Technical Assistance
HYDROLOGY PROJECT

World Bank & Government of The Netherlands funded

Training module # WQ - 25

Oxygen Balance in Surface Waters

New Delhi, October 1999

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DHV Consultants BV & DELFT HYDRAULICS

with
HALCROW, TAHAL, CES, ORG & JPS

Table of contents

1. Module context

This module introduces the topic of oxygen in surface waters, and the processes affecting oxygen concentrations. Modules in which prior training is required to complete this module successfully and other available, related modules in this category are listed in the table below.

While designing a training course, the relationship between this module and the others, would be maintained by keeping them close together in the syllabus and place them in a logical sequence. The actual selection of the topics and the depth of training would, of course, depend on the training needs of the participants, i.e. their knowledge level and skills performance upon the start of the course.

No.	Module title	Code	Objectives
1.	Basic water quality concepts	**WQ - 01**	• Discuss the common water quality parameters • List important water quality issues
2.	Basic chemistry concepts [a]	**WQ - 02**	• Convert units from one to another • Discuss the basic concepts of quantitative chemistry • Report analytical results with the correct number of significant digits.
3	Understanding the chemistry of dissolved oxygen measurement[a]	**WQ - 11**	• Appreciate significance of DO measurement • Understand the chemistry of DO measurement by Winkler method
4	Understanding biochemical oxygen demand test[a]	**WQ - 15**	• Understand the significance and theory of BOD measurement

a-prerequisite

2. Module profile

Title	:	Oxygen Balance in Surface Waters
Target group	:	HIS function(s): Q2, Q3, Q5, Q6, Q7, Q8
Duration	:	1 session of 60 min
Objectives	:	After the training the participants will be able to: • Explain the importance of oxygen in water • Identify the main processes of oxygen addition and depletion in surface waters
Key concepts	:	• Oxygen saturation • Sources and sinks • Effect on water quality • Sag curve
Training methods	:	Lecture, open discussion and exercises
Training tools required	:	Board, flipchart, OHS
Handouts	:	As provided in this module
Further reading and references	:	• Introduction to Environmental Engineering and Science, Gilbert M. Masters, Prentice Hall of India, 1994 • Water Quality Monitoring, ed. J. Bartram and R. Balance, UNEP & WHO, E & FN Spon

3. Session plan

No	Activities	Time	Tools
1	***Preparations***		
2	***Introduction***: • Discuss the importance of DO in surface waters, ambient water quality standards	10 min	OHS
3	***Oxygen absorption and consumption:*** • Factors affecting saturation value • Processes depleting oxygen	10 min	OHS
4	***Oxygen balance*** • Rates of oxygen absorption and depletion • DO sag curve • Short term changes • Oxygen level as index of water quality	I5 min	OHS
5	***Oxygen sag equation***	10 min	OHS
6	***Exercise***	10 min	Additional handout
7	***Wrap up***	5 min	

4. Overhead/flipchart master

OHS format guidelines

Type of text	Style	Setting
Headings:	OHS-Title	Arial 30-36, Bold with bottom border line (not: underline)
Text:	OHS-lev1 OHS-lev2	Arial 26, Arial 24, with indent maximum two levels only
Case:		Sentence case. Avoid full text in UPPERCASE.
Italics:		Use occasionally and in a consistent way
Listings:	OHS-lev1 OHS-lev1-Numbered	Big bullets. Numbers for definite series of steps. Avoid roman numbers and letters.
Colours:		None, as these get lost in photocopying and some colours do not reproduce at all.
Formulas/ Equations	OHS-Equation	Use of a table will ease alignment over more lines (rows and columns) Use equation editor for advanced formatting only

Oxygen Balance in Surface Waters

- Oxygen is essential for most aquatic life in natural surface waters

- The concentration of dissolved oxygen (DO) is critical

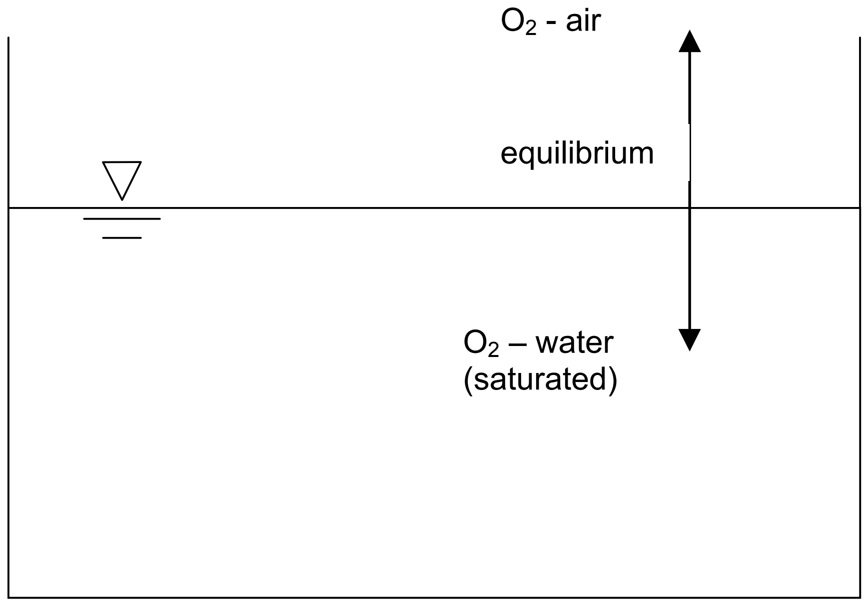
- DO is the most important WQ parameter to indicate the health of a water body

Surface Water Standards

- Indian standards for minimum dissolved oxygen (DO) concentration in surface water:
  - *Drinking water source without conventional treatment, after disinfection: 6.0 mg/L*
  - *Drinking water source with conventional treatment followed by disinfection: 4.0 mg/L*
  - *Out-door bathing: 5.0 mg/L*
  - *Fish culture and wild life propagation: 4.0 mg/L*

Oxygen Saturation

- *Water in equilibrium with the atmosphere attains DO saturation concentration.*



Oxygen Saturation Level (1)

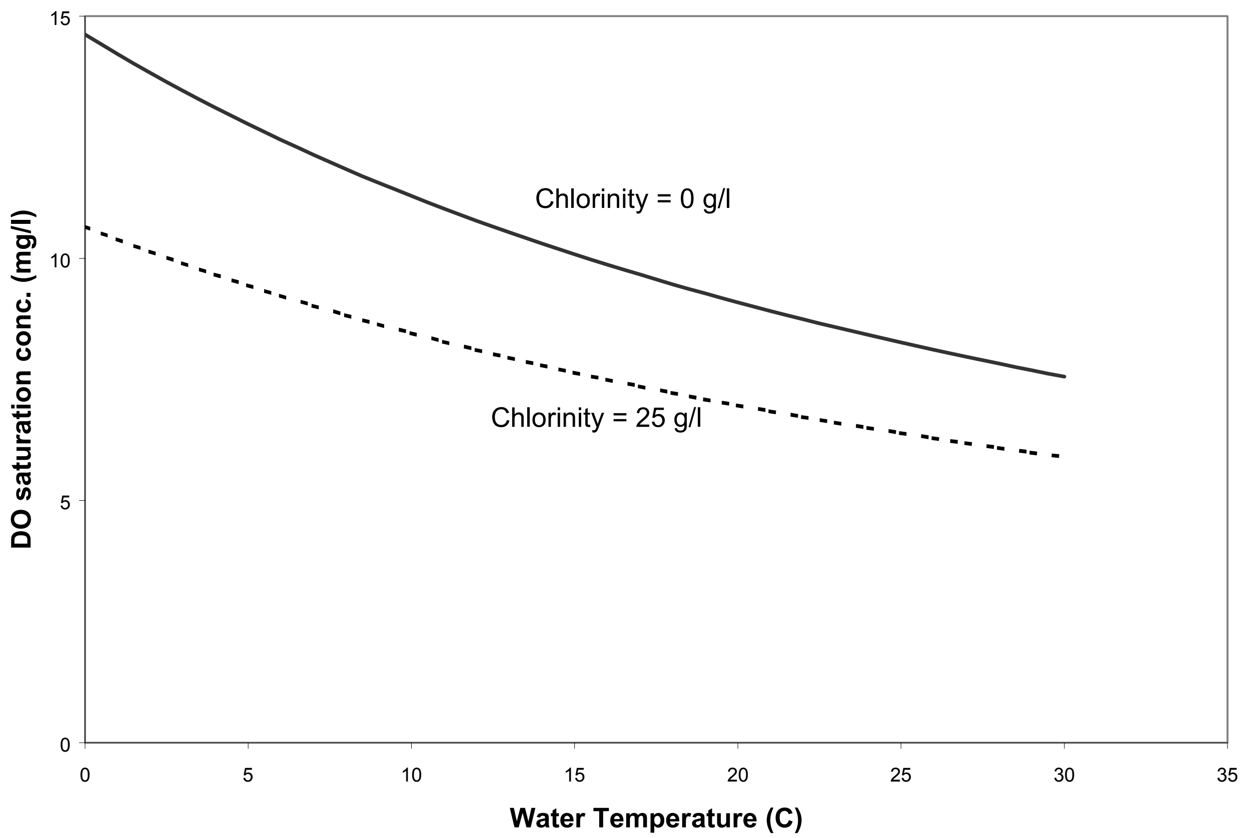
- Saturation concentration of DO in water depends on:
  - *water temperature, T (°C)*
  - *salinity (expressed as Cl in g/L, 'chlorinity')*
  - *air pressure, P (mm Hg).*

- In freshwater (Cl= 0 g/L), at sea level (P= 760 mm Hg), and at T = 20°C, then DO = 9.2 mg/L

- See Table of saturation levels in your text

Oxygen Saturation Level (2)

- Oxygen is less soluble in water as T and Cl increase



Processes Affecting DO Level

- A number of processes add (+) or deplete (-) the DO in water:
  - *absorption from air or reaeration (+)*
  - *production O_2 by plants (+)*
  - *oxidation of organic matter in water (-)*
  - *oxidation of ammonia in water (-)*
  - *oxidation of organic matter in sediment (-)*
  - *respiration by aquatic life (-)*

Rate of Absorption of Oxygen from Air

- Different for different water bodies
- For streams
  - *average depth and velocity*
  - *may be different in different reaches*
- Depends on existing deficit
  - *deficit = saturation concentration – existing concentration*

Discharge of Organic Matter in Surface Waters

- Bacterial oxidation of organic matter (BOD) is important in pollution control terms

- BOD can reduce dissolved oxygen to zero, leading to fish death and putrid conditions

- Oxidation potential of organic matter can be estimated by BOD and COD analyses

Oxygen Balance (1)

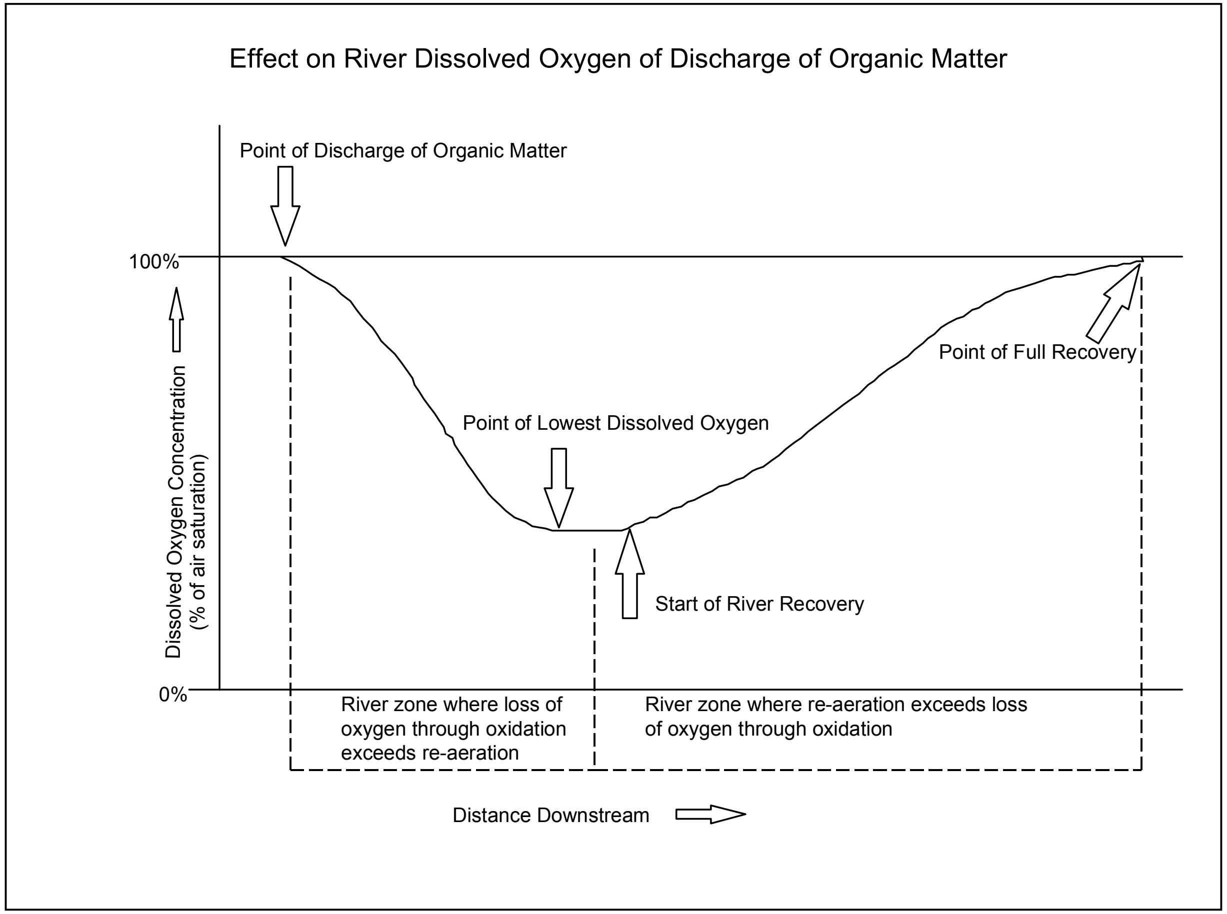
- Oxygen addition and depletion processes change DO concentration from saturated
  - *if addition > depletion: DO is increased, may reach saturation level*
  - *if addition < depletion: DO is decreased, may become anaerobic*
- Percent oxygen saturation is:

$$\% = \frac{Actual\ DO\ Conc}{Saturated\ \ DO\ Conc_{(T,Cl,P)}} \times 100$$

Oxygen Balance (2)

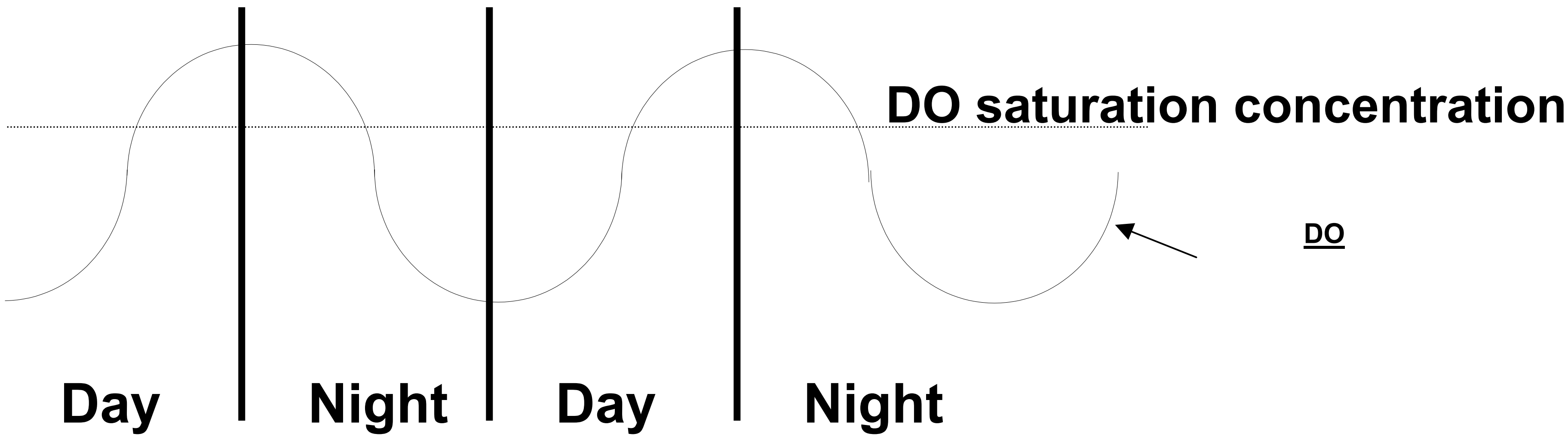
- When BOD is discharged into a river:
  - *DO in river is depleted by BOD*
  - *DO is added to river by aeration*
- Resulting DO concentration along the river has a known profile: ‘DO sag curve’

Oxygen Balance (3): DO Sag Curve



Short-term DO changes

- When significant concentrations of algae are present



- *Day: algae release oxygen (photosynthesis)*
- *Night: algae consume oxygen (respiration)*

DO as Index of Water Quality (1)

1. Dissolved oxygen **< 5%** saturated
   - *black, turbid water*
   - *putrid smell*
   - *pollution tolerant invertebrates - no fish*
2. Dissolved oxygen **5 – 10%** saturated
   - *grey, turbid water*
   - *rotten or stale smell*
   - *‘sewage fungus’ present – no fish*

DO as Index of Water Quality (2)

3. Dissolved oxygen **10 –70%** saturated
   - *transparent or slightly turbid water*
   - *odour free*
   - *vegetation, some invertebrates and fish*
4. Dissolved oxygen **> 70%** saturated
   - *clear and fresh water*
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DO Sag Equation

- Change in deficit = BOD exerted - Reaeration
  - *BOD exerted /day =* K_1 *x remaining BOD*
  - *Re-aeration /day =* K_2 *x existing deficit*
- Example
  - *River BOD = 12 mg/L, DO = 8 mg/L (saturated)*
  - K_1 *= 0.4 /d and* K_2 *= 0.5 /d*

- BOD = 12 mg/L, deficit = 0 mg/L, DO = 8 mg/L
- **1st day**
  - *BOD exerted = 0.4 x 12 = 4.8, Reaeration = 0.5 x 0 = 0*
  - *Deficit = 0 + 4.8 – 0 = **4.8**, DO = 8 – 4.8 = **3.2***
  - *BOD remaining = 12 – 4.8 = **7.2***
- **2nd day**
  - *BOD exerted = 0.4 x 7.2 =**2.9**, Reaeration = 0.5 x4.8 = **2.4***
  - *Deficit = 4.8 + 2.9 – 2.4 = **5.3**, DO = 8 - 5.3 = **2.7***
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Time	River BOD	BOD exerted	Deficit	Reaeration	DO
0	12	-	0	-	8
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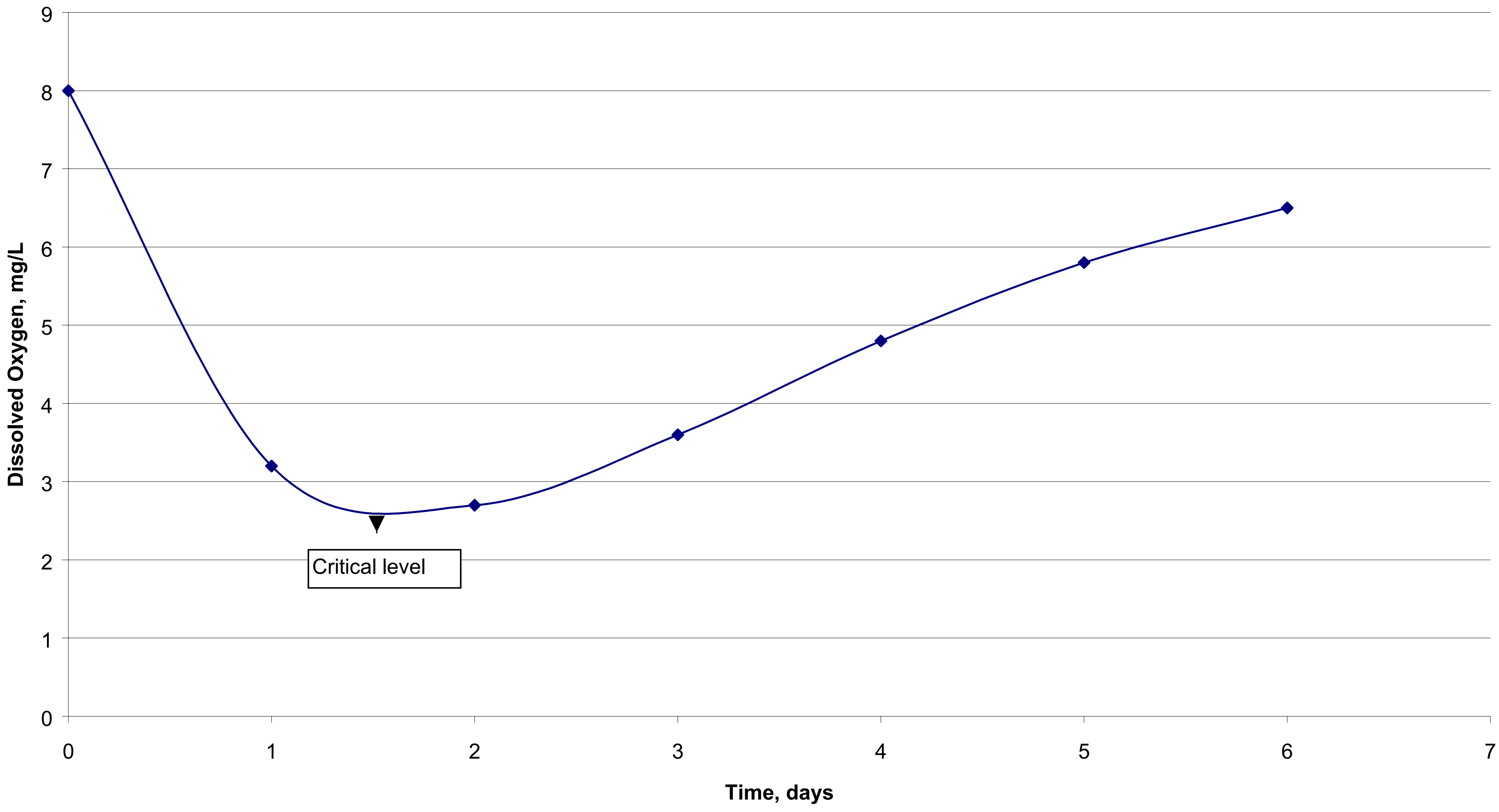
2	4.3	2.9	5.3	2.4	2.7
3	2.6	1.7	4.4	2.6	3.6
4	1.6	1.0	3.2	2.2	4.8
5	0.9	0.7	2.2	1.6	5.8
6	0.6	0.3	1.5	1.1	6.5

Figure 3 Dissolved Oxygen sag curve



5. Evaluation sheets

6. Handout

Oxygen Balance in Surface Waters

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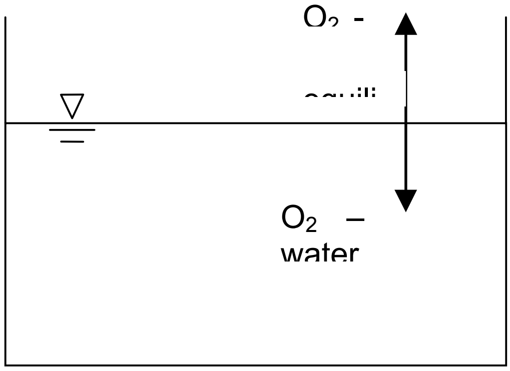

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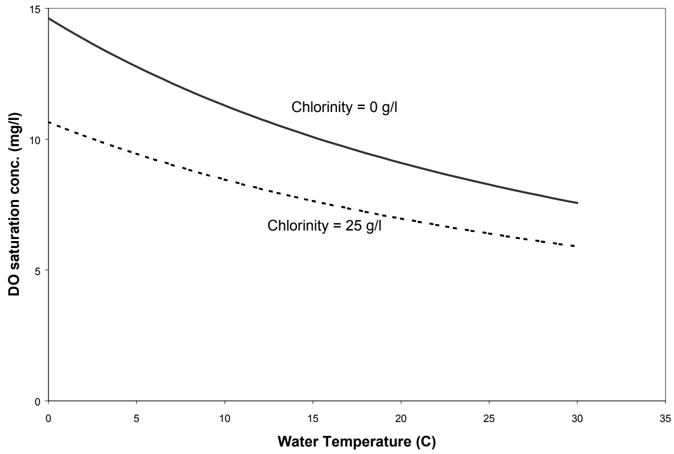

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5	0.9	0.7	2.2	1.6	5.8
6	0.6	0.3	1.5	1.1	6.5

Add copy of Main text in chapter 8, for all participants.

7. Additional handout

These handouts are distributed during delivery and contain test questions, answers to questions, special worksheets, optional information, and other matters you would not like to be seen in the regular handouts.

It is a good practice to pre-punch these additional handouts, so the participants can easily insert them in the main handout folder.

Question

Water containing 0 mg/L DO is released from the lower layers of a reservoir through sluice gates. Calculate the DO concentration in the downstream channel after 1, 2 and 3 days of flow. Assume that there are no oxygen depletion and addition processes except atmospheric re-aeration. The re-aeration rate constant is 25% of the deficit per day and the saturation concentration is 8 mg/L.

Question and Answer

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Answer:

Calculate re-aeration as 25% of deficit at the end of each day and adjust the deficit next day. Calculate DO concentration using the adjusted deficit as (8 – deficit).

Time, day	Deficit, mg/L	Re-aeration, mg/L	DO, mg/L
0	8		0
1	6	2	2
2	4.5	1.5	3.5
3	3.4	1.1	4.6

8. Main text

Contents

Oxygen Balance in Surface Waters

1. Introduction

A supply of free oxygen is essential to most forms of life. In the aquatic environment the main source of the gas for many organisms is oxygen that has dissolved into the water from the air. Therefore, dissolved oxygen (DO) is important for river life and it is for this reason that it is often essential to know the concentration of oxygen in water. In general, DO is one of the most important parameters indicating the quality of water and the health of a water body.

2. Water Quality Standards for Dissolved Oxygen

Because DO is so important for water quality, there are national standards for its minimum concentration in surface water, depending on the intended water use.

Water Use	Minimum DO conc. (mg/l)
Drinking water source without conventional treatment, but with disinfection	6.0
Drinking water source with conventional treatment, and with disinfection	4.0
Outdoor bathing	5.0
Fish culture and wildlife propagation	4.0

3. Saturation of dissolved oxygen in water

Water has the ability to dissolve gases from the atmosphere, in a process known as 'aeration'. When water is in contact with the atmosphere, oxygen from the atmosphere dissolves into the water until it reaches its equilibrium, or 'saturated' concentration (i.e. water in contact with air will dissolve oxygen up to the maximum concentration of the gas which the water can carry). Therefore, in the absence of other influences, rivers, lakes and oceans can be expected to be 'saturated' with dissolved oxygen.

The saturated concentration of dissolved oxygen (DO) in water depends on several factors, namely:

1. Temperature of the water (°C)
2. Salinity of the water (Cl g/l)
3. Atmospheric pressure (mm Hg)

The salinity of water can be expressed as 'chlorinity' e.g. grams chloride per liter.

Table 1 shows the saturated DO concentration in water over a range of temperatures and chlorinity concentrations. For example, in freshwater (Cl = 0 g/l), at sea level (P=760 mm Hg) and at 20°C, the saturated DO concentration is 9.2 mg/l. The saturated DO concentration decreases as temperature increases, and as chlorinity increases (Figure 1).

The actual concentration of dissolved oxygen in the aquatic environment depends upon many processes, which can increase DO above the saturation value (supersaturated), or decrease it below saturation value (under saturated). The main processes which add (+) or deplete (-) the concentration of DO in water are:

- Absorption of oxygen from air (reaeration) (+)
- production of O_2 by plants (+)

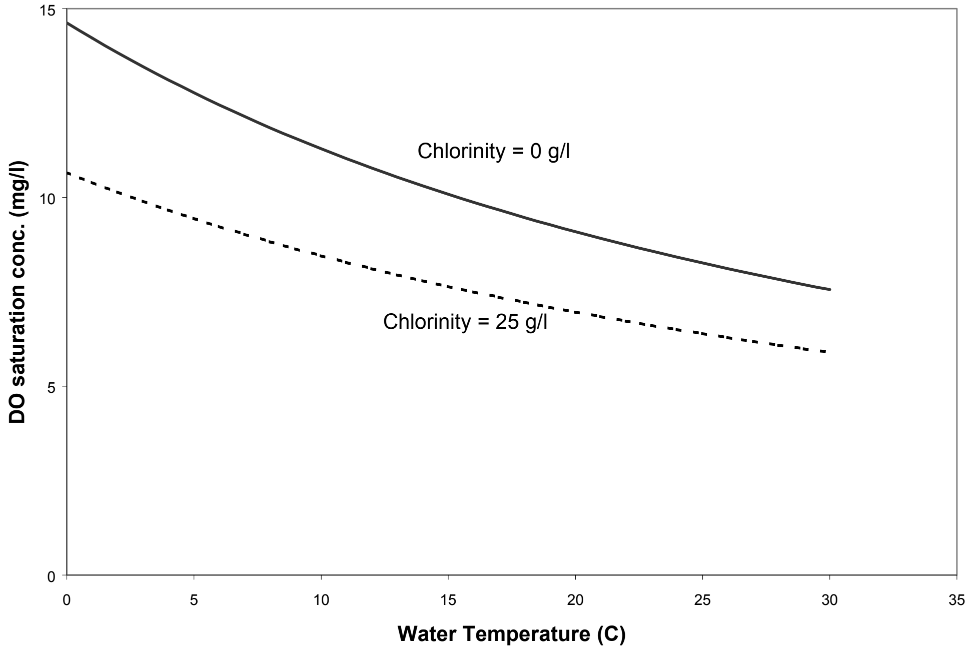
- oxidation of organic matter in water (-)
- oxidation of organic matter in sediment (-)
- respiration by aquatic life (-)

These processes, and how they interact to produce the dissolved oxygen observed at any given point in a water body, particularly streams, are discussed below.

Table 1
Saturation values of dissolved oxygen in water exposed to water saturated air containing 20.90 % oxygen under a pressure of 760 mm of mercury.

Temp. ^0C	Dissolved Oxygen mg/L				Vapour pressure mm Hg
	Chloride concentration in water (chlorinity) g/L			Difference per 100 mg chloride	
	0	5	10		
0	14.6	13.8	13.0	0.017	5
1	14.2	13.4	12.6	0.016	5
2	13.8	13.1	12.3	0.015	5
3	13.5	12.7	12.0	0.015	6
4	13.1	12.4	11.7	0.014	6
5	12.8	12.1	11.4	0.014	7
6	12.5	11.8	11.1	0.014	7
7	12.2	11.5	10.9	0.013	8
8	11.9	11.2	10.6	0.013	8
9	11.6	11.0	10.4	0.012	9
10	11.3	10.7	10.1	0.012	9
11	11.1	10.5	9.9	0.011	10
12	10.8	10.3	9.7	0.011	11
13	10.6	10.1	9.5	0.011	11
14	10.4	9.9	9.3	0.010	12
15	10.2	9.7	9.1	0.010	13
16	10.0	9.5	9.0	0.010	14
17	9.7	9.3	8.8	0.010	15
18	9.5	9.1	8.6	0.009	16
19	9.4	8.9	8.5	0.009	17
20	9.2	8.7	8.3	0.009	18
21	9.0	8.6	8.1	0.009	19
22	8.8	8.4	8.0	0.008	20
23	8.7	8.3	7.9	0.008	21
24	8.5	8.1	7.7	0.008	22
25	8.4	8.0	7.6	0.008	24
26	8.2	7.8	7.4	0.008	25
27	8.1	7.7	7.3	0.008	27
28	7.9	7.5	7.1	0.008	28
29	7.8	7.4	7.0	0.008	30
30	7.6	7.3	6.9	0.008	32

Figure 1: Saturated DO concentration as a function of temperature and chlorinity



4. Dissolved Oxygen Addition Processes

Absorption of oxygen from air

As stated earlier, water in contact with air dissolves oxygen till it attains saturation. If the oxygen is depleted due to any of the oxygen depletion processes, more oxygen is dissolved from the air. This is also called reaeration. The rate at which the oxygen is dissolved is influenced by the physical characteristics of the water body. In the case of streams, it is a function of the depth and velocity. Further, the rate also depends on the degree of undersaturation, which is defined as the saturation concentration minus the existing concentration. Since the undersaturation may change from time to time, the rate of absorption would also change.

Photosynthesis

Algae and larger plants in the water have the ability to add oxygen to the water through photosynthesis. This process, which virtually all green plants use to convert sunlight into food, releases oxygen, as one of its by-products. Pure oxygen is added to the water whenever photosynthesis occurs.

$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2 \qquad \text{(photosynthesis)}$$

The process of photosynthesis can result in the concentration of oxygen in water exceeding its air saturation value and becoming ‘supersaturated’. This is because the water is in contact with pure oxygen, rather than with oxygen in air, and this allows more gas to dissolve in the water. When water is supersaturated with dissolved oxygen, the gas escapes from the water into the air in a process opposite to that which occurs during normal aeration.

5. Dissolved Oxygen Depletion Processes

Oxidation of organic matter and ammonia in water

Of the processes that deplete dissolved oxygen, the bacterial oxidation of carbonaceous organic matter is the most important in pollution control terms. Organic pollutants (e.g., sewage, industrial wastes from sugar factories, distilleries, dairies, etc.) discharged to a water body are oxidised by bacteria and this oxidation removes dissolved oxygen from the water. If the load of organic matter discharged is large enough, the dissolved oxygen in the water can be reduced to zero, which will kill fish and other aquatic life. Further, if no free oxygen is present in a water body (so-called 'anaerobic' conditions) the water becomes aesthetically unpleasant and often foul smelling.

Due to the importance of the oxidation of organic matter to water quality, a number of laboratory analyses have been devised to estimate the likely effect that a discharge of organic matter has on a water body. Of these analyses the two most important are the biochemical oxygen demand (BOD) test and the chemical oxygen demand (COD) test. Full details of each of these analyses can be found in the BOD and COD training modules.

In addition to organic carbon compounds that are oxidised, certain nitrogen compounds in water are also oxidised by bacteria, consuming oxygen in the process. Nitrogen compounds can enter a water system from waste discharges, and include such substances as proteins, urea and ammonia. Most organic nitrogen compounds eventually break down into ammonia.

Ammonia is oxidised by nitrifying bacteria under aerobic conditions first to nitrite:

$$NH_4^+ + 1.5\ O_2 \rightarrow 2H^+ + H2O + NO_2^-$$

The nitrite formed is then oxidised to nitrate:

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$$

Both of these steps consume oxygen in water. For every mole of ammonia oxidised completely to nitrate, 2 moles of oxygen are consumed.

Sediment Oxygen Demand

The discharge of settleable waste may result in the formation of deposits of organic matter in the bottom sediments. The surface layer of the bottom deposit is in direct contact with the water, and usually undergoes aerobic decomposition. In this process, oxygen is removed from the water, as DO diffuses into the surface layer of the sediment.

Respiration

Fish and algae require oxygen for respiration, a process that consumes oxygen for the oxidation of organic matter, producing energy. This process can be considered to proceed continuously in water.

6. The Oxygen Balance

The oxygen depletion processes, which take place in the aquatic environment result in the dissolved oxygen content of the water being lowered from its saturation value. When this occurs, the water will naturally take up more oxygen from the air to restore the saturation value.

Normally, in a water body, many of the above oxygen addition and depletion processes are going on at the same time. Oxygen is, therefore, continually being added and removed from the water. As is usual for natural systems, reactions in a water body will tend to proceed to restore the normal state, which is, in the case of dissolved oxygen, when the water is in an air-saturated state. Therefore, any reduction in oxygen that occurs as a result of an input of organic matter will gradually be restored through the natural re-aeration process. This loss and addition of oxygen is called the 'oxygen balance' in a water body.

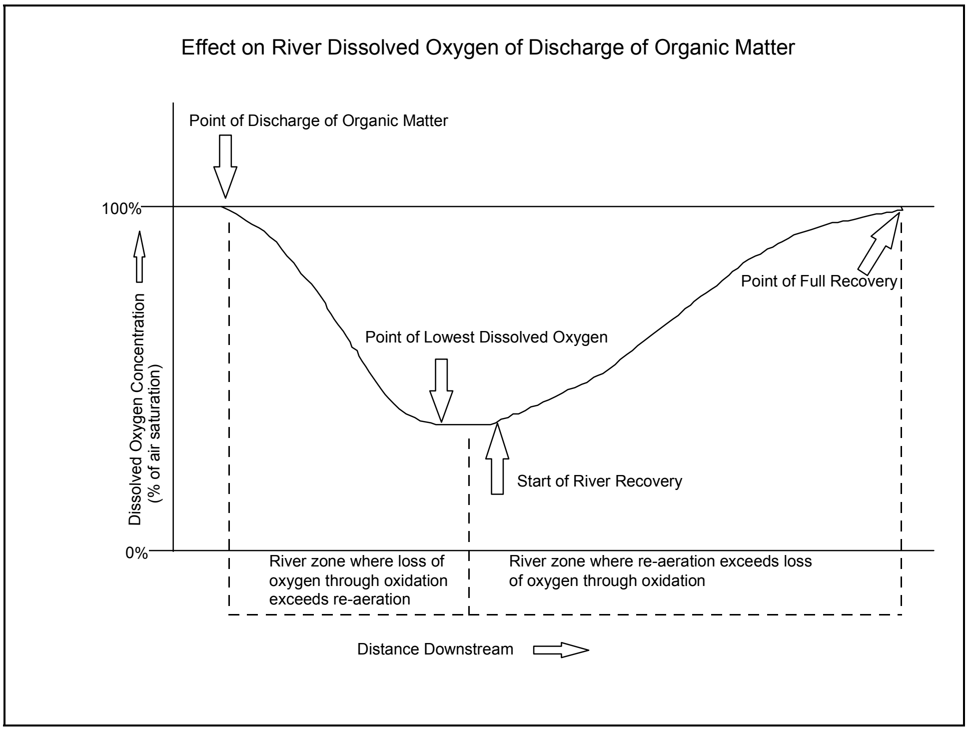


Figure 2: Effect on River Dissolved Oxygen of the Discharge of Organic Matter

Figure 2 illustrates the oxygen balance in a river to which a discharge of organic matter has been made. After the point of discharge, as the river flows downstream, the process of bacterial oxidation of organic matter removes more oxygen than re-aeration can compensate for. Therefore the concentration of dissolved oxygen in the river decreases.

The rate of de-oxygenation reflects the BOD exertion rate in the stream. The re-aeration rate is directly proportional to the DO deficit from the saturation value, i. e., it increases as the deficit increases and decreases as the deficit decreases.

Eventually, however, as the organic matter is consumed, the rate of oxidation slows until it is using oxygen at the same rate as re-aeration is replacing it. This is the point of minimum dissolved oxygen. After this point is reached, re-aeration becomes the dominant force as it replaces the river's oxygen more quickly than the oxidation of organic matter is reducing it.

The river's dissolved oxygen then increases until it is back to its ambient value of 100% of air saturation.

The classical shape of Figure 2 demonstrates a dissolved oxygen 'sag curve', so called because the oxygen concentration reduces or sags downstream following a discharge of organic matter.

The concentration of dissolved oxygen is a good indicator of the polluted state of a surface water body and thus its likely chemical and biological nature. To some degree it is possible, with reference to the concentration of dissolved oxygen present, to assess the polluted state of a surface water in terms of one of the following four categories:

(i) Dissolved Oxygen < 5% of saturation (extremely severe pollution):
The water is likely to be highly turbid and dark grey to black in colour with a faecal or bad eggs smell. The bottom is likely to be covered in black sludge from which gas bubbles may be rising. The predominant chemical species will be hydrogen sulphide (H_2S), ammonia (NH_3) and carbon dioxide (CO_2) gases. In terms of biology, bacteria will dominate and there will be some invertebrates that can tolerate such severe pollution. No fish will normally be present.

(ii) Dissolved Oxygen 5 - 10% of saturation (severe pollution):
The water is likely to be grey in colour with a rotten or stale smell. Bottom sludge may be grey on the surface but black beneath where oxygen is absent. Biologically, this category of water is characterised by 'sewage fungus' which is a mixture of organisms, dominated by the bacterium *Sphaerotilus natans*, which form long grey strands in the water. Fish are normally absent.

(iii) Dissolved Oxygen 10 - 70% of saturation (moderate pollution):
The water is normally transparent or slightly turbid, uncoloured and odour free. Algae may be living in the water in which case there will be a diurnal (daily) swing in oxygen production (see below). The water will be characterised by a rich vegetation and fish and invertebrates which can tolerate some pollution.

(iv) Dissolved Oxygen > 70% of saturation (no or slight pollution):
The water will normally look clear and fresh and will be odour free. 100% saturation with dissolved oxygen will be common. The most pollution-sensitive invertebrate and fish species will be present.

7. Short-term Dissolved Oxygen Changes

Like other aquatic life, algae also consume dissolved oxygen in the process of respiration. During the hours of daylight, however, plants through photosynthesis produce more oxygen than is consumed through respiration. At night no photosynthesis occurs and so the respiration of algae reduces the dissolved oxygen in the water. The net effect of this cycle of respiration and photosynthesis results in a characteristic diurnal (daily) variation in dissolved oxygen concentration in water bodies in which algae are present. During the day dissolved oxygen levels increase and during the night they fall.

8. DO Sag Curve Equation

The classical DO sag curve was developed on the basis of two reactions, namely, DO consumption due to BOD exertion and DO addition due to atmospheric re-aeration. This can be written in the form of a word equation as:

Change in DO deficit = Change due to BOD exertion – Change due to re-aeration

Or $\Delta D/\Delta T = K_1L - K_2D$

Where:
D = DO deficit (saturation level – DO concentration)
T = time
L = BOD of the stream water
K_1 and K_2 = BOD exertion and oxygen addition (re-aeration) rate constants, respectively.

The above equation can be integrated to give dissolved oxygen deficit as a function of time of flow.

Additional terms such as removal of BOD due to sedimentation and volatilisation of organic matter, photosynthetic oxygenation, and BOD exertion due to nitrification and sludge deposits, also can be added. Consideration of these aspects is out side the scope of this lecture. However, the basic equation given above is further elaborated with the help of the following example.

Example

Consider a stream, saturated with DO at 8mg/L, which receives waste from a city sewage outfall. Due to mixing of sewage the BOD of the river becomes 12 mg/L. As the water flows downstream, the micro-organisms in the stream and those present in the sewage start decomposing the organic matter and consume the DO in the stream. Assume that 40% of the remaining BOD is exerted every day. Oxygen is added from the atmosphere in proportion to the deficit. Assume that 50% of the existing deficit is decreased every day due to re-aeration.

If the processes are at steady state, i. e., sewage and stream flow do not change with the time, the temperature remains constant and the DO consumption and re-aeration rates do not change in different reaches of the stream, a balance sheet can be set up for the oxygen resource of the stream. For a constant velocity, the time of flow may be changed for the distance of travel.

The following table is constructed by adjusting the DO level every day against the consumption due to BOD exertion and addition due to re-aeration.

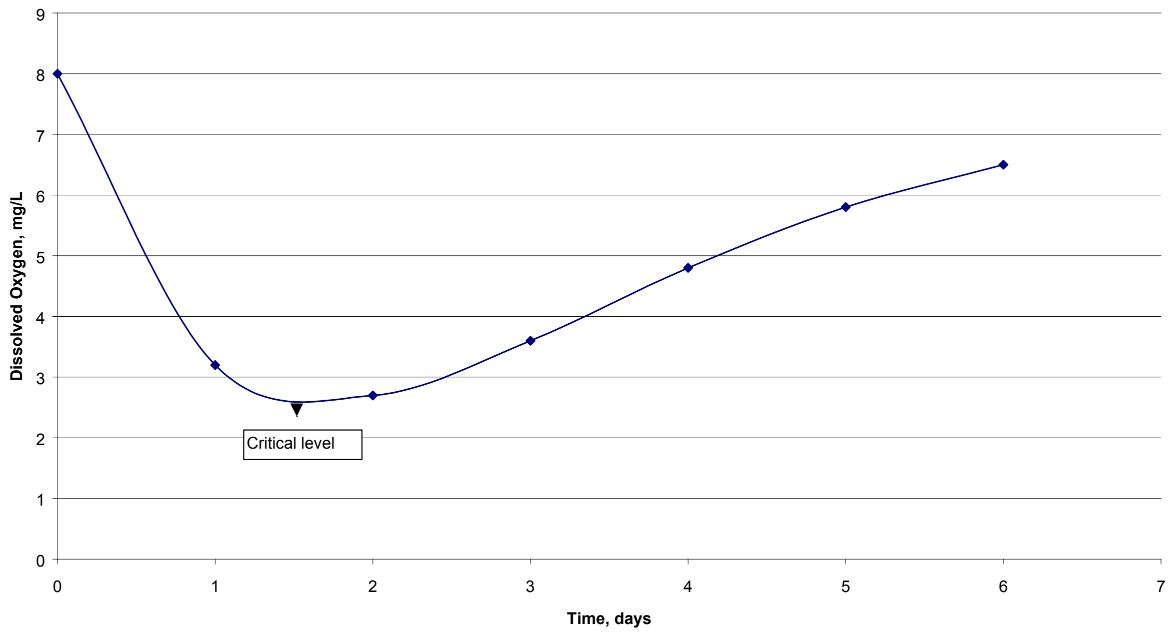
Time	River BOD	BOD exerted	Deficit	Re-aeration	DO
(1)	(2)	(3)	(4)	(5)	(6)
0	12	-	0	-	8
1	7.2	4.8	4.8	0	3.2
2	4.3	2.9	5.3	2.4	2.7
3	2.6	1.7	4.4	2.6	3.6
4	1.6	1.0	3.2	2.2	4.8
5	0.9	0.7	2.2	1.6	5.8
6	0.6	0.3	1.5	1.1	6.5

all values in mg/L, except time which is in days

(1) time of flow downstream of outfall
(2) remaining BOD – BOD exerted
(3) 40% of remaining BOD
(4) deficit on previous day + BOD exerted – re-aeration
(5) 50% of deficit on previous day
(6) 8 – deficit

Note that the minimum DO occurs between one and two days. The stream starts recovering after that and reaches near saturation level in about 6 days. The resulting DO sag curve is shown in Figure 3.

Figure 3 Dissolved Oxygen sag curve



The above solution of the problem is only an approximate one. To obtain an exact solution the balance equation should be integrated and then solved.