

ENVIRONMENTAL TECHNOLOGY

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1. **BACKGROUND TO ENVIRONMENTAL ENGINEERING AND TECHNOLOGY - DEFINITIONS**

Environmental engineering has been defined as the branch of engineering that is concerned with protecting the environment from the potentially deleterious effects of human activity, protecting human populations from the effect of adverse environmental factors thereby improving environmental quality for human health and well-being. Engineering and technology infer a different degree of mathematical and science knowledge and rigour.

The environment globally consists of the atmosphere, hydrosphere and lithosphere, in which the life-sustaining resources of the earth are contained. The biosphere, a thin shell that encapsulates the earth is made up of the atmosphere and lithosphere both adjacent to the surface of the earth together with the hydrosphere. From the beginning of time it is the biosphere that has received and assimilated the wastes generated by plant and animal life. However, in recent times it has become apparent that the sustaining and assimilative capacity of the biosphere is not infinite.

1.1 **Impact of Humans on the Environment**

For some time anthropogenic pollutants have, to a greater or lesser extent, overloaded the system since people began to gather together in stable groupings. This overloading was initially caused in simply meeting their needs for air, water, food and shelter, however, attention was soon directed to other needs beyond those associated with survival. These acquired needs are met by the various industries and these residuals are likely to be less compatible with the environment and less likely to be assimilated into the biosphere. As societies ascent the socio-economic ladder, the list of acquired needs or luxuries increase.

1.2 **Impact of the Environment upon Humans**

Though rivers stink as do dumping grounds, and skies become smoggy, populations generally manage to ignore their impact on the environment until they become aware of the ill-effects upon their health. It has only been in the last century that the correlation between waterborne biological agents and human diseases has been proved and effective preventive measures undertaken to limit consequences through immunisation and environmental control.

Pollution of the atmosphere has also caused deaths. Monitoring of sulphur dioxide, lead and carbon monoxide levels in cities have revealed that the high levels of these and other contaminants are at worrying levels. Other environmentally related health problems also concern the environmental engineer/technologist. The widespread use of chemicals in agriculture and industry has introduced dangerous compounds into the environment. The formation of dioxin is a by-product of a manufacturing process used with herbicides and wood preserving compounds and is extremely toxic.

Our cultural as well as our aesthetic heritage is being lost to pollution; the Parthenon in Athens, the Statue of Liberty in New York are increasingly in danger of being destroyed.

1.3 **Role of the Environmental Engineer**

As pollutants enter air, water or soil, natural processes such as dilution, biological and chemical reactions convert waste material to more acceptable forms. The treatment facilities designed by the environmental engineer are based on the principles of self-cleansing observed in nature but the engineered processes optimise the operations observed in nature to handle larger volumes of pollutants. An understanding of natural and engineered purification processes requires an understanding of the biological and chemical reactions involved in these processes. The environmental engineer/technologist unique role is to build a bridge between biology and technology by applying all the technique made available by modern engineering technology to the job of cleaning up the debris left in the indiscriminate use of that technology. It is essential to adopt a “systems approach”; that is looking at all the interrelated parts and consider their effects on one another.

1.4 **Historical introduction to the water, wastewater and air environment**

From the middle of the 19th Century it has been recognised that improvements to health could be brought about by improvements in sanitation with regards to drinking water, sewage and household wastes. However, by the turn of the century rainwater most commonly abstracted from rivers were subjected to minimal treatment allowing settling of the visible solids only. Sewage continued to be discharged into rivers potentially polluting downstream water abstraction.

In the 20th Century urban areas began to treat water using slow sand filters. The quality of water was good but because of the slow rates of throughput they required large areas and were gradually replaced by rapid gravity filters. Chlorination was added as a later treatment step for microbiological purification.

Regarding industrial discharge it was thought in the 19th Century that the acids present would help to kill the human sewage microbes that caused human diseases, and so be of benefit to river water quality at downstream abstraction. No attention was given to the incidents of fish kills, river water discolourisation from whatever industrial source. In the UK many industries still discharge their wastes into public sewers.

Following the London smog of 1952 the Clean Air Act was introduced in 1956 to reduce urban air pollution generated by coal and oil producing particulates, CO₂, CO and unburned hydrocarbons. Legislative improvements grew and by the 1980's very detailed legislation applies to emission in all developed countries; however, accidents occur. The 1976 dioxin release at a chemical plant in Seveso, Italy contaminated an area occupied by 37,000 people. Also

the widespread use of pesticides and other chemicals in agriculture are affecting our health and concern for the air environment has shifted emphasis to the organics and hydrocarbons produced by industries.

1.5 **Engineering/environmental ethics**

Ethos, the Greek word from which “ethic” is derived means the character of a person as described by their actions. We should treat all of the earth as a sacred trust to be used so that its content is neither diminished nor permanently changed. The recognition of the need for such adaptation has developed into what is now called the environmental ethic.

Some engineers are unhappy about the negative long-term impacts of engineering projects on the natural environment, and no longer can the profession not share responsibility for the ethical dilemmas consequent to their projects. The ethical question requests that we also put aside nationalist views for the long-term greater benefit of the global population and ecology.

As environmental engineers we need to believe in our projects as ecologically and humanely desirable. We need to be more adaptable and flexible and collaborate with environmental and community groups from project inception.

1.6 **Environmental changes and threats to the environment**

Over geological time, the temperature of earth has naturally changed causing climatic changes, continental plates have moved around the surface of the globe and the topography of the land has changed. This has led to changes in the extent and distribution of various biomes on a global scale. Gradual changes in the environment over long time periods do not seriously damage the ecosystem processes as species are able to track the change by either physically moving or adapting.

1.7 **Physical and chemical properties of water**

1.7.1 **Introduction**

Water always contains impurities e.g. calcium and magnesium, in groundwater and are usually of natural origin being due to the dissolution from rocks; nitrogen compounds in groundwater is often due to pollution. The acceptability of a water for use depends on its physical, chemical and biological properties.

1.7.2 Physical

The following are of particular importance:

- Colour:** Colour in water is caused by dissolved minerals, dyes or humic acids from plants. Water colour caused by dissolved or colloidal substances that remain in the filtrate after filtration is called true colour. Colour is measured in units of mg/ℓ of platinum.
- Turbidity:** Turbidity is a measure of cloudiness and is caused by the presence of suspended matter which scatters and absorbs light. Turbidity can be correlated with suspended solids, but only for waters from the same source.
- Odour:** Many organic chemicals are odorous including algae. The threshold odour is determined by diluting a sample with odour-free water until the last perceptible odour is detectable. The result is expressed as a dilution ratio. For drinking water the EU upper limit is a dilution ratio of 3 at 12°C and 4 at 25°C.
- Temperature:** Temperature is important in the river environment as increased water temperature reduces the amount of oxygen in the water, thereby making the river less desirable for fish. For drinking water, EU limit 25°C.
- Solids:** Solids are considered to be particularly important. (TS) Total solids is all of the residue remaining after evaporation at 105°C and is expressed as mg/ℓ. TS may be subdivided in various ways but usually as suspended solids (SS) and total dissolved solids (TDS). The suspended solids (SS) is what is retained on a fine filter of pore size 0.45 µm. $TS = TDS + SS$. A different division of TS is into a settleable and non settleable fraction as determined by the amount of materials settling within 1 hour, i.e. some of the SS will remain in solution.

1.7.3 Inorganic chemical properties of water

The assessment of a water quality may be via the major mineral content e.g. Ca, Mg, Pb, Cu, and/or simply by considering alkalinity, hardness and electrical conductivity.

The two nutrients of greatest importance are nitrogen and phosphorus being essential for plant and organism growth but in excess can be undesirable often leading to eutrophication. Nitrogen is one of the basic components of proteins and is used in cell production. Animals cannot use nitrogen from the atmosphere directly but must be converted into organic form. Large concentrations of organic nitrogen are indicative of organic pollution and limits are set at 1 mg Norg/l for good quality river water.

Nitrates in drinking water are harmful and limits are set at 40 mg/l for drinking water. Phosphorous is often the limiting nutrient in eutrophication because if the ratio of nitrogen to phosphorous exceeds 14 : 1 the limiting nutrient is phosphorus and this is nearly always the case for freshwater. Phosphorus was introduced to detergents in 1935 and is also a key fertiliser component.

Acidity: An acid water is one which has a pH value < 7 . It is one of the most important determinations in water chemistry since many of the processes involved in water treatment are pH dependent. Pure water is very slightly ionized into positive hydrogen (H^+) ions and negative hydroxyl (OH^-) ions.



A solution is neutral when the numbers of hydrogen ions and hydroxyl ions are equal. For all solutions in water i.e. substances dissolved in water, the product of $[H^+]$ and $[OH^-]$ is always 10^{-14} .

$$[H^+][OH^-] = 10^{-14}$$

if $[H^+] = [OH^-]$ for neutrality

$$[H^+] = \sqrt{10^{-14}} = 10^{-7}$$

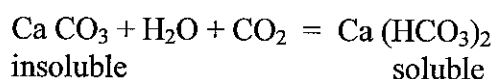
$$pH = -\log(H^+) = -\log(10^{-7}) = 7$$

When the concentration of hydrogen ions exceeds that of the hydroxyl ions the pH is < 7 and the solution has acid characteristics. Conversely when there is an excess of hydroxyl ions the pH value is > 7 , and the solution is said to have basic or alkaline characteristics.

Acidity in an unpolluted water is usually from dissolved carbon dioxide which produce weak carbonic acid. When the acidity is from natural origins the pH value is usually above 3.7. Waters polluted by industrial

effluents can have pH values below 3·7. There is no defined limit for acidity in water, the main requirement being that of non-corrosion. Corrosion would result in attack of concrete pipes and the dissolution of heavy metals such as copper, zinc and lead.

Alkalinity: Caused due to bicarbonate, carbonate and hydroxide ions in water, usually in association with calcium, magnesium, sodium and potassium. Most of the natural alkalinity in waters is due to HCO_3 produced by the action of ground water on limestone or chalk.



Analyses often quote alkalinity in terms of CaCO_3 instead of carbonate and bicarbonate content.

Hardness: This is the property of a water which prevents lather formation with soap and produces scale in hot water systems. There is no health hazard. Also usually expressed in terms of CaCO_3 . Is divided into two forms:

- (a) *temporary hardness.* Also known as carbonate hardness being caused by bicarbonate ions. It is called temporary hardness because it is precipitated by boiling and forms the scale found inside kettles;
- (b) *permanent hardness.* Also known as non-carbonate hardness being caused by sulphate, chloride and nitrate ions. No compound is precipitated on heating.

temporary hardness	permanent hardness
Calcium bicarbonate $\text{Ca(HCO}_3)_2$	Calcium sulphate CaSO
Magnesium bicarbonate $\text{Mg(HCO}_3)_2$	Magnesium sulphate MgSO
	Calcium chloride Ca Cl_2
	Magnesium chloride Mg Cl

Dissolved

Oxygen (DO): Oxygen is a most important element in water quality control. Its presence is essential to maintain the higher forms of biological life and the effect of a waste discharge on a river is largely determined by the oxygen balance of the system. Its solubility decrease with temperature.

temp °C	0	10	20	30
DO mg/ℓ	14·6	11·3	9·1	7·6

Clean surface waters are normally saturated with DO but such DO can be rapidly removed by the oxygen demand of organic wastes. Game fish require at least 5 mg/ℓ DO and coarse fish will not exist below 2 mg/ℓ DO. Oxygen saturated waters have a pleasant taste and waters lacking in DO have an insipid taste.

1.7.4 Organic chemical properties of water

The main element of organic compounds is carbon. Although the organic matter can be divided into various groups such as proteins, lipids, carbohydrates, and tests exist to determine the concentrations of the various compounds, it is usually sufficient to consider only the overall concentration of the organic content. Tests include the BOD, COD and TOC.

Biochemical Oxygen Demand (BOD)

The BOD₅ is the amount of dissolved oxygen used by micro-organisms as they break down material at 20°C over a five-day period. It measures the readily biodegradable organic carbon. Clean waters have BOD₅ values of <1mg/ℓ. Rivers are considered polluted if BOD₅ >5mg/ℓ.

The BOD₅ is set at 5 days and may not be long enough to determine the BOD ultimate which is set arbitrarily at 20 days. The BOD of municipal wastewater ranges from about 150 mg/ℓ to 1,000 mg/ℓ while for industrial wastewater (food industries) the value may be several thousands.

Chemical Oxygen Demand (COD)

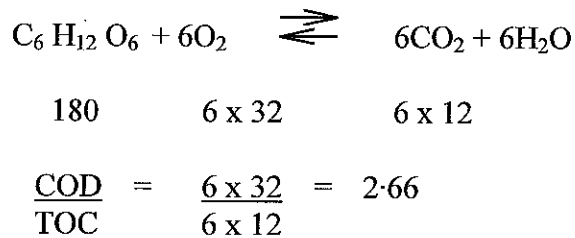
This test determines the amount of oxygen needed to chemically oxidise the organics. A strong chemical oxidising agent is used rather than using micro-organisms as in the BOD test. The oxidising agent is potassium dichromate in an acid solution. COD is attractive since it takes about two hours only.

Total Organic Carbon (TOC)

The TOC test measures all carbon as CO₂ in mg/ℓ and, therefore, the inorganic carbon (HCO₃, CO₂, CO₃) must be removed prior to the test. The TOC is a simple instrumental test and there are many analysers available commercially.

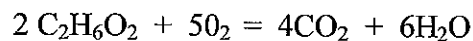
Theoretical Relationship between TOC and COD

The TOC measures the mass of carbon per litre of water whilst the COD measures the mass of oxygen for chemical oxidation. For the breakdown of glucose:



Example:

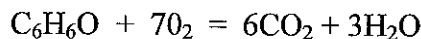
A wastewater is analysed and is shown to contain 100 mg/ℓ of ethylene glycol (C₂H₆O₂) and 120 mg/ℓ of phenol (C₆H₆O). Determine the COD and TOC.



$$(2 \times 62) \quad (5 \times 32) \quad (4 \times 12)$$

$$\text{COD} = \frac{(5 \times 32)}{(2 \times 62)} \times 100 \text{ mg/}\ell = 129.3 \text{ mg/}\ell$$

$$\text{TOC} = \frac{(4 \times 12)}{(2 \times 62)} \times 100 \text{ mg/}\ell = 38.7 \text{ mg/}\ell$$



$$94 \quad (7 \times 32) \quad (6 \times 12)$$

$$\text{COD} = \frac{(7 \times 32)}{94} \times 120 \text{ mg/}\ell = 286 \text{ mg/}\ell$$

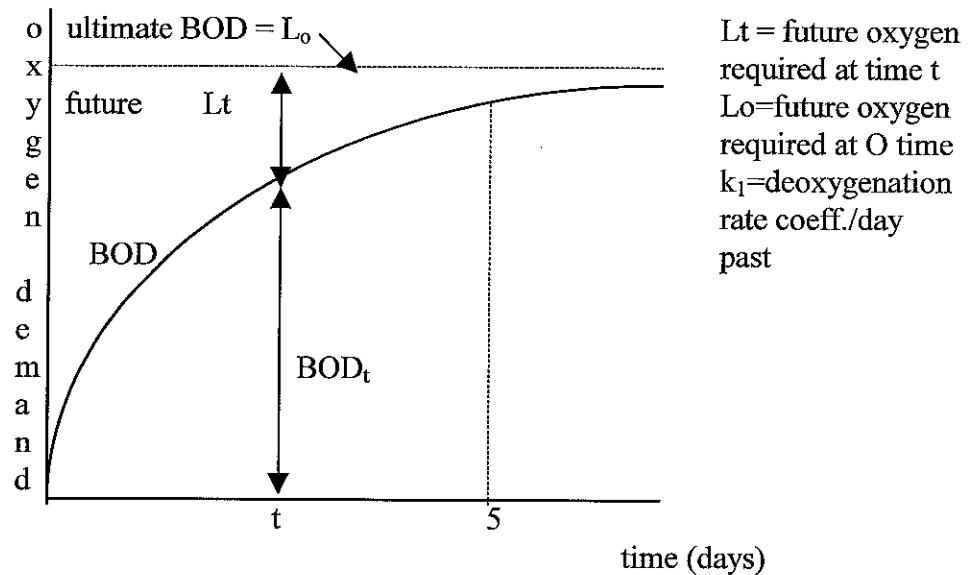
$$\text{TOC} = \frac{(6 \times 12)}{94} \times 120 \text{ mg/}\ell = 91.9 \text{ mg/}\ell$$

for wastewater, COD = 415.3 mg/ℓ and TOC = 130.6 mg/ℓ

1.7.5 Past and future oxygen demand

As stated the BOD test measures the oxygen already consumed by bacteria whilst oxidising organic matter under aerobic conditions. BOD for a particular time period can, therefore, be considered to be the amount of oxygen consumed by the bacteria up to that particular time. At any time the amount of organic matter remaining has a future

oxygen demand L_t which may be considered to be a 'future BOD' demand.



It may be proved that

$$BOD_t = L_o (1 - e^{-k_1 t}) = BOD_{ult} (1 - e^{-k_1 t})$$

Example:

If a wastewater has a deoxygenation rate coeff. of 0.15/day, determine the ultimate BOD if the 5 day BOD is 615 mg/l. Determine the BOD_2 , BOD_4 , BOD_8 and BOD_{10} values and hence draw a graph of oxygen consumed by bacteria against time.

Determine approximately when bacteriological action is 95% complete.

$$BOD_5 = BOD_{ult} (1 - e^{-k_1 t})$$

$$BOD_{ult} = \frac{BOD_5}{(1 - e^{-k_1 t})} = \frac{615}{1 - e^{-0.15 \times 5}} = 1,166 \text{ mg/l}$$

$$BOD_2 = 302 \text{ mg/l}, BOD_4 = 526 \text{ mg/l}$$

$$BOD_8 = 815 \text{ mg/l}, BOD_{10} = 906 \text{ mg/l}$$

By trial and error 95% complete after approximately 20 days.

1.7.6 Determination of BOD

The traditional BOD test is conducted in standard 300 ml BOD bottles. The test for the 5 day BOD of a water sample involves taking two DO measurements when the test begins at time $t = 0$ and a second measurement at $t = 5$, after the sample has been incubated in the dark for 5 days at 20°C. The BOD_5 is simply the difference between the two DO measurements.

Clean surface water usually has a BOD_5 of about 1 mg/l.

$BOD_5 > 10$ mg/l indicate usually the presence of sewage pollution.

When measuring the BOD_5 of sewage it is necessary to first dilute the sample in the BOD bottle. Domestic sewage generally has a BOD_5 value of about 200 mg/l. If the sample was not diluted, all the DO would be quickly depleted and it would therefore be impossible to obtain a DO reading on the 5th day.

mass balance $BOD_{conc} \times Vol_{conc} = BOD_{sol} \times Vol_{sol}$
concept

$BOD_{conc} = \text{BOD of concentrate}$

$BOD_{sol} = \text{BOD of solution.}$

Example:

A 6.0 ml sample of wastewater is diluted to 300 ml with distilled water in a standard BOD bottle. The initial DO in the bottle is determined to be 8.5 mg/l, and the DO after 5 days at 20°C is found to be 5 mg/l. Determine the BOD_5 of the wastewater and compute BOD_{ult} .

Assume $k_1 = 0.23/\text{d}$.

$BOD_{sol} = 3.5 \text{ mg/l}$

$BOD_{conc} = \frac{3.5 \times 300}{6} = 175 \text{ mg/l}, BOD_{ult} = 256 \text{ mg/l}.$

1.8 Atmospheric Chemistry

1.8.1 Composition of the atmosphere

The earth's atmosphere is divided into regions based on consideration of temperature gradients. The temperature at the earth's surface varies from $< 0^\circ\text{C}$ in the polar regions to $> 70^\circ\text{C}$ in the arid desert regions. In very warm areas, the air temperature is 10 - 20°C cooler than the hot surface temperatures. The lower 0 to 1 - 2 km of the troposphere is called the atmospheric boundary layer (ABL) and is the region where the wind velocity is affected by the shear resistance of the earth's

surface. The region of most interest for atmospheric pollution is that within the ABL although higher regions within the troposphere are of interest to global circulation modelling.

In addition to the atmospheric gases which are relatively constant, there are a number of variable constituents of natural origin.

Carbon Dioxide:

From various measurements at different locations the carbon dioxide content of the air has steadily climbed. This rise is due to the use of fossil fuels and the addition of CO₂ to the air through burning vegetation. Much of the addition of carbon (Ω 50%) has been counterbalanced by various removal processes but there has been a steady increase.

Analysis of air trapped in ice caves in Greenland and Antarctica has allowed the reconstruction of the history of CO₂ in the air. In 1750 the CO₂ content was about 275 ppmV after which, when the industrial revolution began in Britain and when large-scale deforestation began in Eurasia and North America the level has climbed at an increasing rate.

The total amount of carbon in CO₂ in the air is about 740 billion tons and is increasing at about 3 billion tons per year.

The oceans are a major *sink* for CO₂. There is about 50 times as much CO₂ dissolved in the oceans as is present in the air. In the surface layers of the ocean where light penetrates, plankton use carbon during photosynthesis if enough nutrients are available. These plankton supply the food for marine life which die carrying carbon down to the deep waters. Carbon dioxide is also being taken up on land, especially in forests which grow vigorously in a CO₂ rich environment and extract carbon from the air placing it in tree trunks etc. It is difficult to estimate the future increase in atmospheric CO₂ because all scenarios depend on assumptions about the rate of emission by human activity and the degree of uptake; however, if emissions continue to grow at 4% a year, about equal to economic growth rates in prosperous countries, then by 2050 the level will be three times the natural level.

Methane:

Methane is a very important atmospheric gas because of its own greenhouse properties and its complicated effects on other important components of the air. It is destroyed in the air in 7 - 10 years and a reduction of atmospheric methane is the most obvious starting point if any serious attempt is made to manage the atmospheric greenhouse effect. The sources of methane include coal, natural gas, old swamps

and trees. Also non-fossil categories such as rice paddies, termites and cows.

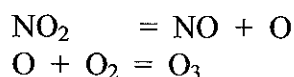
Carbon monoxide:

Carbon monoxide is formed by the incomplete combustion of carbon or carbon compounds when there is insufficient oxygen for complete combustion. The combustion of carbon fuels is $2C + O_2 = 2CO$ and $2CO + O_2 = 2CO_2$. The first reaction is much faster than the second and usually carbon monoxide only has an atmospheric life of 2 months.

In itself carbon monoxide does not cause problems but it scavenges OH from the atmosphere which itself removes methane, and the increase in methane in part is attributed to the increase in CO. Sources of CO are biomass burning, inefficient devices such as Chinese coal stoves and petrol engines not equipped with effective catalytic converters.

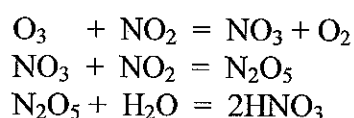
Nitrogen oxides:

Include nitric oxide NO, nitrogen dioxide NO₂, and nitrous oxide N₂O. The NO₂ gas is important in that it increases the ozone in the troposphere.



Ozone is a greenhouse gas. Nitrous oxide itself is a greenhouse gas.

One of the mechanisms for the formation of nitric acid being one of the acids of acid rain is:



Chlorofluorocarbons:

Are entirely man-made and are potent greenhouse gases and are notorious for their reduction of stratospheric ozone concentrations. CFC's are of artificial origin and are very stable. They eventually drift up into the stratosphere where the sunlight finally attacks them liberating chlorine. It takes up to 100 years for a molecule of CFC to diffuse up to the stratosphere and then break down liberating chlorine and removing ozone there. This gas reduction probably cools the high atmosphere but warms the earth's surface. Problems will remain long after production is halted.

Ozone:

Atmospheric ozone can be divided into two categories, tropospheric ozone of which there is now too much and stratospheric ozone of which there is too little

Stratospheric ozone is made when ultraviolet light from the sun strikes an oxygen molecule (O_2) splitting it into two highly reactive oxygen atoms (O) which then combine with another oxygen molecule to form O_3 , ozone. This gas absorbs ultraviolet light and dissociates into O_2 and O ; the O then reforms O_3 with another O_2 molecule and so on. If two oxygen atoms collide, O_2 is formed. The quantity of ozone is relatively very small and is expressed in Dobson Units. One Dobson unit is defined as 0.01 mm of ozone in the atmosphere. Reduced ozone levels therefore have a cooling effect on the stratosphere. This can make it cold enough to enhance the production of ice crystals. these clouds promote chemical reactions that in turn destroy ozone setting in motion a vicious circle. One of the most dramatic atmospheric changes over the past 15 years has been the emergence of an Antarctic ozone hole.

The causes of the Antarctic hole is uncertain but is likely to be caused by the chlorine reaction with ozone; the gas formed then combines with oxygen atoms forming more chlorine to repeat the process. The likely source of chlorine is chlorofluorocarbons. In September 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was developed. The Protocol proposed that CFC production first be frozen and then reduced 50% by 1998. Eighty countries signed the "Helsinki Declaration".

Tropospheric or low-level ozone is increasing in most populated regions and is damaging to life. Apart from being a greenhouse gas, it is highly toxic to plants. It is a familiar component of the air pollution that hangs over many major industrial cities and is caused by a complex chain of reactions involving methane, carbon monoxide and nitrogen oxides.

Ozone is removed naturally at the Earth's surface by soils, plants and the sea.

Acid Rain:

Acid rain is widespread in Europe, and much of the acidity comes from sulphur compounds and nitrogen oxides. The major sources of acidity added by human beings include the burning of coal, smelters, automobiles and sewage and manure that finds its way into waters and enhance DMS production. About 30% of the sulphates falling is of anthropogenic source. British emissions from coal burning have

dropped substantially since 1980. Many forests are suffering because acid rain mobilises soil aluminium which causes root damage.

1.9 **Soil Chemistry**

Soils are made up of solids, liquids and gases; the solids being a combination of organic and inorganic material. One kg of soil may contain a microbial population greater than 100 times the Earth's human population. Many soils have a porosity of 10 - 50% depending on soil type and composition. Soils in arid climates are about 90% inorganic whilst in humid temperate climates the topsoils are predominantly organic. The liquid element commonly referred to as soil solution contains dissolved minerals and colloids and suspensions.

Salinity of soils is a major issue in the arid and semi-arid areas of the world. This is due to salts not being leached from the soil. Chemical and physical weathering of exposed rocks and minerals is the main source of salts. In humid climates, salts are leached down through the soil profile by infiltrating rainwater. The salt concentration of rainwaters near the coast may be up to 200 mg/l and this can add salts to coastal areas by precipitation. Some areas of the globe have naturally high water tables, but low rainfall. The water is drawn to the surface by capillarity where it evaporates and leaves behind the salt. These are called salt pans.

1.10 **Hydrology**

Definition

Hydrology is the study of water and its movement in the atmosphere, rivers and seas, and in soils and rocks.

Hydrological Cycle

Water evaporates from the Earth's oceans and to a lesser extent from the land surfaces. The evaporated water as vapour rises into the atmosphere until it condenses and precipitates. Some of this water may become overland flow and eventually reach a stream or river and be discharged as surface run-off or just run-off. It may infiltrate into the soil and either flow horizontally as interflow or percolate through the soil into the groundwater zone and recharge the waters in the aquifers. A significant volume of precipitation may be returned directly to the atmosphere through evaporation from water surfaces or evapotranspiration from vegetation. Evaporation and evapo-transpiration together are often referred to as total evaporation or interception.

If a land use change is proposed for a catchment e.g. if a grassland catchment is converted to forestry, an appreciable increase in total evaporation would result due to the increased transpiration rates of trees over grassland.

Precipitation

The three means of determining the magnitude of rainfall are precipitation gauges, radar and satellite remote sensing. The traditional means of measurement was to use a network of gauges which were read manually on a daily basis. Today rain gauges are predominantly continuous rainfall recorders with attached electronic data recorders.

Infiltration

Is the movement of water from the soil surface into the soil. The percentage of precipitation that infiltrates is about 76%. A proportion of the water may remain above the water table until it reappears in channels by interflow or may percolate below the water table to become groundwater. 30% of the Earth's freshwater is stored in the groundwater although this represents less than 1% of the total water.

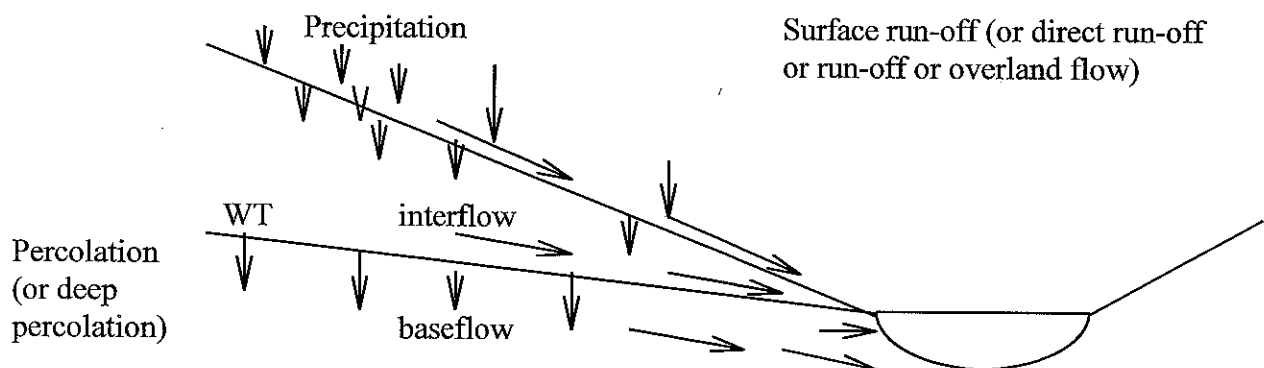
Soil Moisture Deficit (SMD)

When the soil moisture is below field capacity it is said to have a soil moisture deficit. A catchment loses water at rates equal or less than potential evapotranspiration (PE) depending on whether the soil moisture is at or below field capacity.

In spring when $PE > P$ (precipitation), the soil enters SMD, first at the surface layers. In the autumn $P > PE$ and the upper layers become replenished with water whilst the lower layers are still in SMD.

Rainfall - Run-off Relationships

When rainfall occurs the proportion of run-off to infiltration depends on land slope and infiltration capacity. The water flowing in streams and rivers is derived from run-off and a proportion of the water that infiltrates being the interflow element and a proportion of the water that has percolated into the groundwater resurfacing, known as baseflow.



Direct run-off is a consequence of precipitation whilst base flow is the dry weather flow.

The catchment area, watershed or basin is defined by the surrounding topography. The perimeter of the watershed is called a divide and is the highest elevation surrounding the watershed. Water falling outside of the divide is shed to another basin.

The hydrograph is a plot of stream discharge versus time. Baseflow is that component of the flow which is supplied by groundwater. Interflow is that supplied by subsurface flow within the unsaturated soil matrix. The shape of the hydrograph depends on an overland flow, subsurface flow, groundwater flow, land slope, stream slope, land and channel roughness and rainfall pattern, intensity and duration.

Elements of interest for the hydrograph include the peak magnitude, the time to peak, the hydrograph duration and the separation of baseflow, interflow and surface run-off.

The time of concentration (t_c) is the time required for the direct run-off to flow from the hydraulically most remote part of the catchment to the outlet. The following equation may be used for estimating t_c in minutes.

$$t_c = \frac{1.8 (1.1 - C) \sqrt{3.28 D}}{S^{1/3}}, \quad \begin{array}{l} C = \text{run-off coeff.} \\ D = \text{Overland Dist(m)} \\ S = \% \text{ slope} \end{array}$$

t_c in minutes

Example:

Estimate the time of concentration for a school playground of 6% slope if the overland flow distance is 300 m. Run-off coeff. to be taken as 0.20.

$$t_c = \frac{1.8 (1.1 - 0.20) (3.28 \times 300)^{1/2}}{6.0^{1/3}}$$

$$t_c = \frac{50.82}{1.82} = 28 \text{ mins.}$$

An estimate of the peak run-off rate is obtained from the equation:

$$Q_p = 0.278 \text{ CAI m}^3/\text{sec.}$$

where Q_p = peak river flow; C = run-off or impermeability coeff.

I = rainfall intensity in mm/hr. over t_c .

A = catchment area in km^2 .

This technique is known as the rational method.

Example:

What is the peak discharge from a catchment area during a 5 year storm if the average time of concentration is 53 minutes if the composition of the grounds is as follows:

Character of surface	area (m ²)	Run-off Coeff.
Parking area	11,150	0.85
Building	10,800	0.75
Lawns 2% slope	35,000	0.17
Lawns 6% slope	105,050	0.20

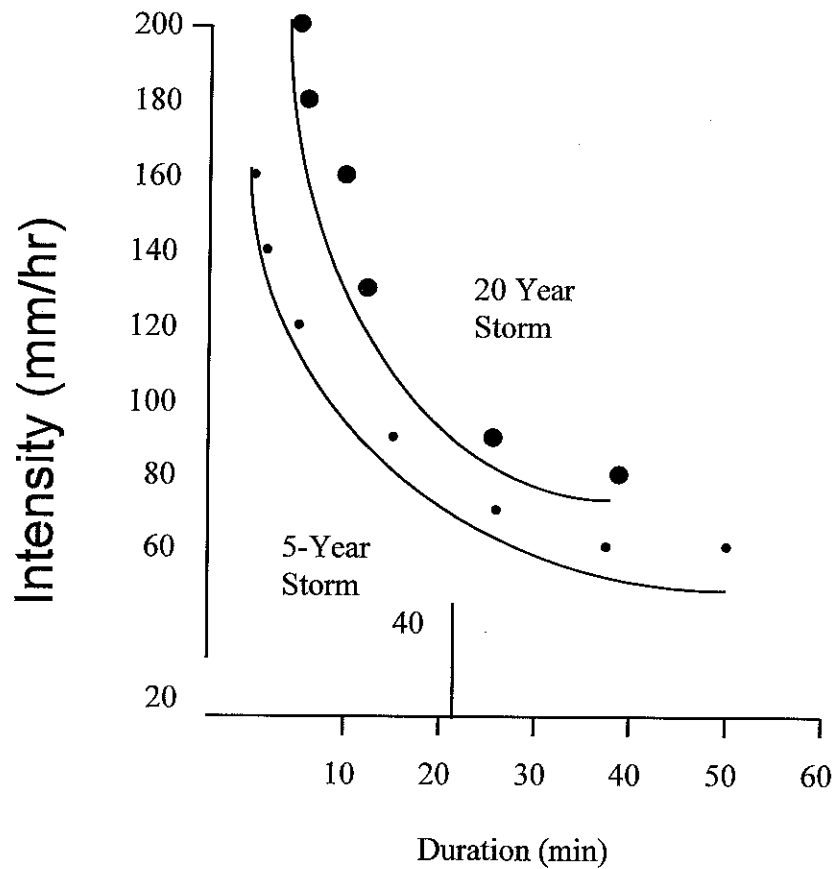
The intensity - duration - frequency curve for the site is as shown:

$$QP = 0.278 \text{ CAI}$$

$$CA = (0.85 \cdot 11,150 + 0.75 \cdot 10,800 + 0.17 \cdot 35,000 + 0.20 \cdot 105,050) \text{ m}^2$$

$$= 44,537 \text{ m}^2 = 0.0445 \text{ km}^2$$

$$= 0.278 \cdot 0.0445 \cdot 60 = 0.74 \text{ m}^3/\text{sec.}$$



Intensity-duration-frequency curve

Groundwater hydrology

A geological formation that bears water is called an aquifer. Because of surface topography the water table occasionally intersects the surface of the ground and at these points of intersection groundwater moves out of the aquifer as a spring.

When an overlying impermeable formation, aquiclude, confines the water in the aquifer under a pressure greater than atmospheric pressure, the groundwater is under artesian pressure, and would if a well was drilled have standing water above the top of the aquifer. Water enters the aquifer at some location called the recharge area.

A perched water table is the surface of a lens of water held above the surrounding water table by a localised impervious layer.

2. **ENVIRONMENTAL POLLUTION**

2.1 **Introduction**

Pollution refers to any change in the natural quality of the environment brought about by chemical, physical or even biological factors and normally refers to the activities of man.

Some communities and ecosystems are only stable within a narrow range of environmental conditions and are therefore very sensitive to pollution and are called dynamically fragile. Others may be stable over a wide range of conditions and are known as dynamically robust.

2.2 **Freshwater Environment**

Any kind of disturbance that reduces oxygen levels will have a dramatic effect on ecosystems such as macroinvertebrates, insect larva and worms. Most of the dissolved and particulate organic and inorganic matter in freshwater is carried in from the surrounding catchment. As such the chemical nature strongly reflects the type of land being drained and the land use.

2.3 **River Pollution**

Any body of fresh water can assimilate a certain amount of pollution without serious effects because of the biological cycle. In a low organic content stream there is little nutrient material to support life. In streams with high organic content, conditions are unsuitable for animals and higher plants so that micro-organisms predominate. Self-purification will eventually stabilise the organic matter and permit the re-establishment of a balanced community. Waste properties of interest in pollution studies are:

2.3.1 **Toxic compounds:**

Result in destruction or inhibition of biological activity in the water. Most of these toxic compounds would originate from industrial effluents and could include materials such as heavy metals from plating and metal finishing, pesticides and radioisotopes. Growths of algae can sometimes be responsible for the release of toxins into the water which then become unsuitable for immediate use.

2.3.2 **Materials which affect the oxygen balance of the water, such as:**

- (a) substances which consume DO which may be either organic materials which are broken down biologically and exert a BOD or inorganic reducing agents;

- (b) substances which hinder reoxygenation. Materials such as oils, detergents etc., can form protective films on water;
- (c) heated discharges can alter the oxygen balance.
- (d) High concentrations of inert suspended or dissolved solids can blanket the bed of a stream preventing the growth of fish food.

2.4 Self-purification of rivers

The assimilation of organic matter in surface waters is a natural activity which may have beneficial effects on fishing. Self purification involve one or more of the following processes.

1. Sedimentation assisted by biological or mechanical flocculation. This may however result in formation of anaerobic bottom deposits which if resuspended can exert high oxygen demands.
2. Chemical oxidation of reducing agents.
3. Bacterial decay - due to inhospitable conditions there is normally a rapid die-off of pathogenic organisms.
4. Biochemical oxidation - the most important process. To prevent serious pollution problems it is essential that aerobic conditions be maintained. The DO content is controlled by various factors such as temperature, BOD, salinity and most important reaeration.

If for any reason the DO of a water falls below saturation it will, if exposed to the atmosphere dissolve more oxygen and approach saturation again.

One of the problems in the study of rivers is to determine the reaeration characteristics of a stream. Solution can only occur at the air-water interface where a thin film of water is rapidly saturated and further re-aeration is controlled by the diffusion of oxygen throughout the main body of water which is a slow process. In a turbulent stream this saturated surface layer is broken up and reaeration can proceed more rapidly.

The deoxygenation of the water is a consequence of bacterial action on the organic matter giving rise to BOD. With increasing amount of oxygen consumed the rate of reaeration increases until a critical point is reached where the rate of deoxygenation and reaeration are equal. At this critical point, minimum DO is reached and as further time passes the DO will increase. Assuming that the only processes involved are oxygen removal by biological oxidation and oxygen replenishment by reaeration from the atmosphere the Streeter-Phelps equation was derived to determine the shape of the dissolved oxygen sag curve.

DO def at time t = D_t
 Oxygen demand at t = O i.e. $BOD_{ult} = L_o$
 Oxygen deficit at t = O = D_o
 Deoxygenation rate/day = k_1
 Reaeration rate/day = k_2

Critical oxygen deficit = D_c at critical time t_c

$$D_t = \frac{k_1 L_o}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) + D_o e^{-k_2 t}$$

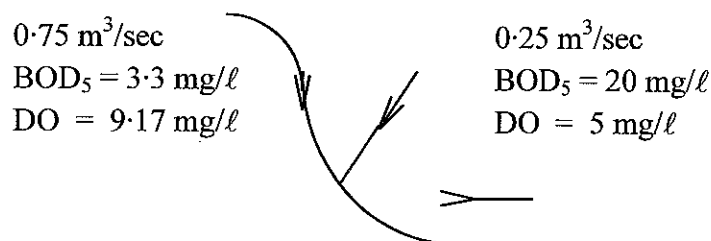
$$D_c = \frac{k_1}{k_2} L_o e^{-k_1 t_c}$$

$$t_c = \frac{1}{(k_2 - k_1)} \log_e \left[\frac{k_2}{k_1} \left(1 - \frac{D_o (k_2 - k_1)}{k_1 L_o} \right) \right]$$

Example:

A stream with a flow of $0.75 \text{ m}^3/\text{sec}$ and BOD_5 $3.3 \text{ mg}/\ell$ is saturated with DO ($9.17 \text{ mg}/\ell$ at 20°C). It receives an effluent discharge of $0.25 \text{ m}^3/\text{sec}$, BOD_5 $20 \text{ mg}/\ell$, and DO $5 \text{ mg}/\ell$. Determine the DO deficit at a point 35 km downstream if the average velocity of flow is $0.2 \text{ m}/\text{sec}$. Assume temperature is 20°C throughout. k_1 for effluent/water mixture is $0.230/\text{day}$ k_2 for stream $0.9210/\text{day}$.

Determine also the deficit after one day. At what distance downstream does the critical deficit occur and what is the dissolved oxygen in the water at this point.



Using mass balance concept for both BOD and DO

$$0.75 \times 3.3 + 0.25 \times 20 = (0.75 + 0.25) \text{ BOD}_5$$

$$\text{at down stream BOD}_5 = 7.475 \text{ mg/l}$$

$$(9.17 \times 0.75) + (5 \times 0.25) = (0.75 + 0.25) \text{ DO}$$

$$\text{at down stream DO} = 8.1275 \text{ mg/l}$$

$$\text{DO} = 9.17 - 8.1275 = 1.04 \text{ mg/l}$$

$$\text{vel} \times \text{time} = \text{distance}$$

$$\text{time} = 35,000/0.2 = 2.025 \text{ days}$$

$$L_o = \text{BOD}_{\text{ult}} \frac{\text{BOD}_t}{(1 - e^{-k_1 t})} = \frac{7.475}{1 - e^{-0.235}} = 10.94 \text{ mg/l}$$

$$D_t = \frac{k_1 L_o}{(k_2 - k_1)} (e^{-k_1 t} - e^{-k_2 t}) + D_o e^{-k_2 t}$$

$$\begin{aligned} D_t &= \frac{0.230 \cdot 10.94}{(0.921 - 0.230)} (e^{-0.23 \cdot 2.025} - e^{-0.921 \cdot 2.025}) + 1.04 e^{-0.921 \cdot 2.02} \\ &= 3.641 \cdot (0.628 - 0.155) + 0.161 = 1.88 \text{ mg/l}. \end{aligned}$$

$$D_t = \frac{k_1 L_o}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) + D_o e^{-k_2 t}$$

$$\begin{aligned} D_1 &= \frac{0.230 \cdot 10.94}{(0.921 - 0.230)} (e^{-0.23} - e^{-0.921}) + 1.04 e^{-0.921} \\ &= 1.443 + 0.414 = 1.86 \text{ mg/l} \end{aligned}$$

$$D_c = \frac{k_1}{k_2} L_o e^{-k_1 t_c}$$

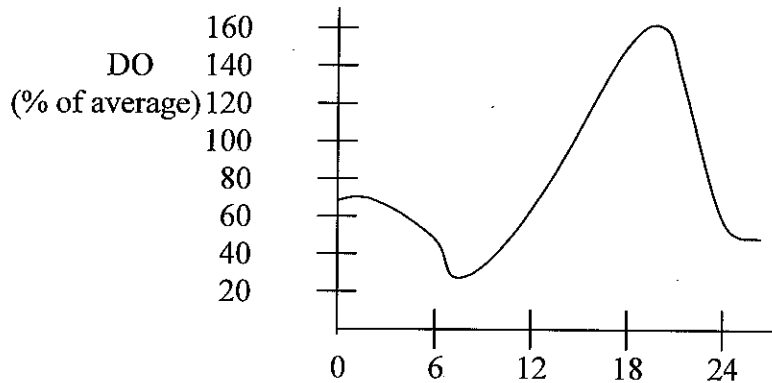
$$\begin{aligned} t_c &= \frac{1}{(k_2 - k_1)} \log_e \left[\frac{k_2}{k_1} \left(1 - \frac{D_o (k_2 - k_1)}{k_1 L_o} \right) \right] \\ &= \frac{1}{(0.921 - 0.230)} \log_e \left[\frac{0.921}{0.230} \left(1 - \frac{1.04 (0.921 - 0.23)}{0.230 \cdot 10.94} \right) \right] \\ &= 1.52 \text{ days}. \end{aligned}$$

$$D_c = \frac{0.230}{0.921} \cdot 10.94 e^{-0.230 \cdot 1.52} = 1.93 \text{ mg/l}$$

$$\text{Dissolved oxygen in water} = 9.17 - 1.93 = 7.24 \text{ mg/l}$$

$$\begin{aligned} \text{Critical deficit occurs at distance} &= 1.52 \times 24 \times 60 \times 60 \times 0.2 \text{ m} \\ &= 26,266 \text{ m} = 26.2 \text{ km}. \end{aligned}$$

There are also diurnal and seasonal differences in oxygen concentration. This variation is related to plant growth, light intensity and temperature. The amount of dissolved oxygen rises to a maximum during the day because of photosynthesis occurring in daylight. It decreases through the night because none is produced by photosynthesis, but respiration, using up oxygen continues as it does during the daylight hours. This extreme diurnal variation occurs mainly between April and October because the lower temperatures during the rest of the year tend to inhibit both the production and consumption of oxygen by plants.



Although the solubility of oxygen in water decreases with an increase in water temperature usually there is an increase in dissolved oxygen in the summer months because of more daylight and, therefore, increased photosynthetic activity. In fact, when photosynthesis is responsible for the oxygenation of the water, rather than atmospheric aeration, oxygen supersaturation can occur, i.e. more oxygen is dissolved in the water than the saturation concentration allows. This occurs because plants produce pure oxygen whereas air contains 21% O_2 . Therefore, when photosynthesis is responsible, up to five times the saturation concentration is theoretically possible at the same temperature.

2.5 Groundwater pollution

2.5.1 Introduction

Groundwater is usually of excellent quality. This is mainly because of the natural filtration that occurs in the layers of soil through which the water moves. Soluble pollutants are not affected at all by filtering action.

2.5.2 Sources of contamination

Groundwater usually contains dissolved minerals but usually natural contaminants found poses no threat to public health. The main problem has been the result of improper disposal of wastes and accidental spills of hazardous substances.

- (a) Industrial waste. Many industrial impoundments such as landfills or lagoons in the past were not properly designed and

contaminated liquids leak out, percolate through the soil and can reach aquifers. The leachate from industrial impoundments often contain trichloroethylene, a chlorinated hydrocarbon used as a degreaser. Heavy metals such as selenium, arsenic and cyanide have also been found.

- (b) Subsurface sewage disposal. Septic disposal systems are frequently the sources of faecal bacteria and virus contamination in private wells. Also the septic tank cleaning fluids that are used may pollute.

- (c) Municipal Landfills

Burial in the ground is one of the most common methods of disposing of municipal refuse. These dumps are often located in low-lying areas and unless properly designed leachate high in BOD and nitrates may enter aquifers.

- (d) Mining

Surface water flowing through mines can absorb dissolved metals and even radioactive substances.

- (e) Petroleum products

Numerous instances of local groundwater pollution due to leaky petrol tanks at filling stations have been reported.

- (f) Agriculture

The most significant groundwater contaminants are fertilisers and pesticides. Nitrates are of particular concern.

- (g) Urban areas

Local authorities spread salt on roads and these are carried into underlying aquifers increasing the chloride and TDS.

- (h) Saltwater intrusion

This may occur along coasts where there is a boundary between fresh groundwater and saline water from the sea. Wells pumping water that is salty because of intrusion have to be abandoned.

2.5.3 Groundwater quality

Aquifers are classified as either confined or unconfined. An unconfined aquifer is not covered by an impervious layer of soil or

rock and may be replenished with water by deep percolation directly from above. An impermeable layer overlies a confined aquifer so that water cannot penetrate directly from the surface and migrates laterally from the unconfined areas. Because confined aquifers are sandwiched between two impermeable layers the water can be under considerable pressure so that the water will rise to the surface if a well is drilled. These are known as artesian wells. The most well-known artesian basin is the one on which London stands.

Ground water in unconfined aquifers originate mainly as rainfall and so is particularly vulnerable to diffuse sources of pollution such as agricultural fertilisers and pesticides. However, the unsaturated zone about the aquifer may eliminate some of these pollutants before they reach the aquifer. Another possibility is that it just retards the movement of pollutant, concealing their effect for some years. Most of the aquifers in Britain have relatively thick unsaturated zones from 10 to 50 m thick which means that surface-derived pollutants can remain in this zone for decades. An example of this is the recent appearance in some UK ground water supplies in SE England of DDT which was banned in the early 1970's.

The quality of ground water depends on a number of factors other than the pollutant actually received directly.

- (a) The nature of the rain water.
- (b) The nature of the existing ground water which may be thousands of years old.
- (c) The nature of the soil above.
- (d) Nature of the rock comprising the aquifer.

Most aquifers in Britain have hard water; limestone and chalk aquifers usually containing high concentrations of calcium bicarbonate, while dolomite contains magnesium bicarbonate. Sandstones are often rich in sodium chloride while granite has elevated iron concentrations. The concentration of salts in ground water is often far greater than for surface waters. The concentrations also increase with depth.

Ground water in confined aquifers is much older and is characterised by a low level of pollutant, especially nitrate and, of course micro organisms. However, they may have high salt concentrations.

2.6 **Ocean Pollution**

2.6.1 **Introduction**

Despite the tremendous volume of the marine environment the natural capacity of estuaries and the ocean to assimilate wastes is limited, although there is a natural tendency to consider the ocean as a convenient 'sink' for wastes of all kinds.

One of the effects of ocean pollution is the destruction of marine life particularly phytoplankton that serves as food for other organisms.

Estuaries are transition zones between freshwater rivers and saline ocean waters. Being adjacent to land, they are the first marine areas to receive wastes carried by river flow. Estuaries are considered to be one of the most biologically productive environments, on which the open ocean is dependent for nutrients.

2.6.2 Sewage

Treated sewage effluent discharged into the sea and the pipes that carry the wastewater are called sea outfalls, and may be more than 2 km in length. When sewage flows out of the open end of an outfall it forms a rising column because it is warmer and less dense than seawater. This column may be carried toward shore raising the coliform counts.

The effectiveness of ocean disposal of sewage depends on how well the effluent is dispersed and spread out in the ocean; this will aid the natural purification process, reduce bacteria concentrations and “prevent pollution at shore areas. Most outfalls are now built with multiport diffusers which distribute the effluent over a large area through many circular holes or ports. Many coastal cities in the USA dumped sewage sludge in the ocean until 1992 when the system was banned.

2.6.3 Oil spills

Accidental discharge of oil can be a serious pollution problem and can cause the deaths of birds that live on the water. It has been estimated that the Torrey Canyon oil spill in 1967 killed 100,000 birds. In 1989 when the Exxon Valdez oil tanker spilled 11 million gallons in Alaska and hundreds of km of shoreline were polluted.

2.6.4 Construction consequences

Marine environments can be damaged by engineering works such as bridges. A rich and diverse reef system in Florida was irrevocably changed into a low diversity algal dominated area by the construction of a causeway which altered the circulation regime. Dredging of sands, gravels etc., can seriously damage shallow water habitats.

2.7 Air Pollution

2.7.1 Introduction

Air pollution may be defined as the presence of certain substances in the air in high enough concentrations and for long enough durations to

cause undesirable effects, may be natural as well as anthropogenic. At certain times pollution from natural sources can be far more severe and long lasting than air pollution from human activities. In addition to volcanic discharges other natural air pollutants include smoke and gases from forest fires, windblown dust from deserts, salt seaspray.

A distinction must be made between primary and secondary pollutants. Primary pollutants are emitted directly into the air from a specific source. Secondary pollutants are formed in the atmosphere by complex chemical reactions involving primary pollutants and sunlight.

Air pollutants may also be subdivided into criteria air pollutants which include substances which are emitted in large quantities and tend to threaten human health or welfare; and hazardous air pollutants which are not as voluminous but are immediately harmful to health.

Small fragments of solid or liquid droplets suspended in the air are called particulates. Particles smaller than 1µm tend to remain suspended indefinitely.

2.7.2 Effects of ambient air pollution

Major health effects are categorized as being either acute, chronic or temporary. It is difficult for public health experts to correlate specific air pollutants with specific diseases with certainty. Some of the factors that must be considered include threshold dosage, total body dosage, exposure time and synergistic effects.

There is much evidence linking lung cancer to air pollution although the actual cause-and-effect relationship is unknown. Some of the facts that support the linkage are that lung cancer deaths are more frequent in urban areas compared to rural areas and carcinogens are typically found in polluted urban air. Air pollutants enter the body by the respiratory system, through the throat, nasal cavities and trachea into the bronchial tubes and alveoli of the lungs. Gas transfer takes place in the small alveolar sacs where the pollutants can be absorbed into the blood.

Typical effects of sulphur dioxide, oxides of nitrogen and ozone include eye and throat irritation and can cause bronchitis and emphysema. These diseases are common in urban areas especially when coupled with the synergistic effects of tobacco smoke.

Carbon monoxide is a colourless and odourless gas virtually unnoticeable to our senses but is acutely toxic since it combines with haemoglobin in blood forming carboxyhaemoglobin leading to asphyxiation. A CO of 1,000 ppm can cause unconsciousness after 1 hour; and death after 4 hours.

The adverse health effects of inhaled particulate matter depend on their content and size. Certain particulates are dangerous due to their toxic or carcinogenic properties; lead fumes and asbestos are also suspected to be carcinogenic.

While particles smaller than 0.1 μm in size will readily reach the alveoli particles larger than 1 μm are usually trapped by protective mucous lining and cilia hairs in the nose and throat. High levels of particulates working synergistically with high levels of SO_2 have been linked to increased rates of respiratory infection and cardiac disorders.

The damage of materials by air pollution is more than just an aesthetic problem. The total cost of cleaning and repairing damage caused by air pollution is estimated to exceed \$1 billion in USA.

Air pollution can damage trees, flowers, fruits and vegetables in various ways. Ozone in particular causes damage to tree foliage and reduces the growth rate of sensitive tree species. Ozone accounts for about 90% of pollution damage to agricultural crops.

2.7.3 Indoor air pollutants

Ventilation dilute and remove indoor air pollutants but the most effective strategy for maintaining good energy-efficient IAQ is to reduce sources of pollutants.

Environmental tobacco smoke (ETS) is a mixture of more than 4,000 compounds, at least 40 of which are carcinogenic. Infants, particularly asthmatic children are especially at risk of experiencing the harmful effects of ETS.

In addition to second-hand smoke other sources of indoor combustion products include stores, space heaters and fires. Pollutants from these include CO , NO_x and particulates.

Radon is a colourless, odourless radioactive gas and is found in varying concentrations in the Earth's crust. When radon enters a building through openings indoor concentrations may accumulate.

Asbestos is still found in pipe and furnace insulation, floor tiles and textured paints. If these materials are disturbed by cutting or sanding excessive airborne asbestos levels can occur. If very small asbestos fibres are inhaled they accumulate in the lungs. Adverse health effects include asbestosis, mesothelioma and lung cancer.

Organic chemicals are widely used in paints, varnishes, waxes, cleansing agents and pesticides. Some of these may be toxic or carcinogenic whilst others cause dizziness, visual problems and memory impairment.

Formaldehyde is an organic chemical used in the manufacture of many building materials. It is a pungent-smelling gas that can cause eye and throat irritation and may be carcinogenic.

Airborne contaminants include bacteria, fungi, viruses, house dust mites and pollen. Controlling the relative humidity level reduces these contaminants as does normal house cleaning.

Many multi-storey buildings have significant air quality problems and when the occupants of a building have symptoms that do not fit the pattern of any particular illness the phenomenon is referred to as sick building syndrome. This term is applied to a building when more than 20% of the occupants complain of health problems for longer than two weeks whose symptoms are relieved when the occupants leave the building. One major cause of sick building syndrome is poor design, operation or maintenance of ventilation systems.

2.8 **Biological Parameters of Water Pollution**

2.8.1 **Introduction**

The presence or absence of living organisms in water can be one of the most useful indicators of its quality. A wide variety of different species indicate little pollution. If the pollution is very severe fish life will vanish completely. Biologists can survey the fish and insect life of natural waters and assess the water quality on the basis of the species diversity index.

2.8.2 **Types of micro-organisms**

The stabilisation of organic wastes is largely achieved by micro-organisms; but they are also responsible for diseases such as typhoid and prolific microbial growths which can lead to quality changes.

The basic division of micro-organisms is between plants and animals but the dividing lines between different types of micro-organisms are often indistinct.

1. **Plants**

Require soluble food which may be either organic or inorganic.

- (a) *Viruses*: The smallest plants can reproduce only within a specific host cell. They are all parasitic and lie on the borderline between living organisms and chemical compounds. Many diseases e.g. influenza, polio are caused by virus infections. they are commonly found

in sewage effluents and are resistant to normal disinfection methods.

- (b) *Bacteria*: Larger than viruses. Are sensitive to temperature and have an optimum growth temperature. They are single-cell organisms and are of vital importance in wastewater stabilisation as well as being responsible for diseases.
- (c) *Fungi*: Are multicellular and are responsible for tastes and odours in water. All chemosynthetic.
- (d) *Algae*: Are photosynthetic plants. In the absence of light some species can exist with a chemosynthetic metabolism in which case they exert an oxygen demand. They do not have definite stems or leaves. Freshwater forms are usually microscopic but saltwater forms can be large e.g. seaweed. Algae and bacteria growing in the same solution do not compete for food but operate in what is termed a synergistic reaction.

2. Animals

Can utilise only organic food and require oxygen.

- (a) *Protozoa*: Live by eating bacteria. A single protozoa can consume many bacteria because of its relatively large size.
- (b) *Crustaceans*: Hard-shelled multi-cellular animals within a shell.
- (c) *Worms and larvae*: Found mainly in bottom deposits where they are important scavengers.

2.8.3 Microbiological Examination

An estimate of the number of living bacteria (viable cell count) in a water sample may be obtained from a plate count on nutrient agar medium. A 1ml inoculum of the sample is mixed with liquified agar at 45-50°C in a petri dish. After the agar has set the plate is incubated. After incubation time has elapsed the original bacteria will have produced colonies visible to the naked eye and results are expressed in counts/ml. They do not record the total bacterial population of a sample since no single medium and temperature will allow all bacteria to grow.

Although it is possible to examine water for a specific pathogenic bacteria a simpler approach for routine analysis uses an indicator

bacteria known as coliform bacteria which is a normal inhabitant of the intestine and is excreted in large numbers. If this bacteria is found in water it is a sign of human pollution and is, therefore, potentially dangerous in that pathogenic organisms might also be present.

2.8.4 Coliforms

Coliforms do not only occur in faeces as they can be normal inhabitants of water and soil but in practice they are assumed to be of faecal origin unless proved otherwise. The total coliform count measures all the coliforms present in the sample.

A particular species of coliform found in domestic sewage is known as *E. Coli*. Detection of coliforms can be achieved using a lactose medium, MacConkey broth inoculated with various dilutions of the sample. The appearance of acid and gas after 24 hours at 37°C is taken as positive indication of coliform bacteria, results being expressed with the aid of statistical tables as most probable number. As a confirmatory test for *E. Coli* positive tubes are subcultured in fresh medium for 24 hours at 44°C under which conditions only *E. Coli* will grow to give acid and gas.

Routine coliform testing comprises of these two tests giving the total coliform count and faecal coliform (*E. Coli*) count.

An alternative technique for bacteriological analysis which is now popular uses special membrane filter papers with a pore size such that bacteria can be separated from suspension. The bacteria retained are then placed in contact with an absorbent pad containing the appropriate nutrient medium in a small petri dish and incubated. Identification of a particular species of bacteria is made on the basis of the type of nutrient provided. Counting the colonies provides the necessary quantitative information.

2.9 Agricultural Pollution

2.9.1 Introduction

The production of food and fibre by an industry called agriculture is an essential and strategic component of society, and a major facet involves managing nutrients N, and P.

2.9.2 Nitrogen cycle

Organic nitrogen is the largest pool of N in the soil. Plants cannot utilise organic N but this N is changed into inorganic forms that are available for plants by soil bacteria as nitrates. Nitrate leaching is especially likely from free draining soils and is both an economic and environmental concern. N from the atmosphere can be transformed

into inorganic forms by lightning. In very wet soils where oxygen in the soil atmosphere is limited, heterotrophic bacteria can transform NO_3 into gaseous N by denitrification.

2.9.3 Waste production on farms

Pollutants from farms can be classified as physical, chemical or biological. The sources of these pollutants include animal wastes, silage effluent, pesticides and fuel oil; animal waste being the most significant. In the EU, 8 tonnes of animal wastes are produced per ha of utilisable agricultural land annually.

Animal wastes are high-strength and have potential to cause serious water pollution problems. These high oxygen demands preclude treating animal waste by conventional processes and land application is the viable and environmentally sustainable method for their removal. Odours are the most recognisable air pollutant arising from this process.

2.9.4 Nitrate Leaching

Although nitrate is the preferred form of nitrogen by plants it is only weakly absorbed by the soil and remains in the soil solution so that it can be leached. In soil there is a tendency for various forms of nitrogen to be converted into nitrate by soil microbes but this is undertaken at a rate such that it is incorporated into microbial biomass. However, fertilisers tend to be converted rapidly to nitrate providing a supply for leaching.

2.9.5 Pesticides

Crop protection chemicals are mostly toxic and are of synthetic organic origin. Three pesticide characteristics influence the potential of a pesticide to be lost in run-off or by leaching. The soil sorption index measures the ease with which it attaches to soil particles; its solubility in water and its half-life being the time required for its original concentration to be halved.

2.10 Effects of Pollutants on the Aquatic Environment

Problems occur when the natural characteristics of a river are altered by pollutant discharges. Pollutants can be organic materials, plant nutrients, toxic pollutants, physical pollutants and biological pollutants.

2.10.1 Organic Material

If the polluting load is heavy, the natural purification processes may be grossly affected. The level of dissolved oxygen can become nought and anaerobic bacteria may thrive and give a foul smell to the water by

producing methane, hydrogen sulphide and ammonia. Few algae are able to thrive under severe organic pollution, so re-oxygenation by photosynthesis is hindered.

De-oxygenation can also occur from inorganic materials, e.g. when ferrous iron enters a river in solution, on combining with the oxygen in the water, it is oxidised to red insoluble ferric iron. The oxidised iron, whilst it remains in suspension reduces light penetration. This type of problem is usually associated with coal-mining effluents.

2.10.2 Plant Nutrients

Of the plant nutrients, the total inflow of phosphorus and nitrogen is the most important. There are two types of algae associated with algal blooms and different conditions are needed for their continued growth. Blue-green algae are able to fix atmospheric nitrogen and, therefore, are not limited by nitrate levels in the water. They are tolerant of high pH. In contrast green algae require nitrate as they cannot fix nitrogen from air and they cannot tolerate high levels of alkalinity.

Generally, increases in both phosphate and nitrate concentrations seem to be the most important in governing the rate of eutrophication in most waters and levels of 0.3 mg/l for nitrate and 0.01 mg/l for phosphate have been suggested as limiting values for algal blooms. A eutrophic lake or land-locked body of water is highly productive in organic material and can result in algal blooms which are short lived and whose decay imposes a heavy oxygen demand on the water. Thus nutrients from sewage and fertilisers can ruin a body of water, as has happened in parts of the Great Lakes, where it is estimated that man-made nutrients have aged the lake 15,000 years quicker than if it were left to its own devices.

2.10.3 Toxic Pollutants

If the effect is death, this gives rise to the expression LD50 (lethal dose) which is the dose large enough to kill 50% of a sample of animals under test. LD50 is normally expressed as mg/kg where kg refers to body weight of the animal concerned. The oral toxicities of some chemicals in small mammals are as follows:

LD50	Examples	Classification
1-10 mg/kg	Arsenic	Highly toxic
10-100 mg/kg	Cadmium, Copper, Lead, Mercury	Moderately toxic
100-1,000 mg/kg	Aluminum, Molybdenum, Zinc	Slightly toxic
1,000+	Sodium, Iodine, Calcium, Potassium	Relatively harmless

A rapid method of assessing the toxicity of a water is the use of a naturally luminescent bacterial species called photobacterium phosphoreum. When in a healthy water the species emits light but

when it is exposed to a toxic solution its light output drops and the reduction in light output is directly proportional to the toxicity of the substance concerned.

An additive effect known as synergism may occur. For example, an equal parts solution of cadmium and zinc is more than twice as toxic as either metal on its own.

2.10.4 Physical Pollutants

(a) *Suspended solids*

All solids tend to reduce light penetration so the growth of plant life in watercourses is inhibited. The bottom-living animals and plants may be smothered as particles settle. Predators which hunt by sight may starve. In turbid water there may be an abundance of leeches as fish are no longer able to see and consume them as food.

One of the most important effects on animals is the damage to fish gills which reduces oxygen intake. The absence of fish in certain streams in Cornwall has been attributed to the SS discharged by the China Clay industry.

(b) *Immiscible liquids*

Oil being lighter than water will spread over the surface to form an extremely thin film which will reduce considerably the rate at which oxygen is transferred from the air to water even though the oil imposes little additional biological load.

(c) *Discharges causing temperature increase*

Within limits a temperature increase causes an increase in the metabolic rates of all aquatic organisms, thereby causing a greater oxygen deficit. A raised temperature also decreases the concentration of dissolved oxygen needed for saturation.

If unacclimatised fish have to pass upstream through a mass of warm water, they may not survive; even though the temperature does not exceed the value such fish are accustomed to elsewhere.

2.10.5 Biological Pollutants

The main types of organisms that are regarded as water-borne pathogens are as follows:-

(a) ***Pathogenic bacteria***

These are bacteria that cause diseases and are due to the activities of humans. Non-pathogenic bacteria are harmless and form an essential part of the aquatic ecosystem.

The usual source is raw sewage, and effluents from sewage treatment works contain some pathogenic bacteria, although 99% of them have been eliminated. Since pathogenic bacteria thrive at 37°C, human body temperature, they do not flourish in river water and die off relatively quickly. For example, 99% of typhoid bacteria present in contaminated river water are said to be destroyed if the river water is stored for seven days. Part of the removal process is due to the activities of predators. Hence, paradoxically, pathogenic bacteria can survive for longer periods in clean water.

Coliforms are a group of bacteria whose absence from drinking water is regarded as a guarantee of freedom from pathogenic bacteria. *Escherichia coli* (*E. Coli*) is the main coliform bacteria present in human excreta but only 1 in 10⁶ may be pathogenic.

Diseases include cholera, typhoid, anthrax, tuberculosis, brucellosis, Weil's disease.

(b) ***Viruses***

The main threat comes from human enteric viruses which are produced by infected persons and excreted faecally, consequently contaminating sewage effluent which may be discharged into a river. Treatment for drinking purposes may not remove all the viruses and it is possible for a person to be susceptible to only one viral particle. The four waterborne viruses which have caused illness in Europe are polio virus, hepatitis virus A, norwalk virus and rota virus.

(c) ***Protozoa***

There have been a number of outbreaks of protozoal infections from water in the UK in recent years; usually cryptosporidiosis. They are not fully removed by sewage treatment processes and may pass through filters used in water treatment. They are not inactivated by chlorination. There is a distinct link between these infections and the pollution of rivers by farm run-off and sewage from an infected population. Dysentery is caused by a protozoa, especially common in warm countries.

2.10.6 Strategy for Controlling Pathogen Transfer

This involves the treatment of wastewater to remove pathogens. As previously discussed, monitoring water supplies for specific pathogens is difficult and the approach is to examine water for indicator bacteria whose presence in water implies a risk of pathogens being present. This approach is a relationship between the indicator bacteria, being usually the coliform group, and the potential risks involved. A water quality guideline is established which specifies an upper limit for the density of an indicator organism above which there is an unacceptable risk.

A barrier approach is, therefore, the strategy for controlling the health risks posed by microbes in drinking waters. This involves the treatment of sewage to remove pathogens as well as the treatment of raw waters, which includes disinfection.

Ideally water destined for human consumption should be free from micro-organisms; however, in practice this is an unattainable goal.

3. ENVIRONMENTAL ENGINEERING TECHNOLOGIES

3.1 Water Treatment Processes

3.1.1 Introduction

The extent of treatment required depends on the quality of the rainwater, the aim being to remove harmful micro-organisms or chemicals. The most common type of treatment for surface water includes clarification and disinfection. Clarification consists usually of coagulation - flocculation, sedimentation and filtration; disinfection usually being by means of chlorine.

3.1.2 Preliminary Treatment

Usually involves a simple screen of about 75 mm to prevent large objects reaching the intake initially. The main screens are usually in the form of a mesh with openings 5 - 20 mm and arranged as a continuous belt. The screening mesh is rotated so that the material collected can be removed. The microstrainer is a development of the drum screen which uses a fine woven mesh 20 - 60 mm which can assist in removal of algae. The mesh is continually washed by high-pressure spray.

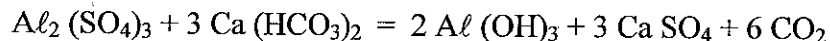
3.1.3 Coagulation

Small turbidity-causing particles called colloids will not settle out of suspension unless a coagulant is added such that the colloidal particles

can collide and form larger heavier particles called flocs. After the initial flash-mix of the coagulant with the water, a gentle agitation follows. The combined process is known as coagulation whereas the slow mixing stage is referred to as flocculation. The most common coagulant is aluminium sulphate $Al_2(SO_4)_3$ known as alum. sometimes synthetic organic chemicals called polyelectrolytes are also added as coagulant aids.

Coagulation and flocculation

Coagulation is always considered along with flocculation and is used to remove particles which cannot be removed by sedimentation or filtration alone. These particles are usually less than 1 μm in size and are termed colloids. They have poor settling characteristics and are responsible for the colour and turbidity of water. They include clays, metal oxides, proteins, micro-organisms and organic substances such as those that give the brown colouration to water from "peaty" catchment areas. The important property which they all have is that they carry a negative charge and this prevents them from aggregating and settling in still water. The particles can be aggregated by adding colloids having an opposite, positive charge. These are added as chemical coagulants. Sufficient alkalinity is required in the water and the insoluble aluminium hydroxide attracts the colloids so they can be removed.



If there is inadequate alkalinity in the water, it can be added in the form of lime or soda ash (sodium carbonate).

In some waters, even with the optimum dose of coagulant, coagulation is poor and it is necessary to add extra substances known as coagulant aids. These aids can be clay, silica or polyelectrolytes. Polyelectrolytes are long-chain organic molecules with positive charges along the chain. The negative colloidal particles are attracted to the positively charged polyelectrolytes. Polyelectrolytes can be used on their own or in conjunction with inorganic coagulants.

After the coagulants are added the water is mixed rapidly in a mixing chamber using a high-speed turbine. Once coagulation has taken place a very fine precipitate or floc of aluminium hydroxide will form. To aid this floc to coalesce with the original colloids in the water, and grow into larger flocs, the water is gently stirred. The process of coalescence is known as flocculation. The gentle stirring continues for 20-45 minutes.

3.1.4 Sedimentation

Under quiescent conditions particles that are denser than water settle. This process is called sedimentation and the layer of accumulated solids at the bottom is called sludge. Settling tanks are designed to operate as the flow slowly continues from the inlet to the outlet, and the water remains in the tank for a period known as the detention time.

$$\text{detention time} = \frac{\text{volume of tank}}{\text{flow rate}}$$

Example:

A sedimentation tank has a capacity of 15,000 m³. If the average flow rate entering the tank is 120,000 m³/day what is the detention time.

$$\text{detention time} = \frac{15,000 \times 24}{120,000} = 3 \text{ hours}$$

Another term of importance is the overflow rate or surface loading and is expressed as m³/m² day, i.e. it is the daily flow rate per unit surface area of tank.

$$\text{overflow rate} = \frac{\text{flow rate per day}}{\text{surface area}} \text{ i.e. } \frac{\text{m}^3/\text{day}}{\text{m}^2} \text{ or } \text{m}^3/\text{m}^2 \text{ day}$$

The effectiveness of a settling tank in removing suspended solids depends more on its overflow rate than on its retention time. This can be seen by references to two tanks of the same volume but of different shapes. Although both have the same retention time for a given flow rate, the shallow tank having a larger area giving rise to a lower overflow rate can be seen to be more effective in removing material as it has less distance to fall before settling.

The concept of shallow depth sedimentation is often used when designing new settling tanks. Prefabricated units comprising a series of included tubes can be installed to effectively increase the effective surface area (or reduce the distance through which material needs to fall to join sludge).

Settling tanks may be rectangular or circular in plan. For the former a continuous chain scrapes the sludge towards a collection hopper; for the latter a rotating mechanism moves it towards a central collection hopper.

Example:

A circular sedimentation tank is to have a minimum detention time of 4 hours and a maximum overflow rate of $20 \text{ m}^3/\text{m}^2 \text{ d}$. Determine the required diameter of the tank and its volume if the average flow rate is to be $6,000 \text{ m}^3/\text{day}$.

$$\text{detention time} = \frac{\text{volume of tank}}{\text{flow rate}}$$

$$\frac{4}{24} \times 6,000 = \text{volume of tank} = 1,000 \text{ m}^3$$

$$\text{overflow rate} = \frac{\text{flow rate per day}}{\text{surface area}}$$

$$\text{surface area} = \frac{6,000}{20} = 300 \text{ m}^2$$

$$\frac{\pi \text{ diameter}^2}{4} = 300 \text{ diameter} = 19.5 \text{ m}$$

An alternative to that of sedimentation is flotation. This uses gas bubbles to increase the buoyancy of suspended solids. The gas bubbles attach to the particles and make their effective density lower than that of the water. This causes the particles to rise through the water to float to the top.

The principal advantage of flotation over sedimentation is that small or light particles that settle slowly can be removed more completely and in a shorter time. Once the particles have reached the surface they are collected by a skimmer.

3.1.5 Filtration

Filtration is a physical process which involves passing through a bed of porous granular material such as sand. As the water flows through the filter bed, the suspended particles become trapped within the pore spaces.

The first filters used very fine sand giving a low flow rate and required manual cleaning when they became clogged. These slow sand filters take up a considerable area although effective.

In modern water treatment plants, the rapid filter has replaced the slow sand filter. The water flows through the filter bed much faster and requires very frequent cleaning. They are cleaned by reversing the direction of flow through the bed, a process known as backwashing.

Many rapid filters use sand but a difficulty that arises is that after backwashing, the larger sand grains settle first and this results in most of the filtering action taking place in the top layer which is finer. The top layer therefore tends to clog up and requires frequent cleaning.

An improved system is known as in-depth filtration when different filter materials are used. If a coarse layer of light density anthracite is used together with smaller grained sand after backwashing the size distribution will be reversed. In effect, the upper coal layer acts as a rough filter, removing most of the large impurities first. This allows the sand layer to remove the finer particles without getting clogged too quickly.

$$\text{flow rate} = \text{filtration rate} \times \text{area.}$$

Example:

A square filter box is to be designed for a filtration rate of $2.8 \text{ l/m}^2 \text{ sec}$. What is the required surface area and side dimension of the unit if the flow rate is $6,000 \text{ m}^3/\text{day}$.

$$\frac{6,000 \cdot 10^3}{24 \cdot 60} = 2.8 \times \text{area} \quad \therefore \text{area} = 24.8 \text{ m}^2$$

$$\text{dimensions} = 4.98 \text{ m} \approx 5 \text{ m.}$$

Example:

If the above detailed filter is back washed once a day for 12 mins. at a rate of $10 \text{ l/m}^2 \text{ sec}$ what % of the total flow rate is used for cleaning the filter?

$$\text{quantity used for back washing} = 10 \times 5 \times 5 \times 60 \times 12 \times 10^{-3} \text{ m}^3$$

$$= 180 \text{ m}^3/\text{day}$$

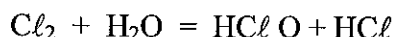
$$\text{daily throughput} = 6,000 \text{ m}^3/\text{day}$$

$$\% \text{ waste} = \frac{180 \cdot 100}{6,000} = 3\%$$

3.1.6 Disinfection

Chlorine is the most commonly used substance for disinfection and chlorination is considered to be the most important process for preventing the spread of waterborne disease.

When chlorine is dissolved in pure water it reacts to form hydrochloric and hypochlorous acid.



The disinfectant element being the hypochlorous acid. However when chlorine is first added to water containing some impurities the chlorine reacts with them and is unavailable for disinfection. The amount of chlorine held up in this initial reaction is called the chlorine demand.

If dissolved ammonia is present in the water, the chlorine will react with it to form compounds called chloramines, and are referred to as combined chlorine. It is effective as a disinfectant but is slow acting. As more chlorine is added some of the chloramines are initially destroyed until the break point dosage is achieved after which the added chlorine becomes available as free chlorine. Free chlorine is the preferred form for disinfection of water as it works faster and does not cause objectionable odours. Sometimes chlorine dosages up to 10 mg/l are needed to obtain a free chlorine residual of 0.5 mg/l.

Ozone is a potent disinfectant but is more expensive. It does not maintain a residual in the water and growths may occur in the distribution system unless chlorine is subsequently added.

Ultraviolet light can be used for disinfection as it is absorbed by genetic material interfering with their ability to reproduce and survive. It uses lamps and does not involve chemical handling thereby minimising safety concerns. Again there is no residual.

3.1.7 Water softening

Generally when the hardness exceeds 500 mg/l it is usual to remove the calcium and magnesium by a process known as water softening; the systems being the lime-soda method and the ion-exchange method.

(a) Lime-soda method

Addition of lime $\text{Ca}(\text{OH})_2$ and soda ash Na_2CO_3 has the effect of converting the soluble salts into insoluble salts which are removed by sedimentation.

(b) Ion-exchange method

Involves passing the water through a special ion-exchange material. Eventually the exchange capacity is destroyed and must be regenerated by washing the exchanger with salt.

3.1.8 Desalination

Two basic methods are available for desalination.

(a) Thermal processes

In distillation freshwater is separated from salt water by heating, evaporation and condensation.

(b) Reverse osmosis

If a semi-permeable membrane separates salty water of two different concentrations there is a natural tendency for the concentrations to become equalised by a flow of water from the dilute side to the concentrated side. This is osmosis. But high pressure applied to the high concentration side of the membrane reverses the direction of flow. Freshwater diffuses through the membrane leaving a more concentrated salt solution behind.

3.1.9 Additional Treatment

As a result of stricter standards set by the EC Directive on the Quality of Drinking Water it is now often necessary for drinking water to have further treatment.

(a) *Nitrate removal*

Nitrate in water has become a significant problem and the Drinking Water Directive sets a maximum concentration of 50 mg/l. High nitrate levels can cause cyanosis or methalinoglobinaemia in babies.

Ion exchange is used in some treatment plants to remove nitrates from drinking water. In this process the water is passed through an ion exchange resin which removes the problem ions and replaces them with ions which do not affect the water quality.



where R is a complex compound.

The RNO_3 can then be removed by passing through a brine solution which then regenerates the $R\ Cl$.

Biological fluidised beds are also used to remove nitrates. Denitrifying (nitrate-removing) bacteria are grown in an

anaerobic environment on the surface of solid particles which are then fluidised by the nitrate-containing water. When a carbon source of methanol is added, the bacteria reduce the nitrate in the water to nitrogen gas.

(b) ***Removal of trace organics***

After conventional treatment a water may still contain trace concentrations of synthetic organic compounds which, if left in the water, can lead to taste and odour problems. The problem is more likely to arise where the raw water abstracted has been badly polluted. The problem can be solved by the process of activated carbon adsorption after the filtration stage. Granular activated carbon can be obtained from roasting vegetable or animal matter at 800 - 900°C in a vacuum furnace. It is extremely porous, having a high surface area per unit mass (1,000 m²/gram). It is an effective adsorbent of organic compounds and can be used for the removal of soluble phenols which would produce strongly smelling and tasting chlorophenols upon reaction with chlorine in the disinfection stage. The GAC once exhausted can be regenerated by heat treatment.

3.2 **Wastewater Treatment and Disposal**

3.2.1 **Introduction**

Untreated sanitary sewage has a BOD of about 200 mg/ℓ and a TSS of about 240 mg/ℓ, 35 mg/ℓ of N and 10 mg/ℓ of P. The amount of pathogens is roughly proportional to the coliform bacteria which is about 1 billion per litre. The basic purpose of treatment is to destroy pathogenic micro-organisms and to remove most suspended and dissolved organic materials. Sometimes it is also necessary to remove the plant nutrients - nitrogen and phosphorus.

Treatment efficiency is a measure of the reduction in the amount of pollutant when comparing the effluent with the influent.

$$\text{efficiency} = \frac{(P_{\text{inf}} - P_{\text{eff}})}{P_{\text{inf}}} 100\%$$

P_{inf} = conc. of pollutant in influent

P_{eff} = conc. of pollutant in effluent

Example:

A sewage treatment plant influent of TSS-250 mg/ℓ and BOD₅ - 200 mg/ℓ has a TSS - 20 mg/ℓ and BOD₅ - 30 mg/ℓ in the effluent. What

is the removal efficiency for TSS and BOD₅. If the flow rate is 5,000 m³/day how many kg of each is discharged in the plant effluent each day.

$$\text{removal efficiency TSS} = \left(\frac{250 - 20}{250} \right) 100 = 92\%$$

$$\text{removal efficiency BOD}_5 = \left(\frac{200 - 30}{200} \right) 100 = 85\%$$

$$\text{TSS effluent load} = 20 \cdot 10^{-3} \cdot 5,000 = 100 \text{ kg}$$

$$\text{BOD}_5 \text{ effluent load} = 30 \cdot 10^{-3} \cdot 5,000 = 150 \text{ kg.}$$

Wastewater discharged by industry may contain toxic chemicals unless pre-treated.

3.2.2 Primary Treatment

This process consisting of physical processes may remove about 60% of the TSS and 35% of BOD.

Bar screens: Retain various debris and consist of metal bars spaced about 25 mm apart.

Comminutor: A mechanical cutting device installed after the coarse screens and shreds rags etc.

Grit removal: Suspended grit can cause wear on pumps and are removed in long narrow tanks called grit chambers. Some may be aerated to keep the organic solids in suspension.

Primary settling: Similar to those used in water treatment. In addition to mechanical sludge collectors that continually scrape the settled solids along the bottom a surface skimming device is used to remove grease from the surface.

3.2.3 Secondary Treatment

This is a biological process whereby microbes metabolise biodegradable organics converting them into carbon dioxide, water and energy for their growth and reproduction. To keep the microbes happy and productive they must be provided with enough oxygen, adequate supply of organic material and suitable temperature. The most common biological treatment systems include the trickling filters and the activated sludge process. The former is a fixed growth system whereby the microbes are attached to a surface while the wastewater

flows over the surface to provide contact with the organics. Activated sludge is a suspended growth system.

Trickling Filter: Consist of a bed of crushed rock about 2 m deep; usually circular up to 60 m diameter. A rotary distributor arm sprays the sewage and an underdrain system collects the wastewater from the bottom of the bed. As the micro-organisms grow the biological slime layer on the rock gets thicker and eventually the flowing wastewater washes it off the surface of the stones. This material which consists of the micro-organisms that have absorbed the organic waste into their bodies are removed in the secondary sedimentation tank. A portion of the effluent from the trickling filter is pumped back to the inlet. This recirculation improves the quality of the effluent and

$$\text{recirculation ratio} = \frac{\text{recirculated flow rate}}{\text{sewage flow rate}}$$

generally in the range 0 to 3.0

The rate at which organic material is applied to the filter is usually expressed in kg of BOD₅ per m³ of bed volume per day, i.e. kg/m³.day.

Example:

The BOD removal efficiency of a trickler filter system is 79% and the efficiency of the primary treatment that precedes it is 35%. If the raw BOD is 200 mg/ℓ what is the effluent BOD?

$$\text{removal in primary} = \frac{35}{100} \times 200 = 70 \text{ mg/}\ell$$

$$\text{removal in secondary} = \frac{79}{100} \times 130 = 103 \text{ mg/}\ell$$

$$\text{effluent BOD} = 200 - 70 - 103 = 27 \text{ mg/}\ell$$

Activated Sludge Treatment: Consists of an aeration tank and a secondary settling tank. Air is provided by either mechanical propeller-like mixers or compressed air. The aerobic micro-organisms for an active suspension of biological solids called activated sludge and the combination of the activated sludge and waste-water in the aeration tank is called the mixed liquor.

After about 6 hours of aeration the mixed liquor flows to the secondary tanks where the supernatant is discharged. A part of the settled sludge is recycled to the aeration tank to ensure a high bacteriological population.

The two main methods by which activated sludge units are aerated are through:-

- (a) Diffused air aeration: are of two categories; coarse and fine bubble aeration. In the former, air is pumped through open-ended pipes or pipes with holes along their length. In fine-bubble aeration, filtered air is pumped through very fine diffusers. Although they are more efficient the air must be free of dust particles or the diffusers become blocked.
- (b) Mechanical aerators consist of submerged or partially submerged impellers attached to motors. The impellers agitate the waste-water vigorously, entraining air from the atmosphere.

At the end of the secondary treatment stage more than 99% of the pathogenic organisms are removed.

Comparison between the biological trickling filter and activated sludge systems.

The advantages of the activated sludge process include the following:-

1. If the quality of the influent is particularly poor, a greater proportion of the settled sludge can be recycled so that the effluent quality can be improved.
2. The nuisance of filter flies is avoided.
3. The loss of head is less, thereby saving pumping.
4. Considerable space is saved. Ten factor difference.

The disadvantages of the system are:-

1. Require continuous attention.
2. Consume large amounts of energy.
3. More vulnerable than filters to toxic materials in influent.
4. Does not convert ammonia to nitrate unless very high concentrations of oxygen are maintained. This requires extra costs and longer retention times.

3.2.4 Other secondary treatment processes

A rotating biological contactor method is gaining popularity. The lightweight discs are about 3 m in diameter and are spaced about 40 mm apart on a shaft. The discs are partially submerged in settled sewage. As the shaft rotates, the disc surfaces are alternatively in contact with air and with waste-water.

In rural areas where land is cheap, sewage lagoons or oxidation ponds are used. Generally about 2 m deep and both aerobic and anaerobic reactions take place. Detention time of the order of 60 days. An alternative technique is known as reed beds.

3.2.5 Tertiary treatment

Although a conventional sewage-treatment plant may be able to produce an effluent of better than 30 : 20 standard at times, the reliable production of an effluent better than 30 : 20 require some form of tertiary treatment. The removal of additional SS and BOD is often referred to as effluent polishing and is often accomplished by using processes similar to a conventional water treatment plant.

The use of sewage as a source of potable water is technically feasible but would be costly as some impurities are completely unaltered by normal water-treatment methods. However, there are examples of situations where emergency conditions have required the treatment of heavily polluted waters without danger to consumers. For example in 1956-7 at Chanute in the USA drought conditions caused a failure of water supply and sewage effluent was recycled into a water-treatment plant. After ten cycles there had been a considerable build-up of impurities; especially TDS.

If the characteristics of a treated sewage effluent is compared with EC recommendations for raw water it is seen that the quality as regards chloride, nitrogen, phosphates and coliforms are exceeded. Various tertiary techniques are available for their removal.

3.2.6 On-site waste-water disposal

Whereby disposal of waste-water is provided for individual households, the most common type of subsurface disposal system is the septic tank. Essentially settleable solids accumulate in the sludge zone at the bottom of the tank and primary effluent flows into the leaching field. Some of the sludge decomposes under anaerobic conditions but to ensure proper operation septic tanks should be pumped every few years. From the leaching field the effluent percolates with micro-organisms and pollutants removed by filtration, adsorption and biological decomposition.

3.2.7 **Sludge management**

This is the treatment of sludge to reduce its volume and to stabilise it previous to disposal. It can account for over 50% of the total cost of a treatment plant.

It is usually impractical to treat watery sludges of concentration <4% and a thickening unit called a gravity thickener is usually used to increase the concentration. It resembles a circular sedimentation tank with stirrers. The thickened underflow of sludge is withdrawn from the bottom of the tank and the effluent is pumped back to the inlet of the plant. Sludge can be thickened >10%. This process is also known as sludge conditioning.

Sludge digestion is a process in which biological decomposition occurs. It reduces the total mass of sludge solids, destroys pathogens and makes it easier to dewater the sludge. Well-digested sludge has the appearance of a rich potting soil.

The digestion process is essentially completed in the first tank within about 15 days of detention time. The sludge then flows to a second tank which serves for sludge settling. The digester supernatant is high in SS and BOD and is recirculated.

The process of removing enough water from a liquid sludge to change its consistency to that of moist earth is called sludge dewatering. The usual system is vacuum filtration. This is a continuous process in which a revolving segmented drum covered with filter cloth is partially submerged. A vacuum is applied to the submerged segments and sludge is attracted to the surface of the cloth. A scraper blade removes the sludge cake assisted by change to positive pressure in the relevant drum segment.

Methods for final disposal of sludge include ocean dumping, landfill, incineration and land application. An EC Directive prohibits the disposal at sea after 1998. Sewage sludge if dewatered to about 30% solids content usually has a sufficiently high calorific value to support self-sustaining combustion.

Large-scale land application is an option that makes beneficial use of the nitrate and phosphate nutrients. However product liability is a concern as is the potential for water pollution; heavy metals and toxic organics being of particular concern.

3.2.8 **Disinfection**

A number of new sewage treatment works utilise ultra violet disinfection which is invisible to the human eye, being beyond the blue

end of the visible spectrum. Usual source is a low pressure mercury vapour lamp of similar construction to a domestic fluorescent lamp. The UV light disrupts the process of division of DNA. However, not all bacteria, protozoa and viruses are killed. The reduction in faecal coliform bacteria can be seen from the likely number present on completion of each stage of treatment.

Raw	+ 10^6 per 100 ml
Primary	+ 10^6 per 100 ml
Secondary	10^4 - 10^5 per 100 ml
UV	1 - 10^3 per 100 ml

As the Bathing Water Directive requires a mandatory limit of 2×10^3 and a guideline quality of 10^2 to meet blue flag standard, depending on dilution characteristics, UV disinfection may have to be installed.

3.3 **Industrial Air Emissions Control**

3.3.1 **Introduction**

The optimum strategy for air quality protection is to reduce the amount of pollution at its source. Several types of air cleaning devices can collect or trap air pollutants; some control only gaseous pollutants whilst others control only suspended particulates.

Dark smoke tends to be released wherever carbon bearing fuels are burnt inefficiently; often the case when the temperature is too low or the supply of air inadequate. The Ringelmann charts serves to assess the darkness of a plume of smoke by visual comparison, whereby 0 is white and shade 5 is black.

In law dark smoke is Ringelmann 2 and black smoke is as dark as Ringelmann 4. All heating installations larger than a domestic boiler must be able to operate continuously without emitting smoke.

Control of grit, dust and gaseous pollutants is preferably by modification of the process involved to avoid the material becoming airborne in the first instance as the cleaning technologies require a considerable amount of energy.

3.3.2 **Control of particulates**

Most ambient particulate air pollutants come from stationary sources e.g. power plants, mining activities, refuse incinerators.

Gravity settlers: The simplest kind of air cleaning device being simply an enlarged section in a flue in which the velocity of the gas is reduced. Baffles are usually added to increase efficiency.

Cyclones: Removes the particulates by causing the carrier gas to flow in a spiral path inside a cylindrical chamber. Dirty gas enters the cyclone chamber from a tangential direction at the outer wall of the chamber. The larger particles move outward and are forced against the wall. Particles are slowed down by friction and slide down the wall into a dust hopper at the bottom.

Wet Scrubbers: The upward flowing carrier gas is washed by water sprayed downward from a series of nozzles onto a porous packing and the particles collected by both the liquid droplets and adhesion to the liquid on the packing.

Electrostatic Precipitators: Particles suspended in the air are given an electric charge as they enter the unit and are removed by the influence of an electrical field. The collecting surfaces comprise a group of parallel rectangular metal plates suspended vertically inside a box-like structure. Electrode wires hang between all the collecting surfaces. Particles which stick to the collector plates are removed periodically when the plates are mechanically vibrated. An electrostatic precipitator can remove particles $> 1 \mu\text{m}$ with a 90% efficiency.

Fabric Filters: Comprises of a solid porous media which allows only gas and very small particles to pass through. The removal efficiency is 100% for particles of $1 \mu\text{m}$ and can remove particles down to $0.01 \mu\text{m}$. Usually preceded by gravity settling chambers or cyclones to reduce the cleaning frequency of the bags.

3.3.3 Control of Gases

Gaseous air pollutants can be controlled using absorption, adsorption and incineration.

Absorption: The transfer of a gaseous pollutant into a contacting liquid is an absorption process. The gas must either be soluble in the liquid or react with the liquid. Wet scrubbers similar to those used for particulates may be used.

Adsorption: Gas adsorption is a surface phenomenon; the gas molecules are sorbed (attracted to and held) on the surface of a solid. Activated carbon is the most common adsorbent material and a unit can have efficiency greater than 95%.

Incineration: Can be used to convert gaseous hydrocarbon pollutants to carbon dioxide and water. To achieve complete combustion sufficient burning time and turbulence must be allowed and efficiencies of 99-95% are achievable.

3.4 Emission Controls from Vehicles

In urban areas 95% of carbon monoxide emissions are from car exhausts. These are controlled by catalytic converters which converts CO and unburned hydrocarbons to carbon dioxide and water.

Other key engine design features that affect emissions include compression ratio and timing. As a result of emission controls today's car emit about 80% less pollution than cars of the 70's.

Fuel composition and removing impurities in fuel reduces pollution. Lead is not only a health hazard but also damages catalytic converters. Another example of an undesirable substance in fuel is sulphur which not only leads to increased sulphur dioxide emissions but interferes with the catalytic converter.

Alternative fuels include compressed natural gas, and hydrogen. Compressed natural gas produces 50% less carbon monoxide and no toxins like benzene. Hydrogen produces no hydrocarbons and has the highest energy content of any combustible fuel.

The only zero-emission vehicles presently capable of mass production are the electric powered car which uses lead-acid batteries. They have a range of about 80 miles but it is likely that emissions from the mining, smelting and recycling of lead needed to operate a large fleet would pose serious threats to public health.

3.5 Agricultural Pollution Control

Controlling agricultural pollution requires an interdisciplinary approach that combines the expertise of engineers, agronomists, soil scientists and biologists. It derives from point sources around the farmyard and from non-point sources such as fields.

Agricultural point source pollution control facilities are in reinforced concrete and should be of adequate capacity to hold the pollutants and rainwater until they can be further managed typically by application to land.

Example:

A dairy farmer milking sixty cows wants to add a below-ground slurry pit to contain animal wastes and runoff from a 15 m x 45 m exercise yard for a period of four months during which time the average precipitation totals 560 mm. What size of tank should be constructed. (Cow daily excreta 41 ℓ/day)

Animal waste generation	$60 \times 41 \times 120 = 295\,10^3 \ell$
Runoff	$15 \times 45 \times 0.56 = 378\, \text{m}^3$
Required volume of tank	$= 673\, \text{m}^3$

Land application of wastes is the most economical, practical and environmentally sustainable method for managing agricultural wastes and codes of practice have been developed to guide the utilization of these wastes.

The techniques by which wastes are applied to land are dictated by the waste characteristics. Wastes that are $>5\%$ dry matter content are land applied by flail-type machinery. Wastes between 4 and 15% are slurries and are applied as liquids. Wastes $< 4\%$ are applied using irrigation equipment.

3.5 Remedial Treatment of Contaminated Land

3.5.1 Introduction

Since the time of Roman lead mining, the UK has seen human activities alter the chemistry of land. It is estimated that 100,000 to 220,000 ha of land in the UK representing 0.4 to 0.8% of the land area is contaminated.

“Land that contains substances which when present in sufficient quantities are likely to cause harm to health or the environment as a result of current or previous use.”

This being the definition given by DEFRA.

The substances causing the contamination are known as hazardous material being materials “which have the potential to cause harm.” Hazards may be chemical (carcinogenic), biological (pathological bacteria) or physical (flammable gas).

Risk is the likelihood that harm will occur to human health, living organisms, environmental quality or to assets. A number of serious incidents from the mid 80's concentrated the Government's thoughts on the risk of constructing on contaminated land which resulted in 1995, in an insert on Contaminated Land in the 1990 Environmental Protection Act.

The risk associated with contaminated land should be assessed in terms of the route by which a hazard comes into contact with a target – the pathway.

hazard → pathway → target

Risk Assessment

The process of assessing whether the existence of contaminated matters is termed risk assessment and is “an evaluation of the likelihood of harm.”

The process of risk assessment consists of

1. hazard(s) identification; what are the toxic substances and their hazards?
2. exposure assessment; what are the pathways?
3. dose-response assessment; how potent/dangerous are the toxic substances?

Risk Management

Risk management consists of the risk assessment element and the risk reduction element. Isolating or removing contaminant sources, intercepting pathways or removing targets reduces risks. It also considers other factors such as the financial and technical feasibility of remedial technologies.

Having carried out risk assessment and decided that the levels of contamination pose unacceptable risks to defined targets it is necessary to develop a remedial strategy, put it into effect and monitor the effect of the action. The reduction required in the level of toxicity will depend upon whether the site is required for residential, horticultural or industrial use.

3.5.2 Site Investigation

Personnel should not enter a site unless a desk study has indicated that it is safe to. Site investigation work is subject to health and safety legislation including the Control of Substances Hazardous to Health (COSHH) Regulations 1988. These require an assessment to be made of all relevant health risks before a work activity commences, and the use of appropriate control measure where necessary. The Management of Health and Safety at Work Regulations 1992 extend the responsibility to the general public. The Construction (Design and Management) Regulations require that projects can be constructed satisfactorily.

Investigations should always seek to balance the degree of confidence required against the total cost of the work.

3.5.3 Remediation Methods

Remediation Methods can be classified into two groups:

Civil Engineering Techniques to remove or contain contamination to block pathway and process-based methods to treat, stabilise or destroy contaminants.

3.5.3.1 Civil Engineering Techniques

Excavation Contaminated sites are frequently remediated by excavation and disposal to controlled landfill. The approach represents a rapid method of dealing with the problem but has been criticised as it represents only a transfer of material from one location to another rather than a final solution. The EU Landfill Directive (2004) has also significantly increased cost. A Waste Management Licence would be required for any on-site disposal.

Containment Based on the use of low permeability barriers to isolate the material or any associated leachate or gaseous products from the environment. The barriers can be constructed from natural or synthetic materials. A cover system consists of a layer or layers of selected materials that covers the area of contamination. Possible materials include clay, geotextiles, concrete and asphalt. Cover systems do not necessarily control groundwater movements or gaseous emissions and odours. In -ground barriers can be used to isolate around and under the mass to achieve complete isolation and is known as macro encapsulation. Vertical barriers can be constructed by excavation followed by the backfill of a barrier material such as clay or concrete. Displacement barriers such as steel sheet piling do not require excavation. Vertical and horizontal barriers may be grouted/injected under pressure and a special auger with under reamer can be used to create a solid horizontal barrier at depth.

3.5.3.2 Process-based techniques.

Physical Processes Separate contaminants from uncontaminated material by exploiting differences in their physical properties such as density, volatility or size and include soil washing and vapour extraction.

Soil washing involves essentially the transfer of the contaminant into an aqueous phase by leaching using water or steam. The contaminant rich liquor can then be treated as wastewater. Known also as soil flushing.

Vapour extraction is an in-situ process whereby a vacuum is applied through extraction wells to suck contaminants through the soil so that they are removed. An air sparging well may also be incorporated to further induce flow. Blast

fracturing by detonation of explosives enhance the procedure by increasing the permeability of the soil.

Biological Processes The aim is the breakdown of contaminants to carbon dioxide, water and simple inorganic compounds. Under optimum conditions a large number of organic compounds can be degraded by microorganisms.

Chemical Processes Chemical reagents are added to the soil to bring about a reaction to destroy contaminants. Reduction/oxidation (redox) reactions are the most common basis for destructive treatments and oxidising agents include chlorine gas, ozone and oxygen. Reducing agents include aluminium, sodium and zinc metals. Lime can also be added to adjust pH to neutralise acidic soils. Treatments can be exist or insitu whereby the chemicals are introduced via wells or by creating permeable reactive barriers whereby the reactive media is placed in a deep trench to intercept a plume of contaminant.

Thermal Processes involves excavation and heating to 600°C-1200°C. At the lower temperature, known as thermal desorption, the residual material is soil-like whilst at the higher temperature, known as incineration the residue is ash with all humus destroyed.

Solidification Processes Binding the contaminants within an insoluble matrix so that the material will not leach. The binder includes portland cement, fly ash, lime, silicates and resins.

3.6 Bioremediation Technologies

3.6.1 **Introduction.**

Bioremediation has been defined as the use of living organism to reduce or eliminate environmental hazards resulting from accumulation of toxic chemicals and is usually brought about by the action of micro-organisms which destroy the contaminant source through biodegradation. Biodegradation has been applied since the 1980's and can be implemented in site via wells or on site which require excavation of the ground. If conditions are not optimal bioremediation may be prevented or hindered. Typically a suitable pH range would be 5 to 8 with temperature 0 to 40° c. The following elements are also required carbon, oxygen, hydrogen, nitrogen, sulphur, phosphorous, potassium, iron, calcium, magnesium and trace elements. A degree of soil moisture is also required.

- 3.6.2 **In- situ technologies** is the treatment of contaminated ground without excavation. This is usually achieved by introducing materials into the subsurface. The material depends on what is limiting bioremediation occurring naturally be it nutrients and/or degrading organisms.

Enhanced in-situ bioremediation whereby nutrients are introduced to a contaminated zone either by applying directly to the soil and relying on percolation or by creating an artificial flow of additives with a borehole.

Bioventing/Biosparging This technique is limited to coarse-grained soils and involves pumping air or oxygen through contaminated land that can encourage microbial activity.

Bioaugmentation involves the addition of microorganisms that are known to deal with the contaminants. Survivability and competition with indigenous organisms can be a major problem.

Permeable reactive barriers are reactive zones through which contaminated water is channelled in which contaminants react to form less toxic products.

Phytromediation Plants can take up contaminants particularly metals and store them in roots and stems. Ranges of plants have been used including grasses and trees. Heathrow Airport has installed reed bed system for the treatment of runoff containing de-icing fluid.

- 3.6.3 **Ex-situ technologies** Extracted material may be treated on or off site. It allows greater control and can be easier to operate successfully.

Biopiles are constructed mounds of soil, which may be static piles or involve an element of composting where additional organic matter is added. Composting can generate significant temperatures encouraging biodegradation. Usually a constructed base is required to ensure that any contaminated liquids are collected and air may be blown through. Typical operations may require 3-6 months for a single biopile and are usually used for petroleum contaminants and not for difficult pollutants such as PCB's and dioxins. The climate and weather has a significant influence.

Windrows. Soil is arranged in long rows usually with a prepared base and is turned regularly to aerate.

Land farming. Soil can be tilled in thin layers using standard agricultural equipment to ensure good mixing of soil.

Bioreactors Involve treating material in liquid or slurry form. The soil may be treated in a lagoon in slurry form or in a closed vessel. Slurries are usually introduced with the necessary additives and are thoroughly mixed for the treatment period. A fixed support is usually required to allow significant growth of microorganisms and usually the bioreactor contains a particulate material usually made of plastic upon which biofilms form which treat passing water.

3.6.4 **Bioremediation problems and advances.**

Bioremediation can be hindered by a number of factors;

Mixed contaminants Microorganisms may specifically attack only one or a few contaminants and the presence of the other chemicals present could be toxic and adversely affect bioremediation. A particular problem is co-contamination with both organic and heavy metals.

Heterogeneity Variability in type of contamination in various locations in the soil can be a problem with insitu bioremediation.

Weather/climate Temperature and moisture levels are important in terms of microbial activity. Flooding can cause practical difficulties.

The microbiological science behind bioremediation technologies is relatively crude relying on the ability of naturally occurring organisms. Genetically modified organisms (GMO's) can be engineered to be better at degrading certain compounds or at resisting the effect of toxic metals. However their use insitu is problematic due to concerns about their long term survival and effects on the natural environment and their main application will be in bioreactors.

There are potential technologies to improve contaminant availability to organisms. Surfactants are particular chemicals that can be added to soils to increase their solubility and hence their bioavailability. Electrokinetics which involves the use of an electric current between electrodes planted in a contaminated site, can be used to attract contaminants to micro organisms.

Phytoremediation in bioremediation is currently in development using genetically engineered plants. Plants are known to have symbiotic relationships with micro organisms in the root system and beneficial relationships can be artificially

created. For example it has recently been discovered that combining a particular fungus with wheat can allow plant growth and cyanide detoxification in soils where neither organism could grow alone. Growing biofuels on contaminated land may have benefits for both contaminant removal and growth of biomass for energy production.

Civil Engineering

- Advantages:*
1. Wide range of contaminants can be handled.
 2. Rapid remediation.
 3. Cover and barriers are low in cost.

- Disadvantages:*
1. Containment either on site or removed to another.
 2. Long term restrictions if not excavated.
 3. Long term monitoring including possible leaching and gas collection

Process based

Physical/Biological/Chemical

- Advantages:*
1. Reduce containment levels
- Disadvantages:*
1. Secondary waste streams may require treatment.
 2. Use of some solvents may have Health and Safety implications.
 3. Slow process normally.

Thermal/Solidification

- Advantages:*
1. Applicable to wide range of containment.
 2. Rapid treatment possible.
- Disadvantages:*
1. For solidification contaminants only contained; for thermal heavy metals can be concentrated in ash.
 2. Control of emissions required.

FORMULAE SHEET

$$\text{BOD}_t = \text{BOD}_{\text{ult}} (1 - e^{-k_1 t})$$

$$\text{Detention time} = \frac{\text{Volume of tank}}{\text{flow rate}}$$

$$\text{Overflow/filtration rate} = \frac{\text{Flow rate per day}}{\text{surface area}}$$

$$D_t = \frac{k_1 L_o}{(k_2 - k_1)} (e^{-k_1 t} - e^{-k_2 t}) + D_o e^{-k_2 t}$$

$$D_c = \frac{k_1}{k_2} L_o e^{-k_1 t_c}$$

$$t_c = \frac{1}{(k_2 - k_1)} \log_e \left[\frac{k_2}{k_1} \left(1 - \frac{D_o (k_2 - k_1)}{k_1 L_o} \right) \right]$$

$$Q_p = 0.278 \text{ CAI m}^3/\text{sec. where I in mm/hr. and A in km}^2.$$

$$P_c = \frac{1.8 (1.1 - C) \sqrt{3 \cdot 28D}}{S^{1/3}}$$

Atomic Mass

Calcium:	20
Oxygen:	16
Chlorine:	17
Hydrogen:	1
Magnesium:	12
Carbon:	12
Sulphur:	16