Module 12 : Self Purification Of Natural Streams

Lecture 15 : Self Purification Of Natural Streams

The self purification of natural water systems is a complex process that often involves physical, chemical, and biological processes working simultaneously. The amount of Dissolved Oxygen (DO) in water is one of the most commonly used indicators of a river health. As DO drops below 4 or 5 mg/L the forms of life that can survive begin to be reduced. A minimum of about 2.0 mg/L of dissolved oxygen is required to maintain higher life forms. A number of factors affect the amount of DO available in a river. Oxygen demanding wastes remove DO; plants add DO during day but remove it at night; respiration of organisms removes oxygen. In summer, rising temperature reduces solubility of oxygen, while lower flows reduce the rate at which oxygen enters the water from atmosphere.

12.1 Factors Affecting Self Purification

1. ***Dilution***: When sufficient dilution water is available in the receiving water body, where the wastewater is discharged, the DO level in the receiving stream may not reach to zero or critical DO due to availability of sufficient DO initially in the river water before receiving discharge of wastewater.
2. ***Current***: When strong water current is available, the discharged wastewater will be thoroughly mixed with stream water preventing deposition of solids. In small current, the solid matter from the wastewater will get deposited at the bed following decomposition and reduction in DO.
3. ***Temperature***: The quantity of DO available in stream water is more in cold temperature than in hot temperature. Also, as the activity of microorganisms is more at the higher temperature, hence, the self-purification will take less time at hot temperature than in winter.
4. ***Sunlight:*** Algae produces oxygen in presence of sunlight due to photosynthesis. Therefore, sunlight helps in purification of stream by adding oxygen through photosynthesis.
5. ***Rate of Oxidation:*** Due to oxidation of organic matter discharged in the river DO depletion occurs. This rate is faster at higher temperature and low at lower temperature. The rate of oxidation of organic matter depends on the chemical composition of organic matter.

12.2 Oxygen Sag Analysis

The oxygen sag or oxygen deficit in the stream at any point of time during self purification process is the difference between the saturation DO content and actual DO content at that time.

Oxygen deficit, D = Saturation DO – Actual DO

The saturation DO value for fresh water depends upon the temperature and total dissolved salts present in it; and its value varies from 14.62 mg/L at 0^oC to 7.63 mg/L at 30^oC, and lower DO at higher temperatures.

The DO in the stream may not be at saturation level and there may be initial oxygen deficit 'D_o'. At this stage, when the effluent with initial BOD load L_o, is discharged in to stream, the DO content of the stream starts depleting and the oxygen deficit (D) increases. The variation of oxygen deficit (D) with the distance along the stream, and hence with the time of flow from the point of pollution is depicted by the 'Oxygen Sag Curve' (Figure 12.1). The major point in sag analysis is point of minimum DO, i.e., maximum deficit. The maximum or critical deficit (D_c) occurs at the inflexion points of the oxygen sag curve.

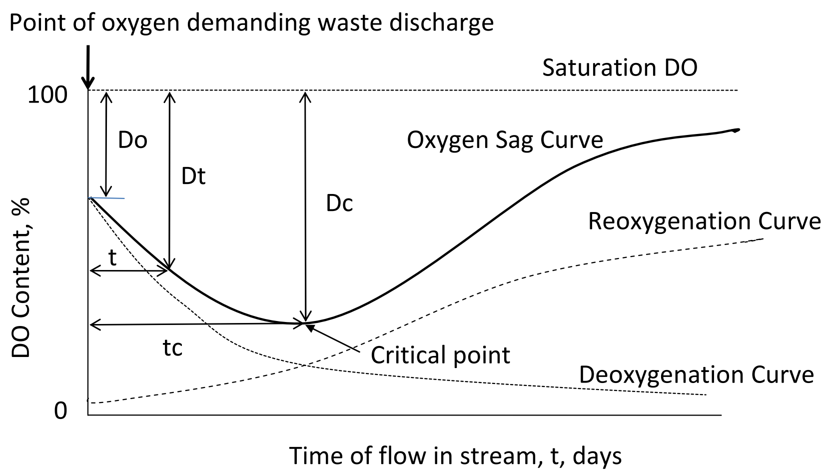

Figure 12.1 Deoxygenation, reoxygenation and oxygen sag curve

12.3 Deoxygenation and Reoxygenation Curves

When wastewater is discharged into the stream, the DO level in the stream goes on depleting. This depletion of DO content is known as deoxygenation. The rate of deoxygenation depends upon the amount of organic matter remaining (L_t) to be oxidized at any time t, as well as temperature (T) at which reaction occurs. The variation of depletion of DO content of the stream with time is depicted by the deoxygenation curve in the absence of aeration. The ordinates below the deoxygenation curve (Figure 12.1) indicate the oxygen remaining in the natural stream after satisfying the bio-chemical oxygen demand of oxidizable matter.

When the DO content of the stream is gradually consumed due to BOD load, atmosphere supplies oxygen continuously to the water, through the process of re-aeration or reoxygenation, i.e., along with deoxygenation, re-aeration is continuous process.

The rate of reoxygenation depends upon:

i) Depth of water in the stream: more for shallow depth.

ii) Velocity of flow in the stream: less for stagnant water.

iii) Oxygen deficit below saturation DO: since solubility rate depends on difference between saturation concentration and existing concentration of DO.

iv) Temperature of water: solubility of oxygen is lower at higher temperature and also saturation concentration is less at higher temperature.

12.4 Mathematical analysis of Oxygen Sag Curve: Streeter – Phelps equation

The analysis of oxygen sag curve can be easily done by superimposing the rates of deoxygenation and reoxygenation as suggested by the Streeter – Phelps analysis. The rate of change in the DO deficit is the sum of the two reactions as explained below:

dDt/ dt = f (deoxygenation and reoxygenation)

OR dDt / dt = K'Lt – R'Dt ….(1)

Where,

Dt = DO deficit at any time t,

Lt = amount of first stage BOD remaining at any time t

K' = BOD reaction rate constant or deoxygenation constant (to the base e)

R' = Reoxygenation constant (to the base e)

t = time (in days)

dDt/ dt = rate of change of DO deficit

Now,

$$Lt = Lo.e^{-K't}$$

Where, Lo = BOD remaining at time t = 0 i.e. ultimate first stage BOD

Hence,

$$\frac{dDt}{dt} = K' Lo.e^{-K't} - R' Dt \qquad \text{....(2)}$$

or $$\frac{dDt}{dt} + R' Dt = K' Lo.e^{-K't} \qquad \text{....(3)}$$

This is first order first degree differential equation and solution of this equation is as under

$$Dt = \frac{K' Lo}{R' - K'}\left[e^{-K't} - e^{-R't}\right] + Do.e^{-R't} \qquad \text{....(4)}$$

Changing base of natural log to 10 the equation can be expressed as:

$$Dt = \frac{KLo}{R - K}\left[10^{-K.t} - 10^{-R.t}\right] + Do.10^{-R.t} \qquad \text{....(5)}$$

Where, K = BOD reaction rate constant, to the base 10

R = Reoxygenation constant to the base 10

Do = Initial oxygen deficit at the point of waste discharge at time t = o

t = time of travel in the stream from the point of discharge = x/u

x = distance along the stream

u = stream velocity

This is Streeter-Phelps oxygen sag equation. The graphical representation of this equation is shown in Figure 12.2.

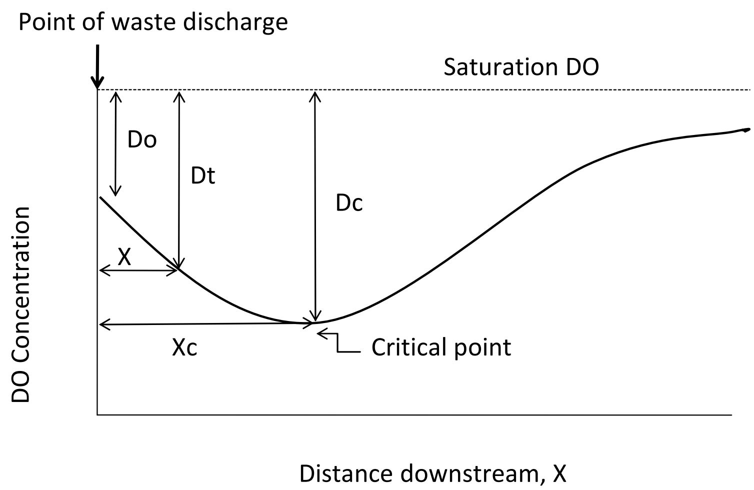

Figure 12.2 Oxygen sag curve of Streeter-Phelps equation

Note: Deoxygenation and reoxygenation occurs simultaneously. After critical point, the rate of re-aeration is greater than the deoxygenation and after some distance the DO will reach to original level and stream will not have any effect due to addition of wastewater. At time t=0 at x = 0.

Determination of Critical DO deficit (Dc) and distance Xc

The value of Dc can be obtained by putting dDt/dt = 0 in equation 3,

Hence,

$$Dc = \frac{K'}{R'} Lo.e^{-K'tc} \quad ....(6)$$

OR

$$Dc = \frac{K}{R} Lo.10^{-K.tc} \quad ....(7)$$

Where, tc is time required to reach the critical point.

The value of 'tc' can be obtained by differentiating equation 4 (or 5) with respect to 't' and setting dDt/dt = 0

Therefore,

$$tc = \frac{1}{R'-K'} \log_e \frac{R'}{K'}\left[1 - \frac{Do(R'-K')}{K'Lo}\right] \quad ....(8)$$

OR

$$tc = \frac{1}{R-K} \log_{10} \frac{R}{K}\left[1 - \frac{Do(R-K)}{K.Lo}\right] \quad ....(9)$$

The distance X_c is given by X_c = tc . u

Where, u = velocity of flow in the stream

The deoxygenation constant K, is obtained by laboratory test or field tests, and varies with temperature as given below:

$$K_T = K_{20}(\theta)^{(T-20)} \quad ....(10)$$

Where, θ varies with the temperature = 1.056 in general or 1.047 for 20°C to 30°C temperature, and 1.135 for 4°C to 20°C

K = 0.1 to 0.3 for municipal sewage, base 10, (0.23 to 0.70 for base e)

The reoxygenation constant R also varies with the temperature and can be expressed as:

$$R_T = R_{20}(1.024)^{(T-20)} \quad ....(11)$$

Where, R'/R = 2.303

R = 0.15 to 0.20 for low velocity large stream

= 0.20 to 0.30 for normal velocity large stream

= 0.10 to 0.15 for lakes and sluggish stream

$R_T = R_{20}(1.016)^{(T-20)}$ (Peavy et al., 1985)

The ratio of R/K (or R'/K') is called the self purification constant f_s and it is equal to 0.50 to 5.0.

Example : 1

A city discharges 20000 m^3/day of sewage into a river whose rate of flow is 0.7 m^3/sec. Determine D.O. deficit profile for 100 km from the following data:

River	Sewage effluent from STP
5 day B.O.D. at 20^0C = 3.4 mg/l	5 day B.O.D. at 20^0C = 45 mg/l
Temperature 23^0C	Temperature 26^0C
D.O. = 8.2 mg/l	D.O. = 2.0 mg/l

Velocity of mix = 0.25 m/sec, R'=0.4, K' = 0.23

Solution

River discharge = 0.7 m^3/sec, Sewage discharge = 20000/(24x 3600) = 0.231 m^3/sec

BOD of mix= $\frac{(0.7 \text{ x } 3.4 + 0.231 \text{ x } 45)}{(0.7+0.231)}$ = 13.72 mg/l

D.O. of mix $\frac{(0.7 \text{ x } 8.2 + 0.231 \text{ x } 2.0)}{(0.7+0.231)}$ = 6.66 mg/l

Temp. of mix $\frac{(0.7 \text{ x } 23 + 0.231 \text{ x } 26)}{(0.7+0.231)}$ = 23.74 ^{0}C

Saturation value of D.O. at 23.74 ^{0}C is 8.57 mg/l

Ultimate B.O.D. $L_t = L_0\,(1 - e^{-kxt})$

$13.72 = L_0\,(1 - e^{-0.23x5})$

$L_0 =$ 20.08 mg/L

Initial D.O. deficit (D_0) = 8.57 - 6.66 = 1.91 mg/L

Deoxygenation and reoxygenation coefficients at 23.74 ^{0}C temperature

$K_T = K_{20}\,(\theta)^{T-20}$ Hence, $K_{23.74} = 0.23\,(1.047)^{23.74-20} = 0.273$ day^{-1}

$R_T = R_{20} (\theta)^{T-20}$ Hence, $R_{23.74} = 0.40 (1.016)^{23.74-20} = 0.424 \text{ day}^{-1}$

Critical time $t_c = \frac{1}{R' - K'} \log_e \frac{R'}{K'} \left(1 - \frac{D_0 \text{ x } (R' - K')}{K' \; x \; L0}\right)$

$= \frac{1}{0.424 - 0.273} \log_e \frac{0.424}{0.273} \left(1 - \frac{1.91 \text{ x } (0.424 - 0.273)}{0.273 \; x \; 20.08}\right)$

= 2.557 days.

Critical D.O. deficit, $Dc = \frac{K'}{R'} \; L_0 \, e^{-K'.tc}$

$= \frac{0.273}{0.424} \; 20.08 \, e^{-0.273 \; X \; 2.557}$

= 6.432 mg/l

Distance at which it occurs = L= velocity x time

= (0.25 m/sec) x (2.557 x 24 x 60 x 60 sec)

= 55231 m = 55.23 km

Similarly time required for mix to reach at 20 km distance, $t_{20km} = \frac{(20 \; x \; 1000)}{(0.25 \; x \; 24 \; x \; 3600)}$

= 0.926 day

And DO deficit at 20 km can be calculated using equation 4

$$Dt = \frac{K' Lo}{R' - K'} \left[e^{-K't} - e^{-R't} \right] + Do.e^{-R't}$$

Where, K’ = 0.273 d^{-1}, R’ = 0.424 d^{-1}, Do = 1.91 mg/L and Lo = 20.08 mg/L and t = 0.926 day

Hence, DO deficit at 20 km = 4.970 mg/L

Similarly DO deficit at 40 km (i.e. t = 1.852 days) = 6.211 mg/L

and DO deficit at 80 km (i.e., t = 3.704 days) = 6.056 mg/L

and DO deficit at 100 km (i.e., t = 4.63 days) = 5.427 mg/L

The DO deficit at different points along length of river is as below:

Distance in km	Time in days	DO deficit, mg/L	DO, mg/L
0	0	1.91	6.66
20	0.926	4.97	3.6
40	1.852	6.211	2.359
55.23	2.557	6.432	2.138
80	3.704	6.056	2.514
100	4.63	5.427	3.143

Questions

1. Explain factors affecting self purification of natural streams.
2. What is reoxygenation? What are the factors that affect reoxygenation?
3. Derive Streeter-Phelps equation for oxygen sag analysis.
4. A river is having discharge of 22 m^3/s receives wastewater discharge of 0.5 m^3/s. The initial DO of the river water is 6.3 mg/L, and DO content in the wastewater is 0.6 mg/L. The five day BOD in the river water is 3 mg/L, and the wastewater added to river has five day BOD of 130 mg/L. Consider saturation DO of 8.22 mg/L and deoxygenation and reoygenation constant values of 0.1 and 0.3 per day, respectively. Find critical DO deficit and DO in the river after one day. The average velocity of flow in the stream after mixing of wastewater is 0.18 m/sec.
5. A municipal wastewater treatment plant discharges secondary effluent to a river. The worst condition occurs in the summer when the treated wastewater in summer is found to have a maximum flow rate of 10000 m^3/day, a BOD_5 of 30 mg/L, dissolved oxygen concentration of 1.5 mg/L and temperature of 25^{o}C. At upstream of the disposal point the minimum flow in the stream is 0.65 m^3/sec with BOD_5 of 3.0 mg/L, dissolved oxygen concentration of 7.0 mg/L and temperature of 22^{o}C. The mixing of wastewater and stream is almost instantaneous at the point of disposal and velocity of the mixture is 0.2 m/sec. The reaeration constant is estimated to be 0.4 per day at 20^{o}C temperature. Determine the critical DO deficit and distance at which it will occur. Also draw the dissolve oxygen profile for 100 km downstream of the river from the point of discharge.

Answers:

Q 4: Critical DO deficit = 2.27 mg/L; and DO in the river after one day = 2.26 mg/L; tc = 0.97 day

Q 5: Critical DO deficit = 2.48 mg/L; and distance at which it will occur = 33.83 km