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Water and Wastewater

1.1 HYDROLOGICAL CYCLE

Water, one of the abundant compounds found in nature, is covering approximately three-fourths of the surface of the earth. Over 97% of the total quantity of water is in the oceans and other saline bodies of water and is not readily available for our use. Over 2% is tied up in polar ice caps and glaciers and in atmosphere and as soil moisture, which is inaccessible. An essential element for livelihood, domestic, industrial and agricultural activities, we have to depend upon only 0.62% of water found in fresh water lakes, rivers and groundwater supplies, irregularly and non-uniformly distributed over the vast area of the globe.

Solar radiation causes evaporation. Through evaporation from surface waters or by evapotranspiration from plants, water molecules convert into atmospheric vapour. Atmospheric water condenses and falls to the earth as rain and snow. Once on the earth's surface, water flows into streams, lakes and eventually oceans or percolates into the soil and into aquifers.

Water in nature is most nearly pure in its evaporation state. Gases as SO_2, NO_x may find their way into it at the very moment of condensation causing *acid rain*. Impurities are added as the liquid water travels through the remainder of the hydrological cycle and comes into contact with materials in the air and on or beneath the surface of the earth. Human activities contribute industrial and domestic wastes and agricultural chemicals to water.

The impurities accumulated by water throughout the hydrological cycle and as a result of human activities may be in both suspended and dissolved form. Suspended material consists of particles larger than molecular size that are supported by buoyant and viscous forces within water. Hence it is more common in water bodies in motion as river waters at flood time. Dissolved material consist of molecules or ions that are held by the molecular structure of water. They will be present in higher concentrations in ground waters due to the prolonged contact of percolating water with various beds. Colloids are very small particles that technically are suspended impurities but often exhibit many of the characteristics of dissolved substances.

1.2 WASTEWATER

Water is an essential ingredient of life. House as well as industry consume water and give out wastewater. Sanitary sewage is of domestic origin and its quantity depends on the number of people and nothing to do with the weather. Hence it is called *Dry Weather Flow* (DWF) . On the other hand runoff from catchments (particularly from roofs and roads) because of heavy rainfall is called *Storm Water* and is directly dependent on the intensity and duration of rainfall.

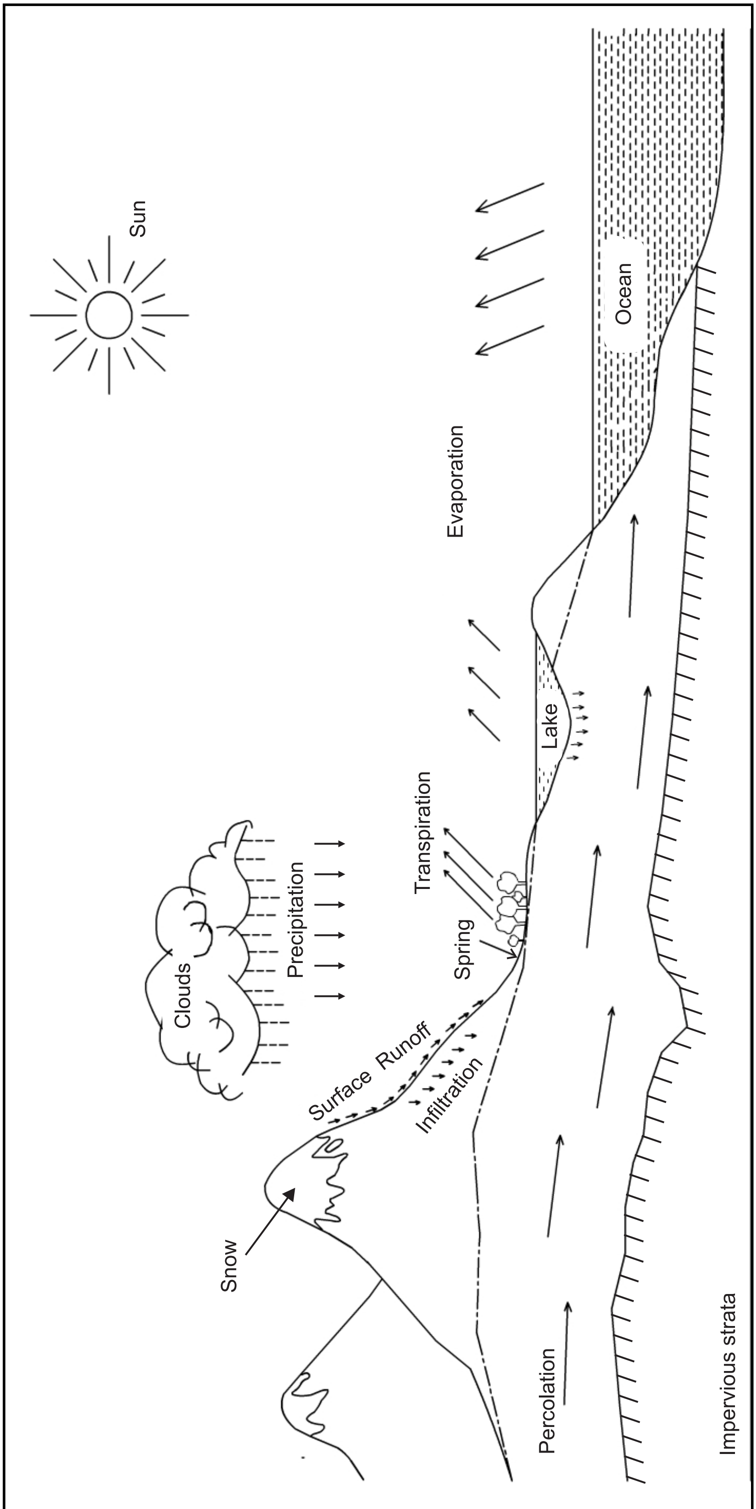

Fig. 1.1: Hydrological cycle

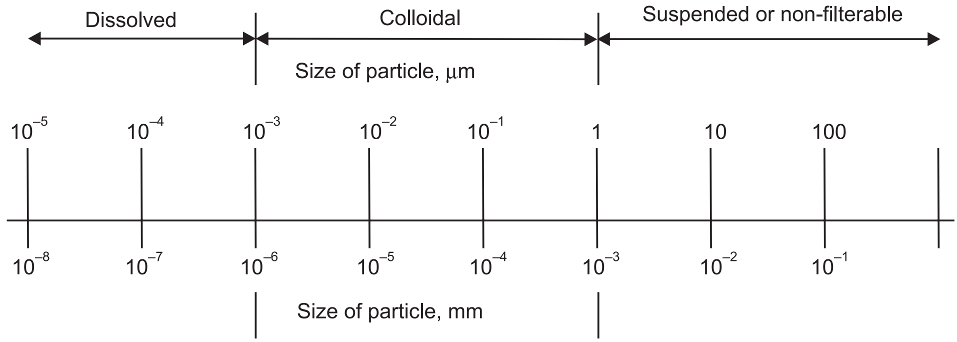

Fig. 1.2: Particles distribution (Size classification of solids)

Industrial wastewater is the effluent delivered out of a particular industry. Its quality and quantity depends upon nature of industry, raw materials used, manufacturing process and house keeping. Their characteristics vary widely from industry to industry.

Water pollution is defined as contamination of water or alteration of the physical, chemical or biological properties of natural water. Water is said to be polluted when it changes its quality or composition either naturally or as a result of human activities, thus becoming unsuitable for domestic, agricultural, industrial, recreational uses and for the survival of wildlife.

A water pollutant can be defined as an agent affecting aesthetic, physical, chemical and biological quality and *wholesomeness* of water.

1.3 PHYSICAL PARAMETERS

1.3.1 Suspended Solids

Solids suspended in water may consist of inorganic or organic particles. Inorganic solids such as clay, silt and other soil constituents are common in running surface water as rivers and streams. Organic material such as plant fibers and biological solids as algal cells and bacteria are also common constituents of surface waters. Because of the filtering capacity of the soil, and because of stagnation as in wells, suspended material is a rare constituent of groundwater. Sanitary sewage usually contains large quantities of suspended solids that are mostly organic in nature. Suspended solids are aesthetically displeasing and provide adsorption sites for chemical and biological agents. Suspended organic solids degrade biologically resulting in objectionable by-products of foul odours.

Total solids of a sample is measured by evaporating the sample to dryness at a temperature of 105° ± 1°C and weighing the residue. The suspended fraction of the solids in a water sample can be determined by filtering the water, drying the residue at ≈ 104°C. The organic content of both total and suspended solids can be determined by heating the residues at 600°C for one hour. The organic fraction of the residues will be converted to carbon dioxide, water vapour and other gases. The remaining material will represent the inorganic or fixed residue.

1.3.2 Turbidity

Turbidity is the property of absorption of light or its scattering by suspended material in water. Both absorption and scattering are influenced by size and surface characteristics of the suspended material. Turbidity may not be caused by transparent suspended solids. Colloidal material of clay, silt, rock fragments and metal oxides from the soil, vegetable fibres and microorganisms cause turbidity. Also soaps, detergents and emulsifying agents produce stable colloids that result in turbidity. Although turbidity measurements are not commonly run on wastewater, discharges of wastewater may increase the turbidity of natural bodies of water.

The colloidal material associated with turbidity provides adsorption site for chemicals, that may be harmful or cause undesirable tastes and odours and shield pathogenic biological organisms from disinfection.

Jackson turbidity unit (JTU) was based on light absorption being equal to the turbidity produced by 1 mg SiO_2 in 1 litre of distilled water. Nephelometric turbidity unit (NTU) is based on light scattering principle.

1.3.3 Colour

Pure water as rain water is colourless. But water is a universal solvent and is often coloured by many substances. Running water carries suspended solids which cause apparent colour. Water whose colour is due to suspended matter is said to have apparent colour. Apparent colour fades out when suspended solids settle. Colour contributed by dissolved solids is known as true colour which remains permanently.

After contact with organic debris such as leaves, weeds and wood, water picks up tannins, humic acid and humates to take a yellowish brown hue. Iron oxide causes reddish water and manganous oxide gives brown or blackish water.

Fresh sanitary sewage is grey in colour and its colour deepens with time. Stale or septic sewage is dark in colour. At a temperature of 20°C, fresh sewage becomes stale in 2 to 6 hours depending on the concentration of organic matter. Industrial wastes from textile and dyeing operations, pulp and paper wastewaters, food processing waste liquids, mining, refining and slaughterhouse operations add to colour of receiving streams.

Colour is a visible pollutant. Coloured water is not aesthetically acceptable for domestic as well as industrial use. Highly coloured water may not be accepted for laundering, dyeing, papermaking, beverage manufacturing, dairy production, food processing, textile and plastic production.

Methods involving measurement of intensity of colouration is based on comparison with standardized coloured materials. Results are expressed in true colour units (TCUs). One true colour unit is equivalent to the colour produced by 1 mg of platinum in the form of chloroplatinate ions along with 0.5 mg of cobalt chloride being dissolved in one litre of distilled water.

1.3.4 Taste and Odour

Substances which comes into prolonged contact with water may impart perceptible taste and odour. Minerals, metals and salts from the soil, end products from biological reaction and constituents of wastewater attribute taste and odour to water. For domestic consumption water should be free from odour and its taste should be agreeable.

Threshold Odour Number (TON) is an index of odour.

Varying amounts of odourous water are poured into containers and diluted with enough odour free distilled water to make a 200 mℓ mixture.

TON = $\frac{A+B}{A}$ where A is the volume of odourous water (mℓ) and B is the volume of odour free distilled water required to produce a 200 mℓ mixture. (Max. acceptable value of TON is 3 for domestic consumption).

Odour is mainly caused because of gases of decomposition of organic matter. Fresh sanitary sewage has mild, earthy, inoffensive odour or it may be even odourless. Because of anaerobic decomposition of proteins and other organic matter rich in nitrogen, sulphur and phosphorous, foul smelling and highly odourous gases as ammonia, hydrogen sulphide, mercaptans ($C_a H_b S_c$) and skatol ($C_x H_y N_z$) are produced.

Odour causes more a psychological stress than any direct harm. Offensive odours reduce appetite for food, lower water consumption, impair respiration, nausea, result in vomitting and mental perturbation and in extreme cases leads to deterioration of personal and community pride, interfere in human relations discouraging capital investments, lowering socio-economic status and deterring growth and decline in value and sales.

1.3.5 Temperature

Temperature is one of the most important parameters. *Temperature is a catalyst, a depressant, an activator, a restrictor, a stimulator, a controller and a killer*. It affects the self purification of streams. Rise in temperature enhances toxicity of poisons and intensity of odour besides changing the taste. Also increase in temperature causes growth of undesirable water plants and wastewater fungus. It influences the biological species present and their rates of biological activity. Temperature has an effect on most chemical reactions that occur in natural water systems. Temperature also has a pronounced effect on the solubilities of gases in water. Aerobic digestion ceases at a temperature greater than 50°C. At less than 15°C anaerobic digestion is affected as methane bacteria become inactive.

Temperature affects the reaction rates and solubility levels of chemicals. Most chemical reactions involving dissolution of solids are accelerated by increased temperatures. The solubility of gases, on the other hand, decreases at elevated temperatures.

1.4 CHEMICAL PARAMETERS

Total dissolved solids, alkalinity, hardness, fluorides, metals, organics and nutrients are chemical parameters of concern in water quality management.

1.4.1 Total Dissolved Solids (TDS)

Dissolved solids result mainly because of prolonged contact of water with the salts of different catchments. They may be of organic or inorganic origin . Inorganic substances are minerals and metals. Decay products of vegetable and animal origin give rise to organic matter. Dissolved salts may produce colour, taste and odour of which some are objectionable. Distilled water or rain water free from dissolved solids is preferred for industrial operations as steam production and manufacturing of soft drinks. Domestic water should be colourless, odourless but of agreeable taste. Presence of dissolved solids alone gives taste. However a concentration greater than 500 to 1000 mg/ℓ of dissolved salts may give rise to bitter taste and laxative effect.

1.4.2 Alkalinity

Alkalinity is the ability of water to neutralize acids. CO_3^{2-}, HCO_3^-, OH^-, $H SiO_3^-$, $H_2BO_3^-$, HPO_4^- and NH_3 which are quite common in atmosphere and soil contribute to alkalinity. These compounds result from the dissolution of mineral substances in the soil and atmosphere. Phosphates from detergents and fertilizers and insecticides of agricultural land may also cause alkalinity.

Alkalinity is classified as (i) hydroxide alkalinity or *caustic alkalinity* (ii) carbonate alkalinity and (iii) bicarbonate alkalinity. Hydroxide alkalinity occurring at a pH greater than 8.3 (generally above 10) causes bitter taste, affects the lacrimal fluid around the eye ball of swimmers, whereas bicarbonate alkalinity occurring below a pH of 8.3 (but above 4.5) mainly causes scale formation in boilers and incrustations in pipe lines.

1.4.3 Hardness

Waters which readily give lather with soap are soft waters. Those which do not readily give lather are hard waters. Hardness is due to dissolved divalent metallic cations as Ca^{++}, Mg^{++}, Fe^{++}, Mn^{++} and Sr^{++} and anions as bicarbonates, chlorides and sulphates of which the most abundant in natural waters are *Calcium* and *Magnesium*. Hence for all practical purposes, hardness is the sum of the calcium and magnesium ions. Carbonate hardness is due to bicarbonates of Calcium and Magnesium which can be easily removed by simple means as boiling and hence is called temporary hardness. Alkalinity alone causes carbonate hardness.

Noncarbonate hardness due to chlorides and sulphates of Calcium and Magnesium cannot be removed that easily and hence is called permanent hardness.

Greater soap consumption by hard waters is an economic loss. Lathering occurs only when all the hardness ions are precipitated and softened by the soap. Boiler scale formed because of carbonate hardness precipitation may cause considerable heat loss as the scale is an insulator.

Table 1.1: Classification of hardness

Nature of water	*Range of hardness*
Soft	0 – 75 mg/ℓ as $CaCO_3$
Moderately hard	75 – 150 mg/ℓ as $CaCO_3$
Hard	150 – 300 mg/ℓ as $CaCO_3$
Very hard	> 300 mg/ℓ as $CaCO_3$

1.4.4 Fluoride

It is an ingredient of igneous and sedimentary rocks. Fluoride is rarely found in appreciable quantities in surface waters but appears in certain ground waters. Concentrations of approximately 1 mg/ℓ in drinking water help to prevent dental cavities in children (*dental carries*). During the formation of permanent teeth, fluoride combines chemically with tooth enamel resulting in harder and stronger teeth that are more resistant to decay. Excessive intakes of fluoride can result in discolouration of enamel of teeth called *mottling* (Dental Fluorosis). Excessive dosages of fluoride can also result in fluorosis of bones and other skeletal abnormalities (Skeletal Fluorosis).

1.4.5 Inorganic Salts

Inorganic salts, which are present in most industrial wastes as well as in natural soils, render the water hard and make it undesirable for industrial, municipal and agricultural use. Salt laden waters deposit scales on municipal water distribution pipelines result in increase resistance to flow and lower the overall capacity of the pipes. Salts of nitrogen and phosphorous promote the growth of microscopic plant life (algae) resulting in *eutrophication* of lakes.

1.4.6 pH

pH is *potential Hydrogen* i.e., the negative logarithm of hydrogen ion concentration. It is an important quality parameter of both waters and wastewaters. The pH range suitable for the survival and nourishment of most biological life is quite narrow and critical i.e., 6.5 to 8.5. Extreme pH values are unfavourable for biological treatment.

1.4.7 Acids and Alkalies

Acids and alkalies discharged by chemical and other industrial plants make a stream undesirable not only for recreational uses as swimming and boating, but also for propagation of fish and other aquatic life. High concentrations of mineral acids lower the pH well below 4.5. Similarly extreme alkalinity causes eye irritation to swimmers.

1.4.8 Chlorides

Chlorides in natural water result from the leaching of chloride containing rocks and soils with which the water comes in contact and in coastal areas from sea water intrusion. In addition, agricultural, industrial and domestic wastewaters discharged into surface waters are a source of chlorides. Human excretions contain about 6 g of chlorides per person per day on average. Conventional methods of waste treatment do not remove chlorides.

1.4.9 Metals

All metals are soluble to some extent in water. Metals harmful in small concentrations are termed toxic. Calcium and Magnesium cause hardness. Iron concentrations of > 0.3 mg/ℓ and Manganese > 0.05 mg/ℓ may cause colour problems. Some bacteria use iron and manganese compounds as an energy source and the resulting *slime growth* may produce taste and odour problems.

Toxic metals: Toxic metals are Arsenic, Barium, Cadmium, Chromium, Lead, Mercury and Silver. Cumulative toxins are Arsenic, Cadmium, Lead and Mercury.

1.4.10 Heavy Metals

Trace quantities of many metals, such as Nickel, Manganese, Chromium, Cadmium, Zinc, Copper and Iron find their way into water. Some of these metals in very small concentrations are necessary for the growth of biological life, but harmful in higher concentrations.

1.4.11 Nutrients

Nutrients are elements required to the growth and reproduction of plants and animals and aquatic flora and fauna.

1.4.12 Nitrogen

Nitrogen is a constituent of proteins, chlorophyll and many other biological compounds. Upon the death of plants or animals, complex organic matter is broken down to simple forms by bacterial decomposition. Proteins are converted to amino acids and further reduced to ammonia (NH_3). If oxygen is present, the ammonia is oxidized to nitrite (NO_2^-) and then to nitrate (NO_3^-). Other sources of nitrogen in aquatic systems include animal wastes, chemical wastewaters (particularly chemical fertilizers) and domestic wastewater discharges. Nitrite has a greater affinity for haemoglobin than oxygen and thus replaces oxygen in the blood complex. The body is denied essential oxygen and in extreme cases, the victim (baby less than 6 months old) suffocates. Because oxygen starvation results in a bluish discolouration of the body, nitrate poisoning has been referred to as the "blue baby" syndrome, although the correct term is "*methaemoglobinemia*".

1.4.13 Phosphorous

Phosphorous appears exclusively as phosphate (PO_4^{3-}) in aquatic environments. Phosphate is a constituent of soils and is used extensively in fertilizer to replace and/or supplement natural quantities on agricultural lands. Phosphate is also a constituent of animal waste and may become incorporated into the soil grazing and feeding areas. Runoff from agricultural areas is a major contributor of phosphates in surface waters. Municipal wastewater is another major source of phosphate in surface water.

1.4.14 Organics

Most natural organics consist of the decay products of organic solids, while synthetic organics are usually the result of industrial wastewater discharges or agricultural runoffs.

1.4.15 Proteins

Proteins are the principal constituents of the animal origin. They occur to a lesser extent in plants. All raw animal and plant food stuffs contain proteins. Proteins are complex in chemical structure and unstable, being subjected to many forms of decomposition. Some are soluble in water and others insoluble. All proteins contain carbon along with hydrogen, nitrogen and oxygen, which is common to all organic substances. When proteins are present in large quantities extremely foul odours are produced because of their decomposition.

1.4.16 Carbohydrates

Widely distributed in nature are carbohydrates like sugars, starches, cellulose and wood fiber, all found in wastewater. Carbohydrates contain carbon, hydrogen and oxygen. Some carbohydrates, notably the sugars, are soluble in water; others such as the starches are insoluble. The sugars tend to decompose, the enzymes of certain bacteria and yeasts set up fermentation with the production of alcohol and carbondioxide. The starches, on the other hand, are more stable but are converted into sugars by microbial activity as well as by dilute mineral acids.

1.4.17 Fats, Oil and Grease

Fats and oils are the third major component of food stuffs. The term "grease" as commonly used, includes the fats, oils, waxes and other related constituents found in wastewater. Fats and oils are compounds (esters) of alcohol or glycerol with fatty acids. Fats and oils are contributed to domestic sewage in butter, vegetable fats and oils. Fats are also commonly found in meats, in seeds, in nuts and in certain fruits. Oils reach the sewer in considerable volumes from soap manufacturing units, from garages and street washes. These interfere with biological action of microbes and cause maintenance problem of sewers and treatment plants.

1.4.18 Phenols

Phenols and other trace organic compounds are also important constituents of wastewater. Phenols cause taste problems in drinking water, particularly when the water is chlorinated. They are produced primarily by industrial operations and find their way to surface waters in wastewater discharges that contain industrial wastes.

1.4.19 Pesticides and Agricultural Chemicals

Trace organic compounds, such as pesticides, herbicides and other agricultural chemical are toxic to most life forms and cause contamination of surface waters.

1.4.20 Dissolved Oxygen

The living organisms are dependent upon oxygen in one form or another to maintain the metabolic processes that produce energy for growth and reproduction. All the gases of atmosphere dissolve in water to some degree. Both nitrogen and oxygen are poorly soluble. The solubility of atmospheric oxygen in fresh waters ranges from 14.6 mg/ℓ at 0°C to about 7.6 mg/ℓ at 30°C at 1 atmospheric pressure. Dissolved salts of water reduce the solubility of oxygen so also impurities in water.

1.4.21 Biochemical Oxygen Demand (BOD)

Biochemical oxygen demand (BOD) is defined as the amount of oxygen required by microorganisms to stabilize decomposable organic matter at a particular time and temperature. BOD test is widely used to determine the pollutional strength of domestic and industrial wastes in terms of the oxygen that they require to deliver end products as CO_2 and H_2O. The BOD test is essentially a bioassay procedure involving the measurement of oxygen consumed by living organisms (mainly bacteria) while utilizing the organic matter present in the waste as carbohydrates, proteins and fats. It is standardized at 20°C the usual peak temperature of summer of London where the test originated. Theoretically infinite time is required for complete biological oxidation of organic matter of domestic sewage but for all practical purposes, the reaction may be considered to be completed in about (90–95%) 20 days. In case of domestic wastewaters, it has been found that the 5* day BOD value is about 70 to 80% of the ultimate (I stage – carbonaceous) BOD. This is fairly a higher percentage and hence 5 day (at 20°C) values are used for many considerations and unless otherwise mentioned BOD means only 5 day 20°C value only. Nitrifying bacteria is the bacteria which oxidize proteinous matter for energy. The nitrifying bacteria are usually pre sent in relatively small numbers in untreated domestic wastewater. Their reproductive rate at 20°C is such that their populations do not become sufficiently large to exert an appreciable demand for oxygen until about 8 to 10 days. Once the organisms become established, they oxidize nitrogen in the form of ammonia to nitrates and nitric acids in amounts that induce serious error in BOD estimation.

Estimation of BOD:

1. The most widely used parameter of organic pollution applied to both wastewater and surface water is the 5 day BOD (BOD_5) at 20°C.
2. BOD determination involves the measurement of the dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter.
3. The reason is that BOD test results are now used (i) to determine the approximate quantity of oxygen that will be required to biologically stabilize the organic matter present (ii) to determine the extent of waste treatment facilities (iii) to measure the efficiency of the biological treatment processes.
4. In the standard BOD test, a small sample of the wastewater to be tested is placed along with dilution water in a BOD bottle (300 mℓ). The dissolved oxygen concentration of the mixture in the bottle is measured. The bottle is incubated for 5 days at 20°C and the dissolved oxygen concentration is measured again. The BOD of the sample is the decrease in the dissolved oxygen concentration values, expressed in mg/ℓ; divided by the decimal fraction of the sample used.

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* Note: All rivers flow (from origin to the end i.e., before joining the sea) for less than 5 days in Great Britain where the BOD test originated.

Limitations of BOD test:

1. A minimum DO depletion of 2 mg/ℓ is desirable.
2. The final DO should never be 0 mg/ℓ. (as it is impossible to know when the entire DO content got fully depleted i.e., within 1, 2, 3, 4 or 5 days) and preferably it should not be less than 1 mg/ℓ.

1.4.22 Chemical Oxygen Demand (COD)

COD may be defined as the amount of (dissolved) oxygen required to oxidize and stabilize (organic and inorganic content of) the sample solution. It is used to measure the content of oxidizable organic as well as inorganic matter of the given sample of waters. The oxygen equivalent is measured by using a strong chemical oxidizing agent in an acidic medium. Potassium dichromate has been found to be excellent for this purpose. The COD test is used with advantage to measure the oxidizable matter in industrial and municipal wastes containing compounds that are toxic to biological life (which is not possible with BOD test). The COD of a waste is higher than the BOD because more compounds are chemically oxidized in a short interval of time. It had the advantage of getting completed in 3 hours compared to 5 days of the BOD test. It is possible to correlate BOD and COD. BOD_5/COD ratio is called *Biodegradability Index* and varies from 0.4 to 0.8 for domestic wastewaters.

If BOD/COD is > 0.6 then the waste is fairly biodegradable and can be effectively treated biologically.

If BOD/COD ratio is between 0.3 and 0.6, then seeding is required to treat it biologically.

If BOD/COD is < 0.3 then it cannot be treated biologically.

1.4.23 Biodegradable Organics

Biodegradable material consists of organics that can be utilized as food by microorganisms. In dissolved form, these materials usually consist of starches, fats, proteins, alcohols, acids, aldehydes and esters. They may be the end product of the initial microbial decomposition of plant or animal tissue or they may result from domestic or industrial wastewater discharges. Microbial metabolism may be by oxidation or by reduction.

In aerobic (oxygen present) environments, the end products of microbial decomposition are stable and acceptable compounds associated with oxygen as CO_2, NO_3 etc. Anaerobic (oxygen absent) decomposition results in odourous and objectionable end products as H_2S. The oxygen demanding nature of biodegradable organics represents their pollutional strength.

The amount of oxygen consumed during microbial utilization of organics is called the Biochemical Oxygen Demand (BOD). The BOD is measured by determining the oxygen consumed from a sample placed in an air tight 300 mℓ BOD bottle incubated at 20°C for 5 days.

$$\text{The BOD of a diluted sample} = \frac{DO_I - DO_F}{r}$$

Where DO_I and DO_F are the initial and final dissolved oxygen concentration (mg/ℓ) and r is the dilution ratio (a fraction).

The BOD of sanitary sewage may range from 50 to 200 mg/ℓ. A minimum of three dilutions are prepared to cover this range. The sample is placed in the standard BOD bottle and is then diluted to 300 mℓ with organic free, oxygen saturated distilled water.

Problem

The following data were obtained in a BOD test. Find the average BOD of the wastewater.

S.No.	Wastewater (mℓ)	DO_0 (mg/ℓ)	DO_5 (mg/ℓ)	O_2 used (mg/ℓ)	(Dilution ratio)	BOD_5^{20} (mg/ℓ)
1	5	9.0	6.7	2.3	5/300 = 0.0167	138
2	10	9.2	4.5	4.7	10/300 = 0.033	142
3	15	8.2	6.9	1.3	15/300 = 0.05	260
4	20	7.9	0.5	7.4	20/300 = 0.067	110

Of these values the third value cannot be accepted, as the minimum depletion of DO of 2.0 mg/ℓ is not satisfied. Therefore the third value is discarded.

For the fourth reading the final DO is less than 1.0 mg/ℓ and hence this value is also discarded. Therefore acceptable values of BOD 138 mg/ℓ and 142 mg/ℓ.

The average BOD of the wastewater is $\frac{138 + 142}{2} = 140$ mg/ℓ

1.4.24 Mathematical Formulations of the BOD

In a BOD test, the rate at which organics are utilized by microorganisms is assumed to be a first order reaction. The rate at which organics utilized is proportional to the amount of oxidizable organic matter available at that time and temperature.

Mathematically, this can be expressed as follows:

Rate of deoxygenation is proportional to organic matter still present (to get oxidized) $\frac{dL}{dt} = -k^1 L$

where L is the organic matter remaining to get oxidized at a time t, and k^1 is a deoxygenation constant (at 20°C ≈ 0.1 per day.)

$$\frac{dL}{L} = -k^1\, dt$$

Taking integrals on both sides

$$\int_{L}^{L_t} \frac{dL}{L} = -k^1 \int_0^t dt$$

$$\log_e \frac{L_t}{L_o} = -k^1 t$$

$$L_t = L_o e^{-k^1 t} \text{ or } L_t = L_o\, 10^{-kt}$$

The term L_o in this equation represents the total oxygen equivalent to the organics at time = o, while L_t represents the amount remaining at time = t (decays exponentially). The oxygen equivalent remaining is not the parameter of primary importance. However, the amount of oxygen used in the consumption of the organics, the BOD_t, can be found from the L_t value.

If L_o is the oxygen equivalent of the total mass of organics, then the difference between the value L_o and L_t is the oxygen equivalent consumed or the BOD exerted.

BOD exerted = Ultimate BOD – BOD remaining at that time

$$y_t = L_o - L_t = L_o - L_o e^{-k^1 t} = L_o(1 - e^{-k^1 t}) = L_o(1 - 10^{-kt})$$

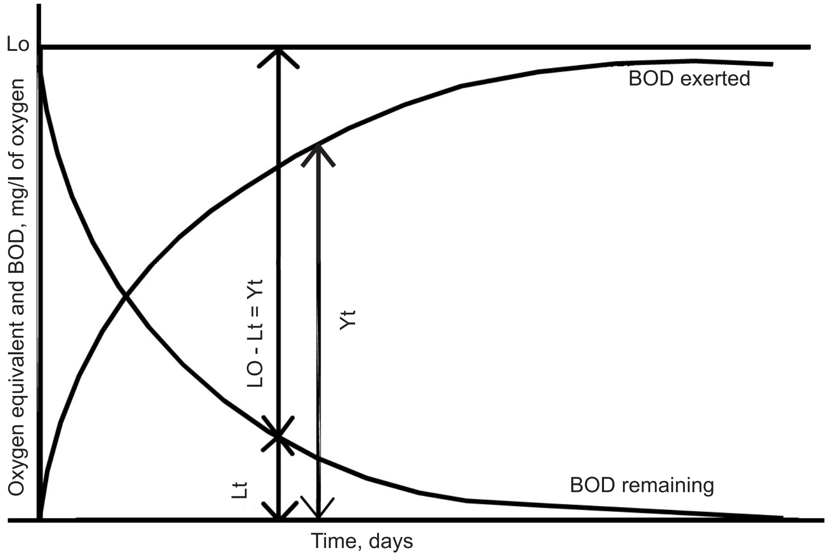

Fig. 1.3: BOD and oxygen equivalent relationships

where y_t represents the BOD_t of the wastewater

The deoxygenation constant (k^1 or k) is not exactly a constant but varies with temperature.

Deoxygenation constant at a temperature T,

$$k_T = k_{20}\,(1.047)^{T-20}$$

Similarly Ultimate BOD or Initial Oxygen Equivalent L_o also varies with temperature.

$$[L_o]_T = [L_o]_{20}\,(0.02T + 0.6)$$

Problems

1. If the 3 day, 20°C BOD of a sample is 300 mg/ℓ, what is its ultimate BOD?

 3 day BOD at 20°C, y_t = 300 mg/ℓ

 $y_t = L_o\,(1 - 10^{-kt})$

 where y_t = 300 mg/ℓ, t = 3 days and k_{20} = 0.1/day

 $300 = L_o\,(1 - 10^{-0.1 \times 3})$

 L_o = 601.428 mg/ℓ

2. If the 5 day BOD at 37°C is 200 mg/ℓ and if the rate of deoxygenation is 0.17/day, what is the ultimate BOD and BOD remaining after 5 days?

 5 day BOD at 37ºC, y_t = 200 mg/ℓ

 $y_t = L_o\,(1 - 10^{-kt})$

 where y_t = 200 mg/ℓ, t = 5 days and k_{20} = 0.17/day

 $200 = L_o\,(1 - 10^{-0.17 \times 5})$

 L_o = 232.9 mg/ℓ

 Ultimate BOD = 232.9 mg/ℓ.

 BOD remaining at any time t, $L_t = L_o\,(10^{-kt})$

 $L_t = 232.9\,(10^{-0.17 \times 5})$ = 32.9 mg/ℓ

BOD remaining after 5 days = 32.9 mg/ℓ.

Or

$y_t = L_o - L_t$

$200 = 232.9 - L_t$

$L_t = 32.9$ mg/ℓ

3. If the 5 day BOD of a sample is 276 mg/ℓ and ultimate BOD at the same temperature is 380 mg/ℓ, at what rate the waste is oxidized?

5 day BOD, $y_t = 276$ mg/ℓ

Ultimate BOD (L_o) = 380 mg/ℓ

$y_t = L_o (1 - 10^{-kt})$

where $y_t = 276$ mg/ℓ, $t = 5$ days and k_T =?

$276 = 380\ (1 - 10^{-k \times 5})$

$1 - 10^{-k \times 5} = 276/380 = 0.726$

$10^{-5k} = 0.2736$

$10^{5k} = 3.6538$

$5k = \log_{10}(3.6538)$

$5k = 0.56275$

$k = 0.1125$/day

4. If the 3 day BOD at 15°C = 425 mg/ℓ, what will be its 7 day BOD at 15°C?

3 day BOD (y_t) at 15°C = 425 mg/ℓ

Assume $k^1 = 0.23$/day

$k^1_{15} = k^1_{20}\ (1.047)^{T-20}$

$k^1_{15} = (0.23)(1.047^{15-20}) = 0.182$/day

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

where $y_t = 425$ mg/ℓ, $k^1 = 0.182$/day and $t = 3$ days

$425 = L_o\ (1 - e^{-0.182 \times 3})$

$425 = L_o\ (1 - 0.579)$

$[L_o]$ at 15°C = 1010.13 mg/ℓ

$y_t = L_o (1 - e^{-k.t})$

$y_7 = 1010.13\ (1 - e^{-0.182 \times 7})$

7 day BOD at 15°C (y_7) = 727.585 mg/ℓ

5. If the 3 day, 15°C BOD is 200 mg/ℓ, what will be its 7 day BOD at 25°C?

3 day BOD (y_t) at 15°C = 200 mg/ℓ

7 day BOD (y_t) at 25°C = ?

Assume $k = 0.1$/day

$k_{15} = k_{20}\ (1.047)^{T-20} = (0.1)(1.047^{15-20}) = 0.07948$/day

$$k_{25} = (0.1)(1.047^{25-20}) = 0.1258/\text{day}$$

$$y_t = L_o(1 - 10^{-kt})$$

where $y_t = 200$ mg/ℓ, $k = 0.07948$/day and $t = 3$ days

$$200 = L_o\,(1 - 10^{-0.07948 \times 3})$$

$$200 = L_o\,(1 - 0.5775)$$

$$[L_o] \text{ at } 15°\text{C} = 473.384 \text{ mg/ℓ}$$

$$[L_o]_T = [L_o]_{20}\,(0.02T + 0.6)$$

$$T = 15°\text{C}$$

$$[L_o]_{15} = [L_o]_{20}\,(0.02 \times 15 + 0.6)$$

$$474.384 = [L_o]_{20}\,(0.9)$$

$$[L_o]_{20} = 527.09 \text{ mg/ℓ}$$

$$[\text{L}_\text{o}]_\text{T} = [\text{L}_\text{o}]_{20}\,(0.02\text{T} + 0.6)$$

where $T = 25°\text{C}$

$$[L_o]_{25} = [L_o]_{20}\,(0.02 \times 25 + 0.6)$$

$$[L_o]_{25} = 527.09\,(1.1) = 579.8 \text{ mg/ℓ}$$

$$y_t = L_o(1 - 10^{-kt})$$

where $[L_o]_{25} = 579.8$ mg/ℓ and $k_{25} = 0.1258$/day

$$y_7 \text{ at } 25°\text{C} = [L_o]_{25}\,(1 - 10^{-k\text{t}})$$

$$y_7 \text{ at } 25°\text{C} = 579.8\,(1 - 10^{-0.1258 \times 7}) = 579.8\,(0.8683)$$

$$7 \text{ day BOD at } 15°\text{C } (y_7) = 503.47 \text{ mg/ℓ}$$

Non-biodegradable organics: Some organic materials are resistant to biological treatment. Tannic and lignin acids, cellulose and phenols are often found in natural water systems. Measurement of non-biodegradable organics is usually done by the chemical oxygen demand (COD) test. Non-biodegradable organics may also be estimated from a total organic carbon (TOC) analysis. Both COD and TOC measure the biodegradable fraction of the organics, so the BOD_u must be subtracted from the COD or TOC to quantify the non-biodegradable organics (Refractories).

1.5 BIOLOGICAL CHARACTERISTICS

The principal groups of microscopic flora and fauna found in surface water and wastewater are classified as *protists* which mainly comprise Bacteria (plants), Algae (plants), Fungi (plants) and protozoa (animals). Rotifers and worms to macroscopic crustaceans are the others. Pathogenic organisms found in wastewater may be discharged by human beings who are infected with disease or who are carriers of a particular disease.

From the perspective of human use and consumption, the most important biological organisms in water are pathogens capable of infecting, or of transmitting diseases to humans. These organisms are not native to aquatic systems and usually require an animal host for growth and reproduction. They can however be transported by natural water systems, thus becoming a temporary member of the aquatic community. Many species of pathogens are able to survive in water and maintain their infectious capabilities for significant periods of time. These waterborne pathogens include species of bacteria, viruses, protozoa and helminthes (parasitic worms).

1.5.1 Bacteria

The word bacteria comes from the Greek word meaning "rod" or "staff" a shape characteristic of most bacteria. Bacteria are single cell microorganisms, usually colourless and are the lowest form of plant life capable of synthesizing protoplasm from the surrounding environment. In addition to the rod shape (*bacilli*), bacteria may also be spherical (*cocci*), comma shaped (*vibrio*), or spiral shaped (*spirilla*). Gastrointestinal disorders are common symptoms of most diseases transmitted by waterborne pathogenic bacteria.

1.5.2 Viruses

Viruses are the smallest biological structure known to contain all the genetic information necessary for their own reproduction. It is the demarcation between living and non-living objects. Viruses require a host to live and to multiply. Waterborne viral infection usually involves disorders of the nervous system rather than those of the gastrointestinal tract. Waterborne viral pathogens are *Poliomyelitis* (Polio) and *infectious hepatitis* (yellow jaundice).

1.5.3 Protozoa

The lowest form of animal life, protozoa, are unicellular organisms more complex in their functional activity than bacteria or viruses. Protozoal infections are usually characterized by gastrointestinal disorders as amoebic dysentery.

Table 1.2: Important pollutants in wastewater

S.No.	*Pollutants*	*Significance*
1.	Suspended solids	Development of sludge deposits and anaerobic conditions.
2.	Organics (Biodegradable)	Principally carbohydrates, proteins and fats-starving products (contribute BOD).
3.	Refractory organics (Non-biodegradable)	Principally phenols, agricultural fertilizers and pesticides – cannot be removed by conventional wastewater treatment techniques, may harm biological community and hence biological treatment may be hampered.
4.	Pathogens	Waterborne diseases (cholera, typhoid, dysentery) are transmitted by the pathogenic organisms in wastewater.
5.	Nutrients	Phosphates and Nitrates contribute to *Eutrophication* of static water bodies as lakes and ponds.
6.	Dissolved inorganic solids	Excess salts of sodium and calcium etc. are to be removed to render the water fit for domestic and industrial use.
7.	Heavy metals	Nickel, Manganese, Lead, Chromium, Cadmium, Zinc, Copper, Iron and Mercury in higher concentrations are detrimental for aquatic life.

1.6 DISPOSAL OF WASTEWATER

Methods of disposal:

(i) Natural Methods: Disposal by Dilution

(ii) Artificial Methods: Primary & Secondary Treatment.

1.6.1 Disposal by Dilution

Disposal by dilution is the process whereby the treated wastewater or effluent from treatment plants is discharged either in large static water bodies (such as lake or sea) or in moving water bodies such as rivers or streams. The discharged wastewater or effluent is purified, in due course of time by the so-called Self-purification Process of Natural Waters.

After conveying the wastewater through sewers, it is disposed of, either after complete treatment, primary treatment or even without any treatment. Before being discharged into natural streams the wastewater preferably should satisfy the following criteria:

i. Suspended solids ($\ngtr$50 mg/ℓ)
ii. BOD ($\ngtr$150 mg/ℓ)
iii. Free from oils and greases and should be free from bigger settleable solids.

The stream should satisfy the following requirements:

i. The flow $\nless$ 110 ℓ/s/1000 people.
ii. It is saturated with DO to prevent fish kills.

After discharge by dilution the combined flow should have a minimum dissolved oxygen of 3 mg/ℓ any time thereafter.

$$\text{Minimum dilution ratios} = \frac{\text{Quantity of fresh water flow of the river}}{\text{Quantity of sewage discharged}}$$

Table 1.3: Dilution ratios

Dilution ratio	*Characteristics of wastewater before dilution*
> 500 times	Sewage with no treatment
300 – 500	Suspended solids < 150 mg/ℓ Preliminary treatment is a must
150 – 300	Suspended solids < 60 mg/ℓ

1.7 SELF-PURIFICATION OF NATURAL STREAMS

When the wastewater or the effluent is discharged into a natural stream, the organic matter is converted into ammonia, nitrates, sulphates, carbon dioxide etc. by bacteria. In this process of oxidation, the dissolved oxygen content of natural water is utilized. Due to this, deficiency of dissolved oxygen is created.

As the excess organic matter is stabilized, the normal cycle will be in a process known as Self-purification wherein the dissolved oxygen is replenished by its reaeration by atmospheric oxygen of wind.

Actions Involved in Self-purification:

1. *Dilution:* When wastewater is discharged into the receiving water, dilution takes place due to which the concentration of organic matter is reduced and the potential nuisance of sewage is also reduced. When the dilution ratio is quite high, large quantities of DO are available which will accelerate the chances of purification and reduce pollution effects. Aerobic condition will always exist because of higher dilution. This will however, not be there if dilution ratio is small, i.e., when large quantities of oxygen demanding effluent is discharged into a small stream supplementing little oxygen or aeration.

2. *Dispersion due to Currents:* Self-purification of stream largely depends upon currents, (as rapids, whirlpools, waterfalls and turbulent flow) which will readily disperse the wastewater in the stream, preventing local accumulation of pollutants.
   High velocity accelerates reaeration and reduces the concentration of pollutants. High velocity improves reaeration, reduces the time of recovery, though length of stream affected by the wastewater is increased.
3. *Sedimentation:* If the stream velocity is lesser than the scour velocity of particles, sedimentation will take place, which will have two effects.
   (i) The suspended solids, which contribute largely the oxygen demand, will be removed by settling and hence water quality of the downstream is improved.
   (ii) Due to settled solids, *Anaerobic* decomposition may take place.
4. *Temperature:* At low temperature, the activities of bacteria is low and hence rate of decomposition will also be slow, though DO will be more because of increased solubility of oxygen in water. At high temperatures, the self-purification takes lesser time, though the quantity of DO will be less.
5. *Sunlight:* Sunlight helps *photosynthesis* of certain aquatic plants (as algae) to absorb carbon dioxide and give out oxygen, thus accelerating self-purification. Sunlight acts as a *disinfectant*.

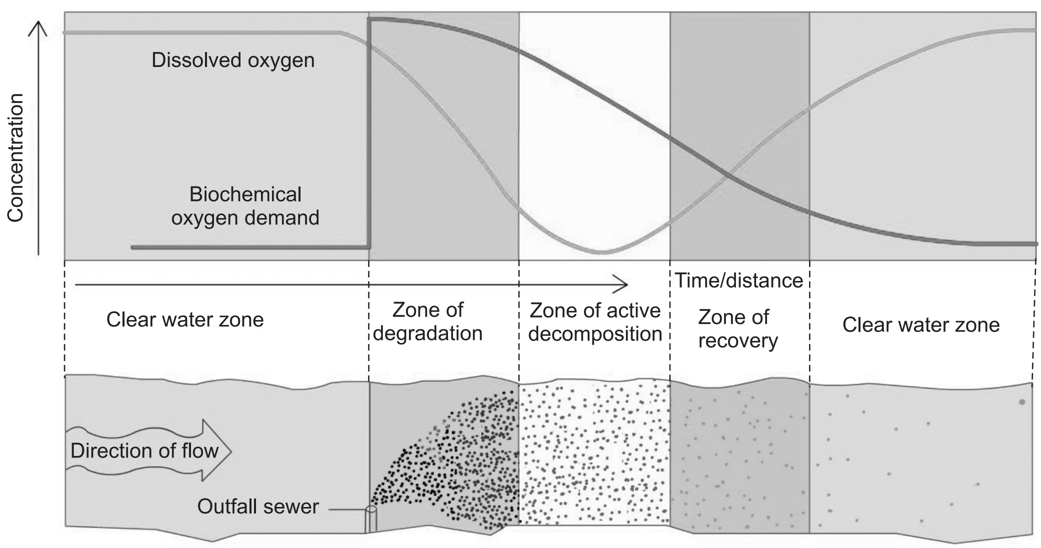

Fig. 1.4: Zones of pollution in streams (Oxygen sag analysis)

Zones of Pollution in the Streams: The Self-purification process of a stream polluted by the wastewater or effluent discharged into it can be divided into the following four zones:

(i) Zone of Degradation (Decomposition zone)
(ii) Zone of Active Decomposition (Septic zone)
(iii) Zone of Recovery
(iv) Zone of Clear Water

Zone of Degradation: This zone is situated just below the outfall sewer while discharging its contents into the stream. In this zone, water is rendered dark and turbid, having the formation of sludge deposits at the bottom. The DO is reduced to 40% of the saturation values. There is an increase in CO_2 content, and *reaeration* is much slower than *deoxygenation*. (Though conditions are unfavourable for aquatic life, fungi at shallow depths and bacteria at greater depths breed along with small worms, which 'work over' and stabilize the sewage and sludge). The decomposition of solid matter takes place in this zone and anaerobic decomposition prevails over aerobic decomposition.

Zone of Active Decomposition: This zone is just the continuation of degradation zone and is marked by heavy pollution. Water in this zone becomes grayish and darker than the previous zone. The DO concentration in this zone falls down to zero. Active anaerobic organic decomposition takes place, with the evolution of Methane (CH_4), Hydrogen sulfide (H_2S), Carbon dioxide (CO_2) and Nitrogen (N_2) bubbling to the surface with masses of sludge forming black scum. Fish life is absent in this zone but bacterial flora will flourish with the presence of anaerobic bacteria at upper end and aerobic bacteria at the lower end. However, near the end of this zone, as the decomposition slackens, reaeration sets in and DO again rises to its original level of 40% (of saturation value).

Zone of Recovery: In this zone, the process of recovery starts, from its degraded condition to its former purer condition. The stabilization of organic matter takes place in this zone. Due to this, most of the stabilized organic matter settles as sludge, BOD falls and DO content rises above 90% value. Near the end of the zone, fungi wave out and algae reappear.

Clear Water Zone: In this zone, the natural condition of stream is restored with the result that
(i) Water becomes clearer and attractive in appearance.
(ii) DO rises to the saturation level, and BOD drops to the lowest value.
(iii) Oxygen balance is attained.

1.8 OXYGEN SAG ANALYSIS

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

The normal saturation DO value for fresh water depends upon the temperature, and its value varies from 14.62 mg/ℓ at 0°C to 7.63 mg/ℓ at 30°C. (at normal atmospheric pressure).

At the point where wastewater is discharged into the stream, the DO content of the stream may be equal to the saturation DO or less. If less, it is termed as initial oxygen deficit D_o.

$$D_o = \text{Saturated DO} - \text{Actual DO}$$

At this stage, when the wastewater with an initial BOD load L_o is discharged into the stream, the DO content of the stream starts depleting and the oxygen deficit D increases initially. The variation of oxygen deficit D along the length of the stream is depicted by the Oxygen Sag Curve as shown in Fig 1.4 .

The major point of interest in the oxygen sag analysis is the point of minimum DO or the point of maximum deficit. The maximum or critical deficit, labeled as D_c occurs at the inflection point of the oxygen sag curve (DO content increase thereafter).

Deoxygenation and Reaeration Curves

When the wastewater (pollution load) is discharged into the stream, the DO content of 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) of the reaction. The variation or depletion of DO content of the stream *versus* time is depicted by the Deoxygenation curve in the absence of aeration. The ordinates below the Deoxygenation curve indicate the oxygen still remaining in the natural stream.

Though the DO content of the stream is gradually consumed due to the pollutional (BOD) load, atmosphere supplies oxygen continuously to the water through the process of reaeration. In other words, along with deoxygenation, reaeration also continuously takes place.

The rate of *Reaeration* depends upon

(i) depth of water in the stream (rate is more at shallow depths)
(ii) velocity of flow in the stream (rate is more for more velocity)
(iii) oxygen deficit below saturation DO (more the deficit rapid is the rate of reaeration)
(iv) temperature of water.

Deoxygenation in Rivers

The DO in rivers and streams is depleted by the bacterial oxidation of the suspended and dissolved organic matter discharged to them by both natural and man-made sources and by the oxygen demand of sludge and benthic deposits.

Reaeration in Rivers

The sources of oxygen replenishment in a river are reaeration from the atmosphere and photosynthesis of aquatic plants as algae. The amount of reaeration is proportional to the dissolved oxygen deficiency. The amount of oxygen supplied by photosynthesis is a function of the size of the algal population and the amount of sunlight reaching the algae.

Oxygen Sag curve in a polluted stream is given by Streeter and Phelp's equation:

$$D_t = \frac{kL_o}{k_2 - k}[10^{-kt} - 10^{-k_2 t}] + D_o 10^{-k_2 t}$$

DO deficit (D_t) = saturated DO – actual DO (mg/ℓ)

D_t = DO deficit in the stream after time t from the instant of pollution or at distance $x = ut$

L_o = initial BOD of stream at $t = 0$ (mg/ℓ)

D_o = initial DO deficit at $t = 0$ (mg/ℓ)

k = BOD reaction rate constant (Deoxygenation constant) (per day)

k_2 = DO deficit reduction rate constant (Reoxygenation constant) (per day)

u = mean velocity of the stream (m/d)

t = time (day)

Critical oxygen deficit and time can be calculated by

$$D_C = \frac{k}{k_2} L_o 10^{-k\,t_c}$$

$$t_C = \frac{1}{k_2 - k} \ln\left[\frac{k_2}{k}\left(1 - \frac{D_o(k_2 - k)}{k L_o}\right)\right]$$

Problem

A wastewater of 5.0 m^3/sec is discharged into a river of flow 50 m^3/sec. The ultimate BOD of wastewater is 200 mg/ℓ and DO is 1.5 mg/ℓ. The river water has a BOD of 3 mg/ℓ and DO of 7 mg/ℓ. The reaeration coefficient of the river water is 0.2/day and BOD decay coefficient is 0.4/day. The river has a cross-sectional area of 200 m^2 and the saturated DO concentration of the river water is 8 mg/ℓ.

(a) At a downstream point of 10 km calculate the DO of the mixture.
(b) At which point the DO is a bare minimum.

Given

Flow rate of river water = 50 m^3/sec

Wastewater flow rate = 5 m^3/sec

BOD of river water = 3 mg/ℓ

BOD of wastewater = 200 mg/ℓ

$$\text{BOD of the mixture} = \frac{(50)(3)+(5)(200)}{50+5} = 20.91 \text{ mg/}\ell$$

DO of the river water = 7 mg/ℓ

DO of the wastewater = 1.5 mg/ℓ

$$\text{DO of the mixture} = \frac{(50)(7)+(5)(1.5)}{50+5} = 6.5 \text{ mg/}\ell$$

Initial oxygen deficit = Saturated DO – Initial DO of the mixture

D_o = 8.0 – 6.5 = 1.5 mg/ℓ

$$\text{Velocity of flow} = \frac{\text{Rate of flow}}{\text{Area of cross-section}} = \frac{50+5}{200} = 0.275 \text{ m/s}$$

Length of flow = 10 km = 10000 m

$$\text{Time} = \frac{\text{Distance}}{\text{Velocity}} = \frac{10000}{0.275} = 36363.63\ s = 0.42\ d$$

Deoxygenation constant (k) = 0.4 /day

Reaeration constant (k_2) = 0.2 /day

Oxygen Sag curve in a polluted stream is given by Streeter and Phelp's equation:

$$D_t = \frac{kL_o}{k_2 - k}[10^{-kt} - 10^{-k_2 t}] + D_o 10^{-k_2 t}$$

$$D_t = \frac{(0.4)(20.91)}{(0.2-0.4)}\left[10^{-(0.4)(0.42)} - 10^{-(0.2)(0.42)}\right] + (1.5)(10^{-(0.2)(0.42)})$$

$$D_t = \frac{8.364}{-0.2}[0.6792 - 0.8241] + (1.5)(0.8241)$$

D_t = 7.289 mg/ℓ

$$t_C = \frac{1}{k_2 - k} \ln\left[\frac{k_2}{k}\left(1 - \frac{D_o(k_2 - k)}{k\,L_o}\right)\right]$$

$$t_C = \frac{1}{0.2 - 0.4} \ln\left[\frac{0.2}{0.4}\left(1 - \frac{(1.5)(0.2 - 0.4)}{(0.4)(20.91)}\right)\right]$$

$$t_C = (-5)\ \ln\left[0.5\left(1 - \frac{(-0.3)}{8.364}\right)\right]$$

t_C = (–5) ln[0.5)(1.0358)]

t_C = (–5) (–0.65797) = 3.289 days

Distance = Velocity × t_c = (0.275 × 3.289 × 60 × 60 × 24)/(1000) = 78.15 km

Problem

A city discharges 1.25 m^3/s of wastewater into a stream whose minimum rate of flow is 8.0 m^3/s. The velocity of the stream is about 3.0 km/h. The temperature of the wastewater is 20°C and that of the stream is 15°C. The 20°C BOD_5 of the wastewater is 250 mg/ℓ and that of the stream is 2 mg/ℓ. The wastewater contains no dissolved oxygen, but the stream is flowing with saturated DO concentration of 9.2 mg/ℓ. Saturated DO at 15°C is 10.2 mg/ℓ. At 20°C, deoxygenation constant (k^1) is estimated to be 0.3 per day and reaeration constant ($k_2{}^1$) is 0.7 per day. Determine the critical oxygen deficit and its location. Also estimate the 20°C BOD_5 of a sample taken at the critical point. Use the temperature coefficients of 1.135 for k^1 and 1.024 for $k_2{}^1$.

Given

Flow rate of river water = 8 m^3/sec

Wastewater flow rate = 1.25 m^3/sec

BOD of river water = 2 mg/ℓ

BOD of wastewater = 250 mg/ℓ

$$\text{BOD of the mixture} = \frac{(8)(2) + (1.25)(250)}{8 + 1.25} = 35.51 \text{ mg/ℓ}$$

DO of the river water = 9.2 mg/ℓ

DO of the wastewater = 0.0 mg/ℓ

$$\text{DO of the mixture} = \frac{(8)(9.2) + (1.25)(0)}{8 + 1.25} = 7.95 \text{ mg/ℓ}$$

$$L_o \text{ of the mixture} = \frac{35.51}{1 - e^{-(0.3)(5)}} = \frac{35.51}{1 - 0.223} = 45.71 \text{ mg/ℓ}$$

Initial oxygen deficit = Saturated DO – Initial DO of the mixture

D_o = 10.2 – 7.95 = 2.25 mg/ℓ

Temperature of the river water = 15°C

Temperature of the wastewater = 20°C

$$\text{Temperature of the mixture} = \frac{(8)(15)+(1.25)(20)}{8+1.25} = 15.7°\text{C}$$

Correct the rate constants to 15.7°C

Deoxygenation constant (k^1) at 20°C = 0.3/day

Temperature coefficient for k^1 = 1.135

$k^1 = (0.3)(1.135)^{15.7-20} = 0.174/\text{day}$

Reaeration constant (k_2^1) at 20°C = 0.7/day

Temperature coefficient for k_2^1 = 1.024

$k_2^1 = (0.7)(1.024)^{15.7-20} = 0.63/\text{day}$

$$t_C = \frac{1}{k_2^1 - k^1}\text{In}\left[\frac{k_2^1}{k^1}\left(1-\frac{D_o\left(k_2^1 - k^1\right)}{k^1 L_o}\right)\right]$$

$$t_C = \frac{1}{0.63-0.174}\ln\left[\frac{0.63}{0.174}\left(1-\frac{2.25(0.63-0.174)}{0.174(45.71)}\right)\right]$$

$$t_C = \frac{1}{0.456}\ln\left[3.62\left(1-\frac{2.25(0.456)}{7.953}\right)\right]$$

t_C = (2.193) ln [3.62(1 – 0.129)]

t_C = (2.193) ln (3.15302) = (2.193)(1.148) = 2.52 d

Distance $x_c = vt_c$ = (3.0 km/h)(24h/d)(2.52 d) = 181.44 km

$$\text{Oxygen deficit at } x_c = D_c = \frac{k^1}{k_2^1} L_o e^{-k^1 t_c}$$

$$D_c = \frac{0.174}{0.63}(45.71)\left(e^{-(0.174)(2.52)}\right)$$

$D_c = (12.624)(e^{-0.43848}) = 8.142$ mg/ℓ

Dissolved oxygen in stream at x_c = 10.2 – 8.142 = 2.058 mg/ℓ

Depending on the purity of its running water the streams are classified as follows:

Table 1.4: Classification of streams

Class	*Standard*	*Use*
A	without filtration < 50 B.coli/100 mℓ	Drinking water after chlorination
B	No visible sewage matter < 100 B.coli/100 mℓ	Bathing, Recreation and shellfish culture
C	DO $\nless$ mg/ℓ & preferable $\nless$ 5 mg/ℓ CO_2 (20 – 40 mg/ℓ)	Fishing
D	Absence of nuisance, odours, unsighty suspended solids, some DO present	Rough industrial use and irrigation

Discussion: Topics and Problems

1. Differentiate between "sewage" and "sewerage".
2. Define wholesomeness of water.
3. Define BOD.
4. Name any four water-borne diseases.
5. Give an account of physical and chemical properties of wastewater.
6. Why BOD content of the untreated wastewater is high?
7. Explain why BOD test is to be conducted for wastewaters.
8. In which case DO is more – sea water or fresh water?
9. Why the BOD test is done for 5 days at 20°C?
10. What are the zones of self-purification of streams?
11. Differentiate between a BOD test and a COD test. Can a COD test be used as a substitute for a BOD test? Justify your answer.
12. Write the advantages and limitations of BOD and COD tests.
13. Derive an expression for first stage BOD exertion. Why COD values are always higher than BOD values?
14. Comment on the treatability of waste whose COD is 35,000 ppm and BOD is 25,000 ppm.
15. If 3 mℓ of raw sewage has been diluted to 300 mℓ and the DO concentration of the diluted sample at the beginning of the BOD test was 8 mg/ℓ and 5 mg/ℓ after 5 day incubation at 20°C, find the BOD of raw sewage.
16. A sewage sample is found to have a BOD_5 of 250 mg/ℓ. If the rate constant is 0.15/d, estimate ultimate carbonaceous BOD of sewage.
17. Calculate BOD of sewage sample if the initial DO, final DO and dilution percentage are 10 mg/ℓ, 2 mg/ℓ and 1% respectively.
18. The following observations were made in the laboratory on 4% dilution of wastewater sample at 20°C. Calculate the 5 day BOD at 20°C of the sample and also the ultimate first stage BOD.

    DO of the aeration dilution water = 10 mg/ℓ

    DO of the original sample of wastewater = 1 mg/ℓ

    DO of the diluted sample after 5 days incubation at 20°C = 2 mg/ℓ

    Assume K_D = 0.1 per day

19. What is the ratio of 2.5 day 35°C BOD to the 5 day 20°C BOD?
20. A sample of sewage has 4-day 20°C BOD value of 60% of the final. Find the rate constant per day.
21. The one-day and two-day BOD values of a sewage sample are 90 mg/ℓ and 115 mg/ℓ respectively at 20°C. Calculate the five-day BOD at 30°C.
22. If the 3-day, 12°C BOD is 120 mg/ℓ, what will be its 7-day, 25°C BOD?
23. A sample of water from a stream is filled in a standard 300 mℓ BOD bottle and is found to have a DO of 14 mg/ℓ. After 5 day of incubation at 20°C, the DO in the bottle dropped to 6 mg/ℓ. What is the BOD_5 of stream? Comment on quality of water.
24. In a BOD test, the samples gave the following readings:

Sample	*Initial DO (mg/ℓ)*	*DO after 5 days of incubation*
P	7.8	6.6
Q	7.8	4.0
R	7.8	0.5

If the dilution ratio is 50, find the exact BOD of the sample.

25. The following results were obtained during a BOD test, when three samples A, B and C are taken of different dilutions. Find the average BOD of the wastewater.

Sample	*Waste water*	*Initial DO*	*Final DO*
A	5 mℓ	9.2	8.9
B	10 mℓ	9.1	4.7
C	15 mℓ	8.9	0.5

26. If a river water has a BOD of 5 mg/ℓ and the flow is 2000 litres per second, containing 6 mg/ℓ of dissolved oxygen, what will be the volume of an industrial effluent containing 300 mg/ℓ BOD, to be mixed so that the river water BOD does not increase beyond 10 mg/ℓ?
27. Sketch DO sag curve and describe the salient features.
28. Write the basic Streeter – Phelps equation to describe and predict the behaviour of polluted stream. From this equation, determine critical travel time and critical deficit.
29. The BOD_L in a stream is 3 mg/ℓ and the DO is 9 mg/ℓ. Stream flow is 15 MLD. A treated sewage effluent with BOD_L 50 mg/ℓ is discharged into the stream at a rate of 5 MLD. The DO of the sewage effluent is 2 mg/ℓ. Assume the deoxygenation and reaeration constants as 0.2/day and 0.5/day respectively and the saturated DO level is 11 mg/ℓ, determine the minimum DO level in the stream. If stream velocity is 1.5 m/s, where does the minimum DO occurs.
30. Explain the importance of the following operations in BOD test
    i. pH adjustment
    ii. Seeding wastewater
    iii. Incubation at controlled temperature.