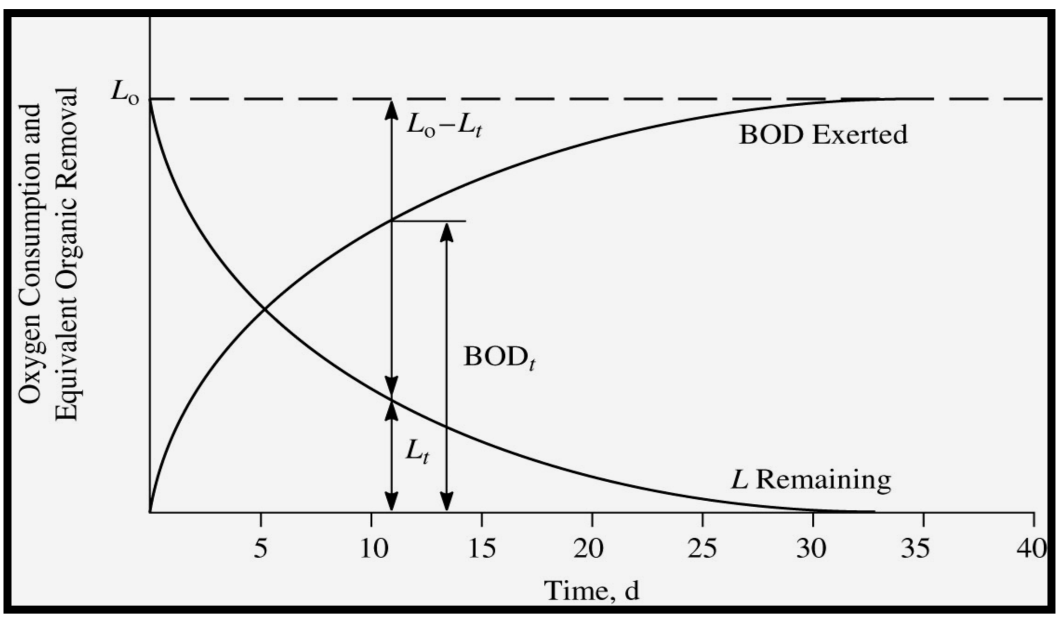



**Figure 1: BOD and oxygen equivalent relationships[6].**

**Table 2: Typical values for the BOD rate constant[2]**

| Sample Type | ***k*** (20°C), $d^{-1}$ (e base) | ***K*** (20°C), $d^{-1}$(10 base) |
|---|---|---|

| | | |
|---|---|---|
| Raw waste | 0.35 – 0.70 | 0.15 – 0.30 |
| Well-treated sewage | 0.12 – 0.23 | 0.05 – 0.10 |
| Polluted river water | 0.12 – 0.23 | 0.05 – 0.10 |

- **Factors affecting k Values**
  - *Nature of Waste*
  - *Ability of organisms to use Waste*
  - *Temperature*

- **Modeling BOD-Nitrogen oxidation**
  - So far, the assumption was that only the carbon in the organic matter is oxidized.
  - Actually, many organic compounds such as proteins also contain nitrogen that can be oxidized with the consumption of molecular oxygen.
  - Logically, oxygen consumption due to oxidation of carbon is called carbonaceous BOD (**CBOD**), while that due to nitrogen oxidation is called nitrogenous BOD (**NBOD**) (Figure 2).

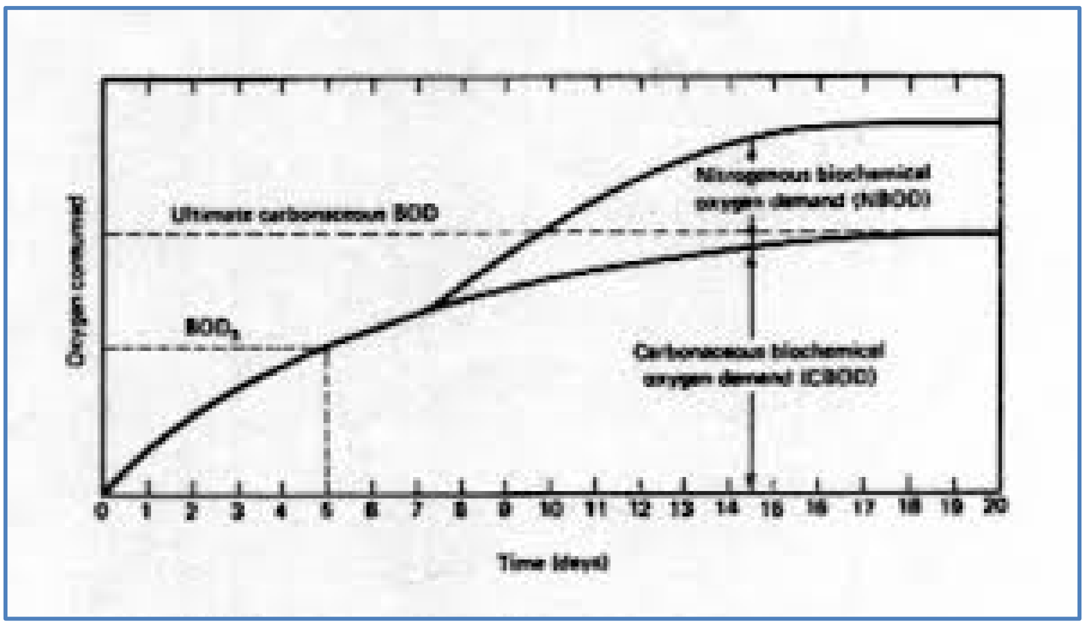



**Figure 2: Illustration of Carbonaceous and Nitrogenous Biochemical Oxygen Demand[6].**

Nitrification → $NH_4 + 2O_2 \xrightarrow{microrganisms} NO_3^- + H_2O + 2H^+$

(14x1+1x4) + (2x16x2) = (14+16x3) + (1x2+16x1) + (2x1)

[*Gram* atomic *weight (GAW) of N = 14, H = 1,* and *O = 16*]

= 18 + 64 = 62 + 18 + 2

From this equation the theoretical NBOD can be calculated as

$$\text{NBOD} = \frac{\text{grams of oxygen used}}{\text{grams of nitrogen oxidized}} = \frac{64}{14} = \mathbf{4.57}\ \text{g } O_2/\text{ g N}$$

**Example 2:** If the $BOD_3$ of a waste is 75 mg/L and $K$ is 0.15 day$^{-1}$, what are the ultimate $BOD$ ($BOD_u$ or $L_o$) and the 5-day $BOD$ ($BOD_5$)?[6]

***Solutions:*** *Given,* $t$ = 3 days, $y_t = BOD_3$ = 75 mg/L, $K$ = 0.15 day$^{-1}$

*Using 10 base,* $y_t = L_o(1 - 10^{-Kt})$

$75 = L_o(1 - 10^{-0.15x3}) = L_o(1 - 0.355) = 0.645L_o$

$\therefore \quad L_o = 75/0.645 = 116.28 \approx \underline{116}$ *mg/L Ans.*

*Using e base,* $y_t = L_o(1 - e^{-kt})$, *where* $k = 2.303x0.15 = 0.345$ day$^{-1}$.

$75 = L_o(1 - e^{-0.345x3}) = L_o(1 - 0.355) = 0.645L_o$

$\therefore \quad L_o = 75/0.645 = 116.28 \approx \underline{116}$ *mg/L Ans.*

$y_5 = L_o(1\text{-}10^{-Kt}) = 116(1 - 10^{-0.15x5}) = 116 \text{ x } 0.8222 = 95.37 \approx$ $\underline{\mathbf{95}}$ ***mg/L Ans.***

[$y_5 = L_o(1\text{-} e^{-kt}) = 116(1 - e^{-0.345x5}) = 116 \text{ x } 0.8218 = 95.33 \approx \underline{95}$ *mg/L Ans.]*

**Practice Problem:** If the $BOD_5$ of a waste is 210 mg/L and $BOD_u$ *(Lo)* is 363 mg/L. What is the BOD rate constant, $k$ or $K$ for this waste? *(Ans:* $k = 0.173\ d^{-1}$ *or* $K = 0.075\ d^{-1}$*)*[6]

## 11. Graphical Determination of BOD Constants

The equation for **BOD** at time ***t*** is

$$y_t = L_o(1 - e^{-kt}) \quad \text{.......(7)}$$

**Thomas Graphical Method:** After doing all the series expansion the exponential function and rearranging the terms the following equation is obtained.

$$e^x = \sum_{x=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$$

$$\left(\frac{t}{y_t}\right)^{1/3} = (kL_o)^{-1/3} + \frac{(k)^{2/3}}{6(L_o)^{1/3}}(t) \quad \text{.......(8)}$$

Eq.(8) is an equation of straight line, ***y = mx + c*** ……………………………... (9)

where in (9),

$$y = \left(\frac{t}{y_t}\right)^{1/3}, x = t, m = \frac{(k)^{2/3}}{6(L_o)^{1/3}}, c = (kL_o)^{-1/3}$$

- Solving for $k$ and $L_o$ from the above equations,

  $k = 6(m/c)$……………..(10) and $L_o = \dfrac{1}{6mc^2}$ ………………… …….(11)

- The procedure for determining the BOD constants by this method is as follows:

  1. From the experimental results of BOD for various values of $t$, calculate $(t/y_t)^{1/3}$ for each day.

2. Plot $(t/y_t)^{1/3}$ versus *t* on simple graph paper and draw the line of best fit by eye.
3. Determine intercept © and slope (m) from the plot.
4. Calculate *k* and $L_o$ from the above equations.

**Example 3:** Using the Thomas Method, calculate the BOD rate constant (*k*) in base *e* and the ultimate BOD ($L_o$) from the following data[4].

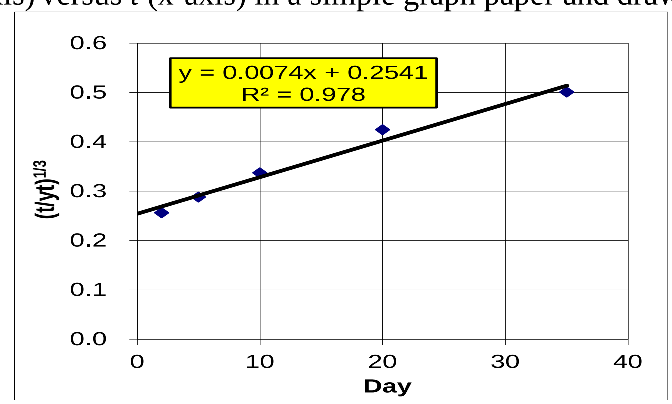
| | | | | | |
|---|---|---|---|---|---|
| *Day* | *2* | *5* | *10* | *20* | *35* |
| *BOD, mg/L* | *119* | *210* | *262* | *279* | *279.98* |

## Solutions:

**Step 1:** Calculate $(t/y_t)^{1/3}$ for each day.

| **Day** | 2 | 5 | 10 | 20 | 35 |
|---|---|---|---|---|---|
| **BOD, mg/L** | 119 | 210 | 262 | 279 | 279.88 |
| **$(t/y_t)^{1/3}$** | 0.2562 | 0.2877 | 0.3367 | 0.4154 | 0.5000 |

**Step 2:** Plot $(t/y_t)^{1/3}$ (y-axis) versus *t* (x-axis) in a simple graph paper and draw a best-fit straight line.




**Step 3:** Calculate intercept, c and slope, m from the above graph.

From the graph: intercept, ***c = 0.2541*** and slope, $m = \frac{(0.5-0.25)}{(34.0-0)} = 0.00735$

**Step 4:** Calculate *k* and $L_o$ from Eqs.(10) and (11)

$k = 6(m/c) = 6 \times 0.00735/0.2541 = 0.1764 \approx$ ***0.18*** $d^{-1}$ **Ans.**

$L_o = 1/(6mc^2) = 1/(6 \times 0.00735 \times 0.2541^2) = 362.81 \approx$ ***363*** mg/L. **Ans.**

## 12. Laboratory Measurement of BOD

Standard Methods of the Examination of Water and Wastewater published by American Water Works Association (**AWWA)** is followed to determine **BOD** in laboratory.

- Prepare Dilution of Wastewater Sample
- Prepare a Blank
- Incubate Sample and Blank 5 d @ 20ºC
- Measure DO Remaining and Calculate BOD
- Figure 3 shows the pictorial view of dilution factor

$$BOD_t = (DO_{s,t} - DO_{b,t}) \times D.F.$$

$$\text{Sample Size (\%)} = \frac{\text{V of Undiluted Sample}}{\text{V of Diluted Sample}} \times 100$$

$$\text{D.F.} = \frac{100}{\text{Sample Size (\%)}}$$

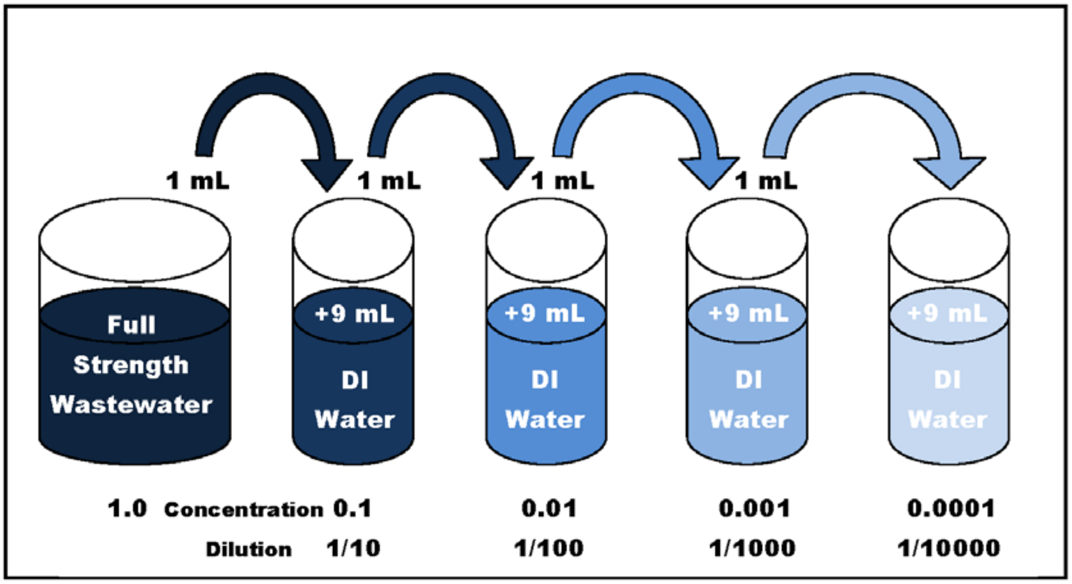



**Figure 3: Pictorial presentation of dilution factor[5]**

- **Additional Notes on BOD**
  - Although 5-day BOD has been chosen as the standard value for most wastewater analysis and regulatory purposes, ultimate BOD is actually a better indicator of total strength.
  - Figure 4 shows the effect of *k* value on ultimate BOD for two wastewaters having same $BOD_5$[4].
  - Figure 5 shows the effect of *k* value on $BOD_5$, when the ultimate BOD is constant [4].

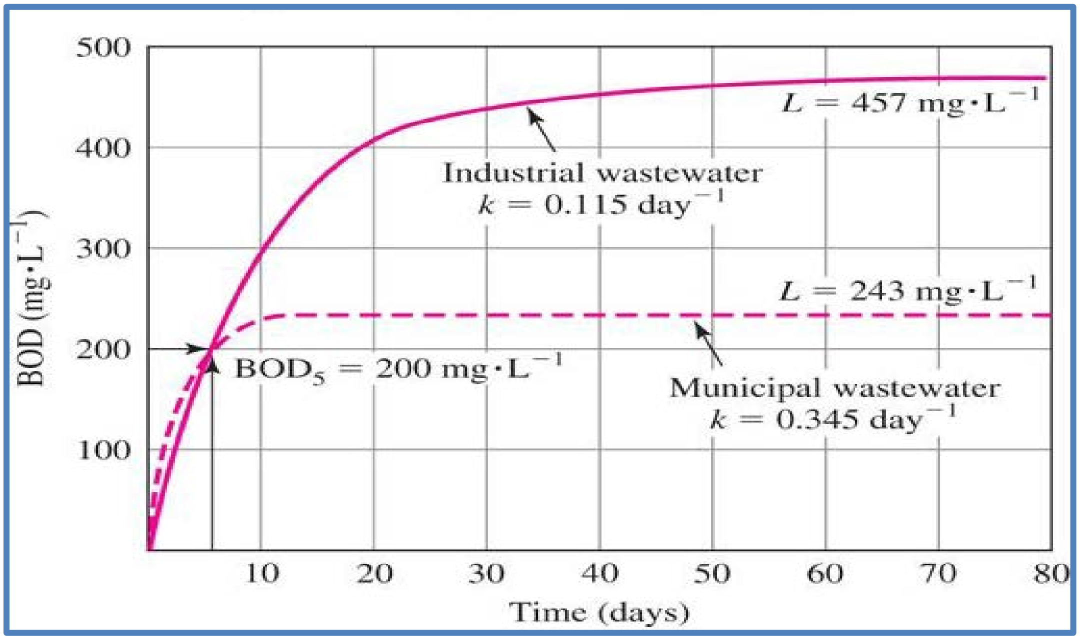



**Figure 4: The effect of *k* value on ultimate BOD for two wastewaters having same $BOD_5$[4].**

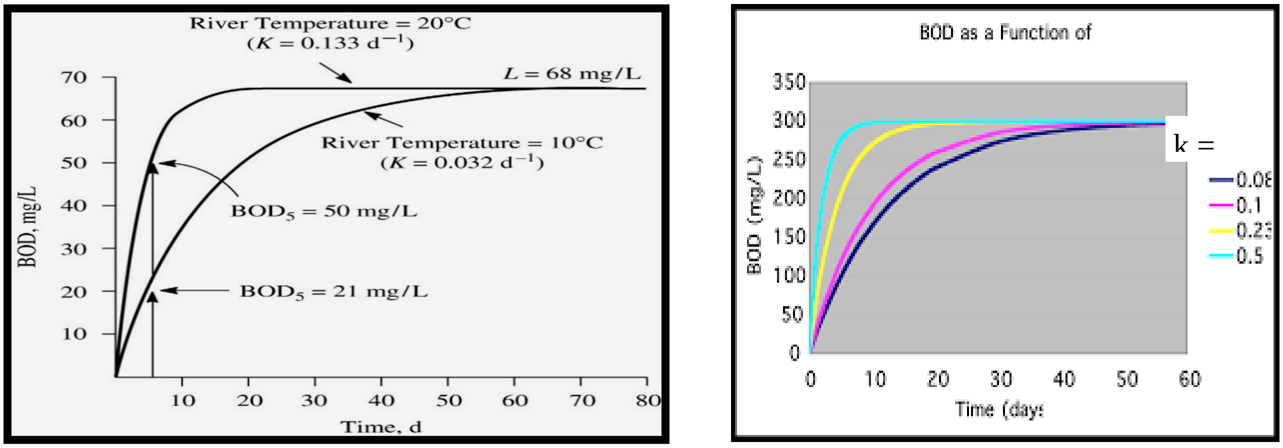



**Figure 5: The effect of *k* value on $BOD_5$, when the ultimate BOD is constant[4,5].**

## 13. DO Sag Curve

DO Sag Curve is also known as DO Sag Model or Streeter Phelps Equation. The concentration of dissolved oxygen in a river is an indicator of the general health of the river that also represents the capacity for self-purification. One of the 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. The profile is called the **DO sag curve** because the DO concentration dips as oxygen-demanding materials are oxidized and then rises again further downstream as the oxygen is replenished from the atmosphere. A typical and a real-life DO sag curves are shown in Figures 6 and 7, respectively.

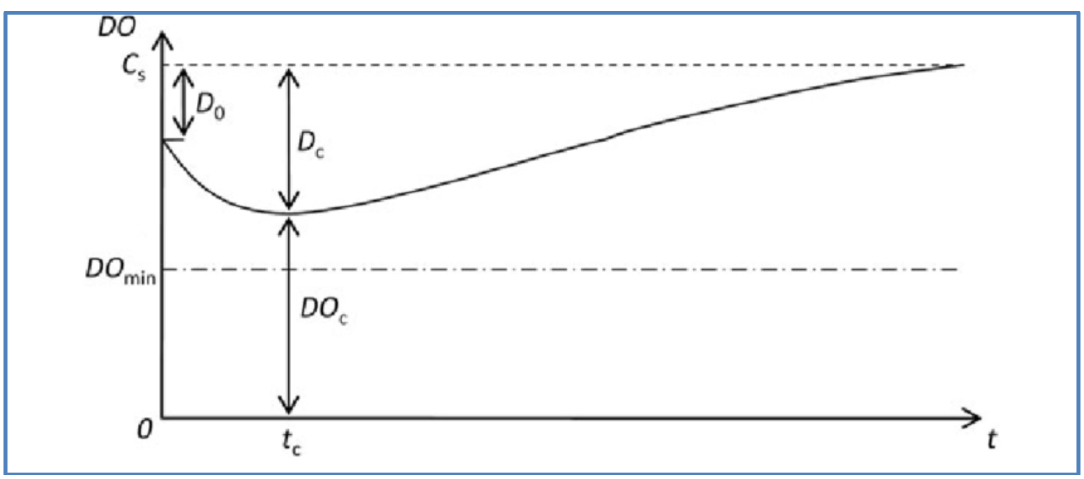



**Figure 6: Typical DO sag curve [5]**

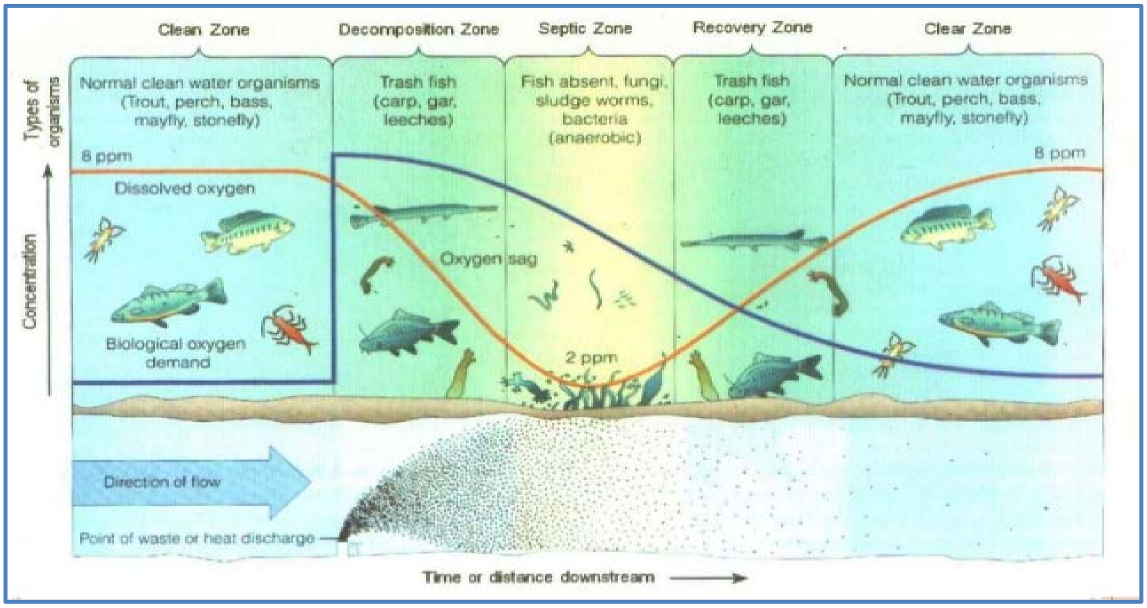



**Figure 7: DO sag downstream of a biodegradable organic chemical source**[5]

- **<u>Mass balance approach:</u>**

Mass of DO in Wastewater

Mass of DO in River → → Mass of DO in River after mixing

- The product of water flow and the DO concentration yields a mass of oxygen per unit time:
  Mass of DO in wastewater = $Q_wDO_w$
  Mass of DO in River = $Q_rDO_r$
  where, $Q_w$ = flow rate of wastewater, m$^3$/s
  $Q_r$ = flow rate of water in river, m$^3$/s
  $DO_w$ = dissolved oxygen concentration in wastewater, g/m$^3$
  $DO_r$ = dissolved oxygen concentration in river, g/m$^3$
- The mass of DO in the river after mixing equals the sum of the mass flows:
  - **Mass of DO after mixing = $Q_wDO_w + Q_rDO_r$**
- Similarly, for ultimate BOD
  - **Mass of BOD after mixing = $Q_wL_w + Q_rL_r$**
  - where, $L_w$ = ultimate BOD of wastewater, mg/L
    $L_r$ = ultimate BOD of the river, mg/L
- The concentrations of DO and BOD after mixing are the respective masses per unit time divided by the total flow rate (wastewater flow + river flow).

$$DO = \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r} \quad \text{.........(12)}$$

$$L_0 = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r} \quad \text{.........(13)}$$

where, $L_o$ = initial ultimate BOD after mixing.

- Similarly, the final river temperature ($T_f$) and the starting temperature of the wastewater and the river water is:

$$T_f = \frac{Q_w T_w + Q_r T_r}{Q_w + Q_r} \quad \text{.....................(14)}$$

- **Example 4:** Two streams converges as shown in Figure 8 below. Determine the flow, temperature, and dissolved oxygen in the merged stream at point C[4].

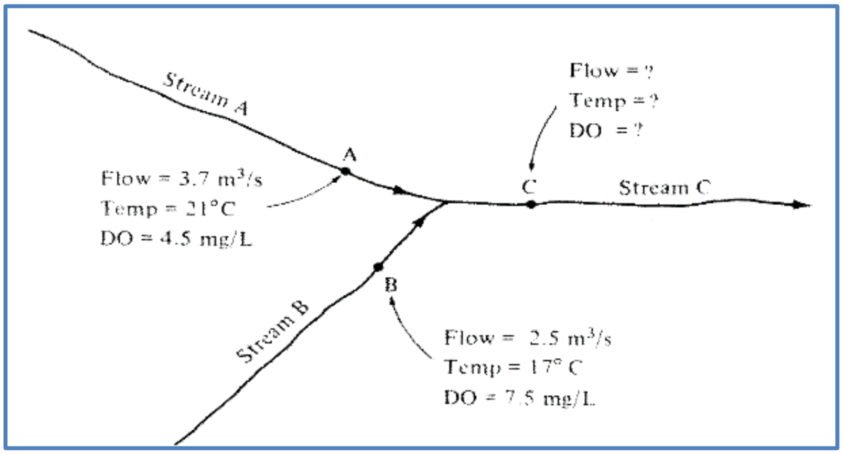



**Figure 8: Mixing of two streams into one stream[4].**

## Solutions:

- Flow at point C, $Q_C = Q_A + Q_B$
  $= 3.7 + 2.5$
  $=$ **6.2 m³/s** Ans.

$$T_C = \frac{Q_A T_A + Q_B T_B}{Q_A + Q_B} = \frac{3.7 \times 21 + 2.5 \times 17}{6.2} = 19.387 \approx 19.4^{\circ}\text{C} \ \ \text{Ans.}$$

$$DO_C = \frac{Q_A DO_A + Q_B DO_B}{Q_A + Q_B} = \frac{3.7 \times 4.5 + 2.5 \times 7.5}{6.2} = 5.71 \text{ mg/L} \ \ \text{Ans.}$$

- **Oxygen Deficit:**
  - The DO sag curve has been developed using oxygen deficit rather than dissolved oxygen concentration, to make it easier to solve the integral equation that results from the mathematical description of the mass balance.
  - The oxygen deficit is calculated as follows:

$$\boldsymbol{D = DO_s - DO} \quad \text{.....................(15)}$$

where, ***D*** = oxygen deficit, mg/L

***DO$_s$*** = saturation concentration of dissolved oxygen, mg/L

***DO*** = actual concentration of dissolved oxygen, mg/L

- The values of ***DO$_s$*** for fresh water are given in Table 3. Figure 9 shows the plots of equations that can be used to find the DO saturation level for any temperature.

**Table 3: Maximum Dissolved Oxygen Concentration Saturation[1]**

| Temperature (°C) | DO (mg/L) | Temperature (°C) | DO (mg/L) | Temperature (°C) | DO (mg/L) |
|---|---|---|---|---|---|
| 0 | 14.62 | 16 | 9.95 | 31 | 7.51 |
| 1 | 14.23 | 17 | 9.74 | 32 | 7.42 |
| 2 | 13.84 | 18 | 9.54 | 33 | 7.28 |
| 3 | 13.48 | 19 | 9.35 | 34 | 7.17 |
| 4 | 13.13 | 20 | 9.17 | 35 | 7.07 |
| 5 | 12.80 | 21 | 8.99 | 36 | 6.96 |
| 6 | 12.48 | 22 | 8.83 | 37 | 6.86 |
| 7 | 12.17 | 23 | 8.68 | 38 | 6.75 |
| 8 | 11.87 | 24 | 8.53 | 39 | 6.51 |
| 9 | 11.59 | 25 | 8.38 | 40 | 6.41 |
| 10 | 11.33 | 26 | 8.22 | 41 | 6.31 |
| 11 | 11.08 | 27 | 8.07 | 42 | 6.22 |
| 12 | 10.83 | 28 | 7.92 | 43 | 6.13 |
| 13 | 10.60 | 29 | 7.77 | 44 | 6.04 |
| 14 | 10.37 | 30 | 7.63 | 45 | 5.95 |

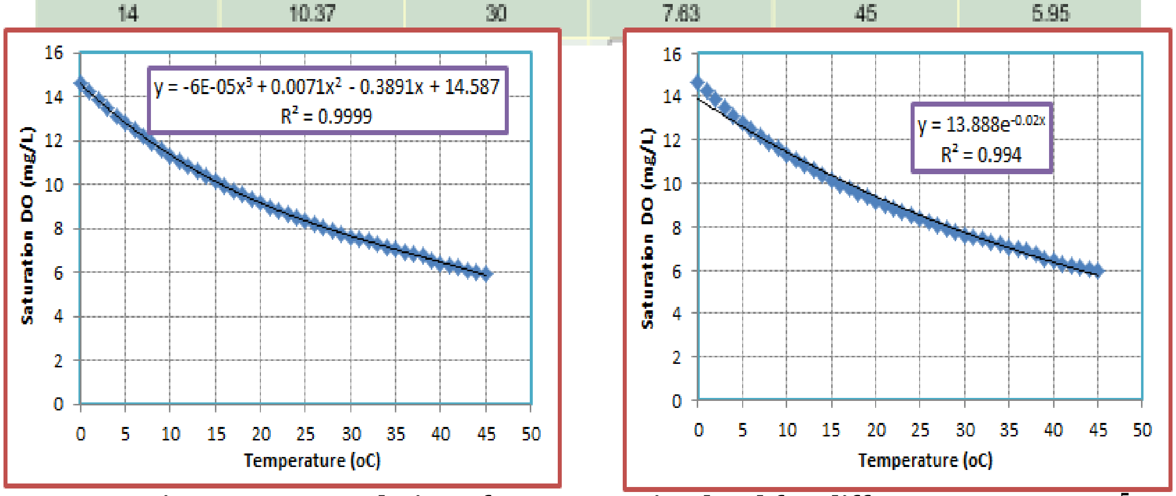



**Figure 9: Interpolation of DO saturation level for different temperature[5]**

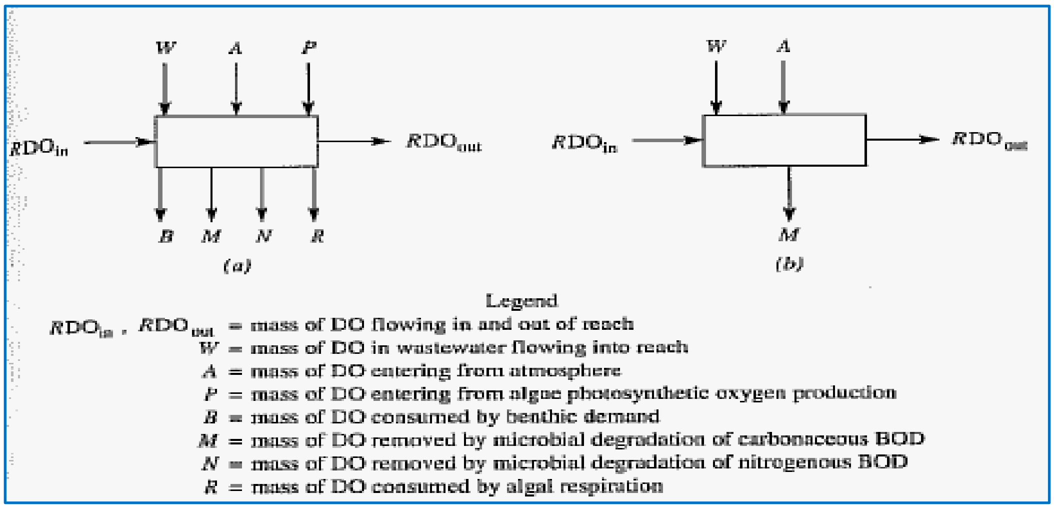
- **Initial Oxygen Deficit**
  - The beginning of the DO sag curve is at the point where a waste discharge mixes with the river. The initial deficit is calculated as the difference between saturated DO and the concentration of DO after mixing.

$$D_0 = DO_s - \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r} \quad \text{.........(16)}$$

**where, $D_0$ = initial deficit after river and wastewater have mixed, mg/L**

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

- **Development of DO sag curve equation (DO Model):**
  - A mass balance diagram of DO in a small reach (stretch) of river is shown below:




(a) Mass balance diagram of DO in a small reach (b) simplified mass balance for Streeter-Phelps Model[4].

The rate at which *DO* disappears from the stream as a result of microbial action (*M*) is exactly equal to rate of increase in *DO* deficit. With an assumption that the saturation value for DO remains constant [$d(DO_s)/dt = 0$], differentiation of equation, $D = DO_s - DO$, yields:

$$\frac{d(DO)}{dt} + \frac{dD}{dt} = 0 \qquad \text{and} \quad \frac{dD}{dt} = -\frac{d(DO)}{dt} \quad \text{.........(17)}$$

The rate at which *DO* disappears coincides with the rate that *BOD* is degraded, so

$$\frac{dD}{dt} = -\frac{d(DO)}{dt} = -\frac{d(BOD)}{dt} \quad \text{.........(18)}$$

But, we know that $BOD_t = L_o - L_t$

Differentiating this equation we get,

0, as *Lo* is a constant

$$\frac{d(BOD)}{dt} = \frac{dL_o}{dt} - \frac{dL_t}{dt} \qquad \therefore \frac{d(BOD)}{dt} = -\frac{dL_t}{dt} \text{.......................................(19)}$$

This leads to see that the rate of change in deficit at time *t* due to BOD is a first order reaction proportional to the oxygen equivalent of organics remaining:

$$\frac{dD}{dt} = -kL_t \text{..........................................................................(20)}$$

The rate constant *k*, is called the ***deoxygenation rate constant*** and is designated by $k_1$.

The rate of oxygen mass transfer into solution from the air (***A***) has shown to be a first-order reaction proportional to the difference of the saturation value and the actual concentration (DO deficit):

$$\frac{d(DO)}{dt} = k(DO_s - DO) = kD \text{.......................................................(21)}$$

From equations (17 and 21) we get,

$$\frac{dD}{dt} = -kD \text{...........................................................................(22)}$$

The rate constant *k*, is called the ***reaeration rate constant*** and is designated by $k_2$.

From equations 20 and 22 we can see that oxygen deficit is a function of the competition between oxygen utilization and reaeration from the atmosphere:

$$\frac{dD}{dt} = k_1 L_t - k_2 D \text{..................................................................(23)}$$

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

$k_1$ = deoxygenation rate constant, $d^{-1}$

$L_t$ = BOD of river water at time t, mg/L

$k_2$ = reaeration rate constant, $d^{-1}$

$D$ = oxygen deficit in river water, mg/L

From Eq.(4), $L_t = L_0 e^{-kt}$

$$\frac{dD}{dt} = k_1 L_0 e^{-k_1 t} - k_2 D \text{.................................................................(23a)}$$

Therefore, Eq.(23a) becomes,

$$\Rightarrow \frac{dD}{dt} + k_2 D = k_1 L_0 e^{-k_1 t} \text{.........................................................................(23b)}$$

which is a first-order differential equation of the form of

$$\frac{dy}{dx} + Py = Q$$

, where, $P = f(x)$ and $Q = f(x)$

Solving this equation by using of integrating factor, $e^{\int P dx}$, the integrating factor is $e^{\int k_2 dt} = e^{k_2 t}$

Multiplying both sides of Eq.(23b) by the integrating factor, $e^{k_2 t}$, we get

$$e^{k_2 t} \frac{dD}{dt} + k_2 D e^{k_2 t} = k_1 L_0 e^{(k_2 - k_1)t} \text{..................................................................(23d)}$$

$$\Rightarrow \frac{d}{dt} De^{k_2 t} = k_1 L_0 e^{(k_2 - k_1)t}$$

Separating variables and integrating

$$\int e^{k_2 t} dD = k_1 L_0 \int e^{(k_2 - k_1)t} dt$$

$$\Rightarrow De^{k_2 t} = \frac{k_1 L_0}{k_2 - k_1}\left(e^{(k_2 - k_1)t}\right) + C \quad \text{.......................................}(23e)$$

Using the known boundary conditions, that is $D = D_0$ at $t = 0$, we get

$$D_0 = \frac{k_1 L_0}{k_2 - k_1} 1 + C$$

$$\therefore C = D_0 - \frac{k_1 L_0}{k_2 - k_1}$$

$$De^{k_2 t} = \frac{k_1 L_0}{k_2 - k_1}\left(e^{(k_2 - k_1)t}\right) + D_0 - \frac{k_1 L_0}{k_2 - k_1}$$

Or

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

The final form is

$$D = \frac{k_1 L_0}{k_2 - k_1}\left(e^{-k_1 t} - e^{-k_2 t}\right) + D_0 e^{-k_2 t} \quad \text{.......................................}(24a)$$

where, $D$ = oxygen deficit in rivers after exertion of BOD for time, $t$, mg/L
$L_0$ = initial ultimate BOD after river and wastewater have mixed, mg/L
$k_1$ = deoxygenation rate constant, $d^{-1}$
$k_2$ = reaeration rate constant, $d^{-1}$
$t$ = time of travel of wastewater discharge downstream, d
$D_0$ = *initial oxygen deficit after river and wastewater have mixed, mg/L*

In *10* base, the equation becomes:

$$D = \frac{K_1 L_0}{K_2 - K_1}\left(10^{-K_1 t} - 10^{-K_2 t}\right) + D_0\left(10^{-K_2 t}\right) \quad \text{.......................................}(24b)$$

where, $D$ = oxygen deficit in rivers after exertion of BOD for time, $t$, mg/L
$L_0$ = initial ultimate BOD after river and wastewater have mixed, mg/L
$k_1$ = deoxygenation rate constant, $d^{-1}$
$k_2$ = reaeration rate constant, $d^{-1}$
$t$ = time of travel of wastewater discharge downstream, d
$D_0$ = initial oxygen deficit after river and wastewater have mixed, mg/L

When $k_2 = k_1$, Eq.(24a) reduces to:

$$D = (k_1 t L_0 + D_0)e^{-k_1 t} \quad \text{.......................................}(25)$$

where, $D$ = oxygen deficit in rivers after exertion of BOD for time, $t$, mg/L
$L_0$ = initial ultimate BOD after river and wastewater have mixed, mg/L
$k_1$ = deoxygenation rate constant, $d^{-1}$
$t$ = time of travel of wastewater discharge downstream, d
$D_0$ = initial oxygen deficit after river and wastewater have mixed, mg/L

The lowest point on the DO sag curve, which is called the *critical point* (***D**c*), corresponds to the time to the *critical point* ($t_c$) can be found by differentiating Eq.(24), setting it equal to *0*, and solving for ***t*** using base ***e*** values for $k_2$ and $k_1$:

$$t_c = \frac{1}{k_2 - k_1} \ln\left[\frac{k_2}{k_1}\left(1 - D_0 \frac{k_2 - k_1}{k_1 L_0}\right)\right] \quad (26)$$

The corresponding equation for critical oxygen deficit ($D_c$) is:

$$D_c = \frac{k_1}{k_2} L_0 e^{-k_1 t_c} \quad (27)$$

When $k_2 = k_1$, Eq.(26) reduces to:

$$t_c = \frac{1}{k_1}\left(1 - \frac{D_0}{L_0}\right) \quad (28)$$

The corresponding equation for critical oxygen deficit ($D_c$) reduces to:

$$D_c = L_0 e^{-k_1 t_c} \quad (29)$$

**DO sag curve: Deoxygenation rate constant ($k_1$):**

- Deoxygenation rate constant differs from the BOD rate constant because there are physical and biological differences between a river and a BOD bottle.
- BOD is exerted more rapidly in river due to turbulent mixing, large number of "seed" organisms, and BOD removal by organisms on the stream bed as well as by those suspended in water.
- BOD rate constant rarely has a value of greater than 0.7 $day^{-1}$, $k_1$ may be as large as 7 $day^{-1}$.
- Bosko has developed a method of estimating $k_1$ from $k$ using characteristics of stream:

$$k_1 = k + \frac{v}{H}\eta \quad (30)$$

where, $k_1$ = 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 varies from 0.1 for stagnant or deep water to 0.6 or more for rapidly flowing streams.
- **Temperature Correction:** Same as BOD rate constant ***k***.

**DO sag curve: Reaeration rate constant($k_2$):**

- The value of $k_2$ 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 much lower $k_2$ than a wide, shallow river.
- The reaeration rate constant can be estimated from the following equation:

$$k_2 = \frac{3.9 v^{0.5}}{H^{1.5}} \quad \text{..........(31)}$$

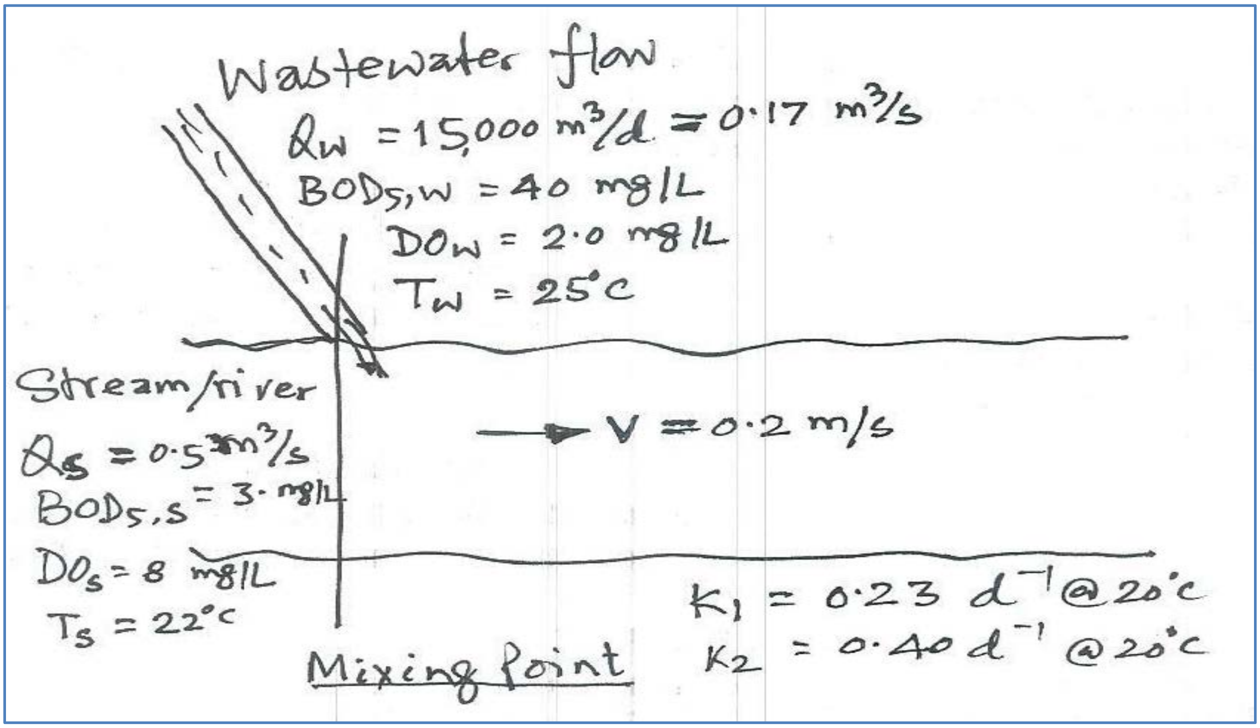
where, $k_2$ = reaeration rate constant at 20°C, $d^{-1}$
$v$ = average speed of stream flow, m/s
$H$ = average depth of stream, m
3.9 = a conversion factor to make the equation dimensionally correct.

**Temperature Correction:** $\boldsymbol{k_T = k_{20}(\theta)^{T-20}}$ where, $\theta = \mathbf{1.016}$ …………(32)

**Example 5:** A municipal wastewater treatment plant discharge secondary effluent to a surface stream. The worst conditions are known to occur in the summer months when stream flow is low and water temperature is high. Under these conditions, measurements were made in the laboratory and in the field to determine the characteristics of the wastewater and the stream flows. The wastewater is found to have a maximum flow rate of 15,000 $m^3$/day, a $BOD_5$ of 40 mg/L, a dissolved oxygen (DO) concentration of 2 mg/L, and a temperature of $25^0$C. The stream (upstream from the point of discharge) is found to have minimum flow rate of 0.5 $m^3$/s, a $BOD_5$ of 3 mg/L, a DO concentration of 8 mg/L, and a temperature of $22^0$C. Complete mixing of the wastewater and stream is instantaneous, and the velocity of the mixture is 0.2 m/s. From the flow regime, the reaeration rate constant, $k_2$ is estimated to be 0.4/day for $20^0$C conditions. Sketch the DO profile (DO sag curve) a 100-km reach of the stream below the discharge. Assume $k_1$ = 0.23/day at $20^0$C[6].

## Example 5: Solutions

Converting the problem language into graph format (Visualization of a problem)




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (a) | Calculate mixed flow rate, Qmix | | | | | 999 | Data entry |
| | Given, Stream flow, Qs | | = | 0.5 | $m^3/s$ | | |
| | Watewater flow, Qw | | = | 15000 | $m^3/day$ | | |
| | | | = | 15000 m^3/day x 1 day/24 hours x 1 min/60 s | | | |
| | | | = | 0.17 | $m^3/s$ | | |
| | Qmix = | 0.5 + 0.17 | = | 0.67 | $m^3/s$ | | |
| | | | | | | | |
| (b) | Calculate mixed BOD5 | | | | | | |
| | Given, Stream BOD, BODs = | | | 3 | mg/L | | |
| | Wastewater BOD, BODw = | | | 40 | mg/L | | |
| | $BOD_{mix} = \frac{BOD_s \times Q_s + BOD_w \times Q_w}{Q_s + Q_w}$ | | = | $\frac{3 \times 0.5 + 40 \times 0.17}{0.5 + 0.17}$ | | | |
| | | | = | 12.4 | mg/L | | |
| | | *t* | = | 5 | days | | |
| | Covenrt to ulitimate BOD, Lo (Assume k1 = | | | | | 0.23 | /day for the mixture at 20oC) |

$$L_0 = \frac{y_t}{1 - e^{-k_1 t}} = \frac{12.4}{1 - \mathrm{EXP}(-0.23 \times 5)}$$

= **18.1** mg/L

**(c) Calculate mixed Dissolved Oxygen (DOmix)**

| | | | |
|---|---|---|---|
| Given, Stream DO, DOs | = | 8.0 | mg/L |
| Wastewater DO, DOw | = | 2.0 | mg/L |

$$DO_{mix} = \frac{DO_s \times Q_s + DO_w \times Q_w}{Q_s + Q_w} = \frac{8 \times 0.5 + 2 \times 0.17}{0.5 + 0.17}$$

= **6.5** mg/L

**(d) Calculate mixed temperature (Tmix)**

| | | | |
|---|---|---|---|
| Stream temperature, Ts | = | 22.0 | °C |
| Wastewater temperature, Tw | = | 25.0 | °C |

$$T_{mix} = \frac{T_s \times Q_s + T_w \times Q_w}{Q_s + Q_w} = \frac{22 \times 0.5 + 25 \times 0.17}{0.5 + 0.17}$$

= **22.8** °C

## 2. Correct reaction constants for temperature

**(a) Calculate corrected BOD rate constant, k1**

**Given, k1 at 20°C** = 0.23 /day

k1 at 22.8oC, $k_{1,T} = k_{1,20}(1.047)^{T-20}$ = **0.23{1.047^(22.8-20)}**

= **0.26** /day

**(b) Calculate corrected reaeration rate constant, k2**

**Given, k2 at 20°C** = 0.4 /day

k2 at 22.8oC, $k_{2,T} = k_{2,20}(1.016)^{T-20}$ = **0.4{1.016^(22.8-20)}**

= **0.42** /day

## 3. Determine initial oxygen deficit, $D_0$.

(a) At T = 22.8°C, the equilibrium concentration of oxygen in fresh water is (From Table 3), DOs = 8.7 mg/L

Therefore, $D_0$ = *DOs - DOmix* = 8.7 - 6.5 = **2.2** mg/L

**4. Determine the critical deficit and its location**

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

= 1/ (0.42 - 0.26) ln[0.42/0.26(1 -2.2x(0.42 - 0.26)/(0.26x18.1)]

= **2.51** day

(b) $$D_c = \frac{k_1}{k_2} L_0 e^{-k_1 t_c}$$ = (0.26/0.42) x 18.1 EXP(-0.26x2.51)

= **5.83** mg/L

© **This condiction occurs at a distance of**

Given velocity of flow, *u* = 0.2 m/s = 0.2 m/s x 86,400 s/d x 1 km/1,000 m

= **17.28** km/d

$x_c$ = 0.2 m/s x 86,400 s/d x 2.51d

= **43,397.61** m = **43.40** km

**5. Determine the deficit at points 20, 75, and 100 km from the points of discharge.**

(a) $$t = \frac{x\ km}{u\ km/d}$$

| Distance, x (km) = | 20 | 75 | 100 |
|---|---|---|---|
| Time (d) = | 1.16 | 4.34 | 5.79 |

(b) **The deficits at these times are**

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

$D_{20}$ = $\frac{0.26 \times 18.1}{0.42 - 0.26}$ {EXP( 0.26 x 1.16 - EXP(-0.42 x 1.16)} + 2.2 EXP(-0.42 x 1.16)

= **5.03** mg/L

$D_{75}$ = **5.12** mg/L

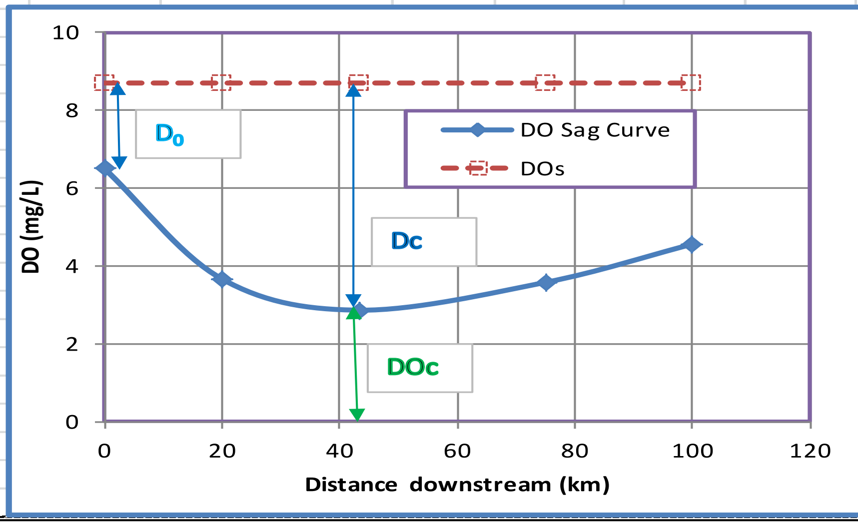
$D_{100}$ = **4.14** mg/L

**(c) The DO concentrations at each points are:**

| | | | |
|---|---|---|---|
| $DO_0$ = | 8.7 - 2.2 = | **6.50** | mg/L |
| $DO_{20}$ = | 8.7 - 5.03 = | **3.67** | mg/L |
| $DO_{43.2}$ = | 8.7 - 5.83 = | **2.87** | mg/L |
| $DO_{75}$ = | 8.7 - 5.12 = | **3.58** | mg/L |
| $DO_{100}$ = | 8.7 - 4.14 = | **4.56** | mg/L |

**6. Arrange the data and plot the DO sag curve.**

| Distance (km) | DO (mg/L) | DOs (mg/L) |
|---|---|---|
| 0 | 6.50 | 8.7 |
| 20 | 3.67 | 8.7 |
| 43.40 | 2.87 | 8.7 |
| 75 | 3.58 | 8.7 |
| 100 | 4.56 | 8.7 |




- **Management Strategy:**
  - The beginning point for water quality management in rivers using DO sag curve is to determine the minimum DO concentration that will protect the aquatic life in the river
  - This value, called DO standard, is generally to protect the most sensitive species that exist or could exist in the particular river.
  - For a known waste discharge and a known set of river characteristics, the DO sag equation can be solved to find the DO at the critical point.
  - If this value is higher than the standard, the stream can adequately assimilate the waste.
  - If the DO at critical point is less than the standard, additional waste treatment is needed.
  - Usually, environmental engineer has control over just two parameters, $L_o$ and $D_o$
  - When using DO sag curve to determine the adequacy of wastewater treatment, it is important to use the river conditions that will cause lower DO concentration (Specially in summer).
  - A frequently used criterion is the "10-year, 7-day low flow" which is the recurrence interval of the average low flow for 7-day period estimated using the partial series technique.
  - Low flow causes higher values for $L_o$ and $D_o$ due to reduced dilution.
  - The value of $k_2$ is reduced by low flow due to reduced velocities.

- Higher temperatures increase $k_1$ more than $k_2$ and also decrease DO saturation, making the critical point more severe.

- **Limitations of DO sag curve:**
  - The DO sag curve equation is based on the assumption that there is one source of BOD when there may be several point or non-point sources of BOD.
  - Additional discharges can be taken into consideration by subdividing a river into short reaches, each fed by a single point source.
  - If tributaries empty into the mainstream, any discharge they may have received must also be taken into consideration, as well as the increase in flow of the receiving stream.
  - Replacement of oxygen is also affected by many factors not taken into consideration by the formulas used to derive DO sag curves, notably the reaeration contribution by algal photosynthesis.

- **Confirmation/calibration of DO sag curve:**
  - The DO sag curve equation obtained from the mathematical model should be confirmed/calibrated by actual field measurement.
  - Representative and comprehensive samples should be taken during field investigation.
  - Once the DO deficit and the time of critical of DO concentration have been verified by a detailed water-quality survey, DO sag curves can be used to forecast stream conditions that can be expected for a given waste load and a stream flow.

## 14. Effect of Nutrients on Water Quality in Rivers

Nutrients can contribute to deteriorating water quality in rivers by causing excessive plant growth as nutrients are those elements required by plants for their growth. They include carbon, nitrogen, phosphorous, variety of trace elements.

- **Effects of Nitrogen**
  - There are 3 reasons why nitrogen is detrimental to a receiving body
    - In high concentration, $NH_3$-N is toxic to fish.
    - $NH_3$ in low concentration and $NO_3^-$ serve as nutrients for excessive growth of algae.
    - The conversion of $NH_4^+$ to $NO_3^-$ consumes large quantities of DO
- **Effects of Phosphorus**
  - Phosphorous serves as a vital nutrient for the growth of algae.
  - Excessive phosphorous help to grow excessive algae, when excess algae die, they become oxygen-demanding organic material as bacteria seek to degrade them.
  - This oxygen demand frequently overtaxes the DO supply of water and as a consequence, causes fish to die.

- **Management strategy associated with excessive nutrients**

- It is based on the sources of each nutrient
- Controlling the sources and discharge of higher nutrients waste to the stream

**Example 6:** A tannery with a wastewater flow of 0.011 $m^3/s$ and a $BOD_5$ of 590 mg/L discharges into a creek. The creek has 10-year, 7-day low flow of 1.7 $m^3/s$. Upstream of the tannery, the $BOD_5$ of the creek is 0.6 mg/L. The BOD rate constant k are 0.115 $d^{-1}$ for the tannery and 3.7 $d^{-1}$ for the creek. The temperature of both the creek and the tannery is 20°C. Calculate the initial ultimate BOD after mixing[6].

## Solutions:

**Given:**

Tannery, $Q_w = 0.011\ m^3/s;\ BOD_5 = 590\ mg/L;\ k = 0.115\ d^{-1}$

Creek, $Q_r = 1.7\ m^3/s;\ BOD_5 = 0.6\ mg/L;\ k = 3.7\ d^{-1}$

Calculation of ultimate BOD using equation, $y_t = L_o(1-e^{-kt})$

Tannery: $L_o = L_w = \dfrac{590}{1-e^{-0.015\times 5}} = 1{,}349.2 mg/L$

Creek: $L_o = L_r = \dfrac{0.6}{1-e^{-3.7\times 5}} = 0.6 mg/L$

Initial ultimate BOD after mixing,

$$L_{mix} = \frac{L_w Q_w + L_r Q_r}{Q_w + Q_r} = \frac{1{,}349.2\times 0.011 + 0.6\times 1.7}{0.011+1.7} = 9.27\text{mg/L} \approx 9.0\,\text{mg/L}$$

## 15. Water Pollution Control

The various methods for the control of water pollution are discussed below:

1. The sewage pollutants are subject to chemical treatment to change them into non-toxic substances or make them less toxic.
2. Water pollution due to organic insecticides can be reduced by the use of very specific and less stable chemicals in the manufacture of insecticides.
3. Oxidation ponds can be useful in removing low level of radioactive wastes.
4. Thermal pollution can be reduced by employing techniques—through cooling, cooling ponds, evaporative or wet cooling towers and dry cooling towers. The purpose is that the waters in the rivers and streams should not get hot.
5. Domestic and industrial wastes should be stored in large but shallow ponds for some days. Due to the sun-light and the organic nutrients present in the waste there will be mass scale growth of those bacteria which will digest the harmful waste matter.

6. Polluted water can be reclaimed by proper sewage treatment plants and the same water can be reused in factories and even irrigation. Such a treated water being rich in phosphorus, potassium and nitrogen can make good fertilizer.
7. Suitable strict legislation should be enacted to make it obligatory for the industries to treat the waste water before being discharged into rivers or seas.
8. Water hyacinth popularly known as Kaloli and Jalkumbhi, can purify water polluted by biological and chemical wastes. It can also filter out heavy metals like cadmium, mercury, lead and nickel as well as other toxic substances found in industrial waste waters.

## 16. What are the Effects of Water Pollution?

Some people believe pollution is an inescapable result of human activity: they argue that if we want to have factories, cities, ships, cars, oil, and coastal resorts, some degree of pollution is almost certain to result. In other words, pollution is a necessary evil that people must put up with if they want to make progress. Fortunately, not everyone agrees with this view. One reason people have woken up to the problem of pollution is that it brings costs of its own that undermine any economic benefits that come about by polluting.

Sewage is a good example of how pollution can affect us all. Sewage discharged into coastal waters can wash up on beaches and cause a health hazard. People who bathe or surf in the water can fall ill if they swallow polluted water—yet sewage can have other harmful effects too: it can poison shellfish (such as cockles and mussels) that grow near the shore. People who eat poisoned shellfish risk suffering from an acute—and sometimes fatal—illness called paralytic shellfish poisoning. Shellfish is no longer caught along many shores because it is simply too polluted with sewage or toxic chemical wastes that have discharged from the land nearby.

Pollution matters because it harms the environment on which people depend. The environment is not something distant and separate from our lives. It's not a pretty shoreline hundreds of miles from our homes or a wilderness landscape that we see only on TV. The environment is everything that surrounds us that gives us life and health. Destroying the environment ultimately reduces the quality of our own lives—and that, most selfishly, is why pollution should matter to all of us.

## 17. How Can We Stop the Water Pollution?

There is no easy way to solve water pollution; if there were, it wouldn't be so much of a problem. Broadly speaking, there are three different things that can help to tackle the problem—education, laws, and economics—and they work together as a team.

**Education:** Making people aware of the problem is the first step to solving it. In the early 1990s, when surfers in Britain grew tired of catching illnesses from water polluted with sewage, they formed a group called Surfers Against Sewage to force governments and water companies to clean up their act. People who've grown tired of walking the world's polluted beaches often band together to organize community beach-cleaning sessions. Anglers who no longer catch so many fish have campaigned for tougher penalties against factories that pour pollution into our rivers. Greater public awareness can make a positive difference.

**Laws:** One of the biggest problems with water pollution is its transboundary nature. Many rivers cross countries, while seas span whole continents. Pollution discharged by factories in one country with poor environmental standards can cause problems in neighboring nations, even when they have tougher laws and higher standards. Environmental laws can make it tougher for people to pollute, but to be really effective they have to operate across national and international borders. This is why we have international laws governing the oceans, such as the 1982 UN Convention on the Law of the Sea (signed by over 120 nations), the 1972 London (Dumping) Convention, the 1978 MARPOL International Convention for the Prevention of Pollution from Ships, and the 1998 OSPAR Convention for the Protection of the Marine Environment of the North East Atlantic. The European Union has water-protection laws (known as directives) that apply to all of its member states. They include the 1976 Bathing Water Directive (updated 2006), which seeks to ensure the quality of the waters that people use for recreation. Most countries also have their own water pollution laws. In the United States, for example, there is the 1972 Clean Water Act and the 1974 Safe Drinking Water Act.

**Economics:** Most environmental experts agree that the best way to tackle pollution is through something called the polluter pays principle. This means that whoever causes pollution should have to pay to clean it up, one way or another. Polluter pays can operate in all kinds of ways. It could mean that tanker owners should have to take out insurance that covers the cost of oil spill cleanups, for example. It could also mean that shoppers should have to pay for their plastic grocery bags, as is now common in Ireland, to encourage recycling and minimize waste. Or it could mean that factories that use rivers must have their water inlet pipes downstream of their effluent outflow pipes, so if they cause pollution they themselves are the first people to suffer. Ultimately, the polluter pays principle is designed to deter people from polluting by making it less expensive for them to behave in an environmentally responsible way.

**Our clean future:** Life is ultimately about choices—and so is pollution. We can live with sewage-strewn beaches, dead rivers, and fish that are too poisonous to eat. Or we can work together to keep the environment clean so the plants, animals, and people who depend on it remain healthy. We can take individual action to help reduce water pollution, for example, by using environmentally friendly detergents, not pouring oil down drains, reducing pesticides, and so on. We can take community action too, by helping out on beach cleans or litter picks to keep our rivers and seas that little bit cleaner. And we can take action as countries and continents to pass laws that will make pollution harder and the world less polluted. Working together, we can make pollution less of a problem—and the world a better place.

## 18. Summary

In this course we defined several terms related to water pollution, such as TMDL, BOD, COD, and DO. We explained the effect of oxygen demanding wastes in water pollution, how we can control the water pollution, what are the effects of water pollution, and how we can stop the water pollution. We learned how to determine $BOD_5$ in the laboratory, BOD reaction rate constant, $k$ with graphical method. We also derived BOD model and DO sag curve equations using first-order kinetics. We solved several problems to understand the extent of water pollution.

## 19. References

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2. *West, Larry (2006-03-26). "World Water Day: A Billion People Worldwide Lack Safe Drinking Water". About.com.*
3. *CHNRI. (2010). "An overview of diarrhea, symptoms, diagnosis and the costs of morbidity" (PDF). Archived from the original (PDF) on May 12, 2013.*
4. Introduction to Environmental Engineering by **Mackenzie L. Davis and David A. Cornwell**, McGraw-Hill Book Company.
5. Personal work experience and open source internet.

+++++++++++++++ **The End** ++++++++++++++

**Any questions please contact the instructor at** makarim@juno.com

**QUIZ for Water Pollution and Its Control**

1. In 1972, the Congress established that it was the national interest to "restore the chemical, physical, and biological integrity of the nation's waters.
a. True
b. False

2. In addition to making the water safe to drink, the Congress also established a goal of "water quality which provides for the protection and propagation of fish, shellfish, and wildlife, and provides for recreation in and on the water."
*a. True
b. False

3. The water pollutants are:
a. Oxygen demanding materials
b. Nutrients
c. Pathogens and suspended solids
d. All of the above
e. None of the above

4. The wide range of pollutants discharged to surface water can be grouped into broad classes as ___________ ___________ and ___________ _____________.
a. point source and non-point source.
b. permanent source and non-point source.
c. unknown source and temporary source.
d. all of the above
e. none of the above

5. Domestic sewage and industrial wastes are called ____________ ____________ because they are generally collected by a network of pipes of channels and conveyed to a single point of discharge into the receiving water.
a. point source
b. non-point source
c. unknown source
d. known source

6. Urban and agricultural runoff are characterized by multiple discharge points and these are called____________ ___________.
a. point sources
b. non-point source
c. unknown source
d. known source

7. Non-point pollution from urban storm water, and, in particular, storm water is collected in __________ ___________ that carry both storm water and municipal sewage.
a. combined sewers
b. separate sewers
c. trunk sewers
d. main sewers

8. Major pollutants that affect river water quality are ________________ _______________.
a. BOD and Ammonia ($NH_3$)
b. COD and Ammonia ($NH_3$)
c. BOD and Nitrogen ($N_3$)
d. COD and Nitrogen ($N_2$)

9. The adverse effects of $NH_3$ are ____________________ ________________________, and ___________________.
a. Toxic to fish
b. Oxygen demand
c. Nutrient for algal growth
d. All of the above
e. None of the above

10. Under Section ___________ **of the 1972 Clean Water Act**, states, territories, and authorized tribes are required to develop list of impaired waters.
a. 303(d)
b. 304(d)
c. 303(e)
d. 304(e)

11. A _____________ specifies the maximum amount of pollutant that a water body can receive and still meet the water quality standards.
a. TMDL (Total maximum daily load)
b. BOD
c. COD
d. ThOD

12. Under 1972 amendments to the Federal Water Pollution Control Act and Clear Water Act (Public Law 95-217), established the permit system, which calls for limitation on the amount or quality of effluent and requires all municipal and industrial discharges to obtain permits.
a. BOD Limit Permits
b. National Pollutant Discharge Elimination System (NPDES)
c. COD Limit Permit
d. All of the above
e. None of the above

13. The amount of oxygen required to oxidize a substance to carbon dioxide and water may be calculated by stochiometry if the chemical composition of the substance is known. This amount of oxygen is known as ___________ ___________ ____________.
a. Theoretical Oxygen Demand (ThOD)
b. Biochemical Oxygen Demand (BOD)
c. Chemical Oxygen Demand (COD)
d. No Oxygen Demand (NOD)

14. The major advantage of *COD* test is the short time required for evaluation. The determination can be made in about ____ ________ rather than the 5-day required for the measurement of *BOD*.
a. 3 hours
b. 5 hours
c. 3 days
d. 7 days

15. In conjunction with the BOD test, the COD test is helpful in indicating toxic conditions and presence of biologically resistant organic substances.
a. True
b. False

16. The factors that affect *k* values are _____________, ______________, and ________________.
a. Nature of Waste
b. Ability of organisms to use Waste
c. Temperature
d. All of the above
e. None of the above

17. Logically, oxygen consumption due to oxidation of carbon is called _________________, while that due to nitrogen oxidation is called ______________.
a. *carbonaceous BOD* (***CBOD***); *nitrogenous BOD* (***NBOD***).
b. BOD; COD
c. BOD, ThOD

18. The concentration of dissolved oxygen in a river is an indicator of the general health of the river that also represents the capacity for ________________**.**
a. self-purification
b. self-cleaning
c. self-treating
d. all of the above
e. none of the above

19. One of the 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 dissolved oxygen concentration downstream from a waste discharge. The profile is called the _____ _________ ________ because the DO concentration dips as oxygen-demanding materials are oxidized and then rises again further downstream as the oxygen is replenished from the atmosphere.
a. DO sag curve
b. BOD sag curve
c. COD sag curve
d. ThOD sag curve

20. There are several reasons why nitrogen is detrimental to a receiving water body and these are:
a. In high concentration
b. $NH_3$-N is toxic to fish
c. $NH_3$ in low concentration and $NO_3^-$ serve as nutrients for excessive growth of algae
d. The conversion of $NH_4^+$ to $NO_3^-$ consumes large quantities of DO
e. All of the above
f. None of the above

21. Phosphorous serves as a vital nutrient for the growth of algae. Excessive phosphorous DO NOT help to grow excessive algae, when excess algae die, they become oxygen-demanding organic material as bacteria seek to degrade them.
a. True
b. False

22. When using DO sag curve to determine the adequacy of wastewater treatment, it is important to use the river conditions that will cause higher DO concentration.
a. True
b. False

23. The beginning point for water quality management in rivers using DO sag curve is to determine the minimum DO concentration that will protect the aquatic life in the river. This value, called _______ _________, is generally to protect the most sensitive species that exist or could exist in the particular river.
a. BOD standard
b. DO standard
c. COD standard
d. CBOD standard

24. The DO sag curve equation is based on the assumption that there is one source of BOD when there may be several point or non-point sources of BOD.
a. True
b. False

25. BOD model is developed using:
a. Zero-order kinetics
b. First-order kinetics
c. Second-order kinetics
d. None of the above
e. All of the above

26. Two streams, Stream A and Stream B converges and make the stream C. The flow rates of streams A and B are 3.7 $m^3/s$ and 2.5 $m^3/s$ and dissolved oxygen (DO) of streams A and B are 4.5 mg/L and 7.5 mg/L, respectively. The DO at Stream C is nearly:
a. 4.5 mg/L
b. 5.7 mg/L
c. 8.0 mg/L
d. 9.3 mg/L

27. Two streams, Stream A and Stream B converges and make the stream C. The flow rates of streams A and B are 3.7 $m^3/s$ and 2.5 $m^3/s$ and the temperatures of streams A and B are 21$^oC$ and 17$^oC$, respectively. The temperature at Stream C is nearly:
a. 14.5$^oC$
b. 19.4$^oC$
c. 28.0$^oC$
d. 29.3$^oC$

28. The ThOD of 50 mg/L organic compound whose chemical formula is $C_6H_{12}O_6$ (glucose) is nearly:
a. 25 mg/L
b. 50 mg/L
c. 75 mg/L
d. 100 mg/L

29. If the $BOD_3$ of a waste is 75 mg/L and $K$ is 0.10 day$^{-1}$($k = 0.23\ day^{-1}$) , what is the ultimate *BOD* ($BOD_u$ or $L_o$)?
a.  103 mg/L
b. 150 mg/L
c. 175 mg/L
d. 200 mg/L

30. If the $BOD_3$ of a waste is 75 mg/L and $K$ is 0.10 day$^{-1}$ ($k = 0.23\ day^{-1}$) , what is the 5-day *BOD* ($BOD_5$)?
a.  103 mg/L
b. 150 mg/L
c. 175 mg/L
d. 200 mg/L