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Water pollution control

Edited by Suresh T. Nesaratnam

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Contents

Section 1: Water basics

1.1 Introduction

We can all relate to water. We know we need it to survive – indeed, the early great civilisations of Egypt and Mesopotamia were centred on river valleys where there was a plentiful supply of fresh, clean water.

When we take water into our bodies, it is used in several ways. For example:

- for cooling – it helps keep our bodies at around 37 °C
- as a waste disposal medium
- as a conductor for nerve impulses
- as a component in the digestion of food
- as a solvent in which vital chemical reactions take place.

You can see from the above that even if you didn't move an inch, your body would still need water to keep you alive.

Water is a fascinating subject, encompassing chemistry, biology and physics. Apart from keeping us alive, water is used extensively in industrial processes, for recreation and for transport. It is something we can't do without.

The water we use for domestic purposes ought to be free from contaminants, yet water pollution is a major

problem in many countries. According to the World Health Organization (WHO, 2002), about 1.7 million people die each year due to unsafe water, sanitation and hygiene. This text endeavours to outline the need for monitoring of the aquatic environment, leading to effective means of protection being put in place. It details various sources of water pollution, and describes the effects that different pollutants have on water. Sewage treatment is then considered in detail, and various treatment methods are presented; this is followed by sludge treatment and disposal. Next, the important subject of water quality testing is addressed, with details of the different tests. Industrial wastewater treatment is introduced, and the final section looks at river quality modelling.

The self-assessment questions (SAQs) located throughout the text will help you to review and remember what you have read.

1.2 The hydrological cycle

The *hydrological cycle* – the continuous cycling of water between land, open water surfaces and the sea, either directly or indirectly – is a complex process that has been known about for a long time (Figure 1). Probably the oldest reference to the hydrological cycle is found in the *Chandogya*, one of the principal Upanishads, which says 'rivers … lead from sea to sea'. It reveals that as early as 1000 BCE, attempts were being made to

interpret and explain recurrent phenomena on the basis of direct experience.

Figure 1 Early understanding of the water cycle?

View description

The identifiable mechanisms of the cycle are complicated not only by the characteristics of air–water–land interfaces across which the cycle operates, but also by climatic factors that vary in both time and space. The various operations and mechanisms within the cycle are illustrated in Figure 2.
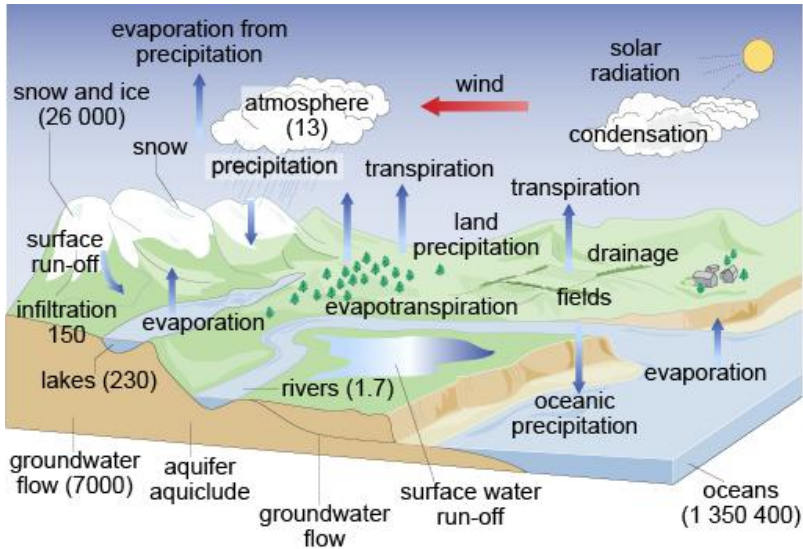
Figure 2 The hydrological cycle (volumes are in Tm^3 = 10^{12} m^3)

1.3 The natural aquatic environment

Now that you have been introduced to the basic hydrological cycle, this subsection will consider the importance of water and how crucial dissolved oxygen is to aquatic life. The physical, chemical and biological characteristics of natural waters will then be explored. Importantly, how the parameters vary will be

considered. Seasonal effects are important, as you might imagine.

1.3.1 Water, the medium of life

Water is an excellent *solvent*, so it is never pure – even in its 'natural' state, it contains a variety of soluble inorganic and organic compounds. Water can also carry large amounts of insoluble material in *suspension*. The amounts and types of impurities vary with location and time of year, and determine some of the characteristics of a particular watercourse.

One of the most important determining factors is the presence of organic material in *solution* or in suspension. Organic material can be used as food by the organisms living in natural water, provided the material is *biodegradable*. The basis of a *trophic system* in a river is the inorganic and organic materials it contains, their biodegradation by decomposer organisms, and the products of the photosynthetic activities of the primary producers (green plants and algae).

In water, as on land, the primary producers are eaten by herbivores (primary consumers) and these in turn are devoured by the secondary consumers (carnivores). The interdependence of these organisms gives a complex food web within which there are many food chains, the successive links in the chains being composed of different species in a predator–prey relationship. For a river, a typical food chain could be:

alga → protozoan → mayfly nymph → small fish (e.g. minnow) → large fish (e.g. pike)

Scavengers eat bottom debris, including dead organisms. Any uneaten dead organisms are broken down by decomposers (mostly bacteria and fungi), releasing nutrients that can be taken up by plants.

Through this cyclic movement of nutrients, the water environment achieves an ecological equilibrium. In theory, in any given stretch of water a balance occurs between the production of living material and the death and decomposition of organisms over a period of time. The river neither becomes choked with living organisms nor is devoid of them – although, depending on location and geological conditions, the numbers and varieties of organisms in the *biota* vary enormously. The maintenance of equilibrium is dependent on the complexity of biota and the interlinking of food chains and webs.

If the water contains low levels of plant nutrients then the conditions are said to be *oligotrophic*. This may occur when the physical and chemical characteristics of the land through which the water passes are such that nutrients are sparse or are not dissolved out of the soil and rocks.

The opposite condition, with high levels of nutrients in the water, is described as eutrophic; the gradual increase with time of plant nutrients in a body of water is called *eutrophication*.

Flowing and standing water

A typical river has several sources in high ground that are characterised by steep gradients, swift current velocities, and erosion of the surrounding rocks and soil. As the gradient lessens, the current velocity decreases and the river deepens and widens. The river then tends to deposit stones, gravel and sand. This variation in the flow downhill has a direct influence on the types of organisms and *substratum* to be found at different points along the river. The whole length of the river can be subdivided into different zones, each characterised by its own typical fauna and flora.

In contrast to rivers, standing bodies of deep water such as lakes and reservoirs may be affected by thermal stratification. Figure 3 illustrates this effect for a typical lake. In the summer, there is very little mixing between the cooler, denser water at the bottom of the lake (hypolimnion) and the warmer, less dense water at the lake surface (epilimnion). Thus, stream and river water running into the lake will tend to stay in the upper layer. This water carries nutrients, so organisms flourish in the epilimnion and there is a high rate of *primary production*. In the hypolimnion, the dead remains of primary production settle out, forming a layer of bottom sediment.
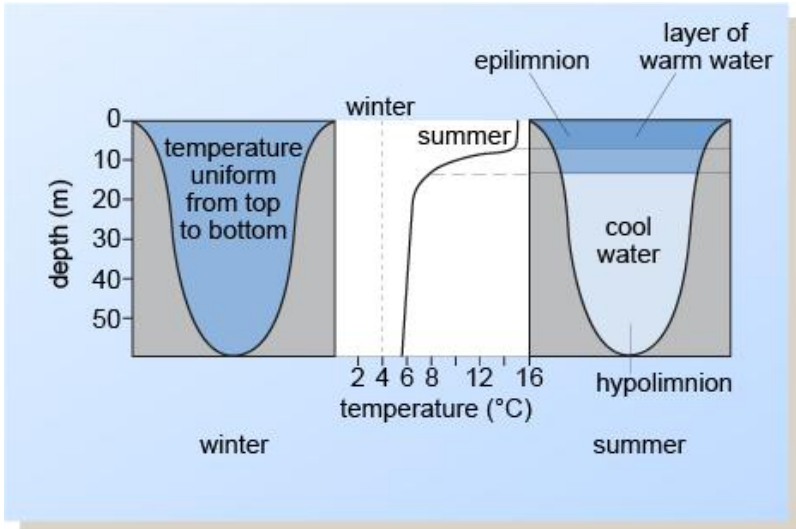
Figure 3 Thermal stratification of a lake

View description

The lack of mixing between the layers (stratification), together with the absence of light penetration to the bottom of the lake, determines the ecological characteristics of a deep lake or reservoir. In a deep lake, the absence of light prevents the growth of plant life in the bottom layers, although decomposer and scavenger microorganisms can live on and in the sediment.

Figure 3 shows that, in contrast to summer conditions, thermal stratification is absent in winter. This is because the density of fresh water is greatest at about 4 °C. Thus when the temperature of the surface layer drops to

this temperature, the layer will fall to the bottom of the lake, displacing any colder (but less dense) water – which will now rise to the surface. The lake 'turns over' and mixing occurs at all levels, leading to uniform temperature and uniform conditions throughout. This mixing process can bring partially decomposed bottom sediments to the surface, where further biodegradation can occur. This can also cause a significant deterioration in water quality.

SAQ 1

Why is eutrophication more likely in a shallow lake than in a river? Describe the conditions it can bring about.

View answer

1.3.2 Dissolved oxygen – measurement

Organic and inorganic nutrients are the basic food supply essential for maintaining the plants and animals in natural watercourses. Equally essential to aquatic life is a supply of oxygen, needed for respiration. Oxygen dissolved in the water is also needed in the biodegradation of organic matter by aerobic bacteria. The more organic matter there is in a river or effluent, the greater the amount of dissolved oxygen that will be

'demanded' by the biodegrading bacteria. A measure of this oxygen demand, the *biochemical oxygen demand* (BOD), can therefore be used as a measure of the polluting capacity of an effluent. BOD can be measured experimentally, and the procedure for its determination will be given in Section 6.

Oxygen dissolved in natural waters arises from two main sources – the atmosphere and photosynthesis. Atmospheric air, which contains 21% oxygen by volume, can dissolve in water up to a limit. Green plants in the presence of sunlight generate oxygen by photosynthesis. These two sources replenish the oxygen used up in aerobic processes by aquatic organisms. The solubility of oxygen in water depends on the temperature, the pressure and the amount of dissolved solids present.

C_S is the maximum amount of oxygen in grams that can be held in one cubic metre of solution – called the *saturation concentration*. It is therefore expressed in $g\,m^{-3}$ (grams per cubic metre). You may also find C_S expressed in units of $mg\,l^{-1}$ (milligrams per litre) or ppm (parts per million); these are the same as $g\,m^{-3}$, so a solubility of $20\,g\,m^{-3}$ is the same as a solubility of 20 ppm, which is the same as $20\,mg\,l^{-1}$. (You may like to verify this for yourself.)

Table 1 shows the solubility of oxygen from air at atmospheric pressure in pure water at various temperatures. This is calculated using the following expression (Baca and Arnett, 1976):

$$C_s = 14.65 - 0.410\,22\,T + 0.007\,91\,T^2 - 0.000\,077\,74\,T^3$$

where C_s is the solubility (in $g\,m^{-3}$) of oxygen in water at 1 atmosphere pressure, and T is the temperature in °C (we will return to this expression in Section 8). As can be seen, the solubility decreases with an increase in water temperature.

Table 1 Saturation concentration of oxygen in water at 1 atmosphere at different temperatures

T (°C)	C_s ($g\,m^{-3}$)
0	14.65
5	12.79
10	11.26
15	10.01
20	8.99
25	8.12
30	7.36

The minimum concentration of dissolved oxygen required to support a balanced population of desirable aquatic flora and fauna is $5\,g\,m^{-3}$. The figures in Table 1 are for water at normal atmospheric pressure of 1 atmosphere. Decreasing the atmospheric pressure on the water decreases the saturation concentration. Therefore streams at high altitude are not able to dissolve as much oxygen as those at the same temperature nearer sea level.

The presence of dissolved solids in the water also affects the solubility of oxygen. Electrical conductivity can be used as a measure of the total dissolved solids in a water sample, i.e. its *salinity* (Table 2). Waters with dissolved salts, also called saline waters, are sometimes treated by desalination to provide drinking water.

Table 2 Relationship between electrical conductivity measured at 25 ºC and salinity

Electrical conductivity ($\mu S\ cm^{-1}$)	Salinity ($mg\ l^{-1}$)
100	51
500	241
1000	493
2000	1016
3000	1558
4000	2113
5000	2678
6000	3253
7000	3836
8000	4426
9000	5022
10 000	5625
12 000	6846

14 000	8087
16 000	9345
18 000	10 621
20 000	11 911

(Adapted from Hoare, 2010)

A correction factor can be used to calculate the saturation concentration of dissolved oxygen in saline waters. Table 3 gives a set of such factors. For a given conductivity and temperature, the factor should be multiplied by the appropriate saturation concentration from Table 1.

Table 3 Correction factors for dissolved oxygen in water, based on conductivity measured at 25 ºC

	Conductivity at 25 ºC ($\mu S\ cm^{-1}$)						
	1000	5000	10 000	12 000	14 000	16 000	18
Temperature (ºC)							
5	0.996	0.981	0.963	0.955	0.947	0.940	0
10	0.996	0.982	0.964	0.957	0.949	0.942	0
15	0.997	0.983	0.965	0.958	0.951	0.944	0
20	0.997	0.983	0.966	0.960	0.953	0.946	0
25	0.997	0.984	0.968	0.961	0.954	0.948	0

(Adapted from USGS, 2006)

> **Exercise 1**
>
> A water supply company contemplates building a desalination plant near an estuary, with a view to producing drinking water from the plentiful *brackish* water in the estuary. When measured at 25 ºC, the conductivity of the water in the estuary is about 16 000 µS cm^{-1} during the ebb tide (which is when water will be drawn for desalination, as the salinity level will be at its lowest). Having dissolved oxygen in the water would be beneficial for the pre-treatment stages of the desalination system. Calculate the dissolved oxygen level in the water when it is at 10 ºC.
>
> View answer

1.3.3 Dissolved oxygen – rate

The *rate* at which oxygen dissolves in water is dependent on several factors. One of these, the oxygen deficit (D), is the difference between the saturation concentration of oxygen (C_S) and the concentration of oxygen actually present (C), i.e.

$$D = C_S - C \qquad\qquad (1)$$

The oxygen deficit is the driving force for the replenishment of oxygen used up in polluted water. The

greater the oxygen deficit, the greater the transfer rate of oxygen into the water. Other factors important in the dissolution of oxygen in water include the turbulence of the water, its ratio of surface area to volume, the presence of animals and plants in the water, and any other dissolved substances. These factors are described further below.

Exercise 2

A river at a certain location has a dissolved oxygen content of 8.1 g m^{-3}. Using the data given in Table 1, calculate the oxygen deficit if the river water has a temperature of 10 °C.

View answer

Figure 4 illustrates how the dissolved oxygen (DO) concentration varies between the water surface and the interior of a water body when oxygen is consumed in the water. The resultant oxygen deficit causes oxygen to be transferred from the surface into the water body. As mentioned earlier, the greater the deficit, the greater the rate of oxygen transfer into the water.
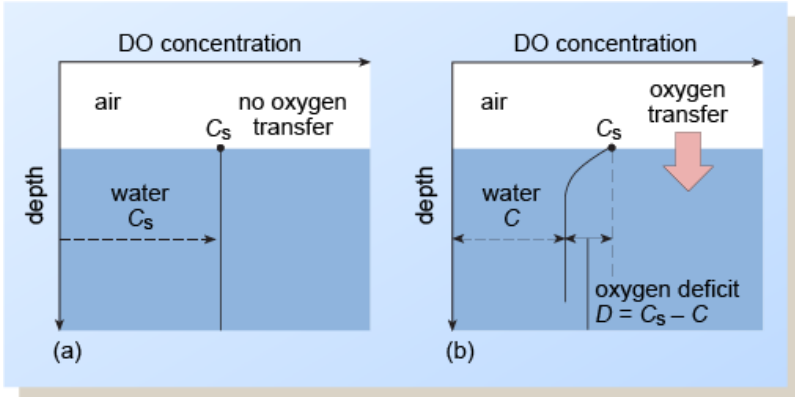
Figure 4 (a) Water body at equilibrium, with no consumption of oxygen; (b) consumption of oxygen in a water body resulting in an oxygen deficit, and oxygen consequently being transferred into the water body

View description

Other factors

The rate of oxygen transfer into a water body also depends on the turbulence of the water, since this helps transport oxygen from the surface layers to the main body of the water. Rapidly flowing, turbulent streams are therefore able to take up oxygen more rapidly than smooth-flowing slow ones.

Another factor governing the transfer of oxygen into a watercourse is the ratio of surface area to volume. A large surface area permits a greater diffusion of oxygen into the water. Hence shallow, wide rivers are

reoxygenated more rapidly than deep, narrow ones. Agitation increases the ratio of surface area to volume – as, for example, when water flows over dams and weirs, and when waves are produced by strong winds. A further advantage of agitation is the entrainment of air bubbles as air is drawn into the water body.

The amount of oxygen in a water body at any given time depends not only on the characteristics mentioned above but also on biological and other factors. Almost all aquatic animals and plants use oxygen in carrying out their metabolic processes and so constantly tend to increase the oxygen deficit. If organic pollutants are present, the oxygen deficit is increased further as biodegradation takes place. At the same time as oxygen is being consumed, oxygen replenishment via photosynthesis and natural aeration takes place.

Figure 5 shows graphically the processes of oxygen demand and replenishment.

- Curve (a) shows the oxygen demand of a polluted water sample.
- Curve (b) shows the reaeration process observed when oxygen is forced to dissolve in the water due to the oxygen deficit created by the biodegradation taking place.
- Curve (c) shows the net result of the oxygen demand and replenishment processes. This is called the dissolved oxygen sag curve. This is, in effect, the difference between the demand and replenishment curves.
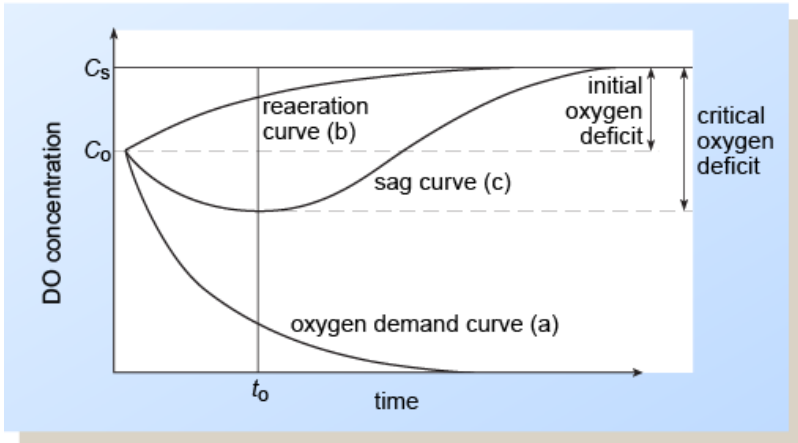
Figure 5 The dissolved oxygen sag curve

View description

SAQ 2

Which of the following events would not affect the rate of oxygen transfer from the atmosphere to a body of water?

Doubling the oxygen deficit

Large amounts of salts being discharged into the water

A slight breeze blowing over the water

The water flowing over a weir

Raising the temperature of the water by 10 °C

View answer

1.3.4 Dissolved oxygen – variation

There are diurnal and (in temperate countries) seasonal differences in oxygen concentration in water. Figure 6 illustrates the diurnal variation that may occur. This variation is related to plant growth, light intensity and temperature. Variations of up to $10 \mathrm{~g~m}^{-3}$ have been recorded in 24 hours.
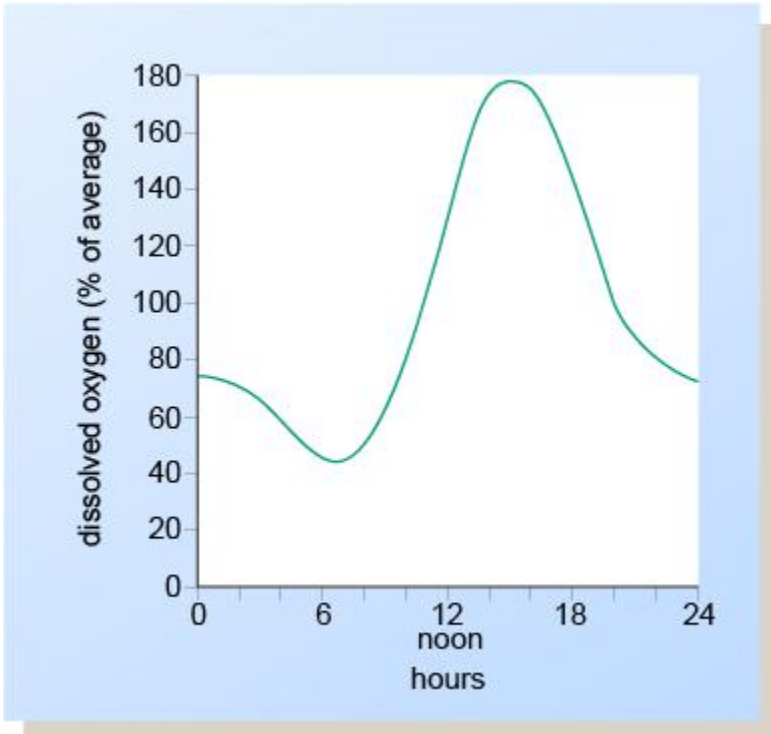
Figure 6 Hourly variation of dissolved oxygen in a water body

View description

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 continues using oxygen as it does during the daylight hours. In temperate countries in the northern hemisphere, this extreme diurnal variation occurs mainly between April

and October, because the lower temperatures during the rest of the year tend to slow down or inhibit metabolic processes and plants become dormant; in temperate countries in the southern hemisphere, it is between October and April. Tropical countries exhibit diurnal variation all year round.

Figure 7 illustrates seasonal changes in dissolved oxygen in a temperate country in the northern hemisphere. An increase occurs in the summer months because of longer days (more daylight) and therefore increased photosynthetic activity.

Figure 7 Seasonal variation of dissolved oxygen in a water body in a temperate country in the northern hemisphere (The Open University, 2007)

View description

In some circumstances 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% oxygen). Therefore, when photosynthesis rather than atmospheric aeration is responsible for the oxygenation of the water, up to five times the saturation concentration is theoretically possible at the same temperature and pressure. In practice 500% is never attained, but up to 200% has been recorded in a shallow river with profuse plant growth on bright sunny days (YSI Environmental, 2005).

SAQ 3

When is the level of dissolved oxygen in a river likely to be at its highest and at its lowest?

View answer

1.3.5 Physical characteristics of natural water

A river's physical characteristics include:

- clarity/*turbidity*
- colour
- speed of flow
- turbulence

- odour
- the presence of plants and macroscopic animal life.

These physical characteristics are determined by the location, geology and climate of the catchment area. In turn, they influence the chemical and biological characteristics of the watercourse.

Figure 8 shows how the aquatic ecosystem is a complex set of physical, chemical and biological interrelationships. Nutrients and dissolved oxygen may be essential to aquatic life, but other conditions must also be satisfactory.
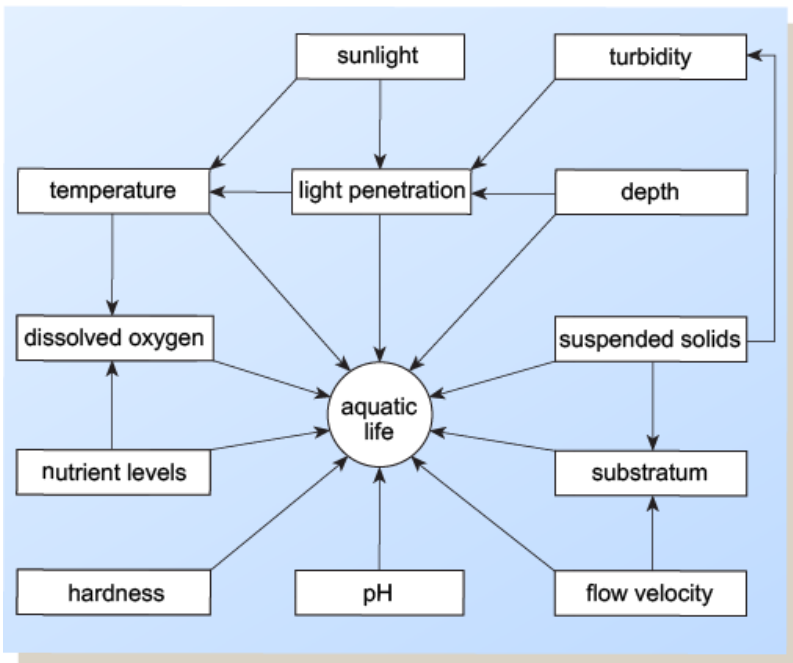
Figure 8 Influences acting on aquatic life

View description

Turbidity, colour and suspended solids

As water runs off the land, some insoluble substances are carried along as suspended solids. Many organisms (down to sub-micron level) present on the suspended solids are also transported. Depending on their sizes and the velocity of the river flow, the solid particles may settle out at a certain point or be carried on further. Quantities are affected by seasonal changes and, in temperate countries, tend to be higher in winter because of increased storm run-off due to higher rainfall and melting snow.

The quantity of suspended solids (measured in $g\,m^{-3}$) affects the turbidity or cloudiness of the water. Suspended solids may also contribute colour to the water. Turbidity is measured in *nephelometric* turbidity units (NTU).

Particles of all sizes tend to reduce light penetration; this reduces the rate of photosynthesis and therefore causes a reduction in the growth of plant life. Very small particles that settle out on the bottom of the stream may have a blanketing effect, thus preventing certain bottom dwellers from living there and green plants from photosynthesising.

Speed of flow and turbulence

To get nutrients and dissolved oxygen to all parts of a body of water, good mixing is important. You have seen one example in the form of thermal stratification in deep lakes in summer, where poor mixing and reduced sunlight led to the bottom layers not being supplied with the necessary conditions for plant growth.

The same principle applies to rivers and streams. Fast-moving, turbulent streams mix and agitate the water, aiding the transfer of oxygen from the atmosphere to the river, and carrying nutrients more efficiently to the plants and animals in the river. Small, rapidly flowing streams are nearly always saturated with dissolved oxygen; large, sluggish rivers may have oxygen concentrations well below saturation levels.

Temperature

All aquatic organisms have a fairly well-defined temperature tolerance range that determines their distribution. As you have already seen, temperature affects the saturation concentration of dissolved oxygen (see Table 1). An increase in water temperature will reduce the oxygen solubility and increase the metabolic activity of aquatic organisms. The combination of these two effects means that oxygen demand by organisms increases just when oxygen supply is being reduced.

Coarse fish such as yellow perch can tolerate water temperatures up to 26 °C (Hinshaw, 2007) and

dissolved oxygen levels as low as 3.5 g m^{-3} (Hart et al., 2006). However, game fish such as the Atlantic salmon (Figure 9) die if the oxygen concentration drops below 5 g m^{-3} (Hendry and Cragg-Hine, 2003) or if the water temperature rises above 20 °C (Fisheries and Oceans Canada, 2012).

Figure 9 An Atlantic salmon

View description

1.3.6 Chemical characteristics of natural water

Since water is such a good solvent, it is not surprising to find many different chemical substances present in it. Water reaching a river will contain inorganic and organic compounds dissolved by rainwater percolating through the soil and rocks. In addition, some gases will dissolve in rainwater during its passage through the air.

The substances present in water may be conveniently grouped into:

- dissolved gases such as oxygen and carbon dioxide
- those involved in the bicarbonate–carbonate equilibrium derived from carbon dioxide (described below)
- other dissolved substances.

All gases will dissolve to a greater or lesser extent in water. As you have seen, oxygen has a low solubility in water, as do nitrogen, argon and some of the other gases present in the atmosphere.

Carbon dioxide, by contrast, is very soluble in water: 1 m^3 of water at 20 °C will hold 878 g of pure carbon dioxide. However, carbon dioxide is also special for another reason: when it dissolves, it reacts with the water to form bicarbonate and carbonate ions. The chemical equation describing this process is the bicarbonate–carbonate equilibrium (Equation 2).

$$CO_2 + H_2O \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$$

dissolved carbon dioxide | hydrogen ion | bicarbonate ion | hydrogen ions | carbonate ion
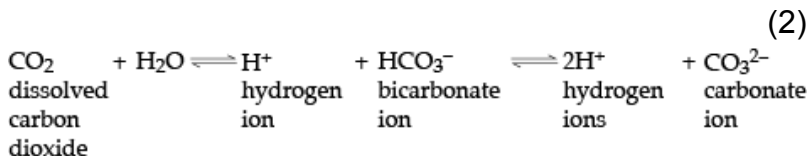
View description

Because all the reactions are reversible, the whole system reaches *equilibrium* – so natural waters will contain various proportions of carbon dioxide, bicarbonate and carbonate.

How the acidity of the water affects the equilibrium in Equation 2

The acidity or alkalinity of water is expressed in terms of pH. This is an index on a scale from 0 to 14 and is derived from the concentration of hydrogen ions (H^+) in a solution. Low values of pH (lower than 7) correspond to 'acid' (high H^+) conditions, whereas high values of pH (greater than 7) correspond to 'alkaline' (low H^+) conditions.

For a reversible reaction, a change in the concentration of one of the chemical species in the reaction will produce a corresponding shift in the concentrations of the other species in order to 'compensate' for the change. So in Equation 2, if the concentration of hydrogen ions (H^+) increases, the reactions move towards the left to compensate.

A new equilibrium is reached with higher concentrations of CO_2 and bicarbonate, and a lower concentration of carbonate. Conversely, a decrease in hydrogen ions shifts the reactions in Equation 2 to the right.

Figure 10 illustrates the relationship between pH and concentrations of CO_2, HCO_3^- and CO_3^{2-}. It shows that in high-pH (alkaline) water, most of the carbon dioxide ends up as bicarbonate and carbonate, whereas in low-pH (acidic) water, the carbon dioxide stays in solution without reacting further.
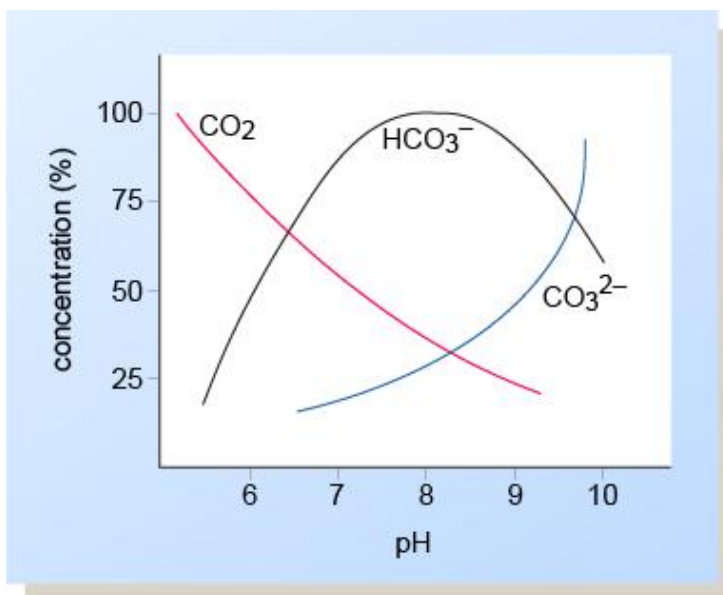
The bicarbonate–carbonate equilibrium is important in photosynthesis, in which aquatic plants take up the inorganic carbon in carbon dioxide in the presence of sunlight for synthesising new cell material. All plants can use dissolved CO_2 for this purpose, but none apparently can use carbonate directly (though blue-green algae can use bicarbonate for photosynthesis). Thus, up to a point, low-pH waters – with available carbon dioxide – are more favourable for photosynthesis. However, if the pH falls much below 6 then the acidity of the water becomes limiting on plant growth.

The supply of carbon dioxide to the aquatic environment comes from the atmosphere through diffusion, and as the product of aerobic and anaerobic metabolism (respiration).

Apart from substances derived from the atmosphere, there are usually other substances dissolved in natural waters. 'Salinity' is a general term that means the concentration of *ionic* constituents (salts) dissolved in water. These include the naturally available carbonates, sulfates and chlorides of sodium, calcium, potassium and magnesium. However, 'salinity' may also mean specifically the sodium chloride content from either

sewage or seawater intrusion. High chloride content in watercourses can also be caused by run-off from salted roads in winter. Some groundwaters may have high mineral content due to the geology of the area.

The pH of natural water usually varies from approximately 6 to 8 depending on the types of rocks and substrate surrounding the watercourse, although in some drainage areas it can be as low as 4.

Water hardness

You might be familiar with hard water from seeing scale deposited in kettles. As well as causing scale formation, both *temporary hardness* and *permanent hardness* make lathering with ordinary soap difficult. The result is the formation of scum that floats on the surface of washing water. On the benefit side, the dissolved solids or minerals often give hard water a pleasant taste; they are of nutritional importance to plants and microorganisms, and may have various medicinal functions for humans.

Hardness in water is mainly due to the presence of *ions* of the metals calcium (Ca^{2+}), magnesium (Mg^{2+}) and iron (Fe^{2+}). Rivers and lakes fed by water that has run from areas of chalk and limestone ($CaCO_3$) contain an abundance of calcium. Calcium and magnesium account for at least 70% of the *cations* in water.

When calcium, magnesium and iron are present in water as bicarbonate salts, e.g. $Ca(HCO_3)_2$, and the

water is boiled or heated above 70 °C, carbonate salts of the metals are precipitated. Such water is said to possess temporary or carbonate hardness because the carbonate salts (e.g. calcium carbonate) are largely insoluble, and are thus removed from the water and deposited as scale (see Equation 3).

$$Ca(HCO_3)_2 \xrightarrow{\text{heat}} H_2O + CO_2 + CaCO_3 \qquad (3)$$

calcium bicarbonate   calcium carbonate (scale)
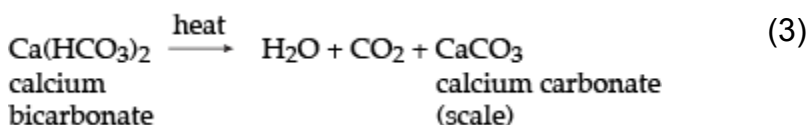
View description

If scale is deposited on the heating elements of kettles and the surfaces of industrial boilers, it shortens their life and makes them less efficient.

When calcium, magnesium and iron are present as chloride or sulfate salts (e.g. $CaCl_2$), the hardness is called permanent or non-carbonate hardness. Although this type of hardness also contributes to scaling, in this case the precipitate is due to the decreased solubility of these metal salts at higher temperatures and not to the formation of new insoluble compounds.

Plant nutrients

Of the major nutrients of plants, nitrogen and phosphorus are important growth-limiting factors in primary production (i.e. if levels of either of these nutrients fall below a certain level, plants will not grow even if other nutrients are in plentiful supply). Increased

levels of nitrogen and phosphorus are the cause of eutrophication, as described earlier. Both nitrogen and phosphorus enter watercourses through natural leaching by water of the soluble nitrates and phosphates found in soils and rocks, as well as from sewage effluent and agricultural sources. Phosphorus is the limiting growth factor for certain types of *blue-green algae*, and both phosphorus and nitrogen limit the growth of *green algae*.

Radiological aspects

Environmental radiation comes from a range of naturally occurring and anthropogenic sources, and varies a great deal with location. Globally, natural sources are estimated to contribute on average about 80% of the radiation dose experienced by people – the remainder is from medical exposure (WHO, 2013a). Any exposure to radiation can lead to cancer and the greater the exposure, the greater the risk.

The contribution that drinking water makes to radiation intake is very small, and is due largely to naturally occurring *radionuclides* in the uranium and thorium decay series.

Radon, a naturally occurring radioactive gas that has no taste, smell or colour, is estimated to contribute some 43% of average world radiation exposure (WHO, 2013a). It is formed in the ground by the decay of uranium, which is often found in granite (and in phosphate-bearing rocks). Dissolved radon is released

during handling of the water. Water that has been left to stand will have reduced radon activity, and boiling will remove radon completely. Exposure to airborne naturally occurring radon is a known health hazard and, after smoking, is the second most likely cause of lung cancer (WHO, 2009). However, human intake through drinking water is not generally seen as a major problem.

Other possible sources of radiation include emissions from the nuclear power industry. There are strict guidelines on emissions of radioactive compounds, and the nuclear industry is carefully monitored. Nevertheless, to ensure water quality, limits are imposed. The maximum dose from one year's consumption of drinking water has been set at 0.1 millisievert (mSv) (WHO, 2011). This is less than 5% of the average dose attributable annually to natural background radiation. For practical purposes, the maximum recommended guideline activity concentration is 100 becquerels per litre $(Bq\ l^{-1})$ for tritium (a substance coming largely from the nuclear industry). This is based on the consumption of 2 litres of water a day.

1.3.7 Biological characteristics of natural water – species

In addition to the easily visible plants and animals that live in or on a river, there are many small and often microscopic species that play a vital role in maintaining the health of a river.

Algae

Algae are photosynthetic organisms that are generally aquatic; they are primary producers. Many freshwater algae are microscopic, but when amassed can be seen as a green, brown or blue-green scum.

The blue-green algae, also known as cyanobacteria, are actually classified as bacteria rather than algae. They are capable of producing toxins strong enough to kill wild animals, farm livestock and domestic pets that drink contaminated water. These toxins can also produce a painful rash on human skin.

Algae may be attached to rocks or be floating; in the latter case they are usually referred to as phytoplankton. There are also some macroscopic ones that are branched and attached to stones and rocks. In the seas and oceans, algae are more commonly called seaweeds; they are of various colours, and can be large and branching.

In contrast to the large green plants that are rooted in the river bed or banks, algae take their nutrients directly from the surrounding water. Both carbon dioxide and water are needed for photosynthesis. I have already mentioned that blue-green algae can use dissolved bicarbonate as a carbon source; the

carbon dioxide entering the cells of other plants is that dissolved in the water.

Some of the common algae found in waters are:

- diatoms (e.g. *Asterionella* spp.)
- blue-green algae (e.g. *Anabaena* spp.)
- green algae (e.g. *Spirogyra* spp.).

These are illustrated in Figure 11.
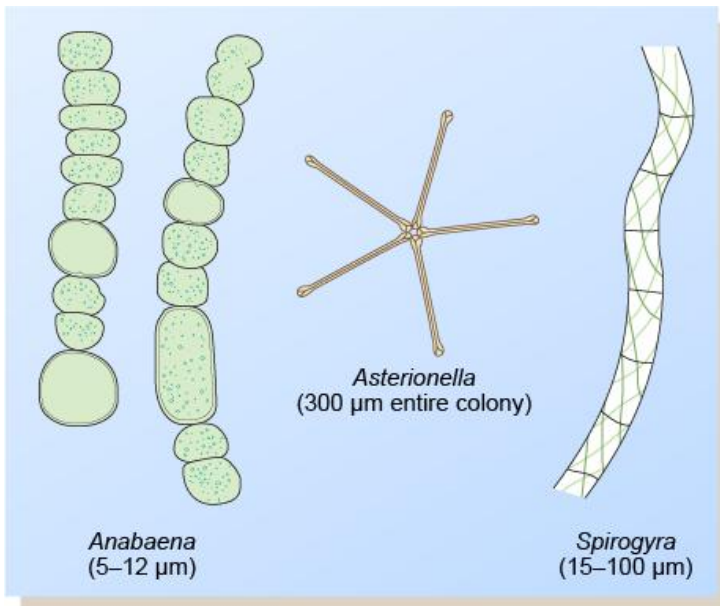
Figure 11 Some common algae

View description

In an aquatic environment there are also decomposers and scavengers. These organisms use dead plants or animals as food, and in so doing release minerals and nutrients that can then be assimilated by other plant and animal life. The decomposers that are important in the life of aquatic ecosystems are bacteria, protozoa and fungi.

Bacteria

Bacteria are organisms of special significance to the study of water quality because they break down organic matter. While most of them are not harmful to humans, some bacteria (e.g. *Clostridium perfringens*) are pathogenic (disease-causing). Bacteria are important in sewage treatment and solid waste disposal.

Bacteria are extremely abundant in almost all parts of the aquatic environment. They occur suspended in the water, on the surface of submerged objects, in riverbed debris, and on and in other organisms. A bacterial cell can be seen through a microscope; individuals of some species can group together to form a colony, which may be visible to the naked eye.

Aerobic bacteria

Most species of aquatic bacteria feed on the biodegradable natural wastes produced by other living organisms, as well as on the remains of the dead ones, as these are energy-rich resources. They can also use biodegradable compounds released into the river by soil run-off or waste flows. Many of these bacteria are classified as aerobes: they require dissolved oxygen for aerobic respiration in order to oxidise the nutrient compounds to obtain energy for their other life processes, such as building new cell material, and for functions such as movement, reproduction and growth.

A generalised equation for aerobic bacterial degradation is shown in Equation 4.

(4)

$$\underset{\substack{\text{carbohydrates}\\ \text{and proteins}}}{C, H, O, N, P, S \dots} + \underset{\text{oxygen}}{O_2} \xrightarrow{\text{aerobes}}$$

$$\underset{\substack{\text{carbon}\\ \text{dioxide}}}{CO_2} + \underset{\text{water}}{H_2O} + \underset{\text{nitrates}}{NO_3^-} + \underset{\text{phosphates}}{PO_4^{3-}} + \underset{\text{sulfates}}{SO_4^{2-}} + \underset{\text{cells}}{\text{new}} + \text{energy}$$
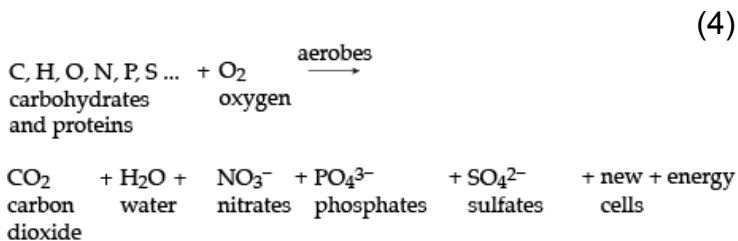
View description

Anaerobic bacteria

If dissolved oxygen is not available in the water, aerobes cannot thrive. Instead, anaerobic bacteria (anaerobes) use the bound oxygen in inorganic salts such as nitrates, sulfates and phosphates. The toxic gas hydrogen sulfide is often produced. Anaerobes also convert organic material to methane and carbon dioxide.

A generalised equation for anaerobic bacterial activity is shown in Equation 5.

(5)

$$\underset{\substack{\text{carbohydrates} \\ \text{and proteins}}}{C, H, O, N, P, S \ldots} + \underset{\text{nitrates}}{NO_3^-} + \underset{\text{phosphates}}{PO_4^{3-}} + \underset{\text{sulfates}}{SO_4^{2-}} \xrightarrow{\text{anaerobes}}$$

$$\underset{\substack{\text{carbon} \\ \text{dioxide}}}{CO_2} + \underset{\text{methane}}{CH_4} + \underset{\text{nitrogen}}{N_2} + \underset{\text{phosphine}}{PH_3} + \underset{\substack{\text{hydrogen} \\ \text{sulfide}}}{H_2S} + \text{new cells} + \text{energy}$$
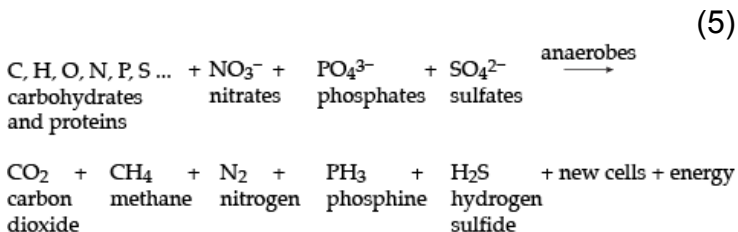
View description

Certain bacteria use dissolved oxygen if it is available but convert to anaerobic processing when dissolved oxygen is absent. Such bacteria are called *facultative anaerobes*.

Besides organic compounds, and oxygen in the case of aerobic decomposition, bacteria require a supply of various elements such as iron,

magnesium, potassium and calcium. If any essential nutrient is below the minimum concentration necessary for certain processes, bacterial growth will be prevented. Temperature also has a direct influence, not only on the rate of decomposition but also on the particular species that accomplish it – between 10 °C and 20 °C is the optimum range for most river bacteria. An increase in temperature within the appropriate range will tend to speed up the general rate of metabolism of bacteria, thereby increasing the rate of decomposition of organic compounds.

Protozoa

Protozoa are microscopic single-cell animals. They mostly use detritus, algae and bacteria as food. In a stream containing little organic degradable matter they can become the predominant microbial type. They play an important part in sewage treatment, where they remove free-swimming bacteria and help to produce a clear effluent.

Rotifers such as *Keratella*, minute multicellular animals that likewise feed on debris and bacteria, also play an important part in sewage treatment.

Fungi

Fungi (e.g. *Penicillium* spp., which are used for the manufacture of antibiotics, and yeast) are generally unicellular, non-photosynthetic organisms that can tolerate acid conditions. They are capable of degrading highly complex organic compounds. They use much the same food sources as bacteria, but they require less nitrogen since their protein content is lower. Fungi play an important role in sewage treatment.

In badly polluted water, particularly near to the outfall from a poorly functioning sewage works, a material known as 'sewage fungus' may be found. This is not a single organism but a mixture of different species of bacteria, fungi, algae and protozoa. They form a slimy, furry growth (not unlike plumes of cotton wool) on the riverbed and bank (Figure 12).

Figure 12 Sewage fungus

View description

1.3.8 Biological characteristics of natural water – biological indicators

A great many biological species occur in unpolluted streams. They differ markedly in their sensitivity to environmental factors and different types of pollution, and their presence or absence can therefore be used as an *indicator* of pollution. The major groups of organisms that have been used as indicators of environmental

pollution include bacteria, fungi, protozoa, algae, higher plants, *macroinvertebrates* and fish. The benthic or 'bottom-living' macroinvertebrates are particularly suitable as ecological indicators because their habitat preference and relatively low mobility cause them to be directly affected by substances that enter their environment. They can thus be a good indicator of water quality. Microorganisms can also be an indicator of faecal pollution; this will be considered in Section 3.

When a clean river is polluted there could be:

- a decrease in the number of different species of organisms
- a change in the type of species present
- a change in the number of individuals of each species present.

These changes are due to the death or moving away of organisms that cannot tolerate the pollution, and an increase in number of those organisms that thrive on it or that can take advantage of reduced competition from the more sensitive species.

Various indices have been developed that use macroinvertebrate populations to assess the degree of pollution in freshwaters. One of these is the Biological Monitoring Working Party (BMWP) score. A visual examination is made of a sample taken from the river sediment and vegetation from a particular site, and a score is allocated to each type of organism found. The more sensitive organisms (e.g. stoneflies) have high scores, while the more tolerant species (e.g. true

worms) have low scores. These scores are added together and the total score gives an indication of the degree of pollution at that site. Figure 13 shows examples of the types of organisms used in calculating the BMWP score.

Mollusca: snails, limpets and bivalves (mussels)

Lymnaea: pond snail

Planorbis: ramshorn snail

Sphaerium: orb-shell

Ancylus: freshwater limpet

Annelida

true worm (up to 150 mm long)

leech

Diptera: fly larvae

Chironomidae: non-biting midge

Simulium: blackfly

Culicidae: mosquito

Odonata

damselfly nymph

Platyhelminthes

flatworm

Crustacea

Gammarus: freshwater shrimp

Asellus: water hog louse

Ephemeroptera: mayfly nymphs

Ecdyonurus

Ephemera

Baetis

Trichoptera: caddisfly larvae

Rhyacophila

Hydropsyche

cased caddis: type A

cased caddis: type B

Plecoptera

stonefly nymph

Coleoptera: beetles

larva

adult Dytiscidae: diving beetle

Hemiptera: bugs

water boatman

Megaloptera

alderfly larva

Arachnida
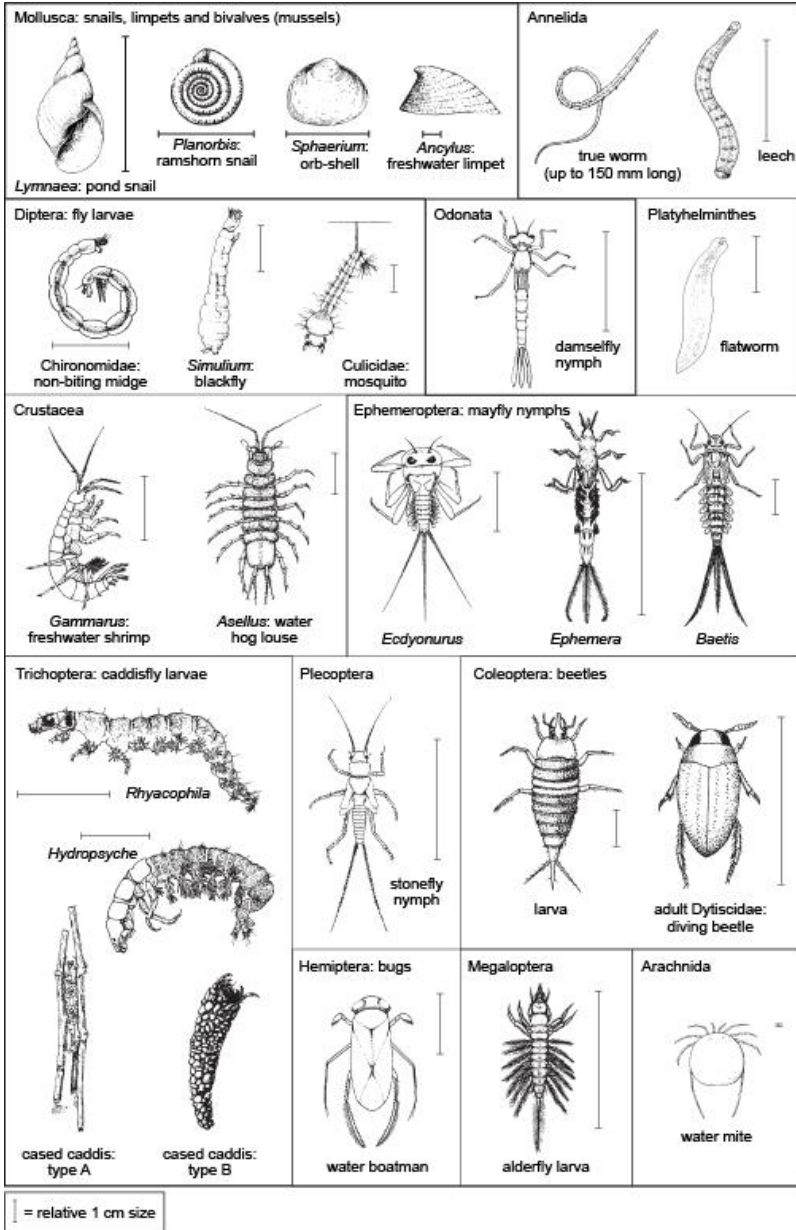
water mite

= relative 1 cm size

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Figure 13 Some of the organisms used in calculating the BMWP score – scale lines indicate typical actual size of fully grown individuals (The Open University, 2009; based on Croft, 1986)

Table 4 gives a simplified version of the BMWP scoring system. When the total score is calculated, each family can only score once – no matter how many organisms of that family are present – and only one needs to be present to score. A total score of 0–10 indicates that the water is heavily polluted, 11–40 polluted or impacted, 41–70 moderately impacted, 71–100 clean but slightly impacted, and more than 100 unpolluted and unimpacted (Bourne Stream Partnership, 2012).

Similar scoring systems can be used in different parts of the world, with a table of scores drawn up using local species.

Table 4 Simplified BMWP scores

Groups (families)	Score
Mayfly nymphs (e.g. Ephemeridae, Ecdyonuridae); stonefly nymphs (all families)	10
Damselflies and dragonflies (all families); freshwater crayfish (Astacidae)	8
Mayfly nymphs (Caenidae only); cased caddis larvae (all families); caseless caddis larvae (e.g. Rhyacophilidae)	7

Freshwater shrimps (Gammaridae); freshwater limpets (Ancylidae)	6
Water bugs (all families); water beetles (all families); caseless caddis larvae (Hydropsychidae only); fly larvae (Simuliidae, Tipulidae); flatworms (all families)	5
Mayfly nymphs (Baetidae only); alderfly larvae (Sialidae)	4
Snails (e.g. Lymnaeidae, Planorbidae, Physidae); freshwater bivalves (Sphaeriidae); leeches (all families); water hog lice (Asellidae); water mites (all families)	3
Fly larvae (Chironomidae only)	2
True worms (all families); fly larvae (e.g. Culicidae, Tabanidae, Chaoboridae)	1

(Adapted from Hawkes, 1997)

Exercise 3

A benthic sample taken from a river contained the following:

- mayfly nymphs from the Ephemeridae and Baetidae families
- three stonefly nymphs from different families
- two cased caddis larvae from different families
- freshwater shrimps (Gammaridae)
- a freshwater limpet (Ancylidae)

The BMWP score can be used both as an instantaneous measure of pollution and as a gauge over a period of time to ascertain how the situation at a particular site is changing.

The two main advantages of biological indicators over chemical methods of assessing water quality are as follows.

- The organisms show a lasting response to intermittent pollution events, which may be missed during sampling for chemical analysis.
- The biological community of a stretch of river responds to all pollutants, known and unknown, including those that might not have been considered in routine chemical analysis.

One disadvantage of all such scores is the assumption that they reflect changes attributable to pollution and not to other factors. Yet there are various environmental factors other than pollution that can have a considerable effect on the composition of communities of aquatic invertebrates, the chief ones being the nature of the stream bed, the presence of aquatic vegetation, the velocity of the water flow and the local geology, which

influences the natural chemical composition of the water.

In addition, the invertebrate community present in fast-flowing sections of river is very different both qualitatively and quantitatively from that present in slow-flowing sections. It is possible to overcome this problem to some extent by sampling in stretches of river that are closely similar in substratum, flow rate and other variables not connected with pollution.

1.4 Further SAQs

SAQ 4

Identify which of the following statements is true, and give reasons why the others are false.

a. 'Sewage fungus' is a single species of fungus.

b. Carbon dioxide and oxygen both react with water.

c. With reference to the bicarbonate–carbonate equilibrium, in a water with high pH, any carbon dioxide that is present will remain as carbon dioxide.

d. Permanent and temporary hardness both contribute to scaling, but for permanent hardness the scaling is due to decreased solubility, while for temporary hardness the scaling is due to the formation of new insoluble compounds.

[View answer](#)

SAQ 5

With reference to the bicarbonate–carbonate equilibrium, explain why the pH of water often rises during photosynthesis by aquatic plants.

[View answer](#)

SAQ 6

An oil-rich state in the Arabian Gulf plans for food security by considering establishing fish-farms in a desert area in the central part of the country, where brackish underground water with a conductivity of 18 000 µS cm^{-1} is available. The intention is to cultivate *Tilapia*, a hardy fish that can survive with

dissolved oxygen levels as low as 0.1 mg l^{-1} but grows best at concentrations greater than 3 mg l^{-1}.

a. What is the salinity of the underground water?
b. Calculate the dissolved oxygen level of the underground water, and comment on its suitability for *Tilapia* cultivation, at a temperature of 25 °C.

View answer

SAQ 7

A benthic sample taken half a kilometre downstream of an effluent discharge pipe in a river contained the following:

- a mayfly nymph (Baetidae)
- snails from two different families
- leeches from two different families
- fly larvae from the Chironomidae and Culicidae families
- true worms from three different families.

Calculate the BMWP score and comment on your result.

View answer

1.5 Summary

Water in its natural state supports a complex yet fragile ecosystem. The ability of natural watercourses to sustain aquatic life depends on a variety of physical, chemical and biological conditions.

Biodegradable compounds, nutrients and dissolved oxygen must be available for the metabolic activities of the algae, fungi, bacteria and protozoa that are at the lower levels of the food chain.

Plant and animal growth cannot occur outside narrow ranges of temperature and pH.

Suspended solids can restrict the light penetration that is necessary for photosynthesis.

Thermal stratification can hinder the mixing of necessary nutrients.

Biological monitoring, e.g. BMWP scores, can be used as an indication of the state of health of a stretch of river.

Section 2: Pollution of the aquatic environment

2.1 Introduction

Having read Section 1, you will realise that there are important physical, chemical and biological properties characteristic of unpolluted water, but that these can vary enormously from one watercourse to another.

In addition, all waters are subject to a degree of 'natural' pollution. This can happen through too much decaying vegetable matter and other materials being washed out of the soil and into the water. However, the greater part of pollution comes from human activities: the daily life of the community and the operations of industry. Here I will detail the main sources of such pollution.

2.2 Sources of pollution

To some extent a river is a self-renewing resource. If polluting discharges to a river are intermittent, the river is often able to return to a clean and unpolluted condition as the pollutants are flushed out and carried down to the sea. In addition, because of the organisms present (e.g. bacteria capable of breaking down organic matter), river water has some capacity for self-purification – unless too many of these organisms are killed off too quickly.

Some pollutants are objectionable because they overload the self-purification processes of the river. As rivers are often the raw water sources for potable supplies, this can have dire consequences.

An example of such pollution is the discharge of domestic sewage effluent to rivers. In small quantities it does no serious harm and may indeed be beneficial, providing a source of organic carbon that provides nutrients to the animals in the river. But if inadequately treated or in excessive quantities, sewage effluent can seriously damage the plant and animal life of a river by reducing the oxygen content of the water. In extreme cases, where the oxygen content is reduced to zero (or nearly so), the river will support very little life, and will become foul smelling and grossly offensive. A river in such a state is obviously not desirable as a water source for potable supply.

Some industrial effluents discharged in large quantities can be similarly harmful. For example, effluents from the food industry are not particularly toxic, but because of their organic content and large volume, they can exert a considerable oxygen demand on the environment in the region of the discharges.

The two pollution sources described above are classified as *point sources*, as the pollutants are generally collected by a network of pipes or channels and conveyed to a single point of discharge. Non-point or *diffuse sources* are characterised by multiple discharge sources that cannot be pinpointed. An

example of a diffuse source is run-off from fields and roads.

Point sources are easily controlled, but diffuse sources are virtually impossible to collect and control. The latter pose great challenges in efforts to upgrade the quality of rivers.

Lakes are much more vulnerable to pollution. Once a pollutant enters a lake it will stay for a long time. The flushing effect that characterises rivers is much less evident in lakes, and the dilution factor is much less than is available in the sea. Only the self-purifying ability of the water will abate the pollution in the long term. Lakes are thus particularly prone to eutrophication (Figure 14) (see also Section 1.3.1).

Figure 14 A eutrophic lake in southern California

View description

Since river pollutants can be controlled more easily at source, it is useful to know where they originate. A list of specific sources would be very long, but the following categories can be identified:

- discharges from sewage works, which often contain some industrial wastes
- discharges from manufacturing and industrial plants, including mines
- discharges from animal rearing, fish farming and agriculture
- seepage from domestic and industrial landfill sites
- urban surface water run-off.

2.2.1 Discharges from sewage works

Inadequately treated sewage and effluents from industry (covered in Section 2.2.2) are major sources of river pollution. They can contribute to high levels of oxygen demand and also introduce toxic substances into the aquatic environment.

Dissolved organic matter (such as sugars, organic acids and detergents), suspended organic matter (such as fats, proteins, carbohydrates, organic acids, soaps and detergents) and inorganic matter (such as compounds containing sodium, calcium, potassium, magnesium,

chlorine, sulfur, phosphorus, bicarbonates and ammonia) may all be present in the sewage effluent.

Discharges from sewage works are a major source of phosphate pollution in river water. In the UK, human faeces and urine together contribute a major part (64%) of the phosphorus in sewage; laundry products account for about 18%, and food wastes about 5%, of the phosphorus load (Water UK, 2008). The other main source of phosphates is agricultural run-off (see Section 2.2.3). The relative contribution from these two sources varies with location and land use.

Microorganisms such as bacteria, viruses and protozoa will also be present in sewage effluent.

Trade wastes entering sewers are very diverse, depending on the nature of the industrial process involved. Some may contribute toxic substances such as heavy metals. There are plants where combined sewer overflows (mixtures of storm water and raw sewage that exceed the capacity of sewage treatment works) can be a major source of pollution in the receiving watercourse.

2.2.2 Discharges from manufacturing and industrial plants

Wastewater from manufacturing plants may contain organic and inorganic material in suspension or in solution.

Manufacturing and industrial plants use water in three ways:

- as a process material – for example:
    - in the fabrication of steel products
    - in soft-drinks manufacture
    - in washing products (e.g. textiles)

- as a heat-exchange medium – for example:
    - in cooling towers at power stations

- as a means of transport – for example:
    - to move potatoes in a processing plant.

Much of the water used is recycled, but there is almost always an effluent discharge that requires treatment.

Food processing generates large volumes of effluent containing natural organic compounds such as carbohydrates, proteins and fats; plants producing chemicals often generate low volumes of highly toxic waste streams. Toxic effluents can also be produced in the paper, leather and electroplating industries – for example, cyanides and heavy metals may be present in wastewaters from electroplating.

Manufacturing and industrial effluents may be treated at their points of origin and discharged into a river, or discharged into a sewer to be treated at the nearest sewage treatment works. In either case, the discharges are subject to stringent standards of quantity and quality.

Wastewaters from industrial processes differ in their strengths, or potential for polluting rivers. The strengths of effluents from various trades and industrial processes are compared in Table 5. The values in column 3 are those of the standard five-day *biochemical oxygen demand* (BOD) test for each waste (see Section 1.3.2). By comparison, clean river water normally has a BOD value of $2\ \mathrm{g\ m^{-3}}$ or less. The values in column 4 are those of the *chemical oxygen demand* (COD) for each waste. This is the amount of oxygen needed to chemically oxidise all the organic and inorganic material present. You will learn more about this later, in Section 6.

Table 5 Typical BOD and COD values for various effluents

Source of waste	Main pollutants	Five-day BOD ($\mathrm{g\ m^{-3}}$) at 20 °C	COD ($\mathrm{g\ m^{-3}}$)	Reference
Brewery	Carbohydrates, proteins, suspended solids	1000–1500	1800–3000	MIGA (n.d.)
Dairy farm	Carbohydrates, organic matter, suspended solids, detergent	1000	5000	University of Hawaii (2008)

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Petroleum refinery	Hydrocarbons, phenols, sulfur compounds	Up to 570	Up to 1020	Diya'uddee et al. (2011
Poultry processing	Suspended solids, proteins, oil	1300	1580	UNIDO (n.d.)
Pulp and paper mill	Suspended solids, carbohydrates, organic acids, sulfur compounds, terpenes, lignins, etc.	1400	7000	Kumar et a (2011)
Sewage	Suspended solids, carbohydrates, oil, grease, proteins	100–300	250–300	Davis and Cornwell (1998)
Sugar mill	Suspended solids, carbohydrates	1000	3200	Saranraj and Stella (2012)
Tannery	Suspended solids, proteins, sulfides	2000	4000	UNIDO (2011)

Another major industrial use for water is in transferring heat. Thermal power stations require vast quantities of cooling water in order to absorb the waste heat from

steam turbine exhausts. The condensate or cooling water from indirect heat exchangers (where the coolant does not come into direct contact with the substance to be cooled) may be non-polluting, so that no treatment other than cooling and possibly aeration is needed. However, leakage can occur in heat exchangers, resulting in process substances being added to the cooling water.

Mining can generate wastewaters – the washing of coal produces an effluent containing coarse and fine particles. Streams receiving such colliery effluents may be opaque, grossly distorting the types and numbers of aquatic inhabitants present. Other types of mine, such as copper, use water in the extraction process. The effluent from this process contains heavy metals, hazardous substances and particulates, and is sent to *tailings dams* for sedimentation and evaporation rather than being discharged into a river.

Disused mines can also generate effluents if mine drainage water seeps out. In early 1982, millions of gallons of effluent from the Wheal Jane tin mine, containing arsenic, mercury, cadmium, iron, zinc and copper, entered the Fal estuary in Cornwall when the pumping to remove the water was stopped. The estuary turned orange due to the formation of coloured compounds when the effluent met the sea water (Environment Agency, 2012).

2.2.3 Discharges from animal rearing, fish farming and agriculture

The intensive rearing of animals results in large volumes of organically polluted washwater from cleaning animal houses. This slurry is often stored in lagoons or tanks prior to spreading on land. However, problems occur when such lagoons or tanks leak or overflow, allowing the slurry to flow into watercourses and cause contamination. The storage of silage for winter feed also produces heavily polluting silage liquors. In addition, leakage of pesticides and fuel oil can sometimes cause pollution of watercourses. If all these wastewaters are not carefully disposed of, serious water pollution can result.

In recent years, fish farming has expanded considerably. These farms use large quantities of water in flow-through systems. The effluent discharged often contains unconsumed food and faecal matter from the fish. It can also contain substances such as antibiotics used in the rearing of the fish, which may cause problems due to:

- their potential *mutagenicity*
- their ability to produce allergic responses
- the possible development of resistant strains of microorganisms.

These aspects are particularly important where the river is used as a source for public water supply.

Wastewaters from animal rearing and fish farming can contribute to the suspended solids, BOD and ammonia loading of a watercourse. Ammonia exerts an oxygen demand, and can be toxic to fish and other aquatic animals. It accelerates corrosion of structures (e.g. bridges) in contact with the water. When converted to nitrate, it contributes to algal blooms.

A further source of agricultural pollution is land that has been excessively fertilised using inorganic chemicals. The run-off may then contain nitrates and phosphates that contribute to eutrophication. Nitrates can also result in methaemoglobinaemia (detailed later, in Section 3). Leaching of nitrates affects groundwater in particular. Excessive use of pesticides can also result in contamination of watercourses, through being washed out by rain.

2.2.4 Seepage from domestic and industrial landfill sites

Many landfill sites – particularly those that are older and less well-designed – generate *leachate*, which is highly polluting. Where industrial waste has been dumped, a toxic chemical stream may also be produced. These leachates have to be collected and treated so that pollution of groundwater and rivers does not arise.

2.2.5 Urban surface water run-off

Rainwater that runs off road surfaces, roofs, parking areas, etc. can be collectively referred to as surface water run-off. It carries with it a variety of components (Table 6), some of which (e.g. lead) may have historic sources. The bulk of the contaminants, however, can be traced to motor vehicles.

Surface water run-off can cause damage to streams, rivers and lakes by degrading the water quality and harming aquatic life. Pollutants can hinder the growth and reproduction of fish and other creatures, and affect photosynthetic activity. Plant nutrients may contribute to eutrophication.

Table 6 Pollutants that may be present in rainwater run-off from roads, and their sources

Pollutant	Likely sources
Sediment	Construction, road surfaces, emissions from vehicles, domestic fires, industrial sources, vehicle wear
Copper	Vehicle brake pads, industrial activities, plumbing and guttering
Lead	Industrial activities and residues from historic activities (plumbing, paint, leaded petrol, sprays), tyre balancing weights, vehicle brake pads, roof flashing

Zinc	Vehicle tyres, galvanised building materials, paint, industrial activities
Hydrocarbons	Vehicle emissions, lubricating oils
Polycyclic aromatic hydrocarbons	Domestic fires, industrial emissions, vehicle exhaust (especially from diesel engines), lubricating oils
Salt	Salt sprayed onto roads to prevent ice formation during winter
Plasticisers	Building materials, plumbing, litter, sprays
Herbicides, pesticides, fungicides	Sprays, paint, residual chlorinated compounds from historic practices
Rubber	Tyre wear
Detergents/ surfactants	Wash-down areas, domestic discharges (e.g. from car washing), industrial discharges
Nutrients	Wastewater discharges and overflows, fertilisers, lawn clippings, leaves, compost heaps
Faecal matter	Wastewater discharges and overflows, illegal stormwater connections
Litter	Discarded material (e.g. plastic bags, cups, cigarette butts), windblown materials, illegal dumping

(Adapted from RCA Forum, n.d.)

You will learn about the effects of some of the above pollutants on watercourses in Section 3. Later, in Section 4, systems for removal of these pollutants will be considered.

SAQ 8

Identify which of the following statements are true. If a statement is false, give the reason why.

a. Any input of pollutants into a river is undesirable.

b. The phosphate content in sewage can largely be attributed to detergents, food wastes and excretion from the human body.

c. The BOD of tannery effluent is approximately 10 times that of domestic sewage.

d. The only concern with antibiotics being discharged with effluents into rivers is the fact that antibiotic-resistant bacteria will emerge.

e. Surface water run-off contains a wide variety of pollutants that can all be said to

originate from our current lifestyle (e.g. heavy vehicle use, keen interest in gardening and hence fertiliser and pesticide use, etc.).

View answer

2.3 Summary

A variety of pollutant discharges are generated by the day-to-day activities of communities. Principally, these waste streams originate from sewage works, manufacturing and industrial plants, animal rearing, fish farming, agriculture, landfill sites and urban surface water run-off. Of the various effluents, potentially the most highly polluting and toxic discharges usually come from farming and industry.

Section 3: The effects of pollutants on the aquatic environment

3.1 Introduction

Problems occur when the natural characteristics of a river are altered by pollutant discharges. This section considers the effects of the following categories of pollutants:

- organic materials
- plant nutrients
- toxic pollutants
- physical pollutants
- biological pollutants.

Please be aware that this categorisation is not absolute. For instance, toxic pollutants may well be organic, too.

3.2 Organic materials

Organic substances constitute the major freshwater pollutants, coming from domestic sewage discharges (even after treatment) and from certain industries such as food processing. This subsection will deal with the biodegradable forms, but there are also inert (non-biodegradable) toxic forms, which are discussed in Section 3.4. Organic substances can be natural (in

which case they are normally biodegradable) or synthetic (in which case they can often be degraded by microorganisms that have adapted to utilising them).

The major polluting effect of biodegradable organic materials is the reduction in oxygen concentration in the water. Bacteria and other organisms (decomposers) break these materials down into simpler organic or inorganic substances. They use up oxygen in the process, and as their population increases there is an extra demand for dissolved oxygen. This was discussed in Section 1.3.2.

When a potentially polluting effluent is released into a stream, there follows a sequence of events in time and distance. This sequence leads to different environmental consequences and different aquatic communities compared with those immediately upstream and the successive reaches downstream. After a certain distance, natural biodegradative processes will break down the pollutants, often returning the river to something like its original condition.

Three stages of organic pollution can be defined.

1. When the load is small, there will be little change in the species of plants and animals present in the water and little variation in the natural cycles. Initially, the dissolved oxygen will be near to saturation level. Any organic pollution apparent at the point of discharge will disappear within a short distance downstream as it is removed by the natural processes of self-purification. It could be

said that, in some instances, mild organic pollution is beneficial to the river, since it increases the nutrient supply for microorganisms present in the natural state. This minimal pollution can benefit the whole aquatic ecosystem.

2. If the load increases, the dissolved oxygen level will drop significantly and the river will be polluted for a considerable distance from the point of discharge. Some species of animals and plants will flourish at the expense of others. In the absence of further pollution, the river will probably recover downstream, but if the area around the discharge remains polluted then this can act as a barrier to the passage of migratory fish (among other disadvantages).

3. If the polluting load is increased still further, the natural ecosystem will be grossly distorted and its effectiveness in coping with the pollutant load greatly reduced. The level of dissolved oxygen will be very low or fall to zero (you may like to refer back to Figure 5, the dissolved oxygen sag curve, in Section 1.3.3). Often the only organisms to flourish will be sewage fungus, certain worms and fly larvae. (These organisms give a low BMWP score, indicating the polluted nature of the river.) Also, anaerobic bacteria may thrive and give a foul smell to the water by metabolising organic substances and producing methane, hydrogen sulfide and ammonia. Few algae are able to thrive under severe organic pollution, so reoxygenation by photosynthesis will be hindered. The river will now remain polluted for a much greater distance downstream.

The sequence of events following significant pollution of a waterway by organic material is shown in Figure 15.
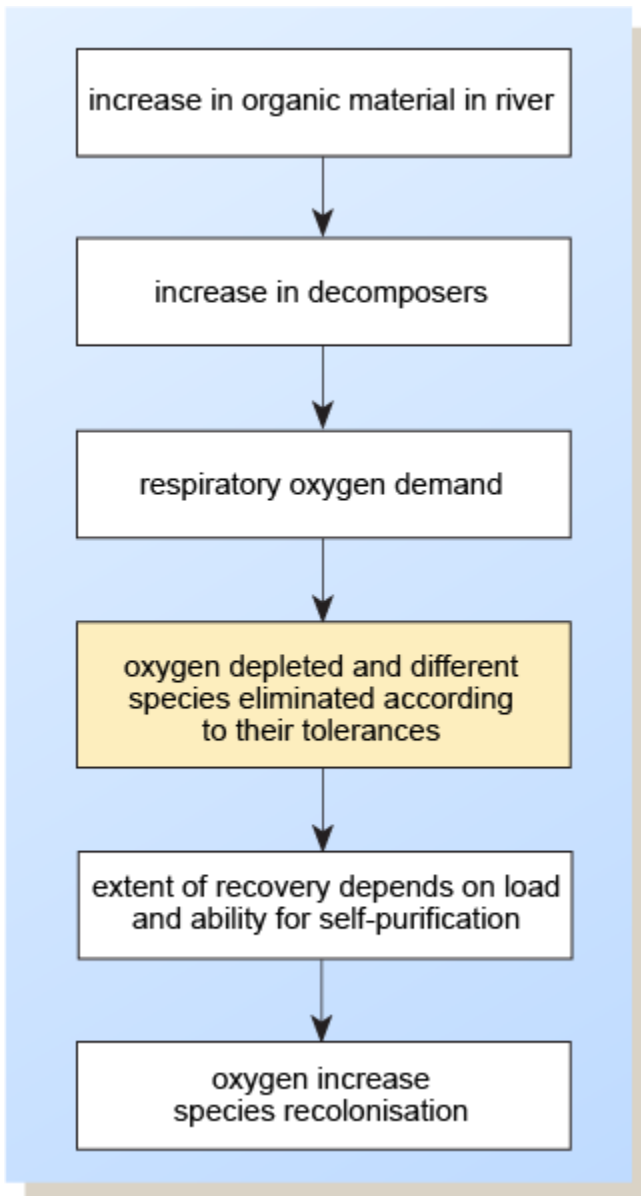
```
┌─────────────────────────────────────┐
│  increase in organic material in river │
└─────────────────────────────────────┘
                   │
                   ▼
┌─────────────────────────────────────┐
│       increase in decomposers        │
└─────────────────────────────────────┘
                   │
                   ▼
┌─────────────────────────────────────┐
│       respiratory oxygen demand      │
└─────────────────────────────────────┘
                   │
                   ▼
┌─────────────────────────────────────┐
│      oxygen depleted and different   │
│    species eliminated according      │
│         to their tolerances          │
└─────────────────────────────────────┘
                   │
                   ▼
┌─────────────────────────────────────┐
│   extent of recovery depends on load │
│      and ability for self-purification │
└─────────────────────────────────────┘
                   │
                   ▼
┌─────────────────────────────────────┐
│           oxygen increase            │
│         species recolonisation       │
└─────────────────────────────────────┘
```

Figure 15 Events following organic pollution

Inorganic materials can also cause deoxygenation, e.g. when ferrous iron from mine drainage water enters a river (Stumm and Lee, 1961). In the reduced ferrous (Fe(II)) state the iron is in solution, but on meeting the oxygen in the river it is oxidised to red insoluble ferric (Fe(III)) iron, a process that reduces the concentration of dissolved oxygen in the river water. The oxidised iron is now in suspension so that, as well as reducing the oxygen content, it reduces light penetration. It finally settles out slowly downstream of the discharge point, giving rise to all the problems associated with suspended solids. This type of problem is usually associated with coal-mining effluents.

3.3 Plant nutrients

Certain inorganic substances are essential for normal plant metabolism but they can reach such levels as to be considered pollutants.

Eutrophication is the increase with time of plant nutrients and biota in a watercourse. Farming contributes 50–60% of nitrates and 20–30% of phosphorus getting into UK waters (GOV.UK, n.d.), with most of the remainder coming from treated sewage effluent. Pollutants from these sources can greatly accelerate the natural process by increasing the inputs

of nutrients so that algae grow rapidly and *algal blooms* may form (Figure 16). The resulting rapid removal of carbon dioxide by photosynthesis can upset the bicarbonate–carbonate equilibrium and cause a pH rise, which in itself is damaging to the ecosystem (see Section 1.3.6).
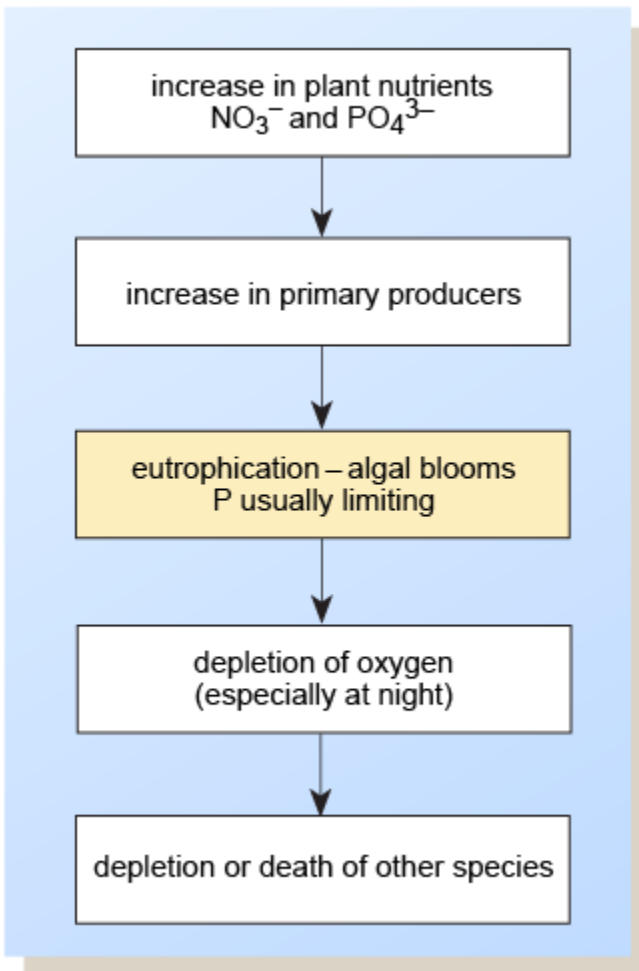

increase in plant nutrients
NO_3^- and PO_4^{3-}

increase in primary producers

eutrophication – algal blooms
P usually limiting

depletion of oxygen
(especially at night)

depletion or death of other species

Figure 16 Events following eutrophication

View description

In addition, at night the excess respiration (without the replacement of oxygen by photosynthesis) can deplete oxygen reserves, causing the death of higher organisms such as invertebrates and fish. This process can be compounded when algal blooms, through their decay, further reduce the oxygen content of the water.

In shallow water, the formation of benthic (bottom-living) mats of algae can create a smothering layer over sediments. This can hinder the supply of oxygenated water to eggs and impede the emergence of fry from salmon spawning grounds, for example.

Of the plant nutrients, the total inflow of phosphorus and nitrogen (especially at the productive time of year, spring and summer) is the most important. The main types of organism associated with algal blooms, and the different conditions needed for their continued growth, are as follows.

- **Blue-green algae (cyanobacteria)**

  Blue-green algae are able to fix atmospheric nitrogen and therefore are not limited by nitrate levels in the water. Neither are they dependent on dissolved carbon dioxide, because they can use the bicarbonate ions present. In addition, they are

tolerant of relatively high pH. Their growth is limited by the phosphorus content.

- **Unicellular green algae**

  Green algae require nitrate, as they are unable to carry out *nitrogen fixation*. They also require fairly high levels of carbon dioxide, as they cannot use bicarbonate ions, and they are not tolerant of high pH values. Their growth is limited by both phosphorus and nitrogen.

Contact with or ingestion of blue-green algae can cause skin rashes, eye irritation, vomiting, fever, and pain in the muscles and joints, due to toxins produced by the algae. In addition, 'red tides' are harmful algal blooms that appear in coastal areas. They can produce toxic effects in humans, marine organisms and birds. The toxins produced may also make the surrounding air difficult to breathe (NOAA, 2013), and the bloom of algae often turns the water red.

Generally, increases in both phosphate and nitrate concentrations seem to be the most important factor in governing the rate of eutrophication in most waters. However, whether this is the only factor that limits the rate of eutrophication is still a matter of controversy. Any eutrophication is contingent on other aspects of the particular ecosystem such as the hardness, the pH value and the original distribution of algal species.

For freshwater plants, about eight times more nitrogen is required than phosphorus. Phosphorus thus limits eutrophication if nitrogen is more than eight times as abundant as phosphorus, while nitrogen limits eutrophication if its concentration is less than eight times that of phosphorus (UNEP, n.d.).

Nitrates can have a more significant effect on human health than phosphates if they are present in drinking water supplies.

- When nitrates are ingested by infants under six months of age, they can be converted to nitrite by bacteria in the digestive system. Nitrites combine with haemoglobin in the bloodstream, preventing it from carrying out its normal function of combining with oxygen and carrying it around the body. This can result in a serious, though rare, condition called methaemoglobinaemia ('blue baby syndrome'), which can be fatal (Skipton and Hay, 1998).
- Ingestion of nitrate and nitrite by people with a low intake of vitamin C increases the risk of stomach cancer (Ward et al., 2011).

Water quality standards exist to control pollution of domestic water supplies. The maximum limit set by the EU for nitrates in drinking water is 50 g m^{-3} (as NO_3^-) (EU, 1998). Water with a high nitrate content can be treated for drinking using reverse osmosis, a process that will be described in Section 4.

The effects on the biota of organic pollution and artificial eutrophication are summarised in Figure 17. When

organic pollution occurs, the main types of organisms present are the decomposers. In the case of eutrophication, the producers are dominant, and in larger quantities than in 'clean' waters.
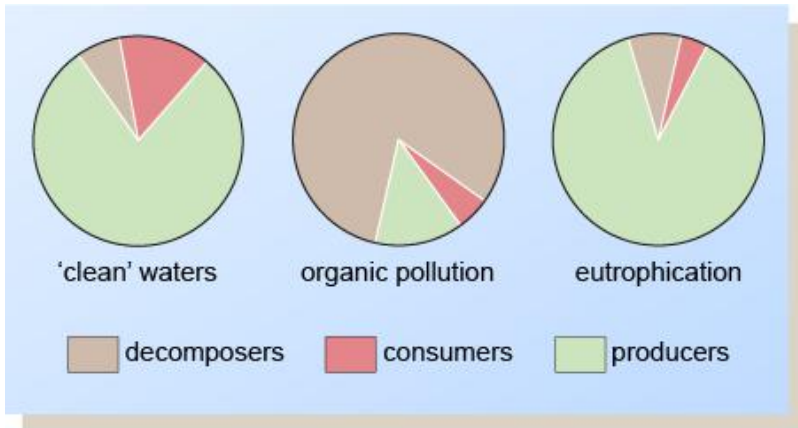

Figure 17 Ecological imbalances caused by organic and inorganic pollutants

View description

3.4 Toxic pollutants

The term 'toxic' is a rather misused one. It is misleading to refer to one material as a toxic substance and to another as non-toxic without qualification. The toxicity of all materials depends on their concentration. Further complications may be introduced by the fact that some materials (e.g. selenium) are essential components of

an animal's diet, yet in anything other than very low concentrations they may have a toxic effect.

Other environmental factors to be taken into account include:

- the extent of biodegradation
- the rate of accumulation of a substance in the biota (and so within the food chain)
- the retention time of a substance within an organism.

An important mechanism for toxicity in the body is the poisoning of *enzymes*, which are the *catalysts* of all the bodily functions.

The terms used when explaining the effects of a toxic substance on an organism are:

- *lethal* – causing death by direct poisoning
- *sublethal* – not sufficient to cause death, but leading to a reduction in the number of species and/ or individuals by, for example, causing a change in behaviour, growth or reproductive success
- *acute* – causing an effect (possibly death) within a short period of time
- *chronic* – causing an effect (lethal or sublethal) over a prolonged period of time
- *accumulative* – having an effect that is increased by successive doses.

To test the effects of toxicity, the LD_{50} (lethal dose) test is commonly used. The LD_{50} is the dose that is large enough to kill 50% of the sample of animals under test.

Some examples of LD_{50} values for different chemicals are given in Table 7.

Table 7 Oral toxicities of some chemicals in small mammals

LD_{50} (mg per kg body weight)	Examples	Classification
1–10	arsenic	highly toxic
10–100	cadmium	moderately toxic
	copper	
	lead	
	mercury	
100–1000	aluminium	slightly toxic
	molybdenum	
	zinc	
>1000	sodium	relatively harmless
	iodine	
	calcium	

Certain inorganic substances, such as cyanides, fluorides, sulfides, sulfites and nitrates, may be classified as toxic.

- Compounds of cyanide and sulfide interfere with the use of oxygen in respiratory reactions in cells.
- Excess fluoride can lead to mottling of teeth and bones in humans.
- Nitrates can cause 'blue baby syndrome' (as discussed in Section 3.3).

However, the final effects of a toxic substance in water depend on environmental factors such as hardness, temperature and pH. Salts of heavy metals such as copper, silver, lead, gold, nickel, chromium, zinc, cadmium and mercury are toxic and will generally kill most aquatic organisms at very low concentrations, but they are generally less toxic in calcium-rich water (Wilson, 1988); a nickel–cyanide complex is 500 times more toxic to fish at pH 7 than at 8, because the complex *dissociates* into cyanide and nickel ions and a proportion of the cyanide forms the highly toxic undissociated hydrogen cyanide (HCN); and ammonia is 10 times more toxic at pH 8 than at 7 (EIFAC, 1968). Also an additive effect, *synergism*, may occur – for instance, evidence has been found for synergism between mercury and uranium (Sánchez et al., 2001).

Two particularly significant groups of toxic pollutants are the heavy metals, and synthetic organic substances such as some of the pesticides.

3.4.1 Pesticides

Pesticides are chemicals used to kill pests such as weeds, insects, fungi and rodents. After the Second World War, pesticides such as DDT (dichlorodiphenyltrichloroethane) – which were highly toxic, persistent and bioaccumulating – were commonly used in agriculture and for vector control (e.g. against the *Anopheles* mosquito, for malaria control). The populations of birds of prey declined due to eggshell thinning preventing the birth of live offspring. This was because of DDE (dichlorodiphenyldichloroethylene), a very stable metabolite of DDT (Faber and Hickey, 1973). Sexual development and behaviour in birds such as gulls was also disturbed (Fry and Toone, 1981). The use of DDT has now been banned in most countries, and the tendency is to opt for pesticides that degrade rapidly in the environment (FAO, n.d.).

Chemicals that exhibit the characteristics of DDT (i.e. high toxicity, persistence and bioaccumulation) are termed *persistent organic pollutants* (POPs), and most of the POPs are pesticides. Pesticides have been found to be carcinogenic in experimental animals, and therefore are possibly carcinogenic to humans. They are suspected of depressing the immune system, and of disrupting the endocrine system, mimicking or blocking

normal hormone activity (Morner et al., 2002). More on endocrine disruptors is given below.

POPs can be transported by wind (e.g. from combustion and high-temperature processes such as those in the iron and steel industry) and water, and as such can affect areas far from the point of their use. Their persistence in the environment, and their potential to move up the food chain, led to the Stockholm Convention of 2001, under which nations agreed to reduce or eliminate the production, use and/or release of POPs (Stockholm Convention, 2008).

Organophosphates (such as malathion, diazinon and chlorpyrifos) are insecticides containing phosphorus. They act by inhibiting enzymes in the nervous systems of animals. Pyrethroids (synthetic versions of the short-lived natural pesticide pyrethrin, which is made from chrysanthemum flowers) are another category of insecticide, often used by householders to control pests such as leaf-eating insects and ants. Organophosphates and pyrethroids can attach to soil particles and get washed into rivers and streams, endangering aquatic life.

Amongst the POPs are polychlorinated biphenyls (PCBs), which are a group of organic chemicals used in a variety of ways (e.g. as hydraulic fluids, plasticisers, fire retardants, heat transfer fluids, paint additives, lubricants and cutting oils). Ingestion of water containing PCBs can lead to an increased risk of cancer, immune deficiency, and problems with the reproductive and

nervous systems (EPA, 2012). Their use was banned in 1977.

The main problem with manufactured substances such as pesticides is that most are unknown in nature and thus organisms have not evolved to deal with many of them. Although some will be broken down into harmless substances by normal digestion processes, others will remain and accumulate in the organism exposed to them. This is known as *bioaccumulation*. If this organism falls prey to another organism, the toxic substances will be passed up the food chain and retained in increasing quantities within the bodies of organisms higher up the chain. The accumulation of toxic substances through the food chain is called *biomagnification*. An example of this was the case of Minamata disease, where consumption of fish contaminated by methyl mercury led to thousands of people suffering symptoms such as numbness in fingers and lips, difficulty in speech and hearing, inability to control their limbs, and seizures. There were many deaths, too (Porteous, 2008).

Endocrine disruptors

As mentioned above, pesticides can be endocrine disruptors. Many other chemicals are also classed as endocrine disruptors, i.e. they interfere with the synthesis, secretion, transport and binding, action, or elimination of natural hormones in the body that are responsible for the maintenance of *homeostasis*,

reproduction, development and/or behaviour (Burkhardt-Holm, 2010).

Most endocrine disruptors are synthetic compounds (e.g. plasticisers such as bisphenol A, used in plastic bottles and food containers; sex steroids in contraceptive pills; paints; pesticides; alkylphenol polyethoxylates used as surfactants in detergents). They can end up in watercourses through sewage treatment works, surface water run-off, direct discharge or leachates from landfill sites. One effect that has been observed on wildlife is the feminisation of male fish (Jobling et al., 2002).

Having said the above, there are also natural sources of endocrine disruptors. For instance, *Fusarium* fungus infesting corn and other grains produces zearalenone, a potent oestrogenic chemical that causes cessation of lactation and hyperoestrogenisation in pigs (Burkhardt-Holm, 2010).

In terms of water supply, endocrine disruptors can be present if untreated groundwater is used for potable supplies, if the groundwater is contaminated with the suspect chemicals. Bottled water can contain endocrine disruptors from plasticisers and detergents used in the production process.

3.4.2 Acidity and heavy metals

Acidity can be detrimental to life forms. Table 8 shows the effects of low pH on fish.

Table 8 Generalised short-term effects of acidity on fish

pH range	Effect
6.5–9.0	No effect
6.0–6.4	Unlikely to be harmful except when carbon dioxide levels are very high (1000 mg l^{-1})
5.0–5.9	Not especially harmful except when carbon dioxide levels are high (20 mg l^{-1}) or ferric ions are present
4.5–4.9	Harmful to the eggs of salmon and trout species (salmonids) and to adult fish when levels of calcium, sodium and chloride are low
4.0–4.4	Harmful to adult fish of many types that have not been progressively acclimated to low pH
3.5–3.9	Lethal to salmonids, although acclimated roach can survive for longer
3.0–3.4	Most fish are killed within hours at these levels

(EPA, 2000a)

In addition, highly acidic waters can dissolve heavy metals, especially if the pH is below 3. This occurs in the case of mine wastewaters. The metals present tend to be brought into solution, especially iron, zinc, lead and molybdenum.

The information that is available on metal pollutants tends to refer to the total concentration of the metals; unfortunately this provides little information on a metal's *bioavailability* (i.e. the ability of an organism to take up the metal) or how long the metal will stay in solution before it is removed into sediment. To be able to predict the adverse effects of metal pollutants in water it is necessary to determine the physical form or *chemical speciation* of the metal present, since metals can exist in a wide range of forms. The subject is too complicated to be covered fully here, but the following two theoretical examples are extreme cases of metal pollution to show the range of events that can occur.

- Example 1: After treatment to remove most of the lead, the effluent from a lead–acid battery factory is discharged into a river. The lead concentration in the effluent is still about 4 g m^{-3}, with a trace of particulate lead in the form of lead sulfate. The lead sulfate settles out quickly. The soluble lead becomes attached to particles greater than 12 μm in size and settles out in the river. The discharge therefore causes a relatively small increase in the lead content of the river.
- Example 2: A sewage effluent is contaminated with cadmium from industrial sources. The cadmium is in the form of organic complexes formed from the organic-rich sewage in the sewage treatment process. In the river this form of cadmium does not settle out and is carried downstream over a long distance, remaining available to biological life throughout.

Metals dissolved in water can enter the food chain by a variety of mechanisms. For example:

- Phytoplankton absorb metals by *diffusion* across the external membrane.

- Fish can take in metals by
    - diffusion across the membrane of their gills
    - ingesting metals, though metals taken in this way are not as readily bioavailable.
- Filter feeders such as oysters and cockles inhabit the surface of sediments and consume considerable amounts of particulate matter from the water that passes through them; they accumulate metals by ingestion.

3.5 Physical pollutants

Physical pollutants include:

- suspended solids
- immiscible liquids
- discharges that result in changes to the temperature or flow rate of the receiving water
- substances that impart a taste, odour or colour to the water.

3.5.1 Suspended solids

Various industries produce suspended material (or particulates) in their effluents, and this has several consequences.

All solids tend to reduce light penetration (as mentioned in Section 1.3.5), so the growth of plant life in watercourses is inhibited. This will have secondary effects on food chains. Bottom-living animals and plants may be smothered as particles settle. If the particles settle on gravels, fish spawning can be seriously disrupted. Predators that hunt by day may be restricted in their activities: for example, 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. Prolonged exposure to high levels of suspended solids (50 mg l^{-1} and above) is likely to lead to sublethal changes due to respiratory distress, and adverse growth and development (Au et al., 2004).

Some effluents pollute because substances in them enter into a chemical reaction with salts already dissolved in the water. For example, iron hydroxide may be precipitated if water containing iron is discharged into a naturally alkaline river. This phenomenon typically arises from abandoned mines, where the clear water pumped out and discharged into a clear stream can produce a bright orange coloration that prevents penetration of light and hence inhibits plant life.

Some suspended solids can also cause harmful effects when soluble toxic components present in them are dissolved into the water by biological or chemical action.

3.5.2 Immiscible liquids

Immiscible liquids may be present as oils, greases or tarry substances, often in the form of an *emulsion* (a *colloidal* suspension of one liquid in another, as in mayonnaise). They may affect turbidity in the same way as suspended solids. However, emulsions are not likely to settle to the bed of the river. Frequently they float on the surface and adhere to vegetation at the waterline. Some immiscible liquids are decomposed slowly by aquatic microorganisms. Many oils and tars are slightly soluble in water and thereby impart tastes and odours to it.

Oil is generally less dense than water and will spread over the surface to form an extremely thin, often visible film; a small quantity of oil is therefore likely to pollute a large area. Even when the oxygen demand in the water is low and oil imposes little additional biological load, the presence of an oil film with a thickness of only one thousandth of a millimetre (1 µm) may reduce the rate at which oxygen is transferred from air to water. It can also affect the life cycle of insects, since the larvae of some species float on the surface.

Oil is one of the more serious pollution problems. As an example, there are now around 3000 pollution incidents involving oil and fuels every year in England and Wales (Environment Agency, 2013). Although some of these affect land, the vast majority affect the water environment.

3.5.3 Discharges contributing to a temperature change

Industrial effluents are frequently discharged at temperatures different from those of the receiving river. Almost invariably the effluent is warmer than the river, since water is widely used for carrying away heat.

Some of the effects of an increase in temperature have already been described in Section 1.3. Within limits, a raised temperature increases the metabolic rates of all aquatic organisms. It also decreases the concentration of dissolved oxygen needed for saturation – for instance, the saturation concentration of oxygen in water at 5 °C is 12.79 g m^{-3}, while at 15 °C it is 10.01 g m^{-3}. The overall effect on the oxygen balance of a particular heated effluent therefore depends to a certain extent on the oxygen balance in the river at the point of discharge.

A small increase in the temperature of a clean, fast-flowing stream may not affect the ecosystem adversely. Provided oxygen is plentiful, plant and animal populations may be altered slightly but remain in a balanced state. Species indigenous to warmer climates may become established in a heated portion of a river. However, heated effluents are usually discharged to watercourses that are already polluted to some degree, so the polluting effects are compounded. A heightened BOD on the river water due to a sewage discharge upstream may be exacerbated by raising the

temperature. Any animals or plants that die as a result of the heat or greater oxygen deficit are decomposed by bacteria, which decreases the oxygen level even more.

3.5.4 Discharges causing variations in flow rate

Variations in the flow of a river can result from excessive abstraction or from intermittent discharges of relatively large volumes of effluent, as when settling ponds (which are used to remove particulates from effluents in the ceramic industry, for example) are emptied. There are, however, maximum limits that must be adhered to.

Since the organisms that become established in a river will be those best suited to its conditions, sudden and repeated fluctuations in the rate of flow will mean that only those organisms that can withstand the changes will survive. Plants growing in silt deposits on the bed of a stream will be destroyed when the silt is washed away by a sudden increase in flow. When the flow falls, organisms that are dependent on a high dissolved oxygen concentration will die if the river reverts to a series of near-stagnant pools.

3.5.5 Substances causing taste, odour and coloration

Very low concentrations of some chemical compounds will produce unpleasant tastes and odours, or will taint the flesh of fish living in water contaminated by them.

Interaction between substances may produce tastes that are apparent at concentrations well below those at which either substance is individually detectable. An 'antiseptic' taste of chlorinated tap water is obvious if the raw water supply contains phenols, since this results in the formation of chlorophenols. (Phenolic compounds can occur naturally in lowland rivers.) Unpleasant tastes and smells, usually earthy or sulfurous in nature, can also occur naturally from decaying vegetation.

The ecological effect of colour will depend on its light-absorptive properties in relation to the spectral requirements of algae and plants (i.e. which wavelengths of light they need). Many rivers are naturally coloured (e.g. those draining peat are light brown due to humic and fulvic acids) and yet are able to support biota, including trout. The ecological effects of colour are usually minimal compared with other factors.

SAQ 9

Each hour, an industrial plant discharges 600 m^3 of treated effluent at 40 °C into a river that has an annual average temperature of 15 °C. The flow rate of the river is a constant 20 000 m^3 per day.

a. Assuming perfect mixing, what will the temperature in the river be after entry of the effluent, assuming no temperature loss to atmosphere?
b. What impact will this have on the river?

3.6 Biological pollutants

Biological pollutants are organisms that may be harmful to other forms of life, but they have to be ingested to have any effect. The most usual form of transmission is the faecal–oral route, in which faecal matter from one human being finds its way into another. This can happen through the ingestion of faecally contaminated water or food. Alternatively, sometimes pathogenic organisms can be consumed through eating contaminated undercooked food, as in the case of certain strains of *E. coli* (which will be discussed in Section 3.6.2).

The effects of the different organisms are varied, and can be more easily ascertained through sources such as the World Health Organization or local health protection agencies. However, in this subsection I will describe the characteristics of the main water-borne pollutants, namely:

- pathogenic bacteria
- coliforms
- faecal streptococci
- *Clostridium perfringens*
- viruses
- protozoa
- helminths

- other biological pollutants.

3.6.1 Pathogenic bacteria

As well as the bacteria that are found naturally in river water and that are essential for the natural cycle of nutrients, there may be other, less desirable bacteria. Pathogenic bacteria (such as *Salmonella typhi*, Figure 18a) can cause disease in a variety of organisms, including humans. Since the presence of pathogenic bacteria is generally due to the activities of humans, it constitutes a form of pollution. Non-pathogenic bacteria, by definition, are harmless; indeed, as already mentioned, they can be beneficial and form an essential part of the aquatic ecosystem.
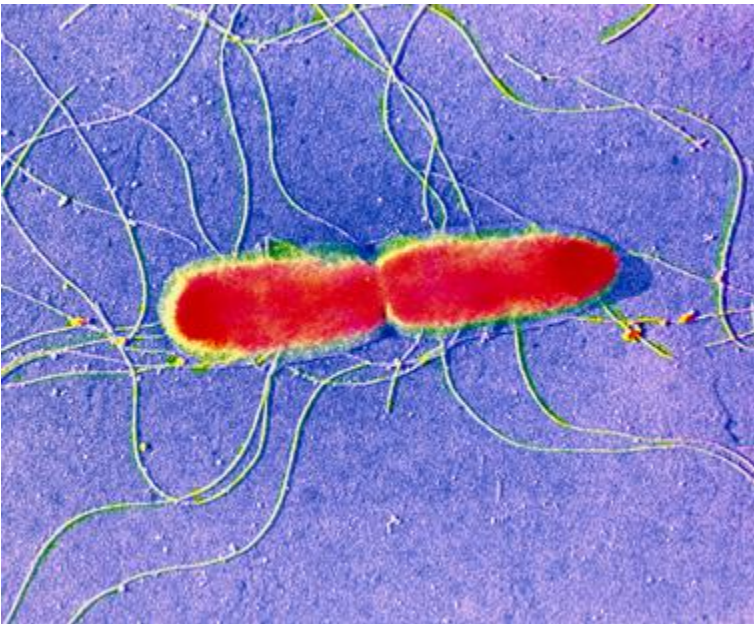
Figure 18a *Salmonella typhi*

View description

Effluents from sewage treatment works (mentioned in Section 2.2) contain some pathogenic bacteria, but in far smaller numbers than in incoming sewage since the sewage treatment processes will generally eliminate more than 99% of them.

Since pathogenic bacteria are accustomed to human body temperature (about 37 °C), they do not flourish in river water and die off relatively quickly.

3.6.2 Coliforms

Coliforms are a large group of bacteria, often of intestinal origin. The coliform *Escherichia coli* (*E. coli*, Figure 18b) is present in the intestines of humans and other mammals. Its presence in water implies that human pathogens from faeces may also be present, and it is therefore a useful indicator organism of faecal contamination.
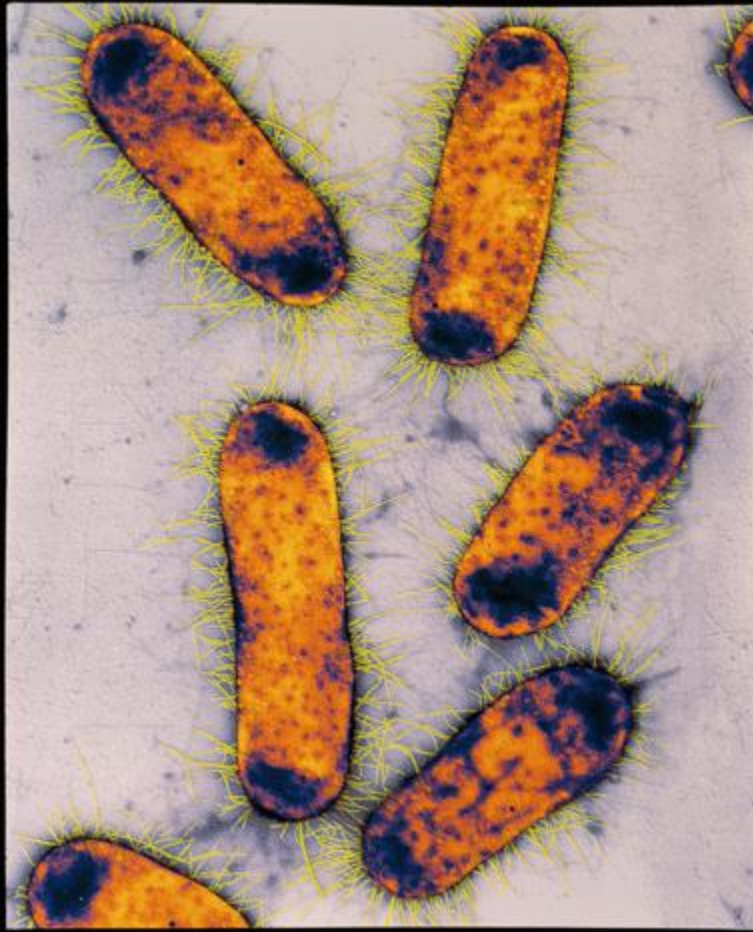
Figure 18b *Escherichia coli*

View description

E. coli is a rod-shaped faecal coliform about 0.5 μm by 2–3 μm in size. The strain of *E. coli* usually present in humans is harmless and occurs consistently in faeces in far greater numbers than pathogenic bacteria. However, there are other strains – such as *E. coli* O157:H7 – that are pathogenic. These have been found in partially cooked meat and have led to deaths (Rangel et al., 2004).

Concentrations of *E. coli* as low as 10 cells per litre can be detected. The presence or absence of *E. coli* in a water sample provides an important indicator of pollution and possible risk to public health.

3.6.3 Faecal streptococci

The faecal streptococci group of bacteria consists of the species *Streptococcus faecalis* (Figure 18c), *S. faecium*, *S. durans*, *S. equinus* and *S. bovis*. The bacteria are approximately 1 μm in diameter and occur in chains of varying length. They die fairly quickly outside their host, so their presence is indicative of recent pollution.
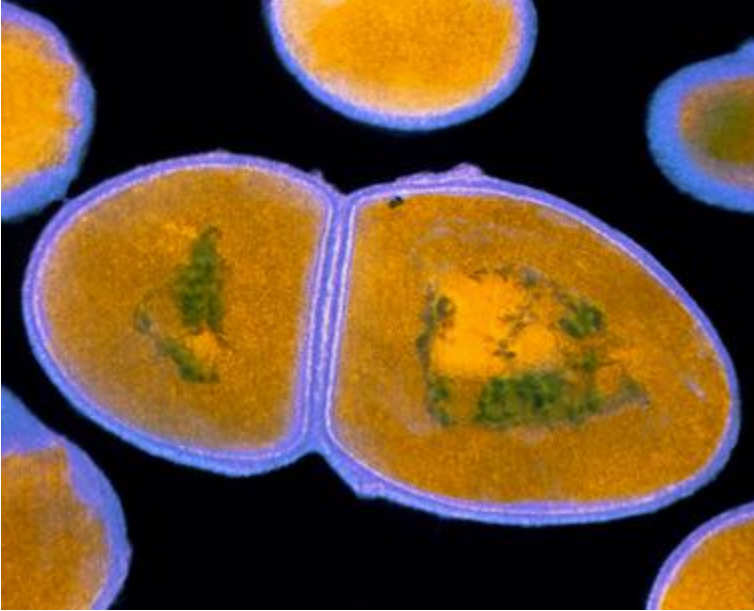
Figure 18c *Streptococcus faecalis*

View description

3.6.4 *Clostridium perfringens*

C. perfringens (Figure 18d) is an anaerobic organism present in the intestines of humans and animals at much lower numbers than *E. coli*. It is a common cause of food poisoning. The cells are rod-shaped (about 5 µm by 1 µm) and can form endospores. They can

cause severe abdominal cramp and diarrhoea if present in water that is ingested.
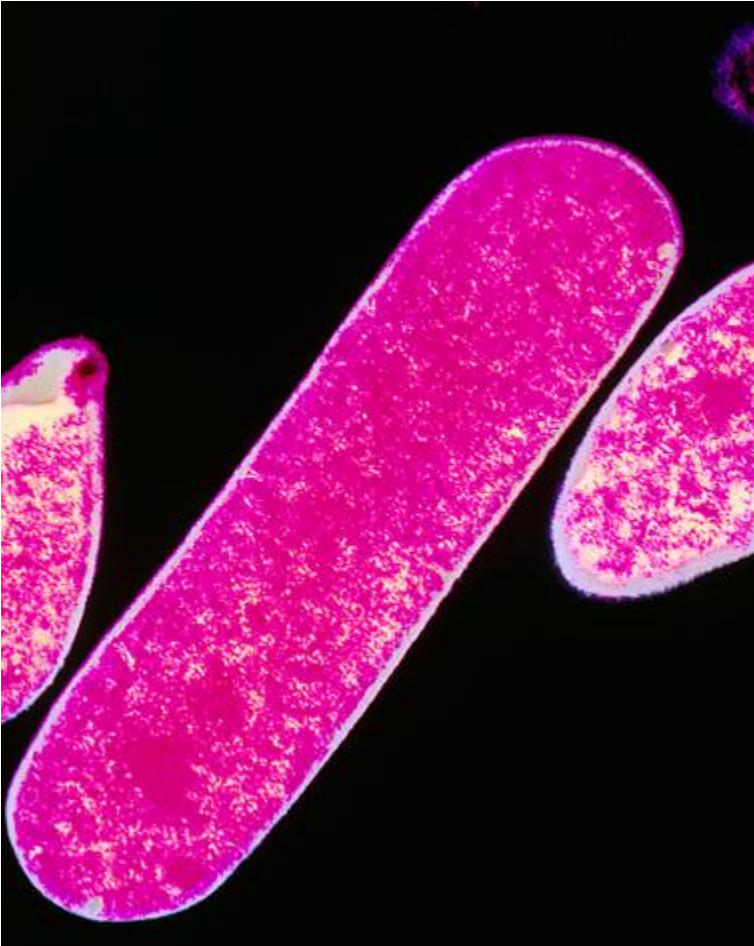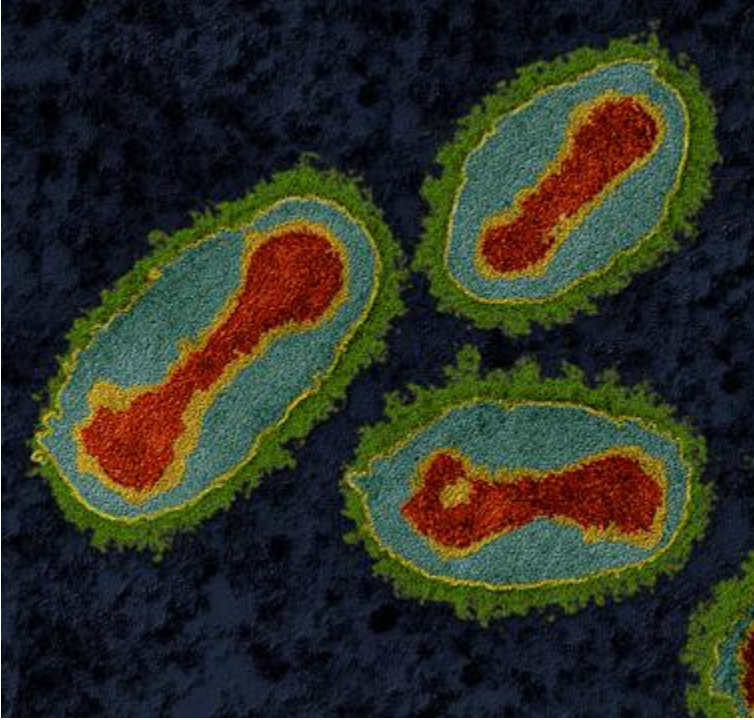

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Figure 18d *Clostridium perfringens*

Endospores – or spores, as they are commonly referred to – are hardy structures that certain bacteria can form when their environment becomes unfavourable for growth. The purpose of the endospore is survival; it is very resistant to heat and desiccation, and may survive for many years at normal temperatures. When environmental conditions are favourable for growth, the endospore reactivates to form a normal, single cell. This ability leads to *C. perfringens* being present in unchanged numbers long after other faecal indicators have died out. Thus its presence in the absence of *E. coli* indicates intermittent faecal contamination.

3.6.5 Viruses

Viruses are tiny (5–30 nanometres in size) infective agents that can grow only in living cells. The virus that causes smallpox, declared eradicated from the world in 1979, is illustrated in Figure 18(e).

Figure 18e Smallpox viruses (*Variola*)

View description

Most viruses are able to remain viable in water at low temperatures, provided there is some organic matter present. Once excreted, the number of viruses cannot increase since they only multiply within living susceptible cells.

The main threat to water quality comes from human enteric (intestinal) viruses that are produced by infected persons and excreted faecally. Depending on local circumstances, this may contaminate river water directly or, if treated, via sewage effluent that may be discharged into a river. If the river water is abstracted and treated for drinking purposes, the viruses may not be completely removed. (It is possible for a person to be susceptible to only one viral particle.)

The presence of any enteric virus can be taken as an indication of the possible presence of other harmful viruses. In temperate climates, enteric viruses occur at peak levels in sewage during late summer and early autumn. The exception is the hepatitis virus, which increases in the colder months.

3.6.6 Protozoa

There have been several outbreaks of protozoal infections from water in several countries. For instance, each year in the UK there are 3000–6000 confirmed cases of cryptosporidiosis, caused by the protozoa *Cryptosporidium*; the largest outbreak was in Torbay, Devon in 1995, when 575 people were taken ill (Hunter et al., 2003).

The most common symptom of cryptosporidiosis is watery diarrhoea. Other symptoms include stomach pain, nausea, vomiting, fever and weight loss (Centers for Disease Control and Prevention, 2010). In addition, some people can act as carriers of *Cryptosporidium*.

Another, similar condition is giardiasis, caused by the protozoa *Giardia*. Giardiasis outbreaks are not common in the UK, but one occurred in Bristol in 1985, when 108 cases were diagnosed (Jephcott et al., 1986).

Techniques for sampling and analysis of *Cryptosporidium* are complicated and time-consuming, requiring the filtration of large volumes of water (100–1000 litres), followed by several stages of elution, isolation and concentration of the oocysts, and then identification and enumeration by immunofluorescent microscopy. Initial testing does not provide information on whether the oocysts are viable and therefore capable of causing disease – this requires further testing. As a result, there is no specific standard for the organism in EU or UK regulations. There is, however, a general requirement that drinking water should not contain any microorganism or parasite at a concentration that would constitute a potential danger to human health (Water UK, 2011).

Cryptosporidium and *Giardia* can be trapped by membrane filtration or slow sand filters. Other types of filters, such as wound fibre filters, are also employed. Chlorination and UV radiation at normal doses are ineffective against these organisms.

3.6.7 Helminths

Helminths (Figure 19) are parasitic worms that can cause ill health in humans. They range from a millimetre long to more than a metre (Baron, 1996).

Figure 19 A helminth, *Ascaris lumbricoides*

View description

Helminths can cause morbidity, and sometimes death, by compromising the nutritional status of the infected person. They can also affect cognitive processes,

induce tissue reactions and provoke intestinal obstruction or rectal prolapse (WHO, 2013b).

Infection occurs through ingestion of helminth eggs that are present in food. For example, helminth eggs may be present in the meat of cattle grazing on land that is contaminated by poorly treated sewage effluent or sludge.

3.6.8 Other biological pollutants

Many other forms of pollution mentioned previously could be considered as biological pollutants, e.g. algal blooms and the growth of sewage fungus. Examples that are more clearly of this type of pollution are the many species of blue-green algae, which produce substances that are toxic to terrestrial organisms and can impart tastes and odours to water.

3.6.9 Typical pathogens

Table 9 lists some of the major pathogens that cause disease to humans and are likely to be found in polluted water.

Table 9 Some of the major pathogens likely to be present in sewage and in faecally polluted streams

Organism	Organism type	Disease	Remarks

Bacteria	*Vibrio cholerae*	Cholera	Transmitted sewage and polluted wate in cholera-ende areas
	Salmonella typhi	Typhoid fever	Common in sewage
	Salmonella paratyphi	Paratyphoid fever	Common in sewage
	Salmonella spp.	Food poisoning	Cause of foc poisoning; usually found contaminate food of anim origin
	Shigella spp.	Bacillary dysentery	Polluted wate are main sou of infection
	Bacillus anthracis	Anthrax	Can be foun effluents from tanneries processing hides from infected animals; spo resistant to treatment
	Brucella spp.	Brucellosis (Malta fever) in	Normally transmitted b

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		humans; contagious abortion in sheep, goats and cattle	infected milk by contact
	Leptospira icterohaemorrhagiae	Leptospirosis (Weil's disease)	Carried by sewer rats; a present in wa contaminated urine from infected anim and humans can infect through cuts skin, or intac skin if immer for a long tim
Viruses	Poliovirus	Poliomyelitis	Transmitted faecal–oral route via contaminated food or wate
	Hepatitis A virus (HAV)	Hepatitis A	Transmitted faecal–oral route via contaminated food or wate
Protozoa	*Entamoeba histolytica*	Amoebic dysentery	Spread by contaminated waters and sludge used

			fertiliser; common in warm countr
	Giardia lamblia	Giardiasis	Found in inadequately treated wate
	Cryptosporidium spp.	Cryptosporidiosis	Carried by agricultural livestock and infected pers
Helminths	*Taenia saginata*	Tapeworms	Eggs very resistant, present in sewage slud and sewage effluents; ca present in contaminate water source and food
	Ascaris lumbricoides	Nematode worms	Present in sewage effluents and dried sludge used as ferti
	Schistosoma haematobium, *Schistosoma mansoni*	Bilharzia	Carried by w snails in rive and irrigation ditches contaminated

human waste
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of the world;
enter human
by direct
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skin

3.7 Further SAQs

SAQ 10

Identify which of the following statements concerning the effects of both organic pollution and eutrophication are true. If a statement is false, give the reason why.

a. Depletion of oxygen occurs because of an increase in the activities of primary producers in both cases.

b. In both cases it is the presence of plant nutrients (nitrates and phosphates) that causes the death of green plants and depletion of oxygen.

c. The difference in the proportion of producers and consumers between organically polluted waters and eutrophic waters is negligible.

d. A reduction of dissolved oxygen in both cases causes the depletion of species.

e. Once the dissolved oxygen content is decreased, only the removal of the offending pollutant can allow an increase in species.

View answer

SAQ 11

Identify which of the following statements are true. If a statement is false, give the reason why.

a. Continuously flowing organic pollutants such as domestic sewage cannot cause long-term damage to a watercourse in the way that toxic pollutants can.

b. A temperature rise in a waterway leads to higher productivity but doesn't affect the BOD.

c. Effluents from fish farms can be badly polluted. Concern has arisen about these effluents mainly because they contain unconsumed food and faecal matter from fish.

d. Pesticide pollution of watercourses is due solely to large-scale use of these compounds by farmers.

e. Metals that are water soluble are able to bioaccumulate by diffusing across the biological membranes of organisms.

SAQ 12

Identify which of the following statements are true. If a statement is false, give the reason why.

a. The toxicities of individual chemicals in a mixture can be summed up to give an overall toxicity figure. This is simpler than testing a complex mixture.

b. In toxicity tests for a proposed discharge, the most sensitive species in the receiving watercourse should be used as the test organism.

c. When suspended solids settle on the river bed, it is only benthic plants that are affected, as the light will not reach the leaves.

d. *E. coli* is a species of bacterium that inhabits human intestines and is always harmless.

e. *Clostridium perfringens* is a pathogenic bacterium that lives in the human gut and can cause food poisoning.

f. Controlling the discharge of the culprit chemicals from industry will overcome the problem of endocrine disruptors.

View answer

SAQ 13

Indicate the causative agent (virus, bacterium, protozoan or helminth) of each of the following diseases:

- cholera
- poliomyelitis
- typhoid
- bilharzia
- anthrax
- cryptosporidiosis.

View answer

3.8 Summary

Different pollutants affect the aquatic environment in different ways. While at low concentrations many pollutants (e.g. organic materials, N and P) may be beneficial, at high levels they can adversely affect the ecology of the system. Excess nitrate can be particularly harmful to babies.

Many of the toxic pollutants in effluents are synthetic, and therefore do not easily biodegrade naturally.

The effects of physical pollution on the ecology of a river system can be complex, affecting the feeding and breeding habits of the different species.

Biological pollutants can spread disease through water, and also disrupt the ecology.

The measurement and control of water quality is therefore of crucial importance in the interests of public health and the maintenance of the environment.

Table 10 gives a summary of the effects of the different pollutants discussed in this section.

Table 10 Classification of pollutants

Pollutant	General effect	Effect on biota	Effect on water supplies	Sour natu
Organic (biodegradable wastes)	Increased oxygen demand; food provided for organisms lower down in food chain	Tolerated in moderate quantities if release not too quick, serious if dissolved oxygen (DO) drops too quickly	Increased need of treatment	Run- seep throu
Plant nutrients	Excessive plant growth	Demand on DO	Increased need of treatment	Natu degr proc
Toxic chemicals (e.g.	Toxic to humans,	Could be lethal	Increased need of	Rare

heavy metals, pesticides, phenols, PCBs)	animals and plants		treatment or control	
Endocrine disruptors	Alteration of ecology	May adversely affect health and reproduction of humans and animals	Can be present in water sold in plastic bottles	*Fusa* spec fung
Acids/alkalis	Lowering/ raising of pH; acids can dissolve heavy metals	Only narrow range of pH tolerable for most plants and animals; heavy metals toxic	Corrosion	Natu acid alkal rock
Suspended solids	Reduction in light penetration (increased turbidity), blanketing, introduction of colour	Photosynthesis reduced; blanketing of benthic plants and animals; obstruction of gills of fish	Obstruction of filters; increased need of treatment	Soil eros storr flooc
Immiscible liquids	Formation of a layer at the water surface that could prevent	Reduced DO; insect breeding affected	Interference with treatment processes	Unlik

	O$_2$/CO$_2$ interchange			
Heat	Decrease in DO; increase in metabolic rate of aquatic organisms	Possible reduced breeding or growth of aquatic organisms	None	Unlik
Taste-, odour- and colour-forming compounds	Taste, malodour, colour	Tainting of fish	Increased need of treatment	Peat
Microorganisms	Pathogenic to humans	None	Increased need of treatment	Anim excr

Section 4: Sewage treatment

4.1 Introduction

Used water is discharged as waste. In built-up areas this is often conveyed by drains and sewers to a treatment plant, where the water is cleaned and reused or – as is more usual – discharged into a receiving water body such as a river. While this is the most popular discharge route, there are some discharges into estuaries and the open sea.

By the end of 2011, there were 2.5 billion people who lacked access to an improved sanitation facility (one that hygienically separates human excreta from human contact). Of these, 761 million use public or shared sanitation facilities, whilst another 693 million use facilities that do not meet minimum standards of hygiene (i.e. unimproved sanitation facilities). The remaining 1 billion (15% of the world population) still practise open defecation. The majority (71%) of those without sanitation live in rural areas, where 90% of all open defecation takes place (WHO and UNICEF, 2013).

However, as of 2010, the majority of the world's population lived in urban areas (WHO, 2013c), and in such locations water-borne sewerage systems are an effective way of managing wastewaters generated by the population. This section of the text concentrates on this mode of wastewater treatment.

Domestic effluent or sewage consists of wastewaters from toilets as well as wastewaters from other activities such as bathing, clothes washing, food preparation and the cleaning of kitchen utensils. The non-faecally contaminated water is referred to as greywater or *sullage*. Domestic sewage is up to 99.9% water, with the remaining 0.1% comprising 70% organic matter and 30% inorganic. The organic portion comprises proteins (65%), carbohydrates (25%) and fats (10%), while the inorganic part consists of grit, metals and salts (Harrison, 2001). In the UK, domestic water usage (which contributes to sewage flow) is about 150 litres per person per day, but with water-saving devices and water reuse this can be reduced considerably, to around 80 litres per person per day (Defra, 2008).

SAQ 14

Using the information given above, calculate the masses of the various components in 250 m^3 of domestic sewage. Assume the density of the sewage to be 1000 kg m^{-3}.

View answer

This section will consider the transport of sewage from its point of origin to the treatment plant, and the various processes carried out at the treatment plant to render the sewage suitable for discharge. Note that sewage is the wastewater generated by a population, while

sewerage is the infrastructure (consisting of pipes, valves, pumping stations, etc.) that takes the sewage to a treatment works.

4.2 Transporting sewage

4.2.1 Drains

In everyday usage, 'drains' are pipes or other conduits that convey water away from a building or area to prevent it from accumulating and causing a nuisance. 'Drain' also has a specific technical meaning, being reserved for the pipe that carries foul drainage (the wastes from toilets and washing facilities) to the public sewer.

In a building, waste pipes take the water discharges from various points to the main underground drain (Figure 20). The drainage pipes in a house will be from the toilets and wash basins. A vertical extension of the waste pipe, opening at roof level, is often used to ventilate the underground drain in a building. Such a vent:

- reduces air pressure fluctuation
- prevents the build-up of offensive smells in the drain
- aids the drying and subsequent flaking-off of deposits from the drain walls.

Smells from drains were once regarded as a major health hazard. Although this is not true, ventilation is

retained as a consideration of amenity, as well as for the practical reasons mentioned.
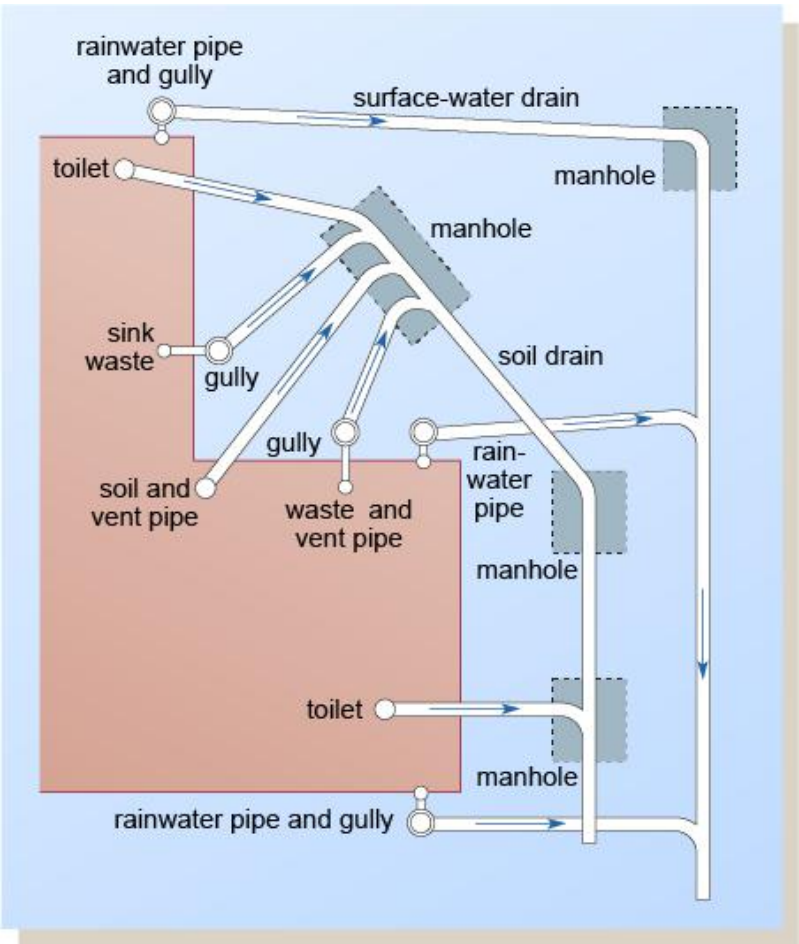
Figure 20 Drainage system for a house, showing separate pathways for sewage and rainwater

View description

Gutters, pipes and drains conveying rainwater constitute a separate system from that used for sewage. The sewer system is said to be separate when rainwater and surface water run-off are not mixed with sewage; instead, they are led to a watercourse after minimal treatment (e.g. screening to trap any large solid material). Combined sewers, on the other hand, convey both sewage and rainwater from roofs together with surface run-off. Such sewers are desirable when draining factories, markets, etc., as these open areas are likely to be sources of pollution.

Whether combined or separate, the drainage systems must include a facility for inspection and maintenance, provided by manholes or inspection covers. For ease of clearing blockages, drains should always be laid in straight lines between inspection points. This layout should ensure that drain-clearing rods can be introduced when necessary. Although there is no clear rule for the location of inspection points, it has been a tradition to provide inspection chambers at all junctions of drains into which waste pipes discharge. These chambers are also provided at intervals along straight (junctionless) lengths of drain to ensure that the whole length of drain can be 'rodded' satisfactorily.

4.2.2 Sewers

Sewage from buildings is carried away by drains to the main sewers. These are large pipes or brick- or concrete-lined tunnels that convey the combined flow to

the treatment works or, in an isolated or coastal area, some other point of disposal.

The primary function of the sewerage system is to maintain a healthy local environment. This includes the avoidance of local flooding and the minimising of river pollution by preventing wastes from running directly into rivers. Figure 21 shows a typical layout of drains and manholes used to connect a single household to the public sewer.
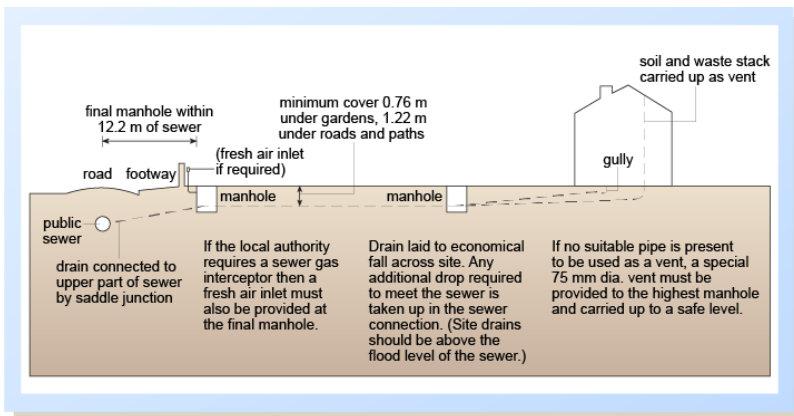
Figure 21 Drain connections to main sewer (The Open University, 2007)

View description

Domestic sewage when first produced (termed 'fresh') is typically light grey to brown in colour. Its organic content is constantly undergoing biodegradation. Provided that a measurable amount of dissolved oxygen is maintained

in the wastewater, biodegradation will remain aerobic. However, should the rate of oxygen demand exceed the rate at which oxygen can be dissolved from the sewer atmosphere, anaerobic conditions will result – the wastewater will rapidly turn a black colour and hydrogen sulfide will be formed. The sewage is then referred to as septic sewage.

Hydrogen sulfide gas evolved in sewers is a hazard to sewer maintenance personnel and is a major cause of corrosion of sewer structures. It also causes severe odour problems in the primary phase of the treatment works. These problems can be particularly severe in hot climates because of the reduced solubility of oxygen at higher temperatures, and the more rapid biological action. Aerobic conditions may be ensured by:

- providing adequate sewer ventilation
- designing sewers with steep gradients so that sewage flows through more quickly
- minimising the total time that the sewage remains in the collection system.

A considerable portion of the water supplied to a community does not reach the sewers. This includes:

- some water used by manufacturing industries and power plants that may be consumed within processes, or discharged directly into a watercourse or estuary
- water used in gardening
- actual consumption, e.g. in cooking and drinking
- leakage
- water used in extinguishing fires.

Ignoring groundwater infiltration into sewers, in south-east England, some 90% of the water supplied is taken as ending up as wastewater in sewers (Thames Water, 2013).

The size of a sewer or underground drain is calculated according to the flow to be carried. The ratio of maximum and minimum flow rates varies with position along the sewer lines. In the smaller upstream sewers serving small areas, the ratio can be large with wide fluctuations of flow. In the larger downstream sewers leading to the treatment plant, the extremes of flow will be less pronounced due to the attenuation of the maximum and minimum flows as a result of differing travelling times from the various tributary areas.

In addition to flows from household sewage and *trade wastes*, surface water and groundwater will also influence the flow rate. During storms, rainwater run-off entering the sewer can dwarf the sewage flow. A properly laid sewer is watertight when laid and installed, but ground movement may cause it to be damaged and leak. If the groundwater level rises above the sewer, water will leak in (infiltrate). This water is called infiltration water. On the other hand, if the groundwater level falls below the sewer, it is possible for sewage to leak out and contaminate underground water supplies.

The critical factors in calculating surface water discharges are the likely intensity and duration of rainfall, and the area and permeability of the surfaces

from which the water is drained – that is, how much soaks in and how much runs off.

Some small coastal communities discharge their sewage directly into the sea from submerged outfalls. In the UK all such discharges have to receive treatment. The effluent gets diluted as a result of being discharged into the sea, with the extent of dilution depending on:

- the velocity of the jet of effluent leaving the end of the pipe
- the depth of water over the outfall
- the tidal velocity at this point.

4.2.3 Dry weather flow

The combined total of average daily flows to be expected in a sewer due to sewage, trade wastes and any infiltration is called the *dry weather flow* (DWF), and other flows may be expressed in terms of this.

The DWF is measured as the average flow during seven consecutive days without rain following seven days during which the rainfall did not exceed 0.25 mm on any one day. Preferably, the flows during two periods of the year – one in summer and one in winter – should be averaged to obtain the average dry weather flow.

The DWF can also be calculated using the equation:

$$DWF = PQ + I + E \qquad\qquad\qquad (6)$$

where

> P is the population served
> Q is the average daily per capita domestic water consumption (in $m^3\,d^{-1}$)
> I is the average rate of infiltration (in $m^3\,d^{-1}$)
> E is the average volumetric flow rate of trade effluent discharged to the sewer (in $m^3\,d^{-1}$).

The expression for DWF takes the worst case and assumes that all the water consumed in the home enters the sewer after use.

The DWF is used in determining the required capacity of a treatment works. A works is usually designed to give full treatment to three times the DWF and preliminary treatment (for removal of gross solids and grit) to six times the DWF (Woods, 2010). Guideline figures are available for the estimation of sewage flows from different establishments (Table 11). The figures are for sewage generation per capita (i.e. per person), so the number of people in a given establishment has to be known to arrive at a flow rate for the establishment.

Table 11 Guideline per capita sewage volumes for different establishments (based on Maryland Department of the Environment, 2012)

Premises	Per capita volume (litres per day)

Hotels	230
Restaurants	95
Campsites with toilets	135
Day schools	95
Boarding schools	380
Offices	60
Airports	20
Care homes (for the frail or elderly)	300
Hospitals	500

4.2.4 Gravity flow

Almost all drainage systems are based on gravity flow and partially filled pipes. Foul drains and sewers slope downwards towards the treatment works or pumping stations, and the sewage flows along the bottom of the pipe rather than filling it completely (for example, foul drains are designed to contain flows to a depth of three-quarters of their diameter). With a sudden discharge, the level in the pipe rises, so the surge is stored temporarily and will flow away over a longer period.

Partially filled gravity sewers possess several advantages over pipes designed to be operated completely full for most flows. This follows particularly from their self-cleansing operation: when they are

designed properly, sewage is not delayed in transit as it would be at low flow rates in full pipes. Further advantages are as follows.

- The maintenance of higher velocities at low flows results in less deposition of material and the sewage arrives at the sewage works fresher than it would otherwise be, the organic matter having undergone relatively little decomposition.
- At normal flows, maintenance work can be carried out in the sewers.
- No power is needed for pumping.

The slope of the sewer must be sufficient to provide a flow of water fast enough to sweep the solids along. A minimum self-cleansing velocity of 0.6 to 0.75 m s^{-1} is needed to avoid stranding solid matter, and the system should be designed so that this velocity is achieved at least once per day. Moreover, the minimum gradients cannot be calculated by assuming that the drains or sewers are perfectly positioned. Irregularities of laying, ground movement and distortion of pipes mean that steeper gradients are needed in practice than would be proposed for ideal conditions.

The depth of flow is also important, since this affects not only the velocity of flow but also the area inside the sewer that is cleansed. When flows in an existing foul sewer are low and give problems of inadequate self-cleansing, it is common practice to supplement the flow with rainwater run-off by connecting in some roof or road gutter flows to the sewer.

It may not always be possible to design drainage and sewerage systems to allow effluent to flow under gravity all the way from its source to the treatment works. The difference in height between the drainage area and the treatment works may be insufficient, or the topography might be unsuitable. In these circumstances it is necessary to pump the effluent to the works. In this situation, the sewer is called a rising sewer main. The diameter of the rising sewer main will be smaller than that of the gravity sewer, to enable efficient pumping, and it will be full of sewage when the pump is operating.

SAQ 15

Which of the following factors can be used to explain the difference between a sewer and an underground drain?

Size

Gravity flow

Pipe material

Jointing

View answer

SAQ 16

Which of the following parameters would you expect to differ between a rising sewer main and a gravity sewer of the same flow rate? How will they differ?

Diameter

Pressure

Type of effluent

Gradient

Speed of flow

View answer

SAQ 17

Estimate the effluent flow rate to a treatment plant serving a population of 20 000 where the total per capita wastewater production (domestic and trade) is 250 litres per person per day. Assume that infiltration accounts for 20% of DWF.

SAQ 18

Estimate the volume of sewage expected daily from a business park with 600 employees working in offices, and a 200-room hotel that has an average occupancy of 75%.

4.3 Overview of sewage treatment

Most cities in industrialised countries are served by a sewer network that transports wastes away for disposal. The sewage is treated in sewage works before discharge into rivers or the sea.

The functions of sewage treatment are:

- to reduce the total biodegradable material and suspended solids (SS) to acceptable levels as measured by BOD and suspended solids concentrations
- to remove toxic materials
- to eliminate pathogenic bacteria.

A typical sequence of treatment is as follows.

1. *Preliminary treatment*:
   a. removal of gross material by screening, and/or
   b. shredding of paper and rags by comminutors (rotating, slotted drums equipped with cutting blades)
   c. removal of grit.

2. *Primary treatment*:
   a. removal of fine solids by settlement
   b. removal of sludge to a separate treatment stream
   c. remaining sewage moved on to secondary treatment.

3. *Secondary treatment*:
   a. biological oxidation of organic matter
   b. removal of solids produced by biological treatment.

   If necessary, the quality of the secondary effluent can be improved by tertiary and advanced wastewater treatment.

4. *Tertiary treatment*:
   a. reduction of the suspended solids content and the BOD concentration still further, typically to 10 g m^{-3} of each
   b. removal of N, P and NH_3.

5. *Advanced wastewater treatment*:

a. removal of trace quantities of organics
b. disinfection to kill any remaining pathogens.

The products of sewage treatment are:

- an effluent of acceptable quality in relation to the receiving watercourse
- sewage sludge
- screenings
- grit.

Figure 22 shows a typical sewage treatment plant that is designed to produce secondary effluent (effluent that has undergone biological treatment).

	Crude sewage	Settled sewage	Final effluent
BOD (g m^{-3})	250	175	<20
suspended solids (g m^{-3})	250	75	<30
ammonia (N) (g m^{-3})	30	20	<5
nitrate (N) (g m^{-3})	<5	<5	5
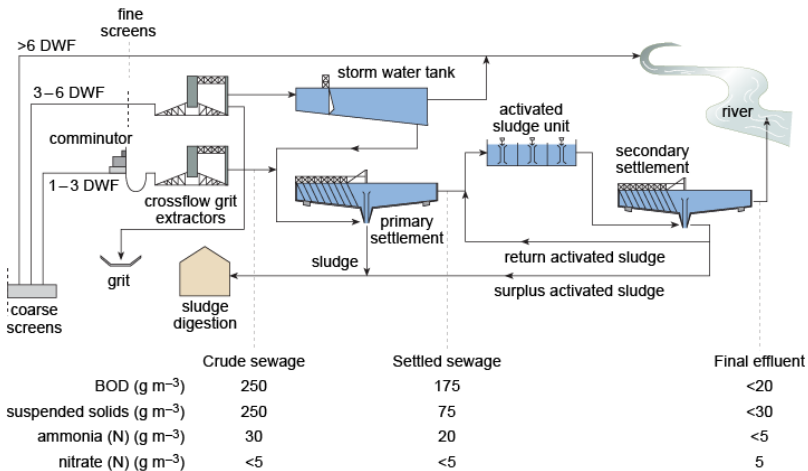
Figure 22 Typical sewage treatment plant designed for secondary treatment

View description

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In practice, it is not considered sensible to treat all the wastewater entering a sewage works at all times. You have seen that the flow in the sewer or rising main reaching a sewage works can fluctuate a great deal. To provide a treatment capacity for the maximum flow would mean that much equipment would be idle for long periods. As mentioned earlier, the plant would usually be designed to give full treatment to 3 × *DWF*.

4.3.1 Storm water tanks

All sewage treatment works are provided with a safety device to avoid the plant being damaged by excessive flows. It is called the storm overflow; its function is to cause the excess flow above the treatment capacity (i.e. 3 × *DWF*) to bypass the works. Between 3 and 6 × *DWF* goes to storm water tanks. These tanks, in series, are filled with the contaminated early storm flow; only when they are full can the now less-polluting storm water reach the river. Typically, a sewer carries the overflow to an open channel near the river serving as the receiving body. The side of the channel nearer to the river is lower than the other, so that when the flow in the channel reaches the maximum capacity, the mixture of storm water and sewage spills over it. If the storm water tanks become filled to capacity, i.e. flow greater than 6 × *DWF*, the sewage goes through coarse and fine screens and is discharged to the river.

In many instances the full capacity of the storm tanks is not reached during any one storm, so when the flow reduces, the storm tanks are emptied by pumping their

contents back to the beginning of the treatment process. Under these circumstances no untreated sewage can reach the receiving water. With climate change resulting in heavy rainfall episodes, however, more and more instances of storm water overflows do now occur, and pressure is being exerted on government to address this issue (Marine Conservation Society, 2011).

SAQ 19

Can you suggest a reason why this treatment would not be sufficient for storm water in a combined system? What could be done to overcome this?

View answer

SAQ 20

What are the problems for sewage treatment posed by a combined sewerage system?

View answer

4.3.2 Design of sewage treatment processes

Sewage treatment processes are often designed using computer programs, thus eliminating the need for detailed calculations by hand. Sections 4.4–4.10 will consider each step of the sewage treatment process, together with the equipment needed.

4.4 Preliminary treatment

The processes of screening, *comminution* and grit removal used in preliminary treatment remove the larger floating and suspended matter. They do not make a significant contribution to reducing the pollution load, but they do make the sewage easier to treat by removing material that could cause blockages or damage equipment.

Screenings may consist of pieces of wood, plastic materials, paper, rags, hygiene products and condoms. The screenings are usually disposed of in a landfill site. Raking of the screens at many small sewage works is still done manually – a job not many people like to do. Even if automatic raking is incorporated, the movement and disposal of screenings is a very unpleasant task. In very large works, screenings are often macerated and returned to the inflow.

In some treatment works, coarse screens are followed by comminutors (Figure 23) instead of fine screens. A comminutor consists of a slotted, rotating drum fitted with cutting blades. Sewage with solids passes through the slots into the drum, where the solids are macerated. Grit removal then follows. In sewage with a high proportion of grit, grit removal may precede comminution to save the comminutor blades from being prematurely worn down.
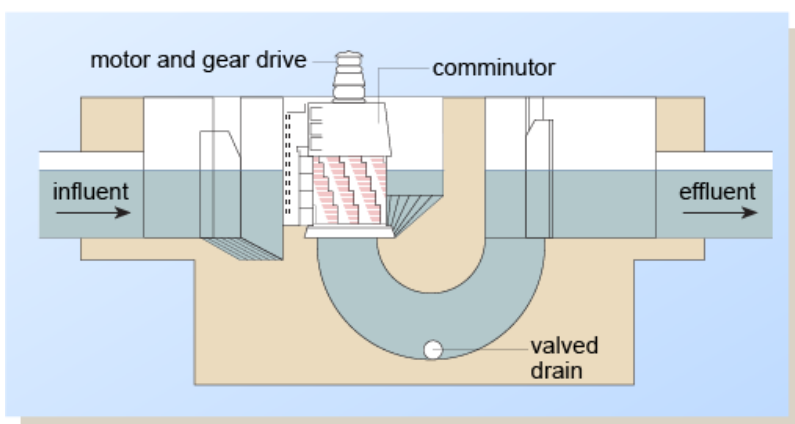
Figure 23 Cross section of a comminutor

View description

Screening does not remove small stones or grit. Grit comes from having been spread on roads in winter (in temperate countries), and to a lesser extent from erosion of roof tiles and cemented areas. Grit may also contain pieces of metal and glass; these abrasive

materials increase the rate of wear of mechanical plant and can also settle easily, causing blockages in pipes.

Grit is usually removed in a parabolic-section grit channel (Figure 24), where the sewage flow is reduced to 0.3 m s^{-1} to allow the grit to settle by gravity. This velocity does not allow the (lighter) organic material to settle, so this material is carried forward. The grit deposited in the grit channel is removed daily using manual and/or mechanical methods, and put into a skip for disposal, usually at a landfill site.

grit channels

Figure 24 Grit channels

View description

Other types of grit removal system are available. In the cylindrically shaped Pista$^{®}$ grit trap (Figure 25), centrifugal action is used to enhance separation of the grit. This system includes an airlift pump, which removes the grit by using compressed air. The air is injected into the lower part of the pipe that transports the thick mixture of grit and liquid at the bottom of the trap up to the grit drainage basin. Since the air has a lower density than the grit mixture, buoyancy causes it to rise quickly up the pipe; by fluid pressure, the grit mixture is taken in the ascendant air flow and moves in the same direction as the air.
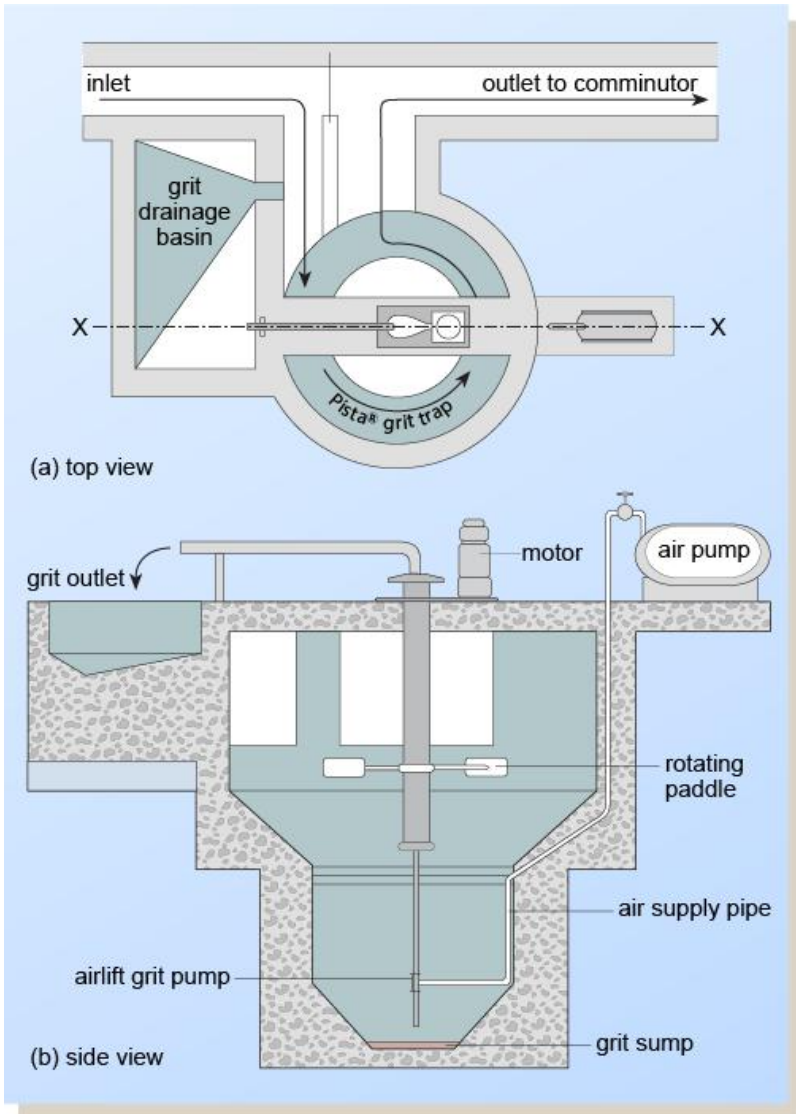
Figure 25 The Pista$^{®}$ grit trap: (a) view from top; (b) side view of section X–X

In the crossflow grit extractor (Figure 26), grit-laden sewage flows at a velocity less than $0.3\,\mathrm{m\,s^{-1}}$ into a large square tank, where grit and some organic solids settle out. In this system, the grit is collected and washed before disposal. It can be used for road gritting if it is thoroughly washed. The washwaters containing the organic matter are returned to the sewage inflow downstream of the grit extractor.

Figure 26 An empty crossflow grit extractor

4.5 Primary treatment

After preliminary treatment, only fine particles remain in suspension in the sewage. The next stage in sewage treatment, primary sedimentation, allows the sewage to travel at low velocity through large tanks so that most of the remaining particles can fall out of suspension. The effluent emerging from the primary sedimentation tank is referred to as settled sewage, and the sludge produced is called primary sludge.

Primary sedimentation removes approximately 70% of the suspended matter. Because some of these solids are biodegradable, the BOD is also reduced by some 30% (as shown in Figure 22).

The tanks used in primary sedimentation can be circular with radial flow, rectangular with horizontal flow or hopper-bottomed with upward flow. Circular tanks are not as compact as rectangular tanks, but do provide a longer relative weir length (the length around the edge of the tank over which the treated effluent flows on its way out). Hopper-bottomed tanks are popular at small sewage works where the extra cost of construction is more than offset by the absence of any scraping mechanism that would require maintenance. Figure 27 shows a hopper-bottomed tank: the scum baffle prevents the floating scum from leaving the tank with the treated effluent, while the stilling box reduces the velocity of flow.
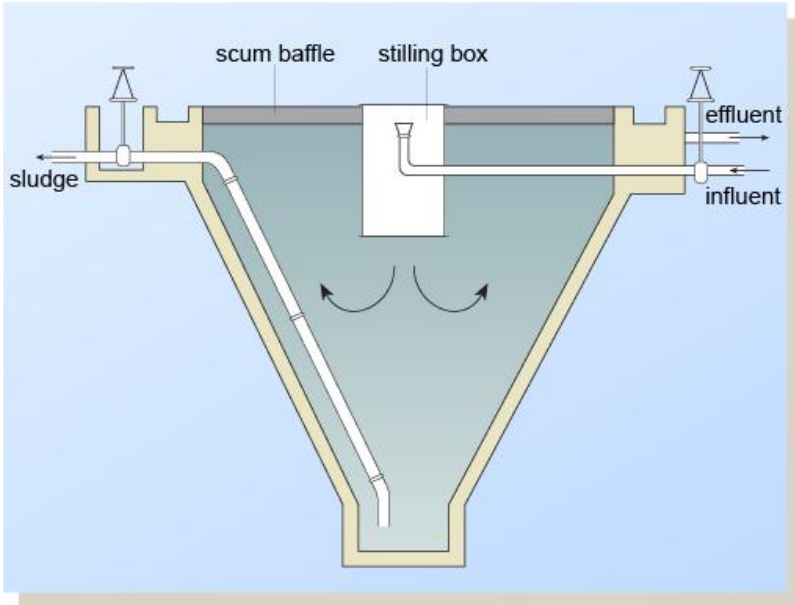
Figure 27 Upward-flow (hopper-bottomed) sedimentation tank as used in sewage treatment

View description

The time the wastewater spends in the sedimentation tank can be calculated using the following equation:

$$\text{retention time} = \frac{\text{volume of sedimentation tank}}{\text{flow rate through sedimentation tank}} \qquad (7)$$

An effluent at a food factory is passed through a sedimentation tank that has a volume of 75 m^3.

    a. If the flow rate of the effluent is 20 $m^3\,h^{-1}$, calculate the retention time of the effluent in the sedimentation tank.

    b. If the tank is rectangular in shape, with a depth of 1 m, calculate its dimensions if the length is three times the width.

View answer

Retention time in primary sedimentation tanks is generally between two and six hours, and (unlike the one in the SAQ) the tanks used have depths of between two and four metres.

The sludge obtained from primary sedimentation is drawn off, and can be sent for further treatment or be dewatered (have the water extracted from it) before disposal. The subject of sludge disposal will be discussed in Section 5.

4.6 Secondary treatment

Before effluent can be discharged from a sewage works, the organic content (measured by BOD) and other polluting components of the effluent must be reduced.

This is achieved by biological oxidation, which uses the same reactions as occur in natural self-purification. The main difference is that biological treatment attains a higher level of purification compared with natural water purification because it provides optimum conditions, with a high concentration of microorganisms and an adequate supply of oxygen for biodegradation to take place.

In sewage treatment, the two major categories of process that use biological oxidation are *biological filtration* and the *activated sludge process*. For both processes, the principal parameter is the organic loading rate, which is the ratio of food to microorganisms (*F/M*). This can be defined as follows:

(8)

$$F/M = \frac{\text{mass of BOD applied to the biological stage each day (kg BOD d}^{-1})}{\text{mass of microorganisms in the biological stage (kg biomass)}}$$

Figure 28 shows a typical biological growth curve that indicates how the concentration of microorganisms (biomass) varies with the food supply.
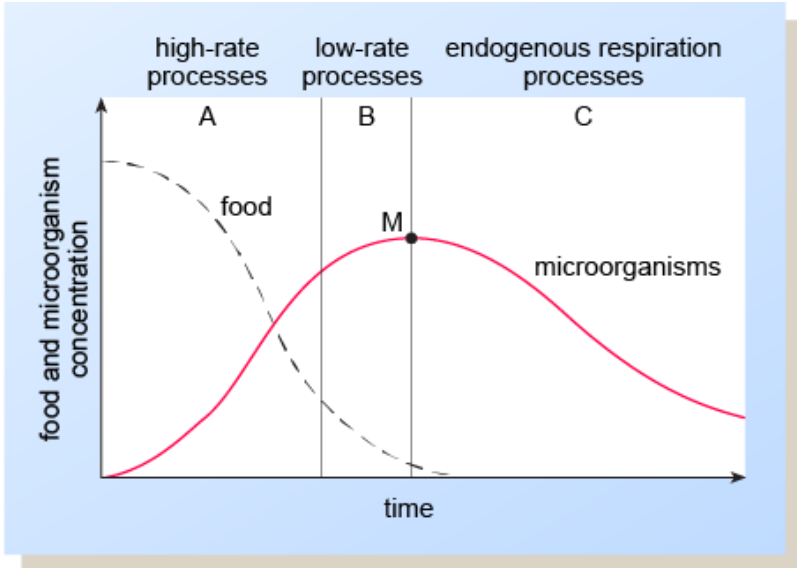
Figure 28 The biological growth curve

When food is present in excess (region A), the growth rate of microorganisms is high. When food supply declines (region B), the rate of organism growth slows down until the food supply is exhausted and the concentration of organisms reaches a maximum at point M. Without food, the organisms die and the total cell mass declines (region C).

In practice, biological treatment processes operate continuously, either in the high growth rate region A with high values of organic loading rate ($F/M > 1.0$), or in the low growth rate region B with low values of F/M (< 0.1).

Selection of the *F/M* ratio to be used in the treatment gives the required size of the biological unit needed, since the size of the unit will be proportional to the quantity of biomass present. Low-rate processes (low *F/M*) require a larger quantity of biomass than high-rate processes (high *F/M*) for the same BOD input, and are consequently of a larger size.

Exercise 4

After sedimentation, a settled sewage with 200 g m^{-3} BOD is to be treated biologically at a flow rate of 2500 m^3 per day.

  a. Calculate the amount of biomass needed if a low-rate process with an organic loading rate of 0.07 kg BOD per kg biomass per day is used.
  b. Calculate the amount of biomass needed if a high-rate process with an organic loading rate of 1.8 kg BOD per kg biomass per day is chosen instead.

View answer

Another feature of biological systems is the net mass increase in biological solids (sludge). It is not feasible to operate biological processes to produce zero net growth of biological solids, because a certain proportion of cell material is always relatively resistant to further degradation. Dead cells are used as food by other

organisms, but some poorly degradable cell residues will remain. This increase in organism mass will be larger for high-rate processes than for low-rate processes, since in the high-rate region (Figure 28) a large fraction of the food supply is used for increasing total cell mass. In the low-rate region, the limited food supply tends to be used mostly for sustaining the energy requirements of the cells, with little increase in total cell mass. The implication of these phenomena is that high-rate biological treatment processes impose larger demands for the withdrawal and disposal of sludge resulting from the net mass increase of biological solids.

As mentioned above, there are two principal methods of bringing the microorganisms into contact with the effluent.

- **Biological filters**: the active mass of microorganisms grows on a solid support, typically a bed of loose material. This is referred to as a fixed-film system.
- **Activated sludge systems**: the microorganisms are suspended in the wastewater. This is referred to as a dispersed growth system.

I will look at the detail of each of these methods in turn.

4.6.1 Biological filters – overview

In the early days of sewage treatment the sewage was allowed to soak away through large areas of land, which gave rise to the term 'sewage farm'. It was found, however, that about 10 times the volume of sewage

could be treated if the sewage was passed through a granular medium of stone, clinker (the incombustible residue that remains after the combustion of coal) or slag (inert waste arising from metal production and refining industries) in a biological filter. The smaller the particles of medium, the larger the surface area offered.

Biological filters can be circular (Figure 29) or rectangular in shape, and are also known as percolating filters, trickling filters or bacteria beds. They operate by oxidation, not by filtration. Rectangular filters tend to be used in large works to reduce the area needed.

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Figure 29 A biological filter

The principle is that settled sewage is slowly sprayed over the surface of the stone or clinker so that it is able to trickle down. In this way, oxidising bacteria on the media are able to come into contact with the organic constituents of the sewage, and oxidation can take place. These bacteria are able to use the ample supply of atmospheric oxygen, as long as the material in the beds has a large surface area and the beds are well ventilated by allowing air to enter at the base.

Temperature affects the performance of biological filters, with reduced removal efficiencies at low winter temperatures and the opposite at high summer temperatures.

4.6.2 Biological filters – process

The biological filtration process contains five important parts:

1. a dosing system or distributor for applying the settled sewage
2. a filter bed in which the oxidation takes place
3. an underdrainage system for collecting the treated effluent
4. a ventilation system to provide oxygen
5. a sedimentation tank to remove biological solids washed through the filter media.

1. Dosing system

The dosing system, or distributor, sprays the settled sewage over the surface of the bed. Circular beds use a rotating arm distributor. The sewage enters at the central column of the filter and is discharged through nozzles spaced along low tubular arms that are supported by the central column. The arms rotate slowly, parallel to the surface of the bed, and so distribute the sewage evenly over the whole surface. In rectangular filters, the distributor sprays the settled sewage across the width of the bed and moves slowly along the length of the filter.

2. Filter bed

The filter bed must have an adequate depth to ensure that the incoming liquid receives sufficient time for the bacteria to act. Usually the depth of the medium is between 1.2 m and 2.0 m. The material forming the filter beds must be durable, strong enough to resist crushing, and frost resistant. Hard-burnt clinker, blast furnace slag, gravel or crushed rock can be used; clinker and slag tend to give the best results.

The ideal filter medium should have:

- a large surface area on which the biomass can grow
- voids that are large enough to allow the growth of the biomass without clogging, and also to permit the passage of air

- a structure that will distribute the sewage over all the surfaces of the bed with maximum turbulence so that oxygen transfer can take place.

The surface area of the medium is an important parameter, and is related to the porosity of the medium. Note, however, that a high porosity is an indication of a large exposed surface only if the pores are open and also interconnected. The parameter that is used to compare the suitability of different media for filters is the specific surface area, defined as the exposed area per unit volume of material.

Media may also be made from plastic sheets, tubes or other shapes, forming regular modular or random patterns (Figure 30). Plastic filter media have the advantage over clinker and slag in that they provide a larger specific surface area, so smaller, lighter and more compact 'packs' may be used for a given flow of sewage. Against this must be set the fact that they are more expensive than conventional filter media.
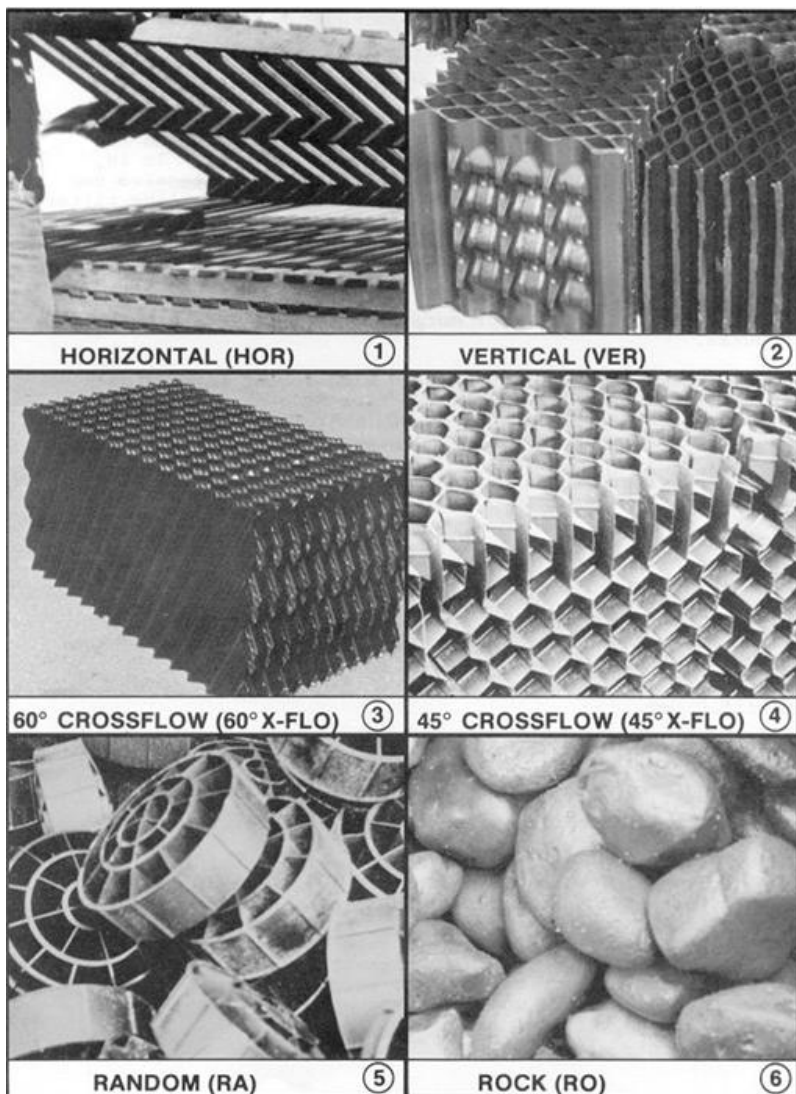
Figure 30 Plastic filter media and rocks

View description

Filters can be distinguished by the flow rate of effluent being treated. High-rate filters treat 10–40 m^3 of effluent per m^2 of filter bed area per day, while low-rate filters treat 1–4 m^3 m^{-2} d^{-1}. Most high-rate filters use plastic media and can be expected to remove only 15–50% of pathogenic bacteria in the sewage; BOD reduction may be up to 85%. Such filters are most useful for relieving some of the load at an existing overloaded works and for treating certain trade effluents. In contrast, low-rate filters can be expected to remove 99% of the pathogenic bacteria as well as reduce the BOD of the sewage by up to 95%.

Plastic media can be used as horizontal, vertical or crossflow. The media with crossflow, when compared to vertical or horizontal flow, result in an increased hydraulic retention time between the biofilm and the influent, and provide superior oxygen transfer (EPA, 2000b).

As liquid passes through a filter it loses a considerable height. For this reason, it is preferable for filters to be built on sloping sites so that gravity can assist the flow between the different stages. On flat sites it may be necessary to raise the flow to the filter by pumping.

Aerobic bacteria grow as a film on the surface of the media in the filter. This will be a mixed population of bacteria. The flow of sewage through the bed entrains air, and updraughts circulate because bacterial decomposition creates temperature differences. The air movement provides oxygen for the bacteria, which

break down the organic matter in the settled sewage to provide energy and make new cell material. Some toxic material can be treated at this stage, but the overall efficiency of the bacteria is much reduced if any toxic material is present.

Bacteria would proliferate and eventually block the filter were it not for the activities of predatory organisms such as protozoa, worms and the larvae of aquatic flies. These live in the filter and graze on the bacteria. Protozoa remove any free-swimming bacteria which, if present, give the effluent a turbid appearance. When larvae emerge as adult flies, however, they tend to be a nuisance. A variety of methods can be employed to control the flies, including:

- the use of bacterial insecticides (bacteria that attack the fly larvae)
- controlled flooding of the filters to drown the larvae
- fine netting to prevent the emerging flies leaving the filters
- the use of naturally occurring parasitic worms that attack and kill fly larvae.

Biological filtration produces high levels of nitrate through the bacterial action of *Nitrosomonas* and *Nitrobacter*. Blue-green algae are present and able to remove nitrogen and minerals; however, beneath the surface where there can be no sunlight, algae are absent.

Some bacterial cell material is shed and discharged from the filter with the effluent, along with solids that did

not settle out in the primary sedimentation tank. This material is known as humus and is removed in the final sedimentation tank (often called a humus tank). The debris that settles out is called humus sludge.

3. Underdrainage

The underdrainage system, which collects the effluent, is constructed as an impervious base beneath the perforated filter floor. The filter floor slopes towards collecting channels. The underdrainage system should be capable of accommodating the maximum flow rate.

4. Ventilation

Ventilation is achieved by natural air circulation. Sufficient openings are provided at the bottom of the filter to allow air to flow in. In cold climates, the air inflow is controlled so that the temperature in the filter does not dip so low as to reduce biological activity.

5. Sedimentation tank

The sedimentation tanks used to remove the humus are similar to those used for primary sedimentation. Unlike in the activated sludge process (more on this shortly), the settled solids are not recycled.

4.6.3 Biological filters – practical applications

It is difficult to estimate the total biomass in a biological filter. Although the total surface area of the media gives some indication of the amount of biomass that could be supported, the active mass cannot be easily determined. So it is customary to take the volume of the bed as the most practical measure of biomass and to express the organic loading rate as the BOD applied per day per unit volume of filter medium. If Q is the sewage flow rate in $m^3\,d^{-1}$ distributed over a filter of cross-sectional area A m^2 and bed depth H m, and if the BOD of the influent is Y $kg\,m^{-3}$ (not $g\,m^{-3}$), then:

$$\text{organic loading rate} = \frac{QY}{AH} \text{ kg BOD m}^{-3}\text{ d}^{-1} \tag{9}$$

Table 12 gives typical values of the different parameters for low- and high-rate biological filters.

Table 12 Typical design values for biological filters

Filter type	Organic loading (kg BOD m^{-3} d^{-1})	Depth of filter medium (m)	BOD removal (%)
Low-rate	0.08–0.32	1.5–3.0	80–90
High-rate	0.32–1.0	1.0–2.0	50–80

(Rousseau and Hooijmans, n.d.)

Exercise 5

A biological filter for the treatment of the sewage from a small group of houses in a remote area in the countryside has a diameter of 2.5 m and a depth of 2 m.

If the filter each day treats 5 m^3 of sewage with a BOD of 210 g m^{-3} after primary settlement, what is the organic loading rate?

View answer

SAQ 22

Identify which of the following statements is true, and give reasons why the others are false.

> a. Comminutors (where used) are always placed after coarse screens but before grit removal in the preliminary treatment of sewage.

> b. In a biological filter, nitrification takes place due to the bacterial activity of *Nitrosomonas* and *Nitrobacter*.

c. One advantage of using biological filters is that they do not require final sedimentation tanks.

d. In a biological filter, bacteria and algae reduce the BOD of the settled sewage.

e. High-rate biological filters remove a greater portion of the BOD compared to low-rate filters.

View answer

SAQ 23

Which of the following considerations is most important (apart from cost) in choosing a medium for a filter?

a. Whether the medium is to be used in a high-rate or a low-rate filter.

b. Whether the filter is to be used for crude sewage or a sewage that has been partially treated by screening and primary sedimentation.

c. The surface-area-to-volume ratio of the filter medium.

d. The regularity of shape of the particles of the medium.

e. The size of the particles of the medium.

View answer

SAQ 24

A settled sewage flow of 1200 m^3 per day with 180 g m^{-3} BOD is applied to a low-rate biological filter of 40 m diameter and 1.8 m depth. What is the organic loading rate? What is the rate of removal of BOD in kg per day if the outlet BOD is 20 g m^{-3}?

View answer

4.6.4 Activated sludge – overview

The activated sludge process (Figure 31) was developed in Manchester in 1913–14. It has become extremely popular in sewage treatment, as it occupies less space than a biological filter and has proved useful

for treating organic industrial wastes that were once thought to be too toxic for biological treatment. The process produces a *flocculent*, microbial culture that is easily settled. However, the process has the disadvantage of being more costly to operate due to its demand for power and maintenance.
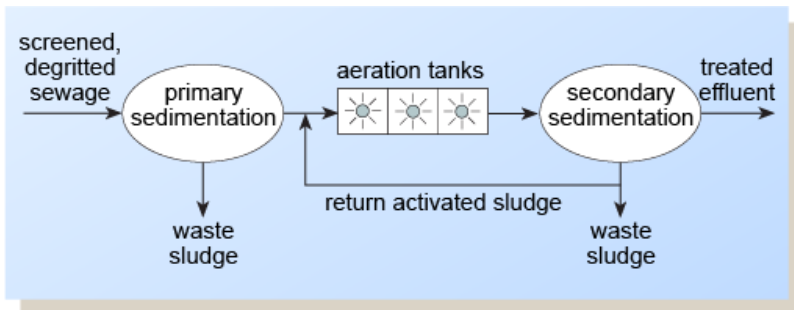
Figure 31 Schematic of an activated sludge system with mechanical aerators

View description

The process consists of the following elements:

1. an aeration tank
2. an aeration system
3. a final sedimentation tank
4. a return activated sludge system
5. a system to remove the excess activated sludge produced.

Air is introduced into the settled sewage as it arrives from primary sedimentation by either bubbling compressed air through the liquid or mechanically

agitating the liquid surface (more information on these systems will be given shortly). Aerobic bacteria suspended in the sewage use the organic matter it contains to form new cell material. The activated sludge unit also contains protozoa, which remove free-swimming non-settleable bacteria, and rotifers, which remove small biological floc particles and so help to produce a clear effluent. Protozoa also play an important role in the reduction of pathogenic bacteria, e.g. those that cause diphtheria, cholera and typhoid.

The mixture of sewage and microorganisms in the activated sludge unit is called the mixed liquor. The total suspended solids content, determined by filtration and drying, is a measure of the microbial mass and the inert substances present, and is referred to as the mixed liquor suspended solids (MLSS). If the MLSS is volatilised at 600 °C, any organic fraction will be decomposed to water, oxides of carbon and ammonia, while the inorganic material will remain as oxides, carbonates or other salts. The volatile fraction is referred to as the mixed liquor volatile suspended solids (MLVSS) and gives a closer indication than the MLSS of the biomass in the biological reactor. However, in routine analysis at treatment plants, it is usually the MLSS that is measured. This is then used in calculating the *F*/*M* ratio (Equation 8):

(10)

$$F/M = \frac{\text{mass of BOD applied to the biological stage each day}}{\text{mass of microorganisms in the biological stage}}$$

$$= \frac{\text{flow rate } (m^3 \, d^{-1}) \times \text{BOD } (kg \, m^{-3})}{\text{volume of aeration tank } (m^3) \times \text{MLSS } (kg \, m^{-3})}$$

Settling is not possible in a constantly agitated liquid, so when the treated sewage containing the activated sludge leaves the aeration unit, it is allowed to settle in a final sedimentation tank similar in design to that used for primary treatment. The treated effluent from the final settlement tank flows over a weir to be discharged to a watercourse, while the sludge settles to the bottom of the tank. From there, it may take one of two paths:

- A portion of the settled sludge is returned to the aeration unit; this is known as return activated sludge, and is often mixed in the ratio 1:1 with the incoming settled sewage. The return activated sludge must be present in sufficient volume to give stabilisation in the aeration unit. If insufficient is returned then poor purification will be achieved, while if too much is returned then poor settlement will result in the final settlement tank.
- Settled sludge from the final settlement tank that is not reused is called surplus sludge, and is usually pumped away for treatment and disposal. It can, however, also be used to aid settling in the primary settlement tank, in which case it is pumped to the inlet of that tank.

It is necessary to maintain a concentration of 1–2 mg l^{-1} of dissolved oxygen in the mixed liquor. This is

particularly important in the final settlement tank: if there is insufficient oxygen present, the activated sludge may become anaerobic before it is returned, leading to poor settlement due to gas production and to the death of the organisms present.

Because of the importance of maintaining good-quality sludge, several indices have been developed to give a guide to sludge quality. Examples are:

- The sludge volume index (SVI), defined as the volume occupied by sludge containing 1 g of solids (dry weight) after 30 minutes' settlement:

$$SVI = \frac{\text{settled volume of sludge in 30 mins (ml l}^{-1})}{\text{mixed liquor suspended solids (g l}^{-1})} \qquad \text{(11a)}$$

- The sludge density index (SDI):

$$SDI = \frac{\text{mixed liquor suspended solids (g l}^{-1}) \times 100}{\text{settled volume of sludge in 30 mins (ml l}^{-1})} \qquad \text{(11b)}$$

A sludge with an SVI value below 100 ml g^{-1} is considered a good settling sludge, while sludges that have poor settlement and exhibit bulking (see Section 4.6.7) in the final settlement tank have values in excess of 150, possibly due to filamentous (thread-like) growth (Turovskiy and Mathai, 2006). For SDI, the figures vary between 1.0–2.0 for a good sludge and 0.3 for a poor sludge (Punmia and Jain, 2005).

Exercise 6

The sludge solids in 1 litre of mixed liquor are found to be 1850 mg l^{-1}, and settle into a volume of 150 ml. Find the SVI of the activated sludge.

View answer

The retention time of the activated sludge in the aeration unit is typically six to eight hours. The sludge is, however, recycled for several days before it is finally removed from the system. A measure of the length of time that the sludge has been undergoing aeration is the sludge age, which is the ratio of the mass of cells in the bioreactor to the mass of cells wasted per day:

$$(12)$$

$$\text{sludge age} = \frac{\text{volume of aeration tank (m}^3) \times \text{MLSS (g m}^{-3})}{\text{flow rate of surplus sludge (m}^3\,\text{d}^{-1}) \times \text{solids concentration of sludge (g m}^{-3})}$$

The sludge age varies according to the type and strength of sewage to be treated. It tells a great deal about the type of activated sludge plant; for instance, a plant with a long sludge age of 25 days would be likely to produce a nitrified effluent (one in which the nitrogenous components are converted to nitrates).

In extended aeration systems, the retention time of the effluent in the aeration tank is typically 24–48 hours. The sludge produced in this type of system is highly stabilised (oxidised) and the amount of inert sludge left for disposal is reduced to a minimum.

4.6.5 Activated sludge – aeration systems

The main functions of the aeration system in an activated sludge plant can be summarised as follows:

- to ensure a continuous and adequate supply of dissolved oxygen for the bacteria
- to keep the activated sludge solids in suspension
- to mix the incoming sewage and the activated sludge
- to remove excess carbon dioxide (resulting from the oxidation of the organic matter) from solution

- to assist flocculation, by which the smaller particles adhere together to settle out later (in the sedimentation tank).

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

- diffused air aeration
- mechanical aeration.

Diffused air aeration

There are three categories of diffused air aeration: coarse-, medium- and fine-bubble aeration.

- In coarse- and medium-bubble aeration, air is pumped through open-ended pipes (Figure 32a) or pipes with holes, often placed along one side of the aeration tank. As the name implies, large air bubbles are formed, with the aeration efficiency less than that of fine bubbles. A circulation pattern is set up in the tank.
- In fine-bubble aeration, filtered air is pumped to porous dome diffusers (Figure 32b) made of ceramic or plastic material. Fine air bubbles (approximately 2.0 mm in diameter) are generated. With porous diffusers it is essential that the air supplied is free of dust particles, as these can clog the diffusers. The dome diffusers are placed in a network on the base of the aeration tank.

Although coarse- and medium-bubble systems have slightly lower aeration efficiencies than fine-bubble systems, their lower cost, easier maintenance and the

absence of stringent air purity requirements have made them more popular.

Diffusers made of high-strength polyurethane membrane, with potentially lower energy needs in operation, are now (in 2013) gaining a foothold.

water
surface

(a)

(b)

(c)

(d)

drive

water level

mixer
blades

air

air
sparger
ring

(e)

air

inlet

steam nozzle

suction
chamber

vacuum gauge
connection

self-centering
flange

diffuser
body

discharge

(f)
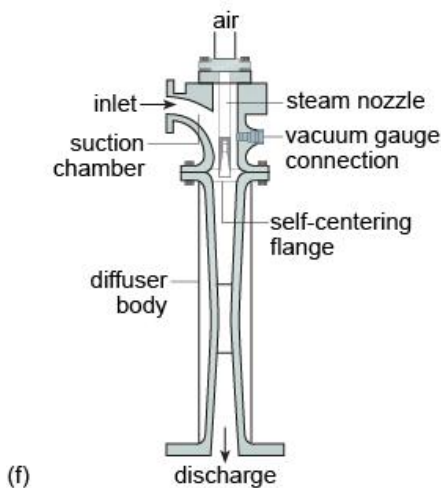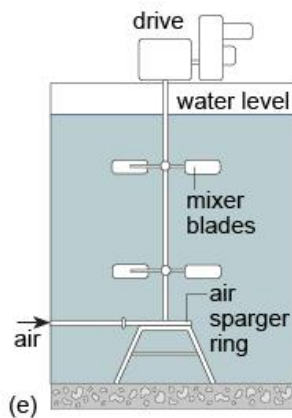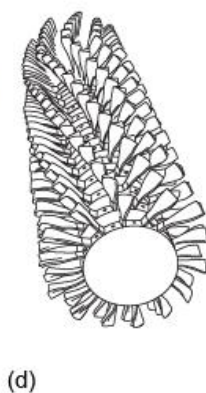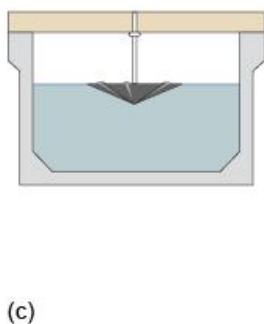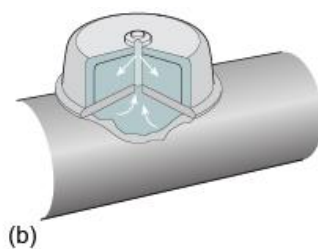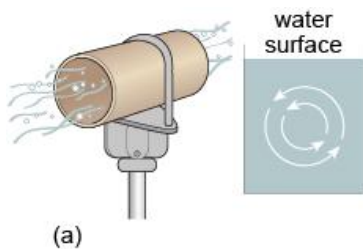
Figure 32 Various aeration systems: (a) coarse air diffuser, with water circulation pattern set up in tank; (b) fine air diffuser; (c) surface aerator; (d) brush aerator; (e) turbine–sparger system; (f) jet aerator

View description

Mechanical aeration

Mechanical aerators consist of submerged or partially submerged impellers attached to motors that are mounted on floats or fixed structures. The impellers agitate the wastewater vigorously, entraining air from the atmosphere into the wastewater. Partially submerged units, called surface aerators (Figure 32c), are popular.

A variant of these is the brush aerator (Figure 32d), commonly used to provide both aeration and circulation in oxidation ditches (more on these in Section 4.8.1).

It is also possible to have submerged turbine–sparger systems (Figure 32e), which disperse air that is introduced beneath the impeller and also mix the tank contents.

Jet aerators (Figure 32f) transfer oxygen by mixing pressurised air and water in a jet nozzle, then discharging the air–liquid mixture into the effluent. The velocity of the air–liquid mixture discharged from the nozzle and the rising plume of fine air bubbles that

forms after discharge result in mixing of the wastewater in the tank.

Typical oxygen transfer rates for the aeration systems described above are given in Table 13.

Table 13 Typical oxygen transfer rates for a selection of aeration systems at standard conditions (tap water at 20 °C, 1 atmosphere) with initial dissolved oxygen concentration at 0 mg l^{-1}

Aeration system	Oxygen transfer rate (kg O_2 kWh^{-1})
Diffused air	
– fine bubble	1.2–2.0
– medium bubble	1.0–1.6
– coarse bubble	0.6–1.2
Mechanical	
Low-speed surface aerator	1.2–2.4
Brush aerator	1.2–2.4
Turbine–sparger system	1.2–1.4
Jet aerator	1.2–1.4

(Metcalf & Eddy, 1987)

It is possible to express the BOD loading of an activated sludge unit in terms of an aeration tank loading rate, defined as:

(13)

$$\text{aeration tank loading rate} = \frac{\text{BOD entering aeration tank per day (kg BOD d}^{-1})}{\text{volume of aeration tank (m}^3)}$$

Nitrification occurs during the later stages of the biological treatment, i.e. at the bottom of a biological filter and at the 'effluent end' of an activated sludge aeration tank. Nitrification puts a heavy demand on the available dissolved oxygen. Indeed, one of the first signs of overloading of a biological treatment system is the loss of nitrification due to the inability of the system to reach a high enough dissolved oxygen concentration.

4.6.6 Activated sludge – BOD removal

Conventional activated sludge processes are 'medium-rate' treatment processes with values of organic loading rate (*F/M*) of about 0.5 kg BOD per kg MLSS per day. With an adequate supply of oxygen in the aeration tanks, the rate of BOD removal depends only on the concentration of active microorganisms in the tanks (Figure 33).
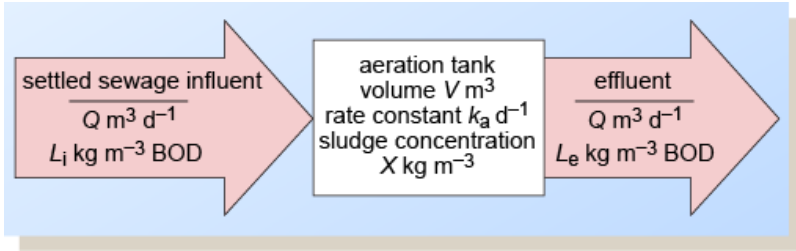
Figure 33 Mass balance for aeration tank in the activated sludge process

View description

That is:

rate of BOD removal (kg d^{-1}) $\propto$ mass of microorganisms or mass of activated sludge

or

$$Q(L_i - L_e) = k_a X V \qquad (14)$$

where

L_i is the BOD concentration in the effluent entering the plant (in kg m^{-3})
L_e is the BOD concentration in the effluent leaving the plant (in kg m^{-3})
Q is the sewage flow rate (in m^3 d^{-1})
X is the concentration of activated sludge (in kg m^{-3})
V is the aeration tank volume (in m^3)

k_a is a constant, the activated sludge rate constant (in d^{-1}).

Exercise 8

Settled sewage at a flow rate of 1500 $m^3 d^{-1}$ and 200 $g\,m^{-3}$ BOD is treated in an activated sludge plant that is equipped with an aeration tank 25 m long × 5 m wide × 4 m deep, with an MLSS concentration X of 2000 $g\,m^{-3}$. The activated sludge rate constant k_a is 0.28 d^{-1}.

a. Calculate the overall percentage BOD removal.
b. Calculate the retention time in the tank.
c. Calculate the aeration tank loading rate in kg BOD $m^{-3} d^{-1}$.
d. Calculate the F/M value in kg BOD kg^{-1} MLSS d^{-1}.

View answer

SAQ 25

A litre of activated sludge is found to settle in 30 minutes to a volume of 280 ml, and has a concentration of solids of 1050 mg l^{-1}. What is the SVI of the sludge, and is this acceptable?

View answer

4.6.7 Activated sludge – secondary sedimentation

The settling tanks in which the activated sludge is separated from the mixed liquor are similar in design to the primary sedimentation tanks. They are usually circular, with floors that slope to the centre, although large tanks have flat floors. In small- and medium-sized tanks the sludge is scraped to the centre by helical blades. The sludge then flows through an outlet pipe to

the sludge well, from which most of it is pumped back to the aeration tank (the rest being taken away for disposal as surplus sludge). Sludge is removed from flat-floored tanks by suction pipes.

Bulking

Sometimes the outflow from the activated sludge tank does not settle in the secondary sedimentation tank to produce a sludge and clear water. Instead, the biological flocs (agglomerations of biological particles) remain suspended throughout the sedimentation tank and are carried out in the overflow. The sludge in this situation is referred to as bulking sludge.

Bulking sludge is attributed to two factors:

- the presence of filamentous organisms (i.e. organisms that grow in a thread-like form under adverse conditions, where oxygen is inadequate)
- the incorporation of water (bound water) into the bacterial flocs of activated sludge, causing a reduction in the density of the flocs.

Neither the filamentous organisms nor the reduced-density flocs settle easily, resulting in a bulking sludge.

Bulking can be caused by fluctuations in wastewater flow, wastewater strength, pH and temperature; excessive organic loading; and/or an inadequate supply of oxygen or nutrients.

Remedial measures include adding chlorine or hydrogen peroxide to the sludge recycle stream to eliminate the filamentous organisms (due to their larger surface area, filamentous organisms are more affected by these biocides than are the normal activated sludge microorganisms). This is followed by measures to stabilise the inflow and other conditions, e.g. pH and temperature. Steps to reduce the organic loading (e.g. by balancing the inflow, increasing the content of mixed liquor suspended solids to have a favourable F/M ratio, etc.) can then be taken. The addition of nutrients (e.g. N, P, trace elements such as Fe, Cu, Zn and Mn) may be required. It is valuable to identify the species of bacteria causing the problem, as the reason for their excessive growth varies between species.

A lack of dissolved oxygen has been noted more frequently than any other as the cause of bulking. If the oxygen transfer rate with aerators is limited, pure oxygen may be injected into the activated sludge tank to increase the available oxygen.

4.6.8 Elimination of pathogens

One of the objectives in treating sewage is the elimination of pathogenic organisms present in the effluent. These pathogens can be grouped broadly into viruses, bacteria and protozoa (see Section 3.6).

Viruses

Viruses are usually adsorbed onto bacterial flocs, which in turn are removed by sedimentation in the secondary sedimentation tank. Some of the viruses are also consumed by protozoa.

Bacteria

Bacteria are killed by a number of methods. Some are killed by viruses. Others are consumed by protozoa, or are eliminated by toxins produced by other species of bacteria. Many of the pathogenic bacteria are simply enveloped by the rapid growth of non-pathogenic bacteria around them, such that they become enmeshed in flocs of non-pathogenic bacteria. The bacterial flocs are then removed in the sedimentation process following biological treatment.

Protozoa

Most of the protozoa become bound to bacterial flocs, which are later removed in sedimentation.

4.6.9 Comparison of systems

Taking the case of an activated sludge system:

- If a poorer than normal quality influent enters the works, the ability to vary the proportion of sludge that is recycled offers a degree of control over the

quality of effluent finally discharged, unlike in a biological filter.

- It avoids the nuisance of filter flies that occurs in biological filters.
- Loss of head (i.e. combined loss of elevation, velocity and pressure) through an activated sludge plant is significantly less than that through a filter bed, which may save on pumping.

- It takes up considerably less space. Where it is necessary to produce an effluent of particularly high quality, the area of land required for an activated sludge plant is about 10 times less than that needed for a conventional filter scheme to treat the same pollution load. For plants required to treat large flows, the smaller area required for activated sludge is the deciding factor.

  (On the other hand, the area required by biological filters is much reduced when high-rate filtration is used, and in recent years the maximum size of new plants that include biological filters has been decreasing.)

Conversely, activated sludge systems:

- require continuous attention – in comparison, the biological filter is simple and requires little attention
- consume large amounts of energy and labour
- are not tolerant of peak loads, whether of flow or composition

- are noisier than filters, which can be important when the plant is sited in an area that is otherwise quiet
- have annual costs (including operating and maintenance expenses) that are higher than for biological filters
- are more vulnerable than filters to toxic materials present in the influent
- unlike biological filters, do not convert ammonia to nitrate unless very high concentrations of oxygen are maintained – which requires extra costs and longer retention times in the aeration unit.

4.6.10 Control and monitoring

Biological filters

Control

The only moving mechanical part of a biological filter is the rotating distributor, and this is powered by the incoming wastewater flow. Maintenance of the system consists largely of lubricating the bearings and 'rodding' the distributor arms to remove any solids that may have come in with the wastewater.

Excess algal growth, as a result of organic overloading and 'ponding' (where the bacterial growth on the media becomes so thick that the air spaces are blocked and settled sewage is unable to trickle through, causing 'ponds' on the surface), may occur as sheets blocking the filter bed; these are removed manually using rakes.

Monitoring

Organic overloading leads to a loss in nitrification, so the biological filtering stage is monitored to avoid it.

- The pH of influent to the plant is measured to verify that it is within the tolerable range of 6.5–8.0.
- Suspended solids content and the BOD value of the final effluent (after secondary sedimentation) are measured to verify compliance with discharge consent conditions.
- Nitrification may also be monitored. If effective BOD removal is not taking place, the incoming BOD, N and P levels would be measured and the N and P levels adjusted, if necessary, to give the BOD:N:P ratio of 100:5:1 that is commonly recommended for effective biological treatment (Metcalf & Eddy, 2003). This relationship is used as a rule of thumb in the treatment of wastewater. If the presence of toxic compounds is suspected then they are sought out and eliminated, preferably at source.
- BOD data take five days to acquire, so for immediate feedback a measurement of the *chemical oxygen demand* (COD) is often also made and the related BOD value obtained from this using the COD/BOD relationship determined for the particular effluent. A COD test can be completed in a few hours.

Other parameters recorded would be pH, temperature, ammonia–nitrogen content, nitrate–nitrogen content, chloride and dissolved oxygen level.

If metal-bearing effluents were being treated, the concentrations of the metals in the outflow would also be determined. Similar specialist data would be acquired if pesticides or other chemicals of interest were present in the incoming wastewater.

The frequency of sampling and analysis depends on the size of the works. Many smaller sewage treatment works are sampled only weekly or even monthly.

Activated sludge process

Activated sludge systems are more complex than biological filters, so a number of tests are made to monitor the treatment process and to pre-empt any upsets that may occur. Measurements of dissolved oxygen (DO), pH, mixed liquor suspended solids (MLSS) and the sludge volume index (SVI) are taken. The suspended solids content of the return activated sludge is also measured. Very often, process upsets can be detected by a change in the normal colour or smell of the mixed liquor or the return activated sludge.

Dissolved oxygen (DO)

Most dissolved oxygen control systems work by measuring the concentration of DO in the mixed liquor leaving the aeration tank; a commonly chosen range is 0.5–2.0 mg l^{-1}. Measurements using a portable dissolved oxygen meter can be undertaken to verify that the required level is being maintained.

Mixed liquor suspended solids (MLSS)

The maximum concentration of MLSS that can be achieved depends on the settleability of the sludge and the surface area of the settlement tank. The optimum concentration is usually in the range 2000–3000 mg l^{-1}, though in an aeration tank providing full nitrification it is higher (e.g. 6000 mg l^{-1}). The MLSS concentration in the aeration tank affects the organic loading (*F/M*), which is crucial to the required performance of the plant. The MLSS concentration can be changed by altering the amount of sludge that is returned from the final sedimentation tank.

Sludge volume index (SVI)

The SVI is measured to gauge the settleability of the sludge. As already mentioned (see Section 4.6.4), an SVI below 100 ml g^{-1} indicates a good settling sludge, whereas a result in excess of 150 ml g^{-1} would suggest that further investigation is needed (Turovskiy and Mathai, 2006).

Suspended solids content in the return sludge

The suspended solids content must be known in order to estimate how much sludge has to be recycled to maintain a given *F/M* ratio in the aeration tank. All the suspended solids are assumed to be composed of microbial mass that would add to the MLSS level in the aeration tank.

Microscopic examination

Microscopic examination by an experienced eye is an excellent method of judging the condition of an activated sludge system. Examination of the activated sludge for floc size and diversity of organisms can give an indication of the performance of the aeration tank. Filamentous organisms are undesirable. The presence of protozoa in the final effluent indicates a clear effluent.

SAQ 27

Compare the activated sludge process with the biological filter in terms of the merits and demerits of each.

View answer

4.7 Secondary treatment of industrial effluents

So far, the focus has been on the treatment of domestic sewage. In modern society industrial effluents are also common, and these will be considered now. In Section 4.7.1 a brief overview of industrial effluents is given. Section 4.7.2 considers the treatability of such effluents, and Section 4.7.3 briefly discusses

bioaugmentation (where microorganisms are brought in to degrade difficult effluents).

4.7.1 Overview of industrial effluents

Industrial effluents (also called 'trade effluents' or 'trade wastes') come from a variety of manufacturing processes such as those producing textiles, metals, food and dairy products (see Section 2.2.2). They usually have a wider range of characteristics than domestic sewage and are more likely to contain toxic and non-biodegradable compounds that require physicochemical treatment rather than biological oxidation. Treatment usually takes place in a series of unit operations designed to remove or modify the characteristics of the pollutants in the effluent. However, there are many trade wastes that can be biodegraded, provided any toxic components are first removed. This is usually achieved using chemical treatment, e.g. oxidation of high concentrations of cyanides.

It can often be advantageous to treat industrial effluents after mixing with domestic sewage: the final composition of the mixed industrial/domestic sewage stream may reach the BOD:N:P ratio of 100:5:1 required for biotreatment. In a mixed industrial/residential area, a single wastewater treatment plant can be cheaper to build and to operate.

In many cities, industrial effluents (especially from the smaller industries) are discharged into the sewer system, after pre-treatment where necessary. The

industry concerned pays a charge to the authority responsible for both the sewers and the receiving treatment plant. The size of the fee usually depends on:

- the polluting potential of the effluent (based on its COD)
- its suspended solids content
- the volumetric flow rate.

You will learn more about this in Section 7.

The receiving plant dictates what can be put into the sewers by issuing a consent to discharge that limits the value of these three parameters and the content of any components of concern (e.g. metals) that may affect the biotreatment process. The toxic content of trade effluent discharged into sewers also has to be controlled to safeguard anyone working in the sewers and to protect the piping and equipment in the sewerage system from chemical attack.

Typical pre-treatment operations carried out on industrial effluents prior to despatch to a sewage treatment plant include:

- solids removal, e.g. screening, sedimentation, filtration or microstraining
- pH adjustment, using acid or alkali to bring the wastewater to a pH value in the range 6.5–8.0
- chemical oxidation, e.g. oxidation of the highly toxic cyanide ion (CN^-) to the much less toxic cyanate ion (CNO^-)

- chemical reduction, e.g. reduction of the toxic chromium (VI) ion (Cr^{6+}) to the chromium (III) ion (Cr^{3+}) using sulfur dioxide
- removal/recovery of heavy metals, e.g. precipitation of cadmium using lime
- oil/fat/grease removal, e.g. using an oil interceptor (Figure 34) or by flotation
- trace organics removal, e.g. adsorption of pesticides using activated carbon.

Figure 34 Section and plan of an oil interceptor – the retention time is sufficient for any oil to rise to the surface, from where it is removed during periodic inspections

View description

SAQ 28

Column A lists some industrial and manufacturing activities. For each activity, select from Column B the pollutant you would expect to find, and from Column C the pre-treatment operation necessary before the effluent can be discharged into a domestic sewer.

Column A	Column B	Column C
a. Ceramic works	• oil and fat	• chemical reduction
b. Distillery	• chromium (VI)	• neutralisation
c. Chicken processing plant	• acid mine waters	• sedimentation
d. Electroplating works	• china clay	• microstraining
e. Copper mining	• spent grain	• flotation

View answer

4.7.2 Treatability of effluents

If industrial effluents are to be discharged to municipal sewers for treatment at the local sewage works, it is important to ascertain whether the effluents are amenable to treatment, and also ensure that they are not going to inhibit the normal biological processes at the treatment works.

The activated sludge respiration inhibition test

This test is based on the fact that activated sludge respires rapidly in the presence of synthetic sewage (a medium made up using chemicals to represent real sewage – this has the advantages of being consistent in quality and being able to be made readily) but that the respiration rate decreases in the presence of a toxic chemical, with the decrease being proportional to the toxicity of the chemical. Activated sludge from a sewage treatment plant is continuously aerated and fed with a stream of synthetic sewage containing varying concentrations of the effluent being tested, for a period of 30 minutes.

The activated sludge concentration (expressed as MLSS) should be maintained at 3000 mg l^{-1}, with the respiration rate expressed in mg O_2 g^{-1} MLSS h^{-1}. The oxygen concentration is recorded over the test period. The respiration rates of the test samples and the control (activated sludge fed with only synthetic sewage) can be

calculated from the measurements of the dissolved oxygen concentration over time. The oxygen uptake of the sample by physicochemical action, when no activated sludge is added, is also measured. The percentage inhibition can then be calculated using the expression:

$$\text{percentage inhibition} = \frac{R_c - R_t}{R_c} \times 100\,\% \qquad (15)$$

where

R_c is the respiration rate of the control with activated sludge and synthetic sewage only
R_t is the respiration rate of the test sample.

Compact computerised systems to analyse and present the data are available (Figure 35).

Figure 35 A system used for the activated sludge respiration inhibition test

The percentage inhibition values can be plotted against the various dilutions of the effluent. The concentration of the effluent at which 50% inhibition of the control occurs (the EC_{50}) can then be ascertained.

This system has been used for testing industrial effluents before they are accepted for treatment at a

sewage works. Discharges may be direct to the sewer or brought by tanker to the treatment plant.

SAQ 29

The manager of a large effluent treatment plant was approached by an industrialist in the area wanting to discharge trade effluent to it. The laboratory staff at the treatment plant carried out a respiration inhibition test that revealed the following:

Respiration rate of control $= 14.67$ mg O_2 g^{-1} MLSS h^{-1}

Respiration rate of test samples:

Concentration of trade effluent (%)	Respiration rate (mg O_2 g^{-1} MLSS h^{-1})
20	13.47
40	12.00
60	9.07
80	8.20
100	6.53

The BOD inhibition test

In this test, the new effluent is assessed by measuring its effect on the oxygen use by heterotrophic microorganisms growing in a readily degradable substrate. The standard 5-day BOD test is used with a substrate consisting of a mixture of glucose and glutamic acid. Various dilutions of the effluent are tested and the percentage inhibition calculated. The standard substrate is made up of $0.15 \, g \, l^{-1}$ glucose and $0.15 \, g \, l^{-1}$ glutamic acid, giving an ultimate BOD of $308–321 \, mg \, l^{-1}$ depending on the extent of nitrification (Standard Methods, 2005). A standard bacterial seed is used.

The percentage inhibition is calculated using the following expression:

$$\text{percentage inhibition} = \frac{BOD_c - BOD_t}{BOD_c} \times 100\,\% \qquad (16)$$

where

BOD_c is the BOD of the control
BOD_t is the BOD of the test solution.

Again, from a plot of percentage inhibition against dilution, the value of the EC_{50} can be determined.

The Microtox™ test

This test uses measurements of light production by a bioluminescent bacterium to determine EC_{50} values. The concentration of effluent (or test chemical) that reduces the light production of *Vibrio fischeri* by 50% with reference to the control is the EC_{50}. Microtox™ has been used at sewage treatment plants to screen new effluents entering the works for toxicity and treatability.

4.7.3 Bioaugmentation

In bioaugmentation, commercially produced microbial species are used in wastewater treatment to break down difficult-to-degrade substances such as complex hydrocarbons. The original microorganisms are usually obtained from areas contaminated with the substance of concern, as natural selection will have ensured that those microbes are adapted to its presence. For example, coastal areas affected by oil pollution can be a source of hydrocarbon-degrading microorganisms, while

meat-processing plants can be a source of microbes capable of degrading fats and proteins.

The microbes collected from such sites are grown in a medium rich in the chemical under investigation. The strains growing best are then isolated and cultured on a larger scale, after which the microbes are harvested and freeze-dried for sale. They are sold in powder form, with the formulation usually containing nutrients, wetting agents and emulsifiers to aid dispersion.

In addition to the main purpose of degrading difficult compounds, bioaugmentation can be used to reduce the inhibitory effects of toxic compounds in effluents entering a treatment plant.

SAQ 30

A research team at an oil refinery in Kuwait was trying to find a microbial culture that would degrade the residual alkanes in its effluent.

  a. What characteristics should the culture have?
  b. Where might it be found?

View answer

4.8 Variants of the biological treatment system

Activated sludge units and biological filters are the most common forms of biotreatment used in effluent treatment, but variations do exist. Each of these variations has distinct advantages in treating a particular wastewater and/or for a particular situation. They are also quite different in their operating mechanisms. Some rely heavily on mechanical systems, whilst others (e.g. reed beds) use nature. Sections 4.8.1 to 4.8.10 describe a range of examples; Sections 4.8.11 and 4.8.12 briefly consider some alternatives to biological treatment; and finally, Section 4.8.13 considers the relative costs of all these treatments.

4.8.1 Oxidation ditch

In this system, biological oxidation takes place in a continuous racetrack-shaped channel (Figure 37) in which the mixed liquor is circulated and aerated by brush aerators, which maintain a liquid velocity sufficient to prevent the settlement of sludge. The ditches may be constructed in concrete or be earth channels lined with plastic sheet. In smaller plants they are usually trapezoidal in cross section to maintain a uniform horizontal velocity throughout the depth of liquid, with a depth of 1–2 m. Larger plants generally have channels of rectangular section and water depths of 3–4 m.
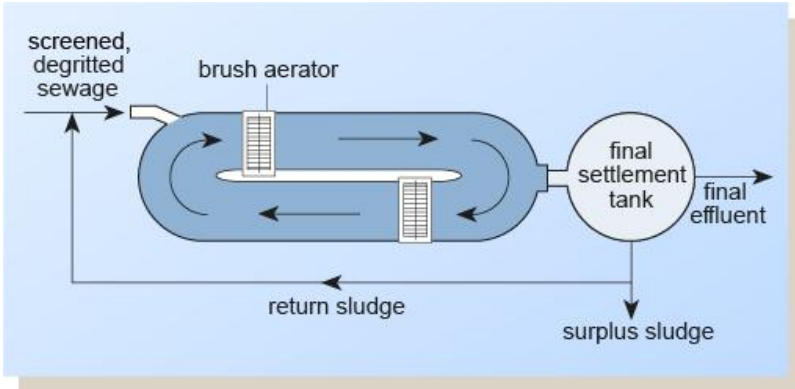
Figure 37 The oxidation ditch system

View description

Retention time in the ditch is in excess of 24 hours (termed extended aeration). The sludge age in oxidation ditches is normally 20–30 days. Consequently, the sludge solids undergo a considerable degree of stabilisation and aerobic digestion, and the system produces less sludge than a conventional activated sludge plant (EPA, 2000c).

Because of the long retention time, the high sludge age and the presence of an adequate supply of oxygen, nitrification usually takes place. However, because there are time intervals between the passages of mixed liquor through successive aeration zones, *denitrification* can also occur. In a number of cases, the period allowed for passage through an anoxic zone is deliberately increased (e.g. by switching off an aerator) to achieve a

substantial reduction in the concentration of nitrate in the final effluent.

No primary sedimentation is required in the oxidation ditch system, so screened, degritted effluent is fed straight into the ditch.

4.8.2 Pure oxygen activated sludge process

The use of pure oxygen rather than air in activated sludge systems can result in higher concentration driving forces. Due to the much greater difference between the concentration of oxygen present in the gaseous phase and that in the effluent, the rate of diffusion of oxygen into the effluent will be much higher. An oxygen-fed reactor can therefore have a higher organic loading than an air system, and an increase in plant capacity can be achieved without a corresponding increase in reactor volume. This feature would be attractive where severe space limitations are present. The development of efficient oxygen dissolution systems has made pure oxygen activated sludge systems competitive against systems using air (Shammas and Wang, 2009).

The oxygen can be purchased as liquid oxygen or produced by on-site generation. In the latter, pressure swing adsorption is often used to adsorb nitrogen from air onto a molecular sieve, to produce 80% oxygen-enriched air. Typically, for a conventional air

system the design organic loading would be 0.2–0.4 kg BOD per kg MLVSS per day (Bitton, 1998), while for an oxygen system it would be 0.3–1.3 kg BOD per kg MLVSS per day (Wilcox and Akinbami, 1974). An added advantage of pure oxygen systems is that the high dissolved oxygen levels enable nitrification to take place.

A commonly used pure oxygen activated sludge system is the UNOX™ process developed by the Union Carbide Corporation (Figure 38). This system consists of a series of completely mixed, roofed tanks, with the wastewater and oxygen gas moving through them together. At each stage, mechanical aerators are used to distribute the oxygen throughout the wastewater. The exhaust gases (containing carbon dioxide, which inhibits bacterial action and can acidify the wastewater) are withdrawn from the headspace.
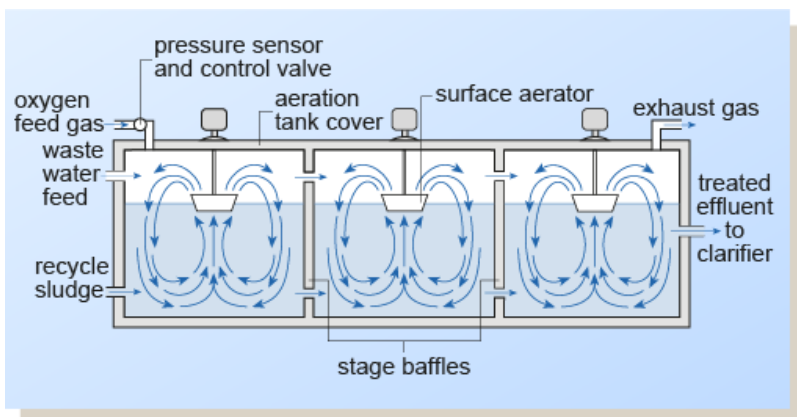
Figure 38 The UNOX™ pure oxygen activated sludge process

The pure oxygen process has been shown to be particularly applicable where:

- available space for the construction of treatment facilities is limited
- wide fluctuations occur in the organic loading to the plant
- strong wastewaters are to be treated.

Care must be taken in pure oxygen systems to prevent explosive atmospheres arising from the possible discharge of hydrocarbons to the treatment plant. In addition, construction materials have to be carefully selected, because corrosion is more rapid in an oxygen-rich environment. Nevertheless, the pure oxygen system has been shown to have the following additional advantages over the conventional activated sludge process:

- a sludge with improved settleability is produced
- lower quantities of sludge are produced
- there is a reduced risk of creating an odour nuisance when treating malodorous wastewaters.

4.8.3 Deep Shaft™ process

The Deep Shaft™ process (Figure 39) is a form of high-intensity activated sludge treatment carried out in

an underground shaft. The process was a spin-off from research into the production of protein from methanol, carried out by Imperial Chemical Industries in the 1970s.
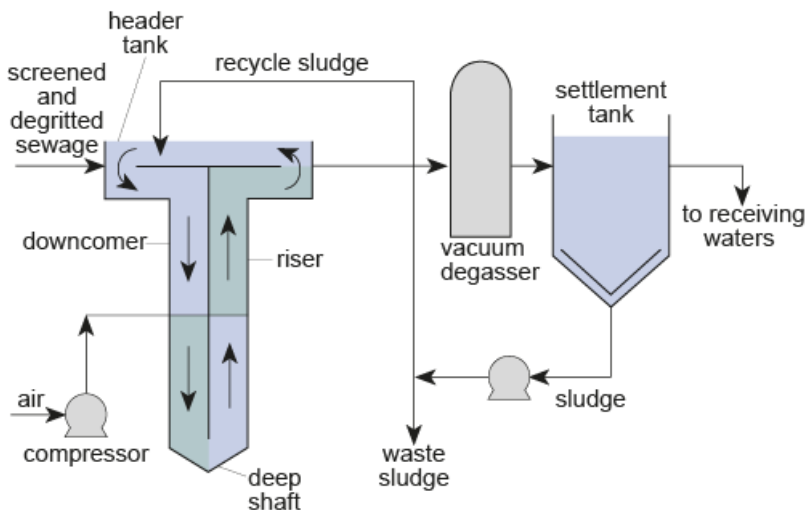
Figure 39 The Deep Shaft[TM] process for treating domestic sewage (the vacuum degasser is a vertical vessel under vacuum)

View description

Raw sewage or strong biodegradable effluent, together with activated sludge, enters a vertical shaft (30–150 m deep, 0.7–6.0 m diameter) made of steel or concrete, where biodegradation takes place. Although the shaft can treat raw sewage, screening and grit removal is first undertaken to prevent blockages and damage to pumps and other equipment. Solids are kept in suspension at the high flow velocity within the shaft, and are carried

out with the outflow. Allowing the solids to go through with the effluent results in a portion of them being degraded.

The shaft consists of an upflow section (the riser) and a downflow section (the downcomer), which may be concentric or side by side. To start the circulation of the mixed liquor, compressed air is injected into the riser, reducing the density of the liquor and acting as an airlift. Since the header tank provides a common water level above both the riser and the downcomer, circulation begins.

The supply of compressed air to the riser is then gradually reduced and transferred to the downcomer. Here, because the downward velocity of the liquid is greater than the upward velocity of the air bubbles, the entrained air is forced downwards. This air is rapidly dissolved in the water at the high pressure in the depths of the shaft, and is readily available for use by microorganisms.

As the mixture travels up the riser and the pressure falls, bubbles of residual dissolved gases come out of solution, serving as an airlift and thus sustaining the circulation velocity of about $1.5 \, \text{m s}^{-1}$. The effluent retention time is one to two hours.

Bubbles of nitrogen and carbon dioxide in the outflow of treated effluent from the shaft attach to the sludge flocs and hinder their settlement. The liquid is therefore degassed by passage through the header tank, and the

process is usually assisted by a vacuum device, or by coarse- or fine-bubble aeration. The mixed liquor, now free from entrained gases, passes forward to the settlement tank; here the sludge settles, to be recycled or taken away for disposal.

Oxygen transfer in the Deep Shaft™ process may be as high as 90% (compared with 15% in a conventional activated sludge system), and the oxygen transfer rate is 0.9–2.7 kg kWh^{-1} (compared with 0.9–1.5 kg kWh^{-1} in the conventional system) (EPA, 1982). This high oxygen uptake results from the greater dissolution of the oxygen at the high pressure in the shaft and the long bubble contact time (about 90 seconds, compared with about 15 seconds in conventional diffused air systems). This results in a lower power consumption and a lower aeration volume requirement.

Another major advantage of the Deep Shaft™ process is that it requires much less land area than a conventional system treating the same load. For this reason, it has found acceptance in densely populated cities (e.g. in Japan) where land availability is at a premium.

4.8.4 Rotating biological contactor

The rotating biological contactor (RBC), as shown in Figure 40, combines the advantages of both the activated sludge system (long retention time in the active area, small space needed for plant) and the biological filter (sludge return not necessary, easy to operate and needing little maintenance or supervision).

It has been employed as a sewage treatment plant for small communities.

Figure 40 A rotating biological contactor with cover removed

View description

Typically the sewage influent, after passing through a primary settlement tank, goes into a tank in which an assembly of vertical discs (usually made of glass-reinforced plastic) is slowly rotated by an electric motor at a speed of about three revolutions per minute. Usually about 40% of the area of these discs is submerged. The discs serve as physical support surfaces for the growth of microorganisms, and the rotation provides alternate immersion and aeration of

the organisms. The discs are fluted or otherwise designed to increase the surface area available for the biological film to grow on. Nitrification can also be achieved with RBCs.

The RBC is similar to a biological filter in that both rely on microbes attached to a surface for biotreatment, but the RBC is more compact and does not result in a fly problem: because the biological film is immersed periodically in the sewage, flies do not colonise the discs. RBCs either have covers or are housed in buildings.

RBCs are quiet, require little attention, and can be made unobtrusive by being positioned partly below ground level. These factors make them suitable for small groups of houses, or for caravan and camp sites.

The RBC has been restricted to relatively small installations due to its high construction cost relative to an activated sludge system.

4.8.5 Hybrid activated sludge system

The hybrid activated sludge (HYBACS) system consists of a rotating biological contactor (RBC)-type unit and an activated sludge system in series (Figure 41). The RBC has discs made of 50 mm thick plastic mesh (with a voidage of 95%), which allows a greater density of biomass to grow. The mesh supports different types of cultures and provides different environments, enabling

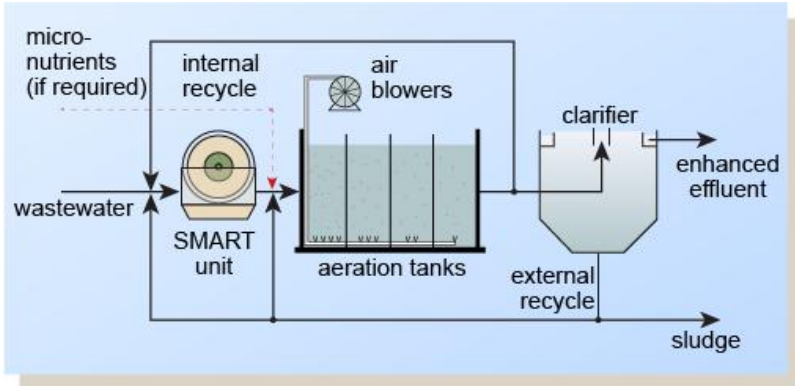carbonaceous oxidation, nitrification and denitrification to occur simultaneously.

Figure 41 The HYBACS system (FWCM, 2009)

View description

4.8.6 Membrane bioreactor

Membrane bioreactors (MBRs) are enclosed biological treatment units with ultrafiltration membranes (with pore sizes of 0.001–0.02 µm) for separating the biomass from the treated effluent prior to its discharge. This means of separation is very effective, and the biomass is returned to the aeration tank, where its concentration is around 20 000 mg l^{-1}. Two different reactor configurations are possible:

- sidestream MBR
- submerged MBR.

Sidestream MBR

Here, the mixed liquor is pumped out of the biological reactor and put through a membrane filtration unit. The permeate is discharged while the biomass is returned to the bioreactor (Figure 42).
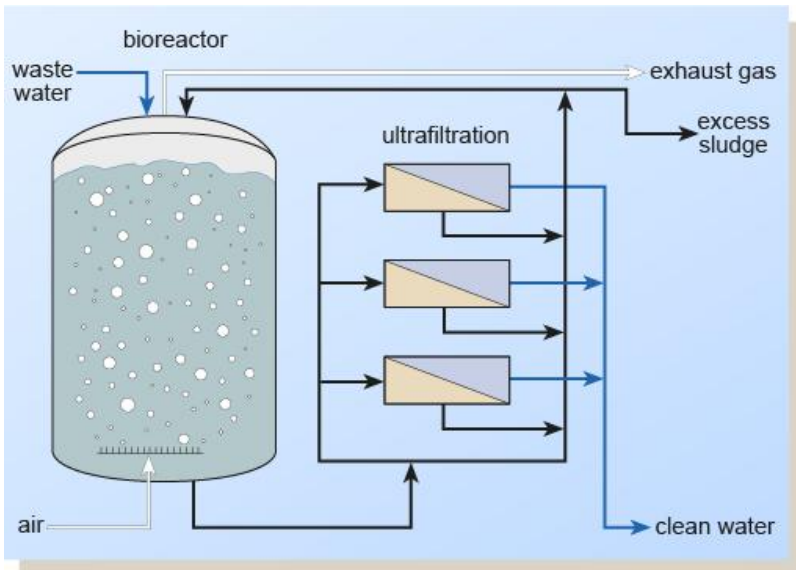
Figure 42 A sidestream MBR system

View description

Submerged MBR

In this variant, the membrane unit is contained within the biological unit such that treated effluent is continuously

filtered out, while the biomass remains within the bioreactor. In one design of this system, the membrane unit is mounted on top of a coarse-bubble diffuser. The mixed flow of activated sludge and air bubbles is channelled between the membrane plates. The bubbles generate an upward flow of the mixed liquor over the membrane surface and minimise fouling.

Advantages of the MBR system (both configurations) over a conventional activated sludge system are as follows:

- it uses smaller reactors
- it produces a higher quality of treated effluent
- it avoids the problems of sludge bulking (since no sedimentation of microbial matter is involved) and odour (since the system is enclosed)
- there is no need for a secondary sedimentation tank.

However, the MBR process is more expensive than a conventional activated sludge system.

A variant of the air-fed MBR has been developed in which oxygen is used. This enables a greater organic load to be applied to the system.

SAQ 31

a. How is the MBR process able to operate with a smaller reactor than a conventional activated sludge system?

4.8.7 Waste stabilisation ponds

Waste stabilisation ponds are a simple means of treating wastewater biologically by harnessing the power of sunlight and wind.

Screened, degritted effluent is passed through a series of ponds with a total retention time of 10–50 days. In the ponds, bacteria oxidise the pollutants and work symbiotically with algae, which provide oxygen through photosynthesis. The algae also use the carbon dioxide, ammonia and phosphate released by the bacteria. Aeration occurs through the action of wind.

No mechanical equipment is used in the ponds, so operation and maintenance costs are very low. A typical layout for a waste stabilisation pond system treating domestic sewage is shown in Figure 43.

raw or screened, degritted sewage

facultative pond

facultative pond

bund

maturation pond

maturation pond

treated effluent

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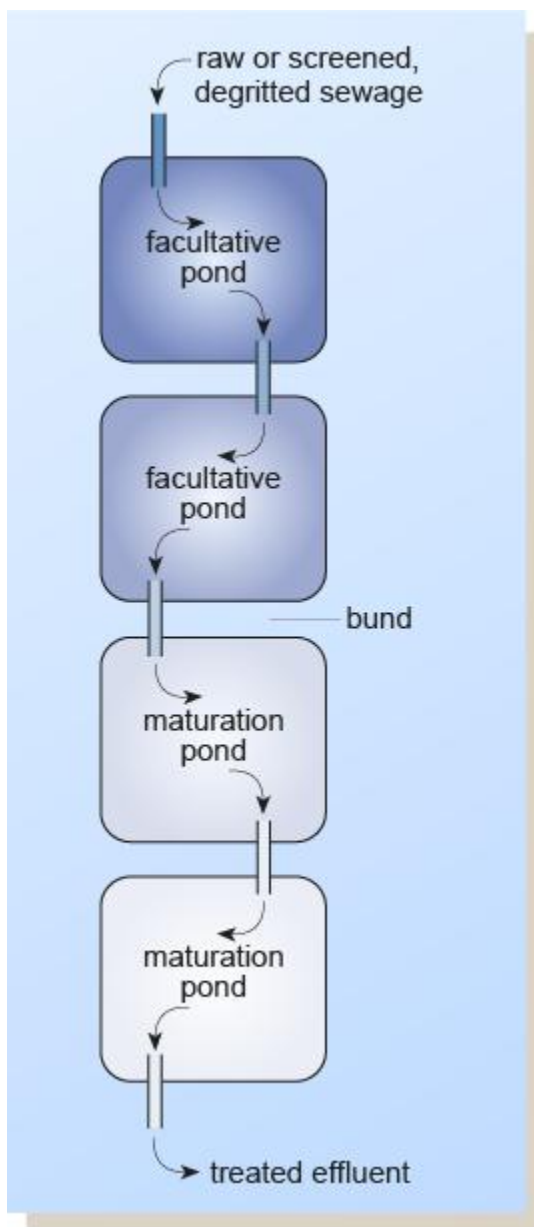
Figure 43 Layout of a waste stabilisation pond system treating domestic wastewater

The major part of the biodegradation of the sewage takes place in the facultative ponds (1–1.5 m deep), which are aerobic at the top and anaerobic at the bottom. Maturation ponds are usually about 1 m deep and serve to inactivate pathogenic bacteria and viruses through the action of UV radiation from sunlight and the greater algal activity in these shallow ponds, which raises the pH (above pH 8.5, pathogens are rapidly killed off) and the dissolved oxygen content. The long retention time in each of the ponds also enhances the sedimentation of parasite eggs and dormant forms of some parasitic organisms.

If the wastewater has a very high BOD (e.g. effluent from the intensive rearing of animals), anaerobic ponds are often used ahead of the facultative ponds. Anaerobic ponds are 2–5 m deep and are nearly devoid of oxygen. A floating crust some 40–60 mm thick forms, insulating the pond, maintaining anaerobic conditions and preventing odours from escaping. Solids settle to the bottom, forming a sludge. Methane production can be high in the summer, with pockets of gas breaking through the crust.

Waste stabilisation ponds are especially efficient in hot climates, but they are also used in colder areas: for example, in France there are about 2500 waste

stabilisation pond systems, in Germany about 3000, and in the USA about 7000 (Mara, 2009). Though they require large areas of land, this need can be satisfied by locating the ponds at the outer perimeter of cities, or on disused land.

Treated sewage can be reused in irrigation (Figure 44) if safe limits of faecal coliforms and intestinal nematode eggs are achieved in the treatment process. Waste stabilisation ponds have been found capable of attaining these standards at low cost and are actively encouraged as a means of supplementing the water supply available for irrigation, especially in developing countries and in southern Europe.

Figure 44 Reusing treated sewage in irrigation

View description

At the same time as treating wastewater, pond systems have been used to increase protein production through the rearing of fish and ducks in maturation ponds.

Maturation ponds are also a tempting source of recreation – a fence had to be put rapidly around a set of these in Malaysia to stop children paddling in them!

4.8.8 Septic tank

Septic tanks (Figure 45) are often used for partial treatment of sewage in areas that are not sewered (for instance, places where the effluent flow generated is small and intermittent, such as farms or individual residences dispersed in the countryside).
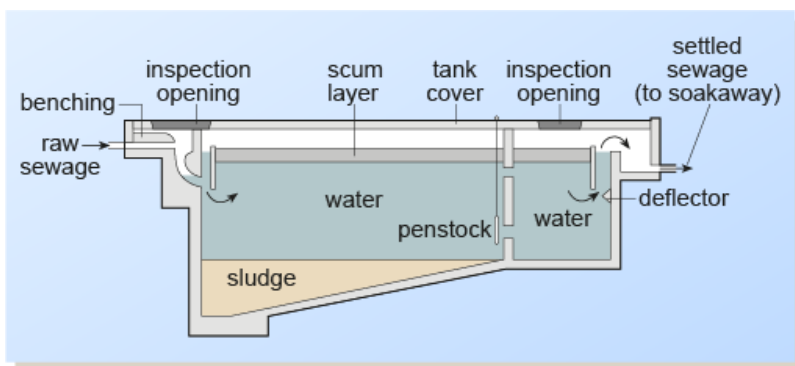

Figure 45 A typical septic tank (based on BSI, 1983)

View description

Septic tanks usually have two compartments and are buried underground. The first compartment (which is usually twice the volume of the second) provides for sedimentation, sludge digestion and sludge storage. The second compartment provides additional

sedimentation and sludge-storage capacity, and thus serves to protect against the discharge of sludge and other material that might escape the first chamber. A thick crust of scum usually forms at the water surface of the tank.

The organic solids that settle out are partially digested by anaerobic bacteria. Sludge accumulates and the tank must be de-sludged, typically every 12 months (depending on loading). The sludge is tankered to a wastewater treatment plant for treatment and disposal.

In order to provide sufficiently quiescent conditions for effective sedimentation of the sewage solids in septic tanks, the liquid retention time for a daily flow rate of up to 6 m^3 should be at least 24 hours (WEDC, n.d.). Since two-thirds of the tank volume is usually reserved for the storage of accumulated sludge and scum, the size of the septic tank should be based on a three-day retention time at start-up.

Effluent from a septic tank (which should be low in suspended solids but could be high in BOD) usually flows into a soakaway (a chamber with perforated or open-jointed walls), from where it percolates into the ground. In selecting a site for a soakaway, it is important to consider the ability of the ground to absorb water, its permeability and the varying level of the water table with the seasons of the year.

4.8.9 Use of plants in wastewater treatment

Reed beds, or artificially constructed wetlands with emergent plants, have been used for secondary treatment of sewage. The plants (typically *Phragmites australis* or *Phragmites communis*) are grown in rows in beds of soil or gravel lined with an impermeable clay or synthetic liner (Figure 46). The effluent requiring treatment is fed into the bed, which typically has a depth of 600 mm. The base of the reed bed has a slope of 2–8% to enable collection of the effluent after treatment.
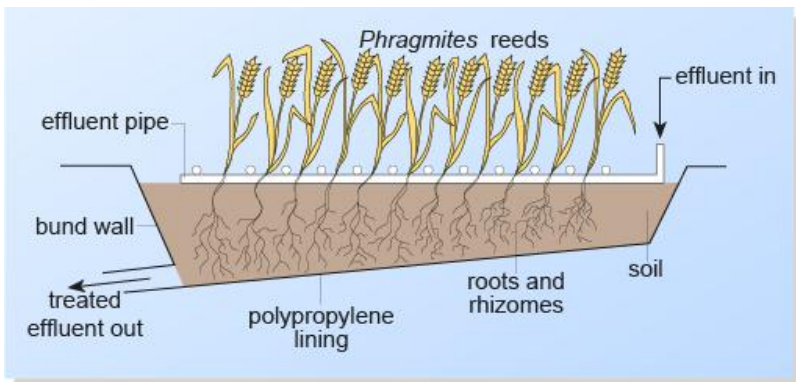
Figure 46 The reed bed system (vertical flow); at maturity, the reeds are 1.5–3.0 m high

View description

In a vertical flow reed bed, the effluent to be treated is distributed through pipes and nozzles onto the reed

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bed, then percolates down to the roots and rhizomes of the reeds. Oxygen is taken through the stomata (apertures) in the underside of the *Phragmites* leaves and passes down the hollow stem of the plant to the rhizome and root system. There are also anoxic zones in the vicinity of the rhizomes. This mixture of environments permits the survival of both aerobic and anaerobic bacteria. Thus the processes of carbonaceous oxidation, nitrification, denitrification and anaerobic biodegradation can all take place. The treatment stages all occur in the root zone of the plants, and hence this kind of treatment is known as root zone treatment.

Owing to the great diversity of microbial species in the soil, a potentially greater range of treatment is possible; for example, the microorganisms *Actinomyces*, *Streptomyces* and *Basidiomyces*, which are capable of biodegrading many synthetic chemicals such as the common pesticides and chlorinated hydrocarbons, are found in soil but are not normally in effluent treatment plants.

Root zone treatment has been used to treat:

- landfill leachate
- acid mine drainage
- contaminated surface run-off
- effluents from chemical plants containing traces of phenol, methanol, acetone and amines
- screened, degritted domestic sewage from small communities.

Unlike mechanical treatment plants, reed beds are not unsightly or noisy. They are almost as expensive as mechanical treatment plants to set up, but their running costs are low (since no electrical or mechanical equipment is needed) and they have no sludge disposal costs.

An equation relating the area of reed bed to the removal of BOD in sewage is as follows (UN-HABITAT, 2008):

$$A = Q\left(\frac{\ln(C_0) - \ln(C_1)}{k_i}\right) \qquad (17)$$

where

A is the area of reed bed in m^2
Q is the influent flow rate in m^3 d^{-1}
C_0 is the influent BOD concentration in g m^{-3}
C_1 is the required final BOD concentration in g m^{-3}
k_i is the BOD rate constant in m d^{-1}, which varies with the type of influent and the substrate in the reed bed.

Due to their low loading rate, reed beds take up large areas of land. Also, in order to give the desired level of treatment to chemical wastes, which are difficult to dispose of, the reeds may require several years to grow to full maturity. They are, however, able to withstand shock loads, and also offer a haven for wildlife, particularly for transmigratory birds. This has often been seen as an advantage by the local community.

4.8.10 Package treatment plants

The sewage from small groups of houses in remote locations is often treated in package treatment plants. These are compact, complete treatment systems that are prefabricated and hence easily installed. They are relatively simple to operate. They have all the unit operations of a full-scale sewage treatment plant except that they are smaller in size.

Both activated sludge and biological filters can be made as package units. Being small in size, package treatment plants are able to use non-concrete tanks, e.g. tanks made of glass-reinforced plastic. This also makes them easy to transport. Rotating biological contactors are particularly favoured for package plants,

as they can be installed partially below ground level and therefore do not significantly visually impair the landscape.

4.8.11 Chemical treatment of sewage

The various biological processes of sewage treatment could be replaced by chemical processes, such as coagulation and flocculation.

Advantages of chemical methods include:

- their ability to process sewage at a faster rate than biological treatment plants
- the fact that they are unaffected by toxic substances and changes in loading and temperature, to which microorganisms are very susceptible.

The two main disadvantages of chemical treatment are:

- the cost – oxidising bacteria can be exploited for approximately 5% of the cost of the cheapest oxidising agent
- the volume of sludge produced – chemical methods, operating by precipitation, produce large volumes of sludge that contain both the solids removed from the sewage and most of the added chemicals. In addition, chemical precipitation removes suspended and colloidal BOD but not soluble BOD. Biological treatment produces less sludge because bacterial oxidation results in the formation of carbon dioxide from organic carbon.

In the final analysis, however, it is economics that dictates the treatment process to be adopted. For biodegradable pollutants, biodegradation works out as more favourable.

4.8.12 Waterless sewage treatment

Water-borne disposal of sewage uses up vast quantities of water. Using the traditional lavatory flush system, each person uses some 50 litres of clean, potable water every day to transport 135–270 g of solid waste and 1.0–1.3 litres of liquid waste to the sewage treatment plant. The sewers and treatment plants needed to handle the tremendous volumes of wastewater are costly, both in the capital outlay and in operation and maintenance.

It would be much more prudent for human waste to be disposed of at source (i.e. within the confines of the house, factory, etc. where it is generated) using dry methods such as composting. Then sewers and treatment plants would need only to handle sullage (and rainwater run-off), and could be smaller and cheaper. The composting of human waste could take place with other biodegradable domestic wastes, such as food waste. The composted material (if free from pathogenic organisms) could then be used beneficially in agriculture or horticulture, thus recycling valuable nutrients. Well-designed, dry composting toilets are already marketed (EPA, 1999).

Thus if we are to conserve water and recycle nutrients usefully, the path to follow is perhaps the increased adoption of waterless sanitary disposal systems. The obstacle to be overcome, however, is the nature of sewage as perceived by the public. The idea that sewage is an obnoxious waste has to be replaced by the view that it is a valuable resource.

4.8.13 Relative costs

It is often difficult to get comparative costs for different treatment options because a lot depends on the scale of the plant, its location, etc. However, as a rough guide, the bandings 'low', 'medium' and 'high' can be allocated to the capital and operating costs of different systems. An attempt at this has been made in Table 14.

Table 14 Relative costs of different treatment options

System	Capital cost	Operating cost
Biological filters	high	low
Conventional activated sludge process	medium	medium
Oxidation ditch	medium	medium
Pure oxygen activated sludge process	high	high
Deep Shaft™ process	high	medium
Rotating biological contactor	medium	low

Hybrid activated sludge system	high	medium
Membrane bioreactor	high	high
Waste stabilisation ponds	low (if land cheap)	low
Reed beds	high	low
Septic tank	low	low
Chemical treatment	medium	high
Composting toilet	high (for the individual)	low

SAQ 33

Select from Column B the most appropriate treatment technique or techniques for each of the effluents listed in Column A.

Column A	Column B
a. Domestic sewage from a single cottage in the countryside b. Domestic and farm wastewaters in a sparsely populated rural area with a lot of land available	• Pure oxygen activated sludge process • Reed beds

c. A high-BOD effluent from a food-processing plant in a built-up area with little available land

d. Domestic effluent from a remote group of houses in an area of low soil permeability

e. An effluent with high ammonia content from a fertiliser plant that has extensive land available

f. An industrial effluent with traces of mixed organics not easily degraded in a conventional mechanical plant

g. A mixed industrial–sanitary wastewater with a high and fluctuating organic load, in a city site

h. Domestic sewage that has to be treated for reuse in watering a golf course

- Rotating biological contactor
- Oxidation ditch
- Membrane bioreactor
- Septic tank
- Deep Shaft™ process
- Waste stabilisation ponds

[View answer](#)

4.9 Tertiary treatment

The processes so far described usually produce an effluent containing no more than 30 g m^{-3} of suspended solids and 20 g m^{-3} of BOD. This is referred to as a '30/20 effluent' in the UK. However, sometimes more stringent standards may be necessary – as, for example, when the effluent forms such a substantial part of a river flow that a dilution of less than 8:1 results. In such cases the effluent should not contain suspended solids in greater concentration than 10 g m^{-3}, or have a BOD greater than 10 g m^{-3}, or contain ammonia–nitrogen in excess of 10 g m^{-3}. This standard is often referred to as the 10/10 standard (strictly speaking, the 10/10/10 standard). The additional processes beyond secondary treatment that are required to reach such a standard comprise tertiary treatment.

4.9.1 Suspended solids removal

Systems typically used to remove suspended solids during tertiary treatment are:

- microstraining
- sand filtration
- further settlement/grass plots.

The reduction in suspended solids also results in a lowering of the BOD, because some of the solids are organic in nature and contribute to the BOD.

Microstraining

A microstrainer (Figure 47) consists of a rotating drum with a stainless steel micromesh fabric. The mesh size can range from 15 μm to 64 μm so that very fine suspended matter can be trapped. The trapped solids are returned to the inlet of the treatment works. To reduce costs, the final effluent is often used as the washwater. To prevent biological growth on the fabric of the microstrainer (as a result of nutrients present in the treated effluent), a UV light is usually mounted alongside the washwater jets.
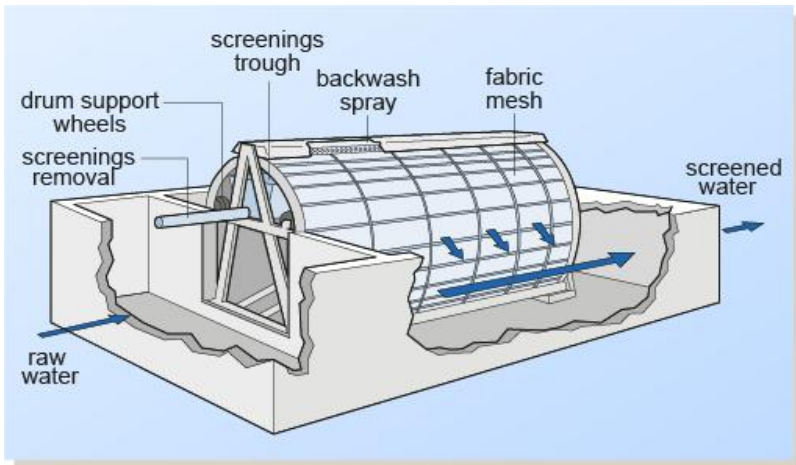
Figure 47 A typical microstrainer

View description

Sand filtration

In sand filtration, the effluent from biological treatment is passed through rapid-gravity sand filters (Figure 48). The flow rate is 4–$8\ \mathrm{m^3\ m^{-2}\ h^{-1}}$. When the flow rate drops significantly (indicating that the bed is full of suspended matter), the filter is cleaned by backwashing: water and air are pumped under pressure backwards through the filter, to wash out the trapped impurities. The washings are pumped back to the inlet of the works.
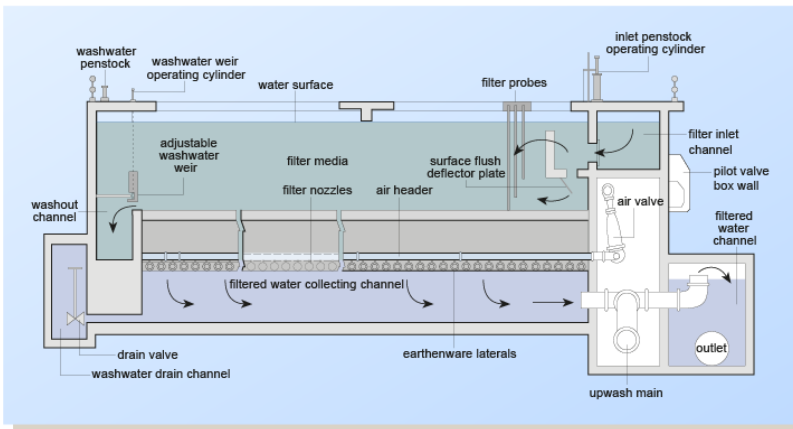

Figure 48 Section through a rapid-gravity sand filter

View description

The DynaSand® system

This is an upflow, deep-bed, granular media filter (Figure 49) with no moving parts. It continuously backwashes without the need for backwash pumps. An inlet pipe (A) feeds dirty water into the annulus (B), and this comes out from the radial pipes (C) into a downward-moving sand bed (D). The sand bed captures the impurities in the water, and travels down the filter to the cone. When it reaches the bottom, it is drawn into the airlift pipe (N) by a small volume of compressed air that is introduced at the bottom of the pipe (F). Meanwhile, the cleaned filtrate continues to move upward (M) and exits at the top of the filter, over the filtrate weir (J) and out through the effluent pipe (E).
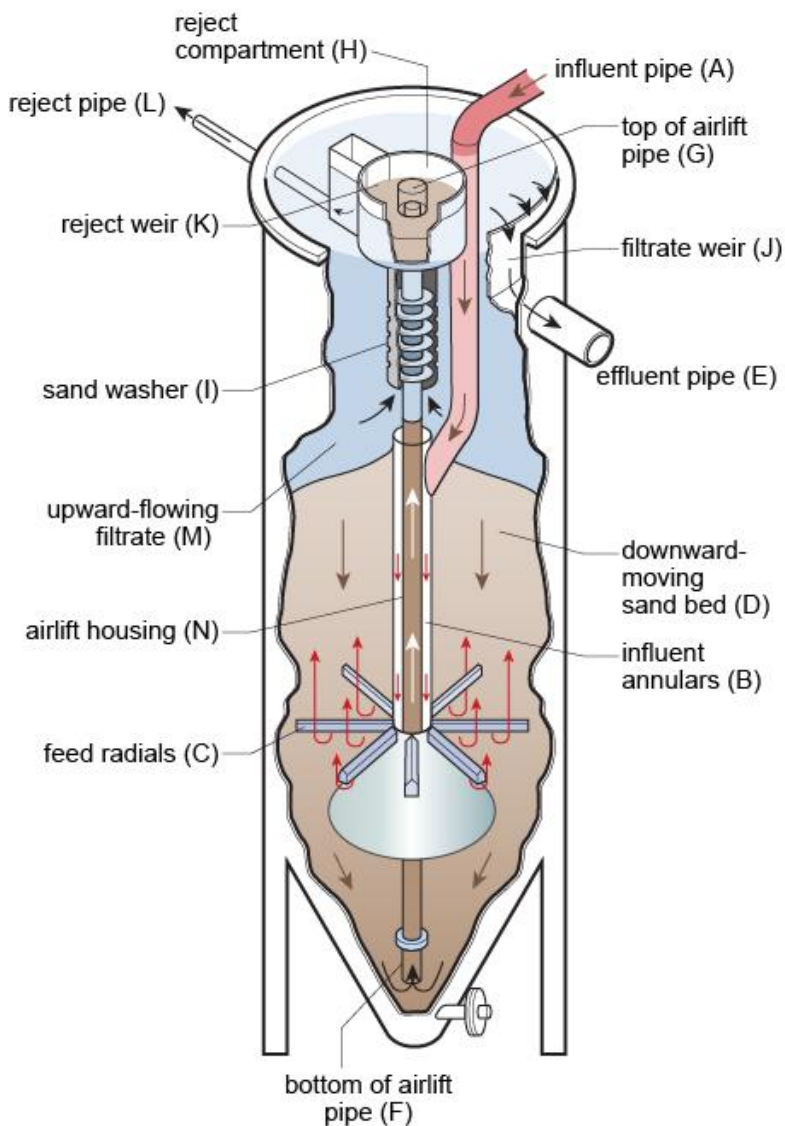
Figure 49 The DynaSand® filter (Parkson, 2010)

The sand is carried up into the airlift pipe, where it is scoured and any solid particles attached to the sand grains dislodged. The dirty slurry is pushed to the top of the airlift pipe (G) and into the reject compartment (H). The rejected solids, being lighter than the sand, are carried over a weir (K) and out through a pipe (L). The heavier sand falls into a sand washer (I), which has concentric stages. Due to the difference in levels between the water in the reject compartment and that in the top of the filter itself, a small amount of polished filtrate (i.e. cleaned water) moves upward through the sand washer. The heavier, coarser sand grains fall through this small counter-current flow, while any remaining contaminants are carried up to the reject compartment. The cleaned sand is deposited on top of the sand bed, where it once again begins its cleaning process.

The sand bed is in slow, constant downward motion through the unit, and water purification and sand washing take place continuously, enabling the unit to remain in service without interruption.

The DynaSand® system is most often used for removing suspended solids, but with the addition of appropriate chemicals it can be used for phosphate removal.

The sand in the system can be used as a carrier for biofilm, and hence the technology has been used for both BOD and ammonia reduction.

Further settlement

Settlement of the final effluent will improve its overall quality. This may be carried out in special settlement lagoons similar to maturation ponds. During storage in the lagoons, the quality of the water improves as a result of some of the solids settling and the activity of bacteria, protozoa and algae. Suspended solids, BOD, pathogenic bacteria, nitrate and phosphate can all be reduced.

Such lagoons, however, take up a considerable area of land and add to the total costs of the treatment works. This additional cost can be avoided if storm tanks are used instead (see Section 4.3.1). The procedure would be always to have one storm tank empty. During storm conditions, this empty tank would be filled first. While it was filling, the other storm tanks would be emptied to allow them to receive the storm water. Once the storm was over, the tanks could be emptied and returned to their tertiary treatment function.

SAQ 34

The use of extended settlement seems simple and not over-costly. What other benefits of the process can you think of?

View answer

Grass plots

In this method the treated effluent is allowed to trickle slowly over grassland, resulting in a further reduction of the BOD and solids. This has the disadvantage of requiring large areas of land with the correct characteristics, including a slope of not greater than 1 in 60. Each cubic metre of effluent flow per day requires an area of 1.2 m^2 of grassland.

Reed beds can also be used to improve the quality of a 30/20 effluent. Lagoon, grass plot and reed bed treatment also remove nitrate and phosphate, and so reduce the possibility of eutrophication in the receiving watercourse.

Specific processes for N, P and NH_3 removal can also be considered to be tertiary treatment operations.

SAQ 35

Which of the following processes are likely to remove more components than just suspended solids and BOD?

Microstrainers

Grass plots

| Lagoons |
| --- |
| Rapid-gravity sand filters |
| Reed beds |

4.9.2 Nutrient removal – ammonia and nitrates

Untreated sewage typically contains 12–50 mg l^{-1} of ammoniacal nitrogen (EPA, 2000b), most of it originating from the urea in urine. If high-ammonia wastewaters (e.g. abattoir effluents, landfill leachate, liquors from the dewatering of sludges from anaerobic digesters) are treated, a high residual quantity of ammonia may be present in the secondary-treated effluent, and this is undesirable for the reasons mentioned in Section 2.2.3.

Ammoniacal nitrogen exists in aqueous solution as either the ammonium ion (NH_4^+) or free ammonia (NH_3), depending on the pH of the solution, in accordance with the following equilibrium reaction:

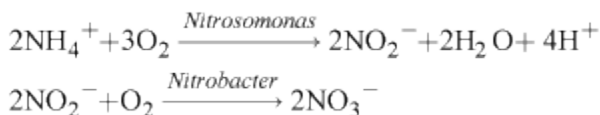$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$
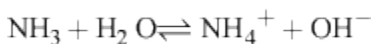
Above pH 7, the equilibrium is displaced to the left and free ammonia predominates; below pH 7, the equilibrium is shifted to the right and the ammonium ion predominates. An increasing level of pH above 7 results in a higher level of free ammonia.

Ammonia can be removed from wastewater in several ways. The methods commonly used are broadly of two types:

- biological nitrification–denitrification

- non-biological methods, including:
   - air stripping
    - breakpoint chlorination.

Biological nitrification–denitrification

This method is probably the most economical means of removing ammonia. Microorganisms are used (usually in an attached growth system) to convert the ammonia to nitrite and then to nitrate:

$$2NH_4^+ + 3O_2 \xrightarrow{\textit{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+$$

$$2NO_2^- + O_2 \xrightarrow{\textit{Nitrobacter}} 2NO_3^-$$

This is the same process that normally takes place in biological filters during secondary treatment, and in soil and natural waters. The nitrates formed are converted to nitrogen gas in an anoxic reactor (a reactor where no dissolved oxygen is present) because the denitrifying

bacteria needed are anaerobic. A carbon source (typically methanol, CH_3OH) is added to facilitate the conversion:

$$6NO_3^- + 2CH_3OH \rightarrow 6NO_2^- + 2CO_2 + 4H_2O$$
$$6NO_2^- + 3CH_3OH \rightarrow 3N_2^- + 3CO_2 + 3H_2O + 6OH^-$$
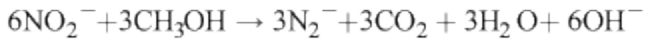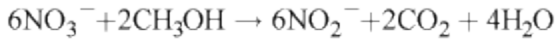
Common denitrifying bacteria are *Pseudomonas denitrificans* and the *Hyphomicrobium* species.

Nitrification is an aerobic process, requiring 3.76 g of oxygen for every gram of ammonia oxidised. Denitrification, on the other hand, occurs under anoxic conditions. The energy required for denitrification is drawn from the organic content of the wastewater. If the carbon content is low, external sources (most commonly methanol) are added. The facultative denitrifying bacteria reduce the nitrate to nitrogen gas. With every gram of nitrate reduced, 0.65 g of oxygen is released. This can be used in nitrification. Similarly, the carbon content in nitrified effluent can be used for denitrification. Figure 50 shows one possible configuration of treatment units to achieve both nitrification and denitrification.
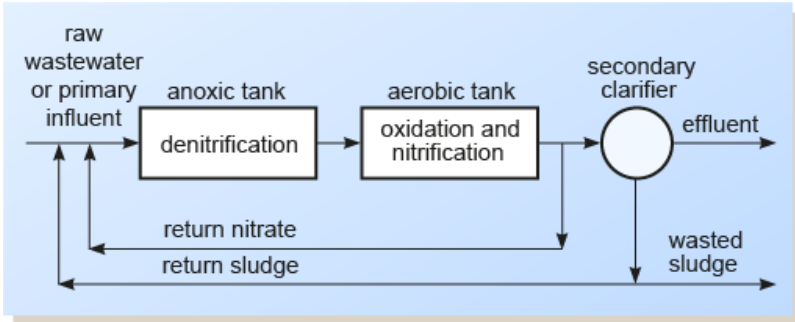
Figure 50 Schematic of the nitrification–denitrification process

There is no aeration in the anoxic tank, and denitrification occurs with a bacterial population high in denitrifiers. From the anoxic tank, the effluent flows to the aerobic tank, where the oxygen level is maintained in excess of 2 mg l^{-1}. A sufficiently long retention time in this tank ensures that carbonaceous oxidation and nitrification take place. A part of the nitrified effluent is returned to the denitrification tank, while the remainder goes for secondary settlement.

Nitrification–denitrification can be incorporated into oxidation ditch systems (Figure 51). Influent is fed to the anoxic zone and removed at the end of the aerobic zone.
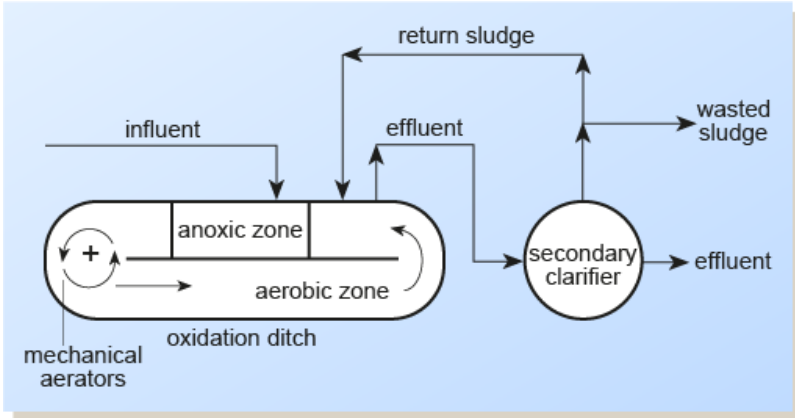
Figure 51 Schematic of an oxidation ditch incorporating denitrification

View description

Non-biological means of removing ammonia

Air stripping

Above pH 7, ammonium ions are converted to free ammonia. In air stripping, the wastewater's pH is increased using lime to about 11 (when 98% of the ammonia content is in the free form, i.e. NH_3 gas). The wastewater is then passed through a packed tower (containing ceramic or other media with a high surface area) in which air is blown countercurrently (Figure 52). The ammonia gas is stripped out of solution by the air. This process requires large volumes of air and can be problematic during cold weather.
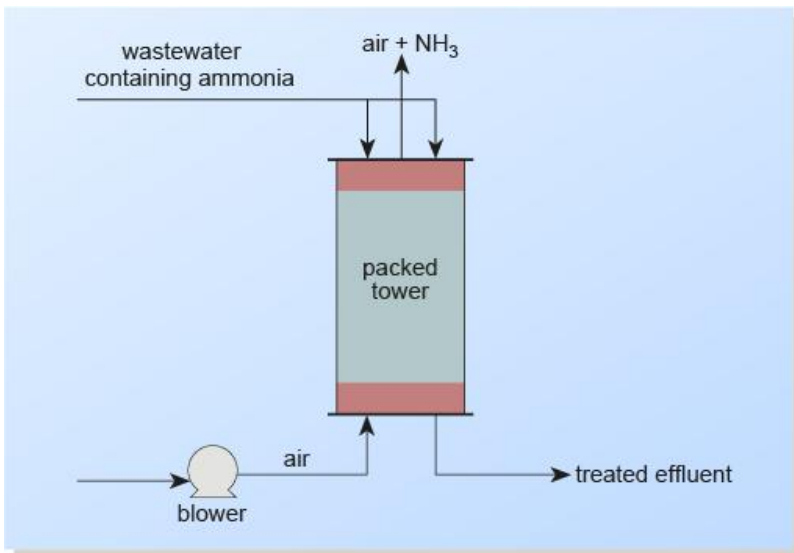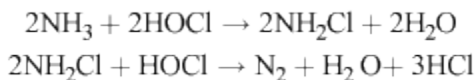
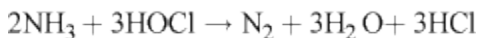**Figure 52** Diagram of a stripping column to remove ammonia from wastewater

View description

Breakpoint chlorination

In this method, chlorine – which is an oxidising agent – is used in excess to oxidise the ammoniacal nitrogen in solution to nitrogen gas, according to the two-stage equation:

$$2NH_3 + 2HOCl \rightarrow 2NH_2Cl + 2H_2O$$
$$2NH_2Cl + HOCl \rightarrow N_2 + H_2O + 3HCl$$

This can be presented as a single overall equation:

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$$2NH_3 + 3HOCl \rightarrow N_2 + 3H_2O + 3HCl$$

The term 'breakpoint' here refers to the point where the chlorine demand has been met – in the case of ammonia being present in water, this is when all the ammonia has been oxidised. After the breakpoint, any chlorine added to the water will remain as chlorine.

The optimum pH operating range for breakpoint chlorination has been found to be 7–8 (AWWA, 2002). Outside this range, the chlorine dosage required to reach the breakpoint increases significantly and the rate of reaction slows.

The chlorine dose required for breakpoint chlorination is about 10 times the concentration of ammonia present. It is thus economically prohibitive except in special situations and where the ammonia concentration has already been significantly reduced. There can also be problems of chlorination by-products being generated, which can be of concern if the receiving watercourse is used for potable water abstraction downstream.

SAQ 36

Which of the following processes results in ammonia in an effluent eventually being expelled as ammonia gas to the atmosphere?

4.9.3 Nutrient removal – phosphorus

Phosphorus may be present in wastewater as:

- orthophosphates
- polyphosphates
- organic phosphorus.

Orthophosphates, often called 'phosphates', include salts containing anions such as PO_4^{3-}, HPO_4^{2-} and $H_2PO_4^{-}$, as well as orthophosphoric acid (H_3PO_4), which are available for biological metabolism without further breakdown.

Polyphosphates comprise two or more phosphorus atoms, oxygen atoms and, in some cases, hydrogen

atoms combined in a complex molecule. Polyphosphates can interact with water and revert to the phosphate form. This hydrolysis is, however, slow.

Organically bound phosphorus is not of major importance in domestic wastewater but can be significant in industrial effluents.

Typically the phosphorus concentration in domestic wastewater is 10–30 mg l^{-1}, with 50–65% coming from human excreta and 30–50% from synthetic detergents (Mara and Horan, 2003). About 10% of the phosphorus in domestic wastewater is insoluble and is removed in primary sedimentation (Metcalf & Eddy, 1987). A proportion is incorporated into new bacterial cells during biological oxidation, with the remainder staying in solution. In the biological oxidation stage of treatment, most of the organic phosphorus and the polyphosphates are converted to orthophosphates.

Biological phosphorus removal in activated sludge systems can be enhanced by applying a sequence of anaerobic and aerobic conditions (Figure 53) that induce polyphosphate storage. The typical phosphorus content of microbial cells is 1.0–3.0% (dry basis) (Bitton, 2005), but with a system comprising an anaerobic and an aerobic zone, species that survive are capable of taking up phosphorus at levels above the normal requirement for growth (6–7%) (Gerardi, 2006). Note that biological phosphate removal is largely independent of temperature over the range 5–20 °C.
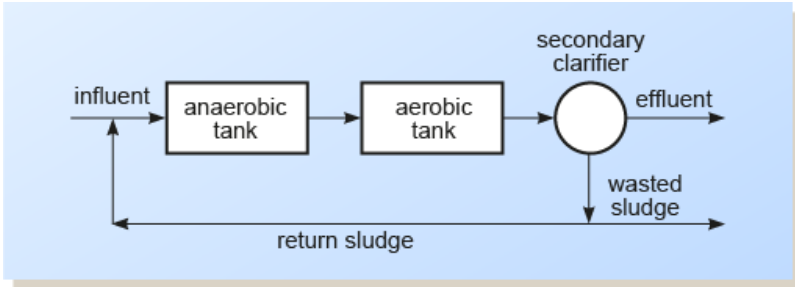
Figure 53 Schematic of a plant incorporating biological phosphate removal

View description

A P-removing bacterium named *Microlunatus phosphovorus*, which was isolated in Japan, was found to accumulate P to a maximum of 23% dry weight (Mara and Horan, 2003).

Acinetobacter spp. is especially effective in the uptake of phosphorus. In the anaerobic zone, the *Acinetobacter* are stressed and use stored polyphosphate as an energy source. They also absorb volatile fatty acids (produced during anaerobic degradation) and store them as food in the form of polyhydroxybutyrate, a short-chain fatty acid (Figure 54). Phosphorus is released from the cells into solution.
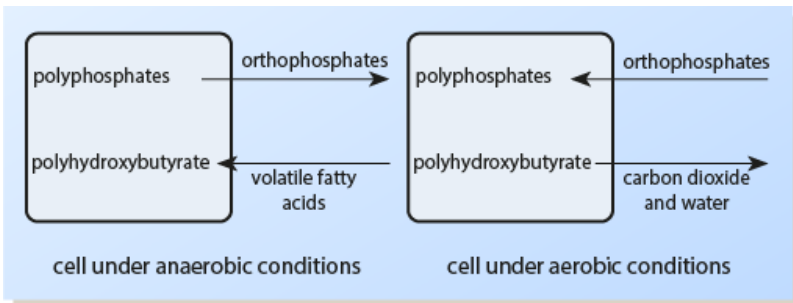
Figure 54 The principles of biological phosphate removal

When the bacteria are put into an aerobic environment, they oxidise the absorbed polyhydroxybutyrate and take up further phosphate to be stored as polyphosphate granules. This storage is termed luxury phosphorus uptake, since an excess amount over that required for growth is taken up.

Phosphorus removal occurs when these bacteria settle out as sludge and are withdrawn for disposal. The sludge, with its high phosphorus content, is ideal for agricultural land. Final levels of under 1 mg l^{-1} of P are possible if the BOD:P ratio in the effluent is greater than 20. Chemical coagulation will be necessary to achieve minimal levels of phosphorus if this ratio is not reached.

Anaerobic conditions occur in activated sludge only when all dissolved oxygen has been removed and no nitrate is present. In a conventional activated sludge

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plant, the return activated sludge will normally contain nitrate and, possibly, dissolved oxygen, which have to be removed. If this is not done, denitrification will consume volatile fatty acids, which would otherwise be available for the production of polyhydroxybutyrate. The removal of nitrate and dissolved oxygen is achieved either by passing return activated sludge through an anoxic zone (where there is no free oxygen but nitrate and nitrite may be present) prior to recycling it to the sewage works' inlet, or by using a large internal recycle of mixed liquor to reduce the overall concentration of nitrate (Figure 55). This process is sometimes called the anaerobic–oxic or A/O process.
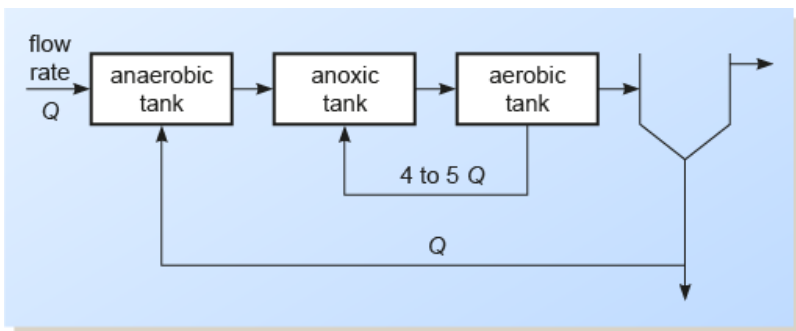

Figure 55 Cycle of mixed liquor (Q is the sewage flow rate)

[View description](#)

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4.9.4 Nutrient removal – combined nitrogen and phosphorus

The Bardenpho® process combines treatment stages for nitrification, denitrification, phosphorus removal and carbonaceous oxidation (Figure 56).
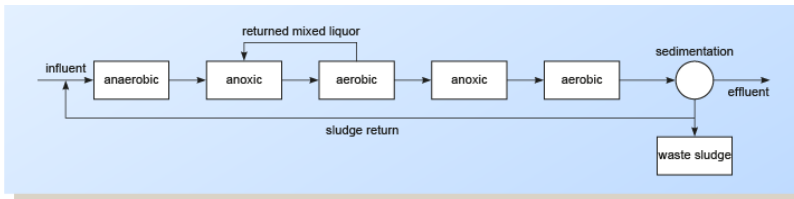
Figure 56 Schematic of the Bardenpho® process

View description

The wastewater enters an anaerobic zone, where the mixed liquor is conditioned for phosphorus uptake. From there, it goes to an anoxic zone where denitrification takes place. Next it enters an aeration tank, where carbonaceous oxidation, nitrification and luxury uptake of phosphorus occur. From here, it goes to an anoxic tank where denitrification takes place. Finally, the effluent goes to a small aerobic tank so that anaerobic conditions do not develop in the final sedimentation tank (this would result in the loss of absorbed phosphorus by the bacterial cells).

4.9.5 Non-biological methods of removing nitrogen and phosphorus

While biological methods are the most economical, other options are available for removal of N and P. Nitrates remaining in the effluent after secondary treatment can be removed using ion exchange or reverse osmosis. These methods are described below.

Phosphorus in the orthophosphate form is easily precipitated using chemicals such as lime, aluminium sulfate, ferric chloride or ferric sulfate. The residual organic phosphorus and polyphosphates are removed by adsorption onto the precipitate. This is the most effective means of phosphorus removal.

The reactions of orthophosphate with lime, aluminium sulfate and ferric chloride are:

Lime: $5Ca^{2+} + 3PO_4^{3-} + OH^- \rightleftharpoons Ca_5(PO_4)_3OH$ (hydroxyapatite)

Aluminium sulfate: $Al_2(SO_4)_3 + 2PO_4^{3-} + 14H_2O \rightleftharpoons 2AlPO_4 + 3SO_4^{2-} + 14H_2O$

Iron (III) chloride: $FeCl_3 + PO_4^{3-} \rightleftharpoons FePO_4 + 3Cl^-$
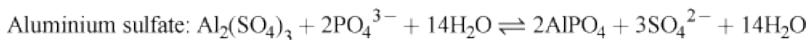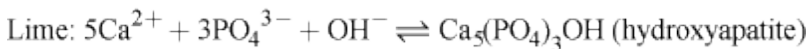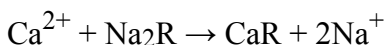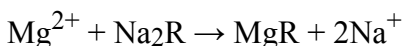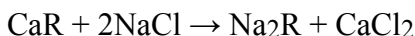
Ion exchange

In this process, the water is passed through a bed of ion exchange resin that removes the undesired ions and

replaces them with ions that do not affect the water quality. This technology for nitrate removal was developed from water-softening systems, which were used to remove the hardness-conferring ions Ca^{2+} and Mg^{2+}.

At first, ion exchange was carried out using zeolites, which are naturally occurring insoluble sodium aluminosilicates. Zeolites were able to exchange sodium ions for ions such as Ca^{2+} and Mg^{2+}. Artificial zeolites such as Permutit are now produced. If the cation exchange sodium resin is represented by Na_2R, where R is the complex resin base, then the reaction for water softening is:

$$Mg^{2+} + Na_2R \rightarrow MgR + 2Na^+$$

$$Ca^{2+} + Na_2R \rightarrow CaR + 2Na^+$$

The treated water then becomes richer in sodium, which is less of a problem unless the water was particularly hard to begin with. When all the sodium ions in the exchange resin have been replaced, the resin can be regenerated by passing a strong solution of sodium chloride through it:

$$MgR + 2NaCl \rightarrow Na_2R + MgCl_2$$

$$CaR + 2NaCl \rightarrow Na_2R + CaCl_2$$
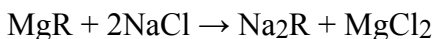
For removal of nitrate ions, the exchange is with R*Cl, where R* is another complex resin base:

$$NO_3^- + R*Cl \rightarrow R*NO_3 + Cl^-$$
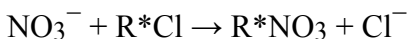
The ion exchange vessels are taken out of service sequentially for regeneration using a brine solution that displaces the captured nitrate ions. The nitrate-rich brine product then has to be disposed of.

Reverse osmosis

This is another method employed to treat waters containing nitrates.

When a solution of a salt is separated from pure water by a semi-permeable membrane that permits the passage of pure water but prevents that of the salt, water will tend to diffuse through the membrane into the salt solution, continuously diluting it. This phenomenon is called osmosis. If the salt solution is in an enclosed vessel, a pressure will be developed. This pressure in a particular solution is known as the osmotic pressure of that solution.

Reverse osmosis is a process in which water is separated from dissolved salts in a solution by filtering through a semi-permeable membrane at a pressure greater than the osmotic pressure caused by the dissolved salts in the water. The pressure required increases in direct proportion to the concentration of salts. The salts could be in any form including nitrates. Using reverse osmosis, nitrates can be reduced by 87–95% (Minnesota Department of Agriculture, n.d.).

The basic components of a reverse osmosis unit are the membrane, a membrane support structure, a containing vessel and a high-pressure pump. Cellulose acetate and nylon are the most commonly used membrane materials. The water to be treated is pumped at high pressure through the membrane module, and clean water is collected as permeate (Figure 57), with the unwanted material remaining in the retained liquid (retentate).
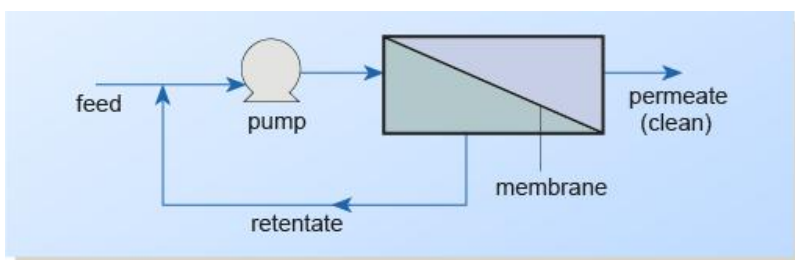
Figure 57 A typical membrane filtration process

View description

The concentration of retained material in the feed builds up with time, and the membrane can get clogged. To prevent this, periodic backwashing with either water or gas under pressure is undertaken.

Continuous filtration with the feed flowing over the membrane surface is preferred over a batch process, as the flow promotes self-cleaning and enables longer runs between backwashing or replacement.

The feed water must be filtered to prevent clogging of the membrane. To reduce scaling, iron and manganese removal may also be necessary. The pH of the feed should be adjusted to within the range 4.5–7.5 to inhibit scale formation. Figure 58 shows a schematic of a reverse osmosis system.
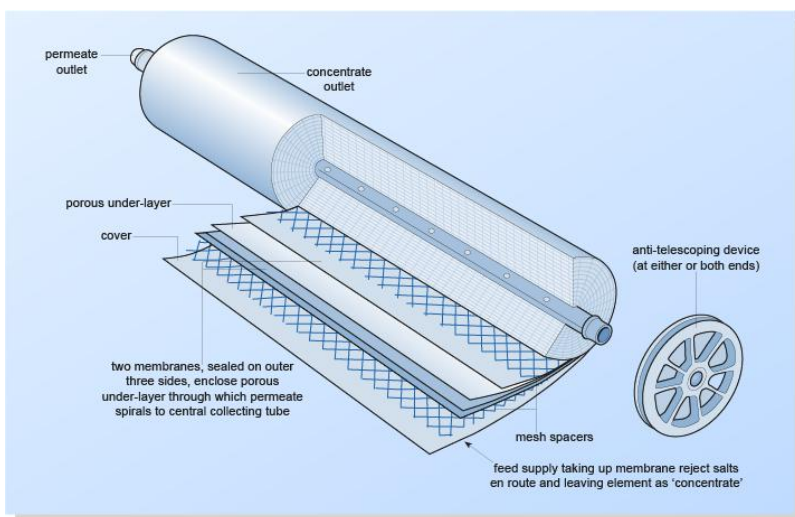
Figure 58 Schematic of a spiral-wound reverse osmosis module

View description

Reverse osmosis is part of a suite of membrane filtration processes that encompass microfiltration, ultrafiltration and nanofiltration.

4.10 Advanced wastewater treatment

Even after tertiary treatment, an effluent could contain impurities (such as trace organics and pathogens) that might cause problems in the receiving watercourse or interfere with its future use. The methods used to remove these impurities are usually classified as advanced wastewater treatment (AWT).

Typical AWT processes are:

- adsorption using activated carbon
- use of ozone
- reverse osmosis, nanofiltration and microfiltration
- disinfection.

Adsorption using activated carbon

Adsorption on activated carbon may be used for the removal of residual non-biodegradable organic substances such as pesticides, or for the removal of compounds causing colour, taste and odour.

Activated carbon is carbon that has been heated in the absence of oxygen. This results in the formation of many pores within each carbon particle. Charcoal is a form of activated carbon but with fewer pores.

Granular activated carbon (GAC) can be obtained from roasting vegetable or animal matter at 800–900 °C in a vacuum furnace. It can have a surface area of up to 1000 $m^2\,g^{-1}$. GAC is therefore an effective adsorbent of organic compounds. Its effectiveness can be measured by the reduction in the COD and the total organic carbon of the water. GAC can be used for the removal of soluble phenols that would produce strongly smelling and tasting chlorophenols upon reaction with chlorine in the disinfection stage of water treatment (discussed below). In the event that trihalomethanes are formed after disinfection by chlorine, GAC can be used to eliminate these toxic compounds. Once exhausted, GAC can be regenerated by heat treatment.

Use of ozone

Organics can be oxidised to harmless products such as CO_2 by using ozone. Ozone and activated carbon are

capable of removing trace quantities of organics present in water.

Reverse osmosis, nanofiltration and microfiltration

Reverse osmosis can be used to remove all the suspended solids and pathogens present in tertiary-treated water. The process also removes any high molecular weight solutes present.

Nanofiltration has been used for pesticide removal. Nanofiltration membranes are similar to those used in reverse osmosis, with particles in the size range 0.5–5 nm being removed.

Microfiltration membranes (capable of removing particles between 0.05 and 5 µm in size) have been used for the removal of bacteria and viruses.

Disinfection

In many countries (e.g. in southern Europe and the Middle East), the reuse of treated sewage for irrigation of trees and bushes, fodder crops, and crops that have to be cooked before eating is encouraged. Disinfection of the treated effluent is carried out to render it free of pathogens. Where treated sewage is discharged into the sea, disinfection is often carried out to prevent pathogens reaching bathing areas.

Typically, tertiary-treated effluent of 10/10 standard is treated with chlorine. The chlorine will initially be consumed by any ammonia present, and then a free residual will develop. Alternatively, UV light can be used for disinfecting effluent in order to protect the environment from potentially harmful compounds generated as by-products of chemical disinfection.

4.11 Decentralised wastewater treatment systems

Centralised wastewater treatment in one large facility, as is seen in most cities of the world, is often criticised as being costly (in terms of both the plant and the pipework needed to convey the wastewater to a central location) and the cause of major pollution incidents. The opposite of this would be a number of smaller treatment plants catering to smaller catchments. These decentralised wastewater treatment systems (DWATS) could be advantageous in terms of:

- economics, for areas with low population density and/or certain topographic conditions
- better public participation and acceptance (less visual and odour impact resulting from smaller plants)
- better adaptation to local contexts and needs
- facilitating the piloting of innovative technologies (as smaller plants are easier to modify)
- better utilisation of products from the treatment process (as treated effluent is produced at many

points it can be more easily reused, and at minimal cost for redistribution infrastructure).

For all the above reasons, we may see more decentralised wastewater treatment systems in the future.

4.12 Sustainable urban drainage systems

Section 2.2.5 described the pollutants likely to be present in surface water run-off. In towns and cities, the amount of permeable ground is limited and so not all the surface water run-off is able to percolate into the ground. Added to this, climate change means that many areas are experiencing heavy and prolonged rainfall, leading to flooding. Whilst infiltratable (permeable) concrete block paving and porous asphalt (which drains rainwater and allows it to percolate into the ground) are available, they are not always used. Hence, surface water run-off is led to sewers, resulting in sewer flooding. One way to overcome the problem is to manage run-off above ground.

So-called 'sustainable urban drainage systems' (SuDS) are a more sustainable, more natural means of improving urban drainage and reducing the volume of urban run-off without the use of mechanical treatment. Several possibilities are available. The surface run-off can be stored or reused at source, its rate of flow to a watercourse decreased, or its quality improved by

natural means. These methods are briefly described below (British Geological Survey, 2013).

- *Source control methods*: these decrease the volume of water entering the drainage/river network by intercepting run-off water from roofs for subsequent reuse (e.g. for irrigation) or for storage and subsequent evapotranspiration (e.g. using *green roofs*).
- *Pre-treatment steps*, such as *swales*: unlike a conventional ditch, a swale is shallow and relatively wide. It provides temporary storage for storm water, reduces peak flows and allows infiltration of the water into the ground. Swales are located close to the source of run-off and can form a network within a development, linking storage ponds and wetlands or filter trenches. They remove pollutants from surface water prior to discharge to watercourses or aquifers.
- *Retention systems*: these delay the discharge of surface water to watercourses by providing storage within ponds, retention basins and wetlands, for example.
- *Infiltration systems*, such as permeable paving, infiltration trenches and soakaways: these mimic natural recharge, allowing water to soak into the ground.

Appropriately designed, constructed and maintained SuDS can achieve the following (CIRIA, 2007; Graham et al., 2012):

- reduce run-off rates, thus reducing the risk of downstream river flooding

- encourage natural groundwater recharge and thus minimise the impact on aquifers (groundwaters help to maintain river and stream flows during periods of dry weather; a reduction in such flows can lead to concentration of nitrates and phosphates, causing an increase in algal blooms, harming wildlife and reducing amenity value)
- enhance evapotranspiration and reduce the *heat island effect*
- reduce the pollutant (e.g. sediment, oil, fuel and toxic metal) concentration in stormwater, thus protecting the quality of the receiving water body, both for the wildlife in it and for downstream uses (e.g. for drinking water supply)
- contribute to the enhanced amenity and aesthetic value of developed areas
- through wetlands, provide habitats for wildlife in urban areas and opportunities for biodiversity enhancement.

Cost–benefit analysis indicates that well-designed and maintained SuDS are more cost-effective than traditional drainage solutions, as they cost less to construct and maintain (Duffy et al., 2008).

SuDS fit in well with *green infrastructure*. This includes 'blue spaces' or '*blue corridors*', which may comprise ponds and watercourses that are used to convey flows in excess of the design capacity of the drainage system safely away from properties to cause less harm. SuDS offer amenity benefits to urban residents, providing high-quality public blue and green spaces in which to relax, play and enjoy wildlife; hence they are favourably

received by residents. Wetland and green infrastructure creation through SuDS allows species migration and reduces habitat fragmentation. Finally, green areas can utilise and contribute to *ecosystem services*, whereby the value of these services can support urban quality of life and, in turn, the green areas can help support biodiversity.

SuDS can involve local communities through their design and management, offering opportunities for learning, recreation and community programmes. This has social and health benefits, giving people a sense of pride, responsibility and ownership of their environment.

SuDS measures are often in a sequence, termed a 'management train', which incrementally improves water quality at each stage. Thus, for example, rainwater can be trapped or filtered by green roofs, before flowing through permeable paving and into the ground where it would be further treated by natural means. There is a hierarchy of treatment stages within the management train, and an order in which they should be used. This is shown in Table 15.

Table 15 The hierarchy of treatment stages within the SuDS management train (Graham et al., 2012)

Prevention:	Site housekeeping measures including removal of soil and other detritus from hard surfaces to reduce impact on water quality downstream. Uses design to prevent polluted run-off from entering system. Scale: individual buildings.

Source control:	Controlling rainfall at or very close to source by using permeable paving, green roofs, rain gardens and filter strips (for example). Incorporates rain-harvesting features such as water butts. Scale: individual buildings.
Site control:	Controlling run-off received from source control features in detention and retention basins, swales or other surface features. Scale: small residential or commercial developments.
Regional control:	Controlling and storing the cleanest run-off received from the site. Scale: large housing developments, or multiple sites that can be targeted for larger 'community-scale' SuDS features such as a wetland or group of wetlands. This is the final treatment stage and where there is any discharge via a controlled outflow to a stream or river, there should not be any negative impacts on water quality. Ideally, the discharge should improve stream water quality.
Conveyance features:	Move water between the different treatment stages. This should be done using above-ground features such as swales and channels to maximise wildlife and people benefits.

In England, legislation in the form of the Flood and Water Management Act 2010 has made the installation of SuDS compulsory for all new developments, as they are presumed to more effectively manage floods.

In the UK, the Construction Industry Research and Information Association (CIRIA) provides comprehensive guidance on all aspects of SuDS, green infrastructure and drainage systems.

4.13 Further SAQs

SAQ 38

a. When is tertiary treatment likely to be required for the final effluent from a sewage works?
b. If the effluent from a sewage works has to be improved in terms of BOD and SS, but there is little space for construction at the works, recommend suitable tertiary treatment processes.

View answer

SAQ 39

Which of the following statements about sewage effluent would be applicable after its treatment?

a. It will contain at most $30\ \text{g m}^{-3}$ of suspended solids and have a BOD of $20\ \text{g m}^{-3}$.

b. It will conform to standards depending on the needs of the watercourse receiving it.

c. It will not be a risk to public health.

d. It will be potable.

e. It will not contain any polluting substances.

View answer

SAQ 40

Look at Figure 59 and identify which label should go in each of the boxes labelled a–f.
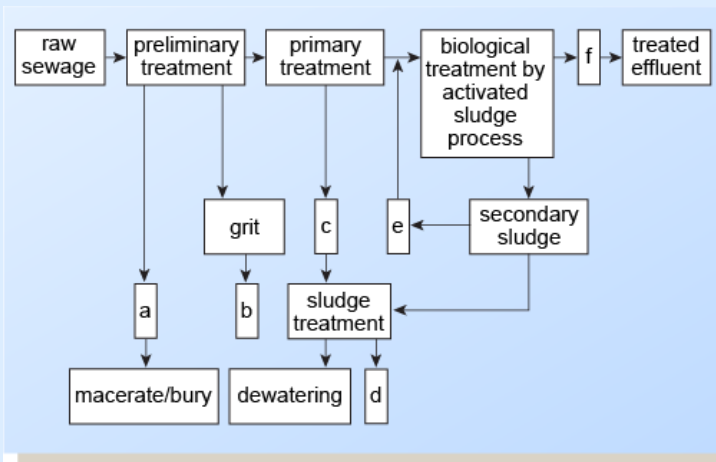
Figure 59 The sewage treatment process

View description

a.

b.

c.

d.

e.

269

f.

tertiary treatment if required, e.g. further settlement or use of grass plots, etc.

screenings

return activated sludge

primary sludge

grit disposal – possible use in road gritting if grit is well washed

anaerobic digestion

4.14 Summary

The aims of sewage treatment are to reduce the content of biodegradable and non-biodegradable material in the sewage, and to eliminate any toxic materials and pathogenic organisms present in the effluent.

Sewage treatment by the traditional mechanical/ biological method can include some or all of the following processes:

- screening
- grit removal
- comminution
- primary sedimentation
- biological oxidation
- secondary sedimentation.

In biological oxidation, bacteria convert the soluble and colloidal organic matter into new cell material. This cell material is removed as sludge in the secondary sedimentation tank. The effluent after biological treatment and sedimentation should be of 30/20 quality or better, i.e. with suspended solids content not exceeding 30 g m^{-3} and BOD not exceeding 20 g m^{-3}. This is on the assumption that the receiving waters dilute the treated effluent eight-fold.

Industrial effluents generally have a wider range of wastewater characteristics than domestic sewage and may contain toxic components. With appropriate pre-treatment, industrial effluents can often be treated together with domestic sewage, resulting in cost savings and more effective control of pollution. In situations where the volume and/or the pollution load of the industrial effluent is high, it has to be treated on its own.

Activated sludge units and biological filters are the main types of bioreactor in wastewater treatment. Many variants of the two exist, each with advantages for a

particular wastewater or situation. The greatest potential for cost-effective treatment and safe reuse of sewage might be in waterless sanitary disposal systems, but first these have to gain public acceptance. Such systems are unlikely, however, to be feasible in urban areas.

Tertiary treatment may be carried out when a particularly high-quality effluent is required. The suspended solids (and associated BOD) concentration is reduced using processes such as:

- microstraining
- sand filtration
- the DynaSand$^{®}$ system
- settlement
- grass plots.

Elimination of ammonia, nitrates and phosphates can be achieved with biological systems, but a variety of non-biological means is also available for elimination of these substances. These include:

- *for ammonia*: air stripping/breakpoint chlorination
- *for nitrates*: ion exchange/reverse osmosis
- *for phosphorus*: precipitation using lime, aluminium sulfate, ferric sulfate or ferric chloride.

Further purification of the treated effluent is possible using advanced water treatment techniques such as:

- activated carbon adsorption
- reverse osmosis and nanofiltration
- use of ozone
- disinfection.

After the appropriate processes are carried out, the treated water can be used in many ways.

Decentralised wastewater treatment systems offer certain advantages and may become more popular in the future.

Sustainable urban drainage systems offer an effective, natural way of managing and treating surface water run-off.

Section 5: Sludge treatment and disposal

5.1 Introduction

Sludge is the product that arises as a result of removing solids from, and reducing the BOD of, sewage and trade wastes. There is potential for reuse of the sludge, either in agriculture or as a source of energy. In some instances, however, it may just have to be disposed of. Sludge treatment and disposal may represent up to 50% of the total cost of sewage treatment.

This section discusses:

- how sludge is produced
- the characteristics of sludge
- the treatment of sludge
- sludge disposal.

5.2 Sludge production and sludge characteristics

Sewage sludge is a direct result of the presence of solids in suspension and an indirect result of the biological treatment of dissolved and emulsified organic matter. The volume of sludge generated in sewage treatment is 1–2% of the volume of sewage treated.

The sludge separated during treatment processes is an evil-smelling, highly putrescible, thick liquid containing a considerable quantity of water. Table 16 gives an indication of the amount of sludge that is produced in sewage treatment. Note that the high water content (low percentage of solid matter) in activated sludge is a result of the complicated nature of activated sludge and the interaction between its particles.

Table 16 The average amount of sludge produced per person in Western Europe, for selected treatment processes

Source of sludge	Volume of sludge produced per capita per day (litres)	Moisture content of sludge (%)	Quantity of total solids per capita per day (g)
Primary treatment	1.80	97.5	45
Biological filter unit	0.63	96.0	25
Activated sludge unit	5.00	99.3	35

(UNEP, 2000)

The sludge produced in sewage treatment will have a wide range of constituents.

You saw in Section 4.1 that the organic component of sewage consists of proteins, carbohydrates and fats produced by the human population as a result of its eating habits. These are present in the sludge. If a combined sewer system (see Section 4.2) is in place, solids will also be collected from hard surface areas, which slightly affects the amount of sludge generated. In

temperate zones, a particular contribution comes from grit spread on roads during frosty weather. Although grit removal is incorporated early in the system, not all the grit is removed and some inevitably passes on to appear in the sludge. Sludge contains 20–30% mineral matter (on a dry basis), most of which is grit.

The composition of sludge is also affected by the trade effluents discharged into the treatment works. There may be inorganic material from metal industry wastes, or organic matter from food processing plants and distilleries. The amounts and characteristics of solid matter in trade effluents vary, despite the limits placed on the suspended solids, BOD, metals, etc. when a consent is given to discharge wastes to a sewer. Sludge can also contain toxic material removed during treatment; it is this toxic material that restricts the use of sludge as a fertiliser or soil conditioner. Heavy metals in particular can end up in the sludge, through either precipitation or adsorption onto the microbial flocs. Thus before disposal, the sludge will require treatment.

5.3 Methods of treatment

Table 16 shows that over 95% of sewage sludge is water. The sludge should be dewatered to reduce the volume and mass of material before disposal. Dewatering also helps to prevent the sludge from decomposing and creating unpleasant odours.

To improve the efficiency of dewatering, it is often necessary to include a preliminary conditioning stage to release as much of the bound water as possible and to allow the solids to agglomerate. There are several such conditioning processes that can be used. The method chosen will depend on the characteristics of the sludge.

Anaerobic digestion may also be used as an intermediate step between preliminary conditioning and dewatering. Each of these methods will be looked at in turn.

5.3.1 Preliminary conditioning

The sludge can be thickened by coagulation, flocculation and sedimentation. Chemicals such as aluminium sulfate, iron salts, lime and polyelectrolytes can be used as coagulants. The coagulants used are costly, but the increase in solids content of the thickened sludge can make up for the extra cost involved.

Heat treatment can also be used to condition sludge. The sludge is heated to 175–230 °C under high pressure (10–20 atmospheres). Under these conditions, bound water in the sludge is released.

Thickening takes place in a tank equipped with a slow-moving paddle or a set of tines (prongs). Sludge settles and *supernatant* is drawn off.

After preliminary conditioning, the sludge can be further treated to increase the solids content by dewatering.

5.3.2 Anaerobic digestion

Many wastewater treatment plants use anaerobic digestion (Figure 60) before dewatering and disposal. Thickened sludge is heated to 35 °C and completely mixed in an airtight tank, where it is partially broken down by anaerobic bacteria to release methane and carbon dioxide. The sludge is heated by pumping it through a coil contained in a hot water tank, or hot water can be pumped through coils inside the digester. The retention time is 15 days or less.
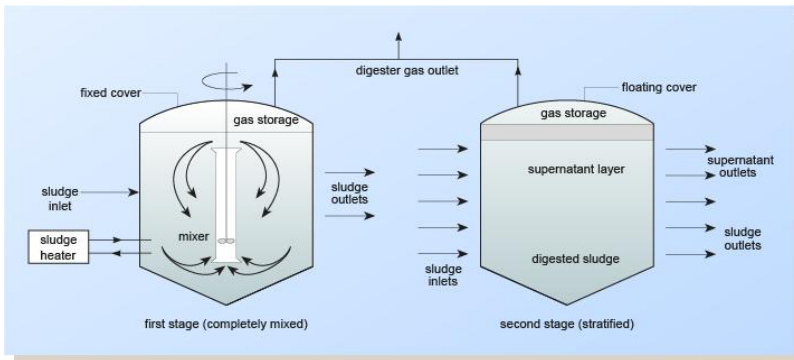

Figure 60 Schematic of the anaerobic digestion process

View description

The output from the digester goes to a second, unheated tank where separation of the digested solids from the liquor takes place.

In the digester, the complex organic material is first broken down by enzymes into simpler molecules. The digestion process occurs in two steps:

Step 1	Intermediate products	Step 2	Final products
raw sludge →(acid-forming bacteria)→	volatile fatty acids carbon dioxide biomass hydrogen ammonium salts sulfides	→(methane-forming bacteria)→	methane carbon dioxide small amounts of hydrogen, nitrogen and other gases
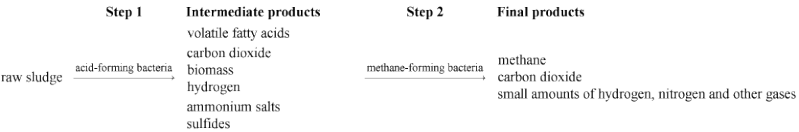
In the first step, acid-forming bacteria (e.g. *Clostridium* spp., *Peptococcus* spp., *Desulfovibrio* spp., etc.) convert the organic material in the sludge to volatile fatty acids (e.g. acetic, propionic and butyric acids) and other compounds.

In the second step, methane-forming bacteria (e.g. *Methanobacterium* and *Methanobacillus* spp.) transform volatile fatty acids to methane and carbon dioxide. Many of the methane-forming organisms identified in anaerobic digesters are similar to those found in the stomachs of ruminant animals and in organic sediments taken from lakes and rivers.

The gas emerging from the digester contains about 60% methane and 40% carbon dioxide (Anaerobic Digestion, n.d.), with small amounts of hydrogen, nitrogen and other gases. It can be used as an energy source. In small plants, the gas is usually used to heat the digester contents in order to maintain the temperature at 35 °C.

Any surplus can be used to heat the offices and laboratories at the treatment plant. Where there are several digesters producing an appreciable quantity of gas, electricity can also be generated, with any surplus being sold to the utility companies.

The pH in the digester should be controlled at about 7.0, since the rate of methane production slows down below this value. Adequate alkalinity ($1000–5000$ g m^{-3} as $CaCO_3$) is required to buffer the sludge. Toxic material input should be controlled, e.g. heavy metal concentration should not exceed 1 g m^{-3}.

Sludge can be introduced continuously or intermittently. Compared with the input, the stabilised sludge (the biosolids):

- has a total solids content 35–40% lower in volume
- is not malodorous
- is smoother and darker
- contains fewer pathogens.

Organic nitrogen compounds are broken down to ammonia and ammonium salts in anaerobic digestion. This increases the immediate availability of nitrogen to crops if the wet sludge is used as a manure and soil conditioner on agricultural land.

The supernatant from digesters is highly polluting with a high BOD, COD and ammonia concentration, together with a strong colour, and can be a problem. Normally it is returned to the works inlet for treatment. This is

usually done at night when the incoming sewage flow is low and the plant is underloaded.

SAQ 41

List the conditions favouring anaerobic decomposition of sludge.

View answer

5.3.3 Dewatering

The traditional method of dewatering sludge is by air-drying on open beds. These drying beds (Figure 61) consist of large areas (0.5 m^2 per person served by the sewage treatment works) usually covered with sand or ash, and enclosed by low walls. The beds are filled with wet sludge to a depth of approximately 0.2 m and left until the sludge (cake) is dry enough (20–50% solids content) to be removed by hand or by mechanical methods.

Figure 61 Sludge drying beds

View description

This method of treatment is entirely dependent upon the weather. For example, in temperate climates, the sludge might be fit for removal after two weeks during the summer, but in the winter it could be months before the sludge can be removed.

Drying beds often give rise to offensive smells. The main argument advanced for their continued use is that

they require only a small labour force using automatic means (or a shovel) for lifting and conveying the sludge cake.

Other methods of dewatering use mechanical systems and include pressure filtration, vacuum filtration and centrifuging.

- In pressure filtration, the sludge is pressed at high pressure between filter cloths.
- In vacuum filtration a slowly revolving drum, partly immersed in the sludge, carries a filter cloth through which water is sucked from the sludge under vacuum.
- In centrifuging, chemically or biologically conditioned sludge falls onto the centre of a rapidly rotating bowl. The solids are thrown to the outer edge of the bowl, from where they are removed by a scraper.

The extracted water, high in BOD and suspended solids, is directed to the inlet of the treatment works.

5.3.4 Composting

As an alternative or additional process, composting may be used. Composting is the process of breaking down organic waste such as grass cuttings, leaves, food waste and paper through the use of microorganisms in an aerobic environment.

Sewage sludge can be composted by mixing sludge cake (produced by pressing or centrifuging liquid

sludge, either untreated or – after digestion – treated with lime or other conditioning agents) with organic bulking agents such as straw, bark or green waste (Moffat, 2006).

Dried sewage sludge has been co-composted with both market waste and household waste (Cofie et al., 2009), but market waste was preferred as it had a higher biodegradable fraction and contained fewer 'foreign materials'.

5.4 Methods of reuse or disposal

Sludge can be:

- spread on land (land application)
- incinerated
- composted and sold
- dumped in sludge lagoons
- buried
- dumped in landfill sites.

Land application

Traditionally, sludge is spread on agricultural land. The value of sludge as a fertiliser is not high, since it contains about 3.3% total nitrogen, 2.3% phosphorus and 0.3% potassium (EPA, 1995a). This is insignificant compared with the nutrients applied each year in the form of artificial fertilisers, which have a N content of

21–46%, a P content of 23–37% and a K content of 41–50% (Natural England, 1999). However, the organic matter in sludge forms a humus that can be a useful soil conditioner.

This disposal method requires large areas of land and suitable weather conditions. In addition, most sludge is produced in large urban areas and it can be extremely expensive to transport it to farming areas. A further practical difficulty is that farmers only require sludge at certain times of the year, whereas it is produced all year round. The amount of agricultural land able to take sludge is also limited. Finally, legislation exists in some countries regarding the use of sludge in growing crops (e.g. EU, 2010).

The disposal of sewage sludge would be greatly facilitated if the concentration of heavy metals in it could be reduced. This can be achieved by strict trade effluent control. Limits on heavy metals (and other toxic components) can be imposed by the company or authority receiving the wastewater for treatment (this will be covered later, in Section 7).

Incineration

Incineration of sludge destroys toxic organic compounds but leaves non-volatile toxic metals, which remain in the ash. The main advantage of incineration is the generation of heat, which can be used to produce electricity or utilised for district heating. Another advantage is the large reduction in the volume of waste

to be disposed of, along with the elimination of the nuisance from biological decomposition. However, incineration still leaves the ash (some 25–40% of the incoming load on a dry basis) to be disposed of, and this can be highly polluting. The gaseous effluent from the incinerator will also have to be treated to meet the required standards for emission.

Incineration is the second-largest disposal route for sewage sludge in England and Wales (Environment Agency, 2009), taking some 19% of the sewage sludge produced (Parliamentary Office of Science and Technology, 2007). In the UK, due to population growth, the quantity of sewage sludge produced is increasing whilst the area of available farmland is decreasing. This may lead to an increase in sludge incineration.

Other methods

Other current methods of sludge disposal include:

- composting (mentioned earlier since it is both a treatment method and a reuse method)
- dumping in large sludge lagoons or sludge beds (used in rural and semi-rural areas – Crosher, 2008)
- dumping in trenches, which are then filled in with soil (EPA, 1995b)
- dumping of dewatered and dried sludge in landfill sites (Government of South Africa, n.d.).

Using lagoons or sludge beds can cause objectionable smells because the sludge dries slowly. If sludge is sent

to landfill, its quality with regard to smell, groundwater pollution, and space and transport requirements is of crucial importance. If the quality is acceptable, landfill disposal is unlikely to add significantly to the problems already arising from the presence of refuse.

It is worth noting that all the methods considered above depend on the availability of land.

5.5 Further SAQs

SAQ 42

Which treatment processes in a sewage treatment works give rise to sludge?

View answer

SAQ 43

A town with a population of 50 000 has a sewage works with primary sedimentation and activated sludge units.

Calculate the total *mass* of sludge produced due to the two processes, given that the density of primary sludge can be 1.03 kg l^{-1} and that of sludge from

the activated sludge unit can be 1.0 kg l^{-1} (Turovskiy and Mathai, 2006).

View answer

SAQ 44

What are some of the benefits of treating sludge by anaerobic digestion?

View answer

5.6 Summary

In a sewage treatment works, apart from screenings and grit, the main products are the various forms of sludge. Treatment and disposal routes depend on the volume and characteristics of the sludges produced.

Sludge treatment and disposal represents up to 50% of the total cost of sewage treatment.

The supernatant from sludge dewatering represents a significant load of recycled suspended solids and BOD to the treatment works. The effects of the final disposal methods and return flows from sludge treatment can have major implications.

Methods of sludge treatment include:

- conditioning with chemicals or heat
- anaerobic digestion
- air-drying
- dewatering using mechanical systems (such as pressure filtration, vacuum filtration or centrifuging)
- composting.

Methods of reuse or disposal include:

- application to agricultural land
- incineration
- composting and subsequent sale

- dumping:
    - in sludge lagoons
    - by burial in trenches
    - in landfill sites.

Section 6: Water quality tests

6.1 Introduction

Water quality tests are used in monitoring discharges (to ensure that they are safe for release into the environment) and in operation of wastewater treatment plants (to verify that the optimum conditions for treatment are being maintained).

Methods of analysis have become increasingly sophisticated, with increasingly low limits of detection. It is now possible to carry out estimations for elements and compounds at extremely low concentrations – micrograms and nanograms per litre. This ability to estimate low concentrations has allowed even stricter standards to be set for pollutants that may be present in water. Of course, care has to be exercised that standards are not set such that the treated effluent is of significantly higher quality than the recipient water body; however, the precautionary principle (i.e. to err on the side of caution) is also important. For that reason, in a case where a component in a discharge has not been proven to be harmful but has the potential to significantly damage the environment of life forms, a more stringent limit may be imposed.

Samples must be collected in appropriate containers (e.g. for bacterial analysis, the container has to be

sterile). For certain parameters, such as metals, a preservative (typically nitric acid) will be put into the sample bottle. Samples will be taken in duplicate, and should be representative of the situation (e.g. taken from streams in flow, etc.).

This section discusses various techniques for assessing water quality by measuring the water's:

- dissolved oxygen content
- physical properties
- chemical content
- microbial content
- toxicity.

It has to be said that the above tests measure components that are specifically identified. It can happen that chemical monitoring shows nothing untoward but biological monitoring (see Section 1.3.8) indicates the presence of a toxic substance. In this case, investigatory methods have to be used (such as considering the types of discharge entering the watercourse in question) to ascertain what the substance might be.

6.2 Oxygen demand

One of the most important measures of overall water quality is the dissolved oxygen content, as mentioned in Section 1.3.2. Dissolved oxygen is essential to maintain most forms of aquatic life and to allow the decomposition of organic matter, including organic

effluents, and thus to ensure the continued existence of rivers, streams and lakes in their natural state and as usable resources. One of the most significant impacts on the oxygen resources of a river comes from the biodegradation of organic matter. Biodegradation uses up dissolved oxygen, and the resulting reduction in dissolved oxygen level in the water is a measure of the oxygen demand of the effluent.

Dissolved oxygen probe

Measurement of the oxygen demand of an effluent requires the determination of dissolved oxygen content. This is commonly measured using a dissolved oxygen probe. Here a potential difference is set up between two metal electrodes immersed in electrolyte (a solution that can carry an electrical current). Figure 62 shows the main elements of such a dissolved oxygen probe.

Figure 62 The main components of a dissolved oxygen probe
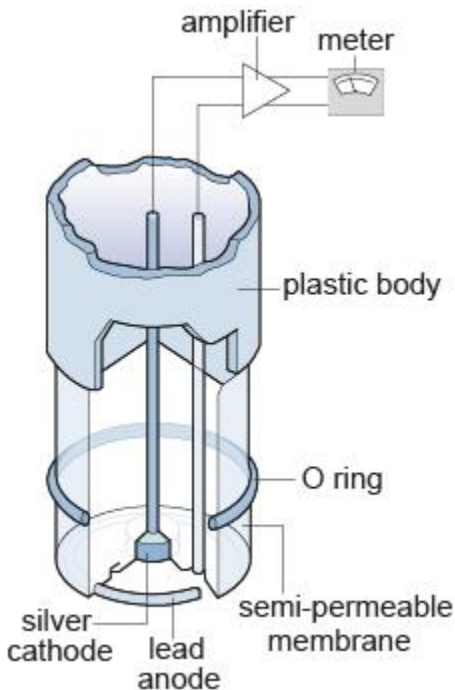
View description

When the probe is brought into contact with a sample solution, dissolved oxygen from the solution diffuses through the semi-permeable membrane. The dissolved oxygen reacts by removing electrons from the electrolyte solution at the cathode. The electrons are replaced by a corresponding reaction at the anode where the anode metal goes into solution.

These two reactions produce a current in the external circuit, the magnitude of which is directly proportional to the rates of reaction at the electrodes; these in turn are proportional to the concentration of dissolved oxygen present. Since the probe consumes oxygen, the water near the probe becomes oxygen deficient so the water must be gently stirred to get an accurate reading.

Calculating oxygen demand

The oxygen demand of an effluent sample can be simply measured as the difference between the initial dissolved oxygen content in the sample and the dissolved oxygen left after the degradable matter in the effluent has been oxidised.

If C_0 is the concentration of dissolved oxygen in the sample initially and C_u is the final or 'ultimate' dissolved oxygen concentration after all the oxidisable matter in the sample has reacted, then the ultimate oxygen demand L_u of the effluent sample is given by:

$$L_u = C_0 - C_u \qquad\qquad\qquad (18)$$

We can think of L_u as a measure of the concentration of oxidisable matter present in the sample. By the end of the reaction, all the oxidisable matter has reacted, which causes a reduction in the dissolved oxygen in the sample. However, things are not quite as simple as this equation suggests.

From Table 1 (Section 1.3.2), the saturation concentration of dissolved oxygen (C_s) at 20 °C is 8.99 g m^{-3}. If demand for oxygen exceeds 8.99 g m^{-3}, a C_u value of zero will be recorded. The measured L_u value will then not truly represent the amount of biodegradable matter in the sample, because more dissolved oxygen could have been taken up had there been a sufficient supply. In many oxygen demand tests, therefore, samples are diluted so that there is at least 2 g m^{-3} dissolved oxygen left in the diluted sample at the end of the reaction. Naturally, with an unknown sample many different dilutions must be tried in the hope that at least one will satisfy this criterion. This standard procedure is known as the 'dilution method'. A 'blank' comprising only dilution water is also incubated to allow for the oxygen demand of the dilution water.

Exercise 11

An effluent has an ultimate oxygen demand of 50 g m^{-3}. A sample is made up for testing by diluting one part effluent by volume with nine parts clean water by volume. What is the ultimate oxygen demand of the diluted sample?

View answer

Exercise 12

If the initial concentration of dissolved oxygen in the diluted sample described in Exercise 11 is measured as 8.2 g m^{-3}, what will be the final dissolved oxygen concentration after oxidation is complete?

View answer

SAQ 45

An effluent is diluted in the ratio one part effluent to 49 parts clean water by volume. In an oxygen demand test, this diluted sample gives the following results:

$$C_0 = 7.6 \text{ g m}^{-3}$$
$$C_u = 1.3 \text{ g m}^{-3}$$

What is the ultimate oxygen demand:

a. of the diluted sample
b. of the original effluent?

View answer

In the UK, the BOD test commonly used to measure the oxygen demand of organic pollutants in water is standardised on a five-day reaction time. The reason for

this will be given in Section 6.2.2. It is important to know the ultimate oxygen demand of a given pollutant because that is a burden upon the watercourse into which it is released. The watercourse will be depleted of the oxygen that is needed to degrade the given pollutant.

6.2.1 Plotting dissolved oxygen concentration

In principle, the measurement of oxygen demand is straightforward. In practice, the major problem is to know how long to leave the sample to ensure that all the required oxygen has been taken up. One way to find out is to plot the change in dissolved oxygen concentration with time. Figure 63 shows how such a plot might look.
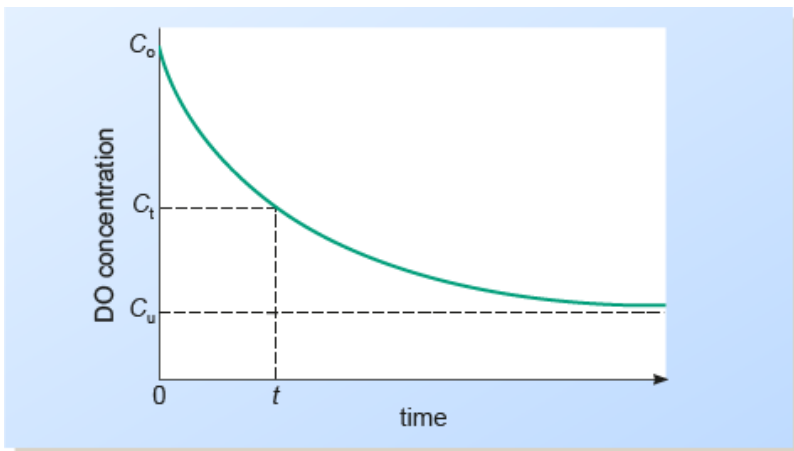

Figure 63 Decay of dissolved oxygen (DO) concentration during oxidation reaction

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At the start of the test, the dissolved oxygen concentration is C_0. As the test proceeds, the oxygen concentration drops rapidly at first but more slowly later. This makes sense if we think about what is happening during the oxidation reaction. At the start there is a lot of oxidisable material present, so the rate of oxygen uptake is high and the oxygen concentration drops rapidly. Later, after most of the material has been oxidised, the reaction rate is lower and the oxygen concentration drops more slowly.

Does the shape of the curve in Figure 63 look familiar? You might recognise that it is very like an exponential decay curve. In fact, it is helpful to describe oxygen demand tests by assuming that the rate of oxygen uptake follows this exponential decay behaviour. At any time t, the dissolved oxygen concentration in the sample, C_t, is given by the following equation:

$$\frac{C_t - C_u}{C_0 - C_u} = e^{-kt} \qquad (19)$$

where k is a constant, called the decay constant.

Equation 19 describes the way in which the dissolved oxygen concentration varies with time during the reaction. At the start $t = 0$, and since $e^0 = 1$, the equation becomes:

$$C_t - C_u = C_0 - C_u$$

in which case

$$C_t = C_0$$

as you would expect.

Exercise 13

How long does it take for C_t to drop to C_u, according to Equation 19?

View answer

SAQ 46

An effluent sample has an initial dissolved oxygen concentration of $8.0 \, g \, m^{-3}$ and an ultimate dissolved oxygen concentration of $2.3 \, g \, m^{-3}$. If the decay constant for the oxidation is $0.2 \, d^{-1}$, what is the dissolved oxygen concentration 14 hours after the start of the test? (The unit d^{-1}, or reciprocal days, should be read as 'per day' – it is usual in oxygen demand tests to measure time in days or fractions of a day.)

View answer

6.2.2 The BOD test

The biochemical oxygen demand (BOD) test measures the oxygen required by microorganisms during the biodegradation of an effluent sample. In its simplest form, it is carried out by incubating a sample of effluent in a sealed bottle for five days at 20 °C.

The UK Royal Commission on Sewage Disposal (set up in 1912) chose an incubation period of five days for the BOD test because that is the longest flow time of any British river to the open sea (Royal Commission on Sewage Disposal, 1912). An incubation temperature of 20 °C was chosen because at that time it was close to the long-term average summer temperature in Britain. The dissolved oxygen concentration of the sample decreases during incubation:

$$\text{BOD}_t = \text{initial dissolved oxygen} - \text{dissolved oxygen after} \quad (20)$$
$$t \text{ days} = C_0 - C_t$$

Thus the BOD for five days at 20 °C (written as BOD_5^{20}) is equal to $C_0 - C_5$. To avoid the analyst having to come into the laboratory at the weekend to take measurements, 5-day BOD tests are usually started on Wednesdays, Thursdays or Fridays.

In Europe the 7-day BOD ($\text{BOD}_7^{20} = C_0 - C_7$) is quite common. This modification frees the analyst to start the test on any day of the week. The 7-day BOD is also

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used for analysis of intractable industrial effluents such as those from pulp and paper mills.

Figure 64 shows the general form of a graph of BOD for a typical effluent sample incubated for different lengths of time. Initially, the BOD rises rapidly as the rate of oxygen uptake by the sample is high. With time, the rate of oxygen uptake becomes lower until eventually the sample has been completely biodegraded, having satisfied its required oxygen demand. This is shown by the approach of the BOD curve in Figure 64 to the horizontal dotted line representing the ultimate oxygen demand (L_u) of the sample.
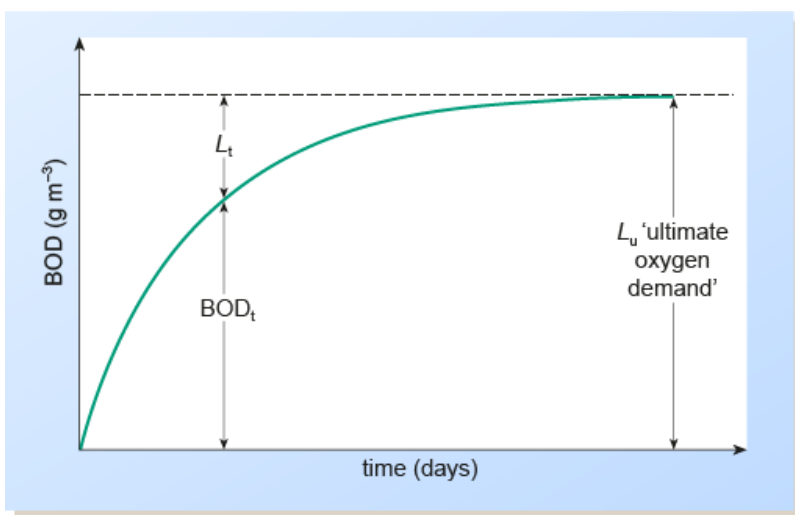
Figure 64 Form of the BOD–time curve

View description

The relationship between the BOD_t at any time t and the ultimate oxygen demand L_u can be expressed as a mathematical model by rearranging Equation 20. Thus:

$$\begin{aligned} BOD_t &= C_0 - C_t \\ &= (C_0 - C_u) - (C_t - C_u) \\ &= (C_0 - C_u)\left[1 - \frac{C_t - C_u}{C_0 - C_u}\right] \end{aligned}$$

But Equation 18 states that:

$$C_0 - C_u = L_u$$

and Equation 19 states that:

$$\frac{C_t - C_u}{C_0 - C_u} = e^{-kt}$$

Therefore:

$$BOD_t = L_u(1 - e^{-kt}) \tag{21}$$

6.2.3 BOD rate constant

The decay constant k in Equation 21 is often called the BOD rate constant. Its value will depend on the type of effluent sample under test: some effluents (e.g. washings from a syrup plant) oxidise very rapidly and have large values of k, while other effluents oxidise slowly and have small values of k. Figure 65 shows a

series of BOD–time curves for three effluents with the same L_u (500 g m^{-3}) but different rate constants. The values of the 5-day BOD for each of the effluents show this difference:

a. $k = 1.0$ d^{-1}: $\text{BOD}_5^{20} = 500(1 - e^{-5}) = 497$ g m^{-3}

b. $k = 0.1$ d^{-1}: $\text{BOD}_5^{20} = 500(1 - e^{-0.5}) = 197$ g m^{-3}

c. $k = 0.01$ d^{-1}: $\text{BOD}_5^{20} = 500(1 - e^{-0.05}) = 24$ g m^{-3}
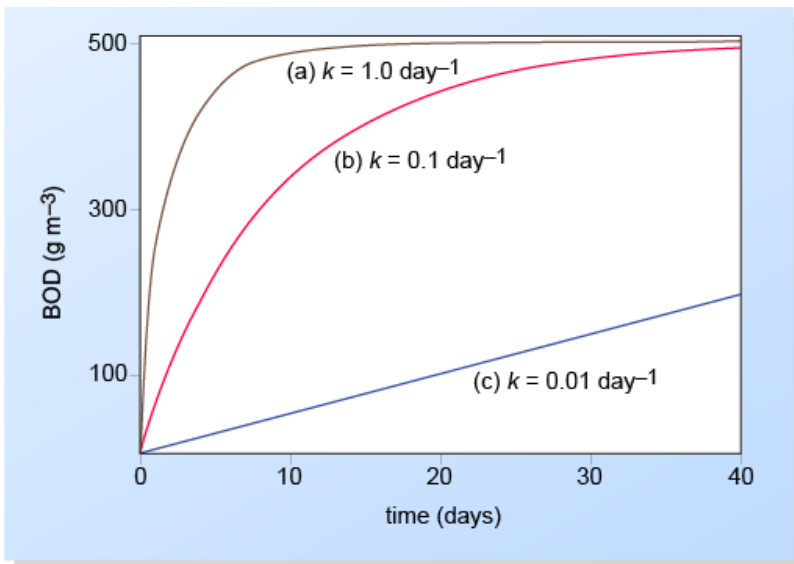
Figure 65 BOD–time curves for different rate constants

View description

The observed BOD rate constant for many sewage effluents is quoted as $k = 0.4$ d^{-1}. This value actually represents an average degradation rate for the many different kinds of materials present in sewage.

SAQ 48

The following experimental results are from a test in which the BOD of an effluent sample was monitored at regular time intervals.

BOD (g m^{-3})	0	2.5	4.4	5.8	7.0	8.1
Time t (days)	0	0.5	1.0	1.5	2.0	2.5

a. Plot the results on a BOD–time curve, using either graph paper or a computer spreadsheet.
b. Plot the results in the form BOD against $(1 - e^{-kt})$, assuming a BOD rate constant $k = 0.4$ d^{-1}, and estimate the ultimate oxygen demand of the sample.
c. Calculate the BOD_5^{20}.

View answer

Of course, this analysis should be considered as a simplified overview. The many reactions occurring in the biological degradation of waste materials include a complex series of interlocking mechanisms. The assumption of an exponential relationship is a convenient theoretical model to explain gross experimental results.

6.2.4 Use of BOD test

The BOD test is widely used as the most important indicator of organic pollution. The BOD value and often the chemical oxygen demand (COD) form the basis of discharge standards for effluents, and are fundamental to the design and operation of effluent treatment plants. Because the BOD test relies on biological action and is a simulation of the actual processes that occur in a receiving water or aerobic treatment plant, it has been adopted universally as the most trustworthy index of organic pollution.

However, the BOD test has limitations.

- It is slow, normally taking five days to yield a result, which does not make it suitable for rapid process control in a wastewater treatment plant.
- It is not a good indicator of industrial pollution – industrial wastes are often toxic or inhibiting to the microorganisms on which the BOD test depends.
- In some effluents there may not be all the nutrients required for microbial degradation to take place, so essential trace elements have to be added.
- The test is used to determine the amount of oxygen required for the oxidation of carbonaceous material. However, oxygen is also used up when ammonia is oxidised to nitrate (nitrification). To prevent this reaction taking place, a chemical such as allylthiourea is used to suppress the nitrifying organisms.

Correlating BOD using pressure measurements

In bottles used to incubate samples for BOD measurement, the oxygen in the headspace is used up. This results in a reduction in pressure, which can be used as a correlation for the BOD values.

Samples of effluent are put in bottles on which a pressure-measuring device with a data-logging capability is used as a cap (Figure 68). The microelectronics in the cap can be set to convert pressure reading to residual oxygen.
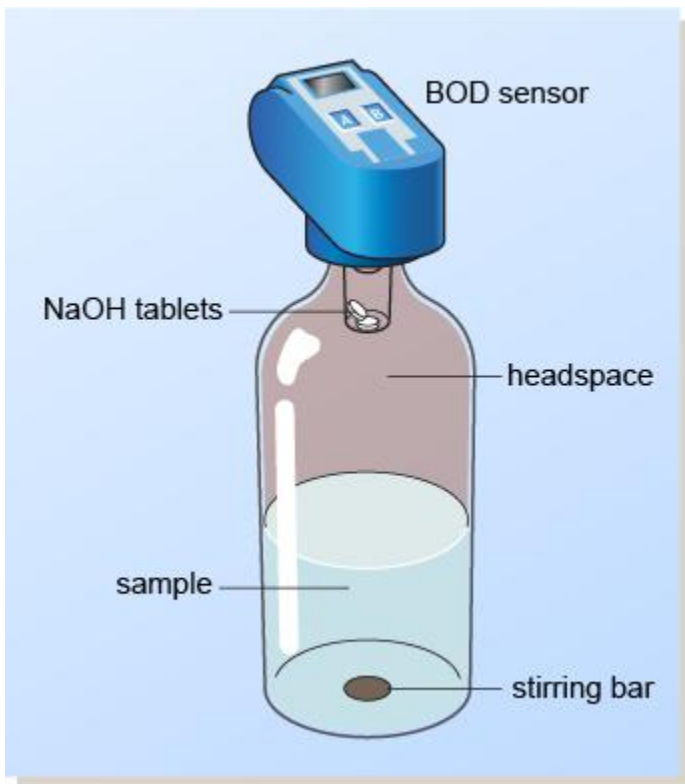
Figure 68 Apparatus for measuring BOD through the reduction of oxygen level (and hence pressure)

View description

During incubation of the sample, oxygen is used up by microorganisms degrading the organic pollutants in the effluent. Oxygen from the headspace diffuses into the effluent. Meanwhile, carbon dioxide generated by the microorganisms is released into the headspace, where it is absorbed by sodium hydroxide (NaOH) pellets in the

cap of the bottle. The net result is a reduction in pressure in the headspace of the sample bottle.

Each day, a measurement of the headspace air pressure is made. After five days, the BOD_5^{20} can be read off directly.

6.2.5 The COD test

Another chemical method frequently used is the chemical oxygen demand (COD) test. The effluent is heated for two hours with potassium dichromate ($K_2Cr_2O_2$) and concentrated sulfuric acid in the presence of silver as a catalyst. Because of the extremely strong oxidising conditions, the COD represents the oxidation of most organic and inorganic compounds; the COD value is therefore almost always higher than the BOD_5^{20}. The measurement can be automated.

The BOD:COD ratio is often used to assess the treatability of an effluent. For example, an effluent with a BOD:COD ratio of 1:2 would be more amenable to biodegradation than one with a ratio of 1:3.5.

SAQ 49

Show that the statement above is true.

The COD test is quicker than the BOD test, taking about two hours. It is often used for routine monitoring of an effluent once its BOD:COD ratio has been established, because the BOD:COD ratio remains relatively constant for a particular waste once steady state is established – though it may vary from one type of waste to another. (Depending on the circumstances, the ratio for domestic sewage can be anywhere from 1:1.25 to 1:2.50.) The COD test, being a chemical test, is more reliable and hence is considered important.

Table 5 (in Section 2) shows some typical BOD and COD values for various effluents.

SAQ 50

What do you conclude from the BOD:COD ratios of sewage and pulp and paper mill effluent?

6.2.6 Total organic carbon

The total organic carbon (TOC) content of a sample can be measured by burning a small amount of the sample

with air in a high-temperature (1000 °C) furnace in the presence of a platinum catalyst.

- The total carbon is first measured by injecting typically 25 ml of the sample onto the catalyst. The carbon compounds are converted into carbon dioxide, which is measured by an infrared detector. (Carbon dioxide absorbs infrared radiation, just as in the greenhouse effect that we experience on Earth.)
- The inorganic carbon (that present in carbonates and similar compounds) is then measured by adding hydrochloric acid to the sample and sparging it with air (i.e. blowing air through it). The resulting carbon dioxide is measured by an infrared detector.
- The total organic carbon will be the difference between the total carbon and the inorganic carbon content.

The TOC test takes only 15 minutes and is useful for testing industrial wastes containing toxins. It is also valuable for measuring organic pollution in highly saline water where the salinity makes other methods unreliable. However, the TOC value does not relate to the biodegradability of the sample. For example, a piece of plastic would register a value of TOC but not of BOD.

The TOC test is also a useful means of determining small, adverse changes in drinking water quality – which, being small, are not easily detected by BOD measurement.

6.3 Estimation of physical, chemical and microbiological components

In monitoring water quality, several different parameters might be measured. This subsection gives an outline of the main parameters:

- temperature
- pH
- solids (suspended, dissolved and total)
- hardness
- alkalinity
- nitrogen compounds (ammonia, nitrites and nitrates)
- phosphates
- chlorides
- metals
- oil
- toxic chemicals (pesticides and phenols)
- radiation
- odour, colour and turbidity
- microorganisms (coliforms, faecal streptococci, *Clostridium perfringens* and viruses).

Note that whilst this text has been mainly discussing effluents, some of the parameters in the list above (e.g. hardness and radiation) would usually only be considered for drinking water.

6.3.1 Temperature

Temperature can be measured using mercury-in-glass thermometers. For robustness in the field, however, metallic temperature probes are preferred. Equipped with digital readouts, these are convenient to use.

6.3.2 pH

It is possible to measure pH in a variety of ways.

- Most often, it is measured using an ion-selective probe that has been calibrated using standards (usually at pH 4 and pH 7). Termed 'buffers', these are solutions of a given pH that resist changes in pH when small quantities of an acid or alkali are added to them. The temperature of the solution being analysed has to be measured first, and this value is used in setting up the probe.
- Titration can also be used. This is a procedure in which a measured volume of an acid or base of known concentration is reacted with a sample of unknown concentration to the point of neutralisation. The volume of reactant used enables calculation of the unknown concentration.
- For rapid measurements, chemical-impregnated paper strips are used. These develop a colour that can then be compared with a colour-coded standard strip (Figure 69).

Figure 69 Test strip for pH

6.3.3 Solids

Suspended solids

The quantity of suspended solids is estimated gravimetrically – by filtering a given volume of sample, then measuring the dry weight of solids present after all the water in the filtered solids has evaporated in an oven. The concentration of suspended solids is expressed in $g\ m^{-3}$.

Dissolved solids and salinity

The concentration of dissolved solids can affect the ecology of a particular site and the usefulness of a water supply for humans, animals and plants. The dissolved solids content of a water sample can be estimated gravimetrically, but it is more usually estimated by measuring the electrical conductivity of the water sample. This is done using a conductivity meter (Figure 70), which measures electrical conductivity in $mS\ cm^{-1}$ (millisiemens per centimetre); this value can then be converted in the meter to an approximate value of the dissolved solids concentration in $g\ m^{-3}$.

Figure 70 A conductivity meter for measuring dissolved solids

View description

If the concentration of dissolved solids is high (above, say, 10 000 g m^{-3}) then the term 'salinity' is used instead – so we refer to the salinity of sea water rather than to its dissolved solids content.

Total solids

The total solids content of a water sample (the sum of suspended solids and dissolved solids) may be estimated by gravimetric means by evaporating a given volume of sample and weighing the residue. The result is expressed in g m^{-3}.

6.3.4 Hardness

As described in Section 1, water hardness is caused by the presence of calcium and magnesium salts. High levels of hardness inhibit the formation of lather with soap and can cause scaling in water systems. Hardness can be measured by titration, and the results are expressed in units of $g\ CaCO_3\ m^{-3}$. (Note that the hardness being measured does not necessarily have to be caused by $CaCO_3$; the value given is the amount of $CaCO_3$ that would be needed to cause the same level of hardness as is present in the sample.)

6.3.5 Alkalinity

The alkalinity of a water is a measure of its capacity to neutralise acids. It is due to the presence of alkaline substances such as bicarbonates, carbonates, hydroxides, and the salts of weak acids such as borates, silicates and phosphates. Such substances act as buffers to resist a drop in pH resulting from acid addition. In polluted water, ammonia and the salts of weak acids such as ethanoic acid, propionic acid and hydrosulfuric acid (dissolved hydrogen sulfide) may also be present, contributing to alkalinity.

Alkalinity is an important test parameter in a number of industrial water uses, notably in boiler water treatment. Boilers and steam-generating plant are normally operated under conditions of high alkalinity in order to minimise corrosion.

Alkalinity is measured by titration and is expressed in units of $g\ CaCO_3\ m^{-3}$. (Again, note that the alkalinity does not have to be caused by $CaCO_3$; the value given is the amount of $CaCO_3$ that would be needed to cause the same level of alkalinity as is present in the sample.)

6.3.6 Nitrogen compounds

Ammonia

Ammonia is a breakdown product of nitrogenous material. It is harmful to fish and other forms of aquatic life. It can be measured using a colour comparator; reagents are added to the water sample and the colour that develops is compared with glass that has the colour of a solution of known concentration of the substance under investigation. This method can easily be used on site. A paper colour chart can be used in a similar way.

The extent of colour development can also be measured by absorbance of light, using a device called a colorimeter or spectrophotometer. Light of the wavelength corresponding to the colour of the solution passes through the filter to the sample holder. Some light passes through the sample and some is absorbed by it; the greater the colour intensity, the more light is absorbed. Thus the amount of light absorbed by the sample is a measure of colour intensity and hence of concentration of the substance under examination. This is called spectrophotometry.

Other methods include test strips, and using an ion-selective electrode specific to ammonium ions.

Values are usually expressed in terms of the nitrogen content in the form of ammonium ions (i.e. $g\ NH_4^+$-N m^{-3}, grams of ammonium nitrogen present per cubic metre). This can be converted to the ammonium concentration since 14 g of N gives rise to 18 g of ammonium.

Nitrites

Nitrites can be found in rivers as intermediates in the conversion of ammonia to nitrate – they are produced by the bacterium *Nitrosomonas* in biological nitrification. Nitrites are harmful to fish and other aquatic organisms. They can be measured using:

- a colour comparator
- a test strip and a colour chart
- an ion-selective electrode
- spectrophotometry.

Values are expressed in $g\ NO_2^-$-N m^{-3} (grams of nitrite nitrogen per cubic metre).

Nitrates

Nitrates enter water sources from:

- the natural breakdown of vegetation
- the excessive use of inorganic fertiliser
- the oxidation of nitrogen compounds in domestic and industrial effluents.

Nitrates can be measured using:

- a colour comparator
- a test strip and a colour chart
- an ion-selective electrode
- spectrophotometry.

Results are usually expressed in g NO_3^--N m^{-3} (grams of nitrate nitrogen per cubic metre).

6.3.7 Phosphates

Measurement of phosphates can be carried out using:

- a colour comparator
- a test strip and a colour chart
- spectrophotometry.

Results are usually expressed in g PO_4^{3-}-P m^{-3} (grams of phosphate phosphorus per cubic metre).

6.3.18 Chlorides

Almost all the chloride we consume in the form of table salt ends up in sewage, with about 1% by mass of urine being sodium chloride (Maurer, 2007). The concentration of chloride ions is unaffected during sewage treatment, so the presence of chloride in a river can indicate pollution by sewage or treated sewage. Chlorides in water can also indicate seawater intrusion into aquifers near the coast. In temperate zones, road run-off in winter also contributes salt, so one has to be a little cautious in interpreting results.

Chlorides are corrosive and their monitoring is vital in the prevention of corrosion. Measurement of chloride concentration is by titration or spectrophotometry, with the results being expressed in g Cl^- m^{-3}. In the field, colour comparators can be used.

6.3.9 Metals

Metal ions can have a range of effects on water: some impart taste and turbidity, whilst others (such as the heavy metals) make it toxic. Metal concentration in a water sample can be ascertained in two ways.

- In the laboratory, atomic absorption spectroscopy is used. Under the right circumstances, all atoms will absorb and emit light. Absorption happens when an electron in an atom is excited into a higher energy level. When this electron falls back down to its ground state, a photon of light is emitted that has an energy determined by the energy gap between the ground and excited states. The emission spectra observed will enable identification of the metals present in the sample.
- In the field, colour comparators may be used for several metals of concern.

The concentrations of metals, usually being low, are expressed in mg m^{-3}. The effects of the common metals that can be found in water are outlined below.

- Iron introduces taste, discoloration and turbidity to the water, as well as encouraging the growth of

'iron bacteria' (which derive energy from the oxidation of dissolved ferrous iron).

- Magnesium increases the hardness of the water, adds taste, and may cause gastrointestinal irritation.
- Zinc introduces taste and turbidity.
- Copper introduces taste and discoloration.

6.3.10 Oil

The presence of oil on the surface of water can affect the rate of oxygen transfer into the water body. Oil can also cause taste, odour and toxicity in water. It is extracted using organic solvents and then quantified using infrared or ultraviolet spectroscopy, in which the interaction of the infrared or ultraviolet radiation with the oil provides information about the molecules in the sample to enable characterisation and quantification of the oil. Concentration is expressed in units of $g\ m^{-3}$.

6.3.11 Toxic chemicals

Pesticides

The measurement of pesticide levels requires sophisticated chromatographic equipment coupled with a mass spectrometer. The concentration of individual pesticides is measured in $g\ m^{-3}$.

Phenols

Phenols can be measured using:

- titration
- a colour comparator
- spectrophotometry.

Results are expressed in g m^{-3}.

6.3.12 Radiation

Radioactive constituents of drinking water can result from naturally occurring radioactive species, as well as manufactured radionuclides that might be inadvertently discharged into watercourses.

Radiation can cause cancer, and there are strict limits on the emission of radioactive compounds. For instance, a limit exists for tritium concentration in water, and the total indicative dose of radioactivity should not exceed 0.10 mSv year^{-1} (excluding tritium, potassium-40, radon and radon decay products).

Tritium levels are measured by chemical analysis. Essentially, the water sample is distilled after addition of potassium permanganate, which ensures that only tritium is carried away in the vapour. A sample of the distillate is then mixed with a scintillation solution (which emits light upon receiving radiation). The tritium emits beta particles, which cause the scintillation solution to emit light, which is then measured with a liquid

scintillation spectrometer. The results are expressed in becquerels per litre (Bq l^{-1}).

6.3.13 Odour, colour and turbidity

Physical aspects such as odour, colour and turbidity affect the acceptability of the water, regardless of their possible health effects.

Odour

Specific substances may be detected by their odours, although the lowest concentration of a substance detectable in this way varies widely (Table 17).

Table 17 Odour thresholds of some compounds in sewage and trade wastes

Compound	Approximate concentration having faint odour (g m^{-3})	Description of odour	Typical sources
Ammonia, NH_3	0.037	Pungent, alkaline	Coal carbonisation, farm wastes
Chlorine, Cl_2	0.010	Pungent	Chemical processes, swimming pools
Chlorophenol, ClC_6H_4OH	0.00018	'Medicinal'	Chlorination of water

			containing phenol
Hydrogen sulfide, H_2S	0.0011	Rotten eggs	Anaerobic decomposition
Skatole, C_9H_9N	0.0012	Faecal, nauseating	Raw sewage
Sulfur dioxide, SO_2	0.009	Pungent, acid	Chemical processes, during striking of a match

Molecules that cause odours can be measured using instrumental methods, but under carefully controlled conditions the sensory measurement of odours by the human olfactory system can also provide meaningful and reliable information. This sensory method is now used most often to measure the odours emanating from wastewater treatment facilities. A panel of human test subjects is exposed to a sample of the odorous air, which is progressively diluted with odour-free air until 50% of the panellists cannot detect any odour. The number of dilutions to this odour threshold value is reported as the threshold number (which may also be called the number of odour units).

Colour

The apparent colour of water is the colour of the whole sample, which is imparted by suspended solids and dissolved substances. The true colour of water is the colour after suspended material has been removed, and

depends only on the substances dissolved in it. Large amounts of suspended organic material can produce an apparent colour that is greenish, yellowish or brownish.

The true colour of water may be measured by filtering a sample through a 0.45-μm filter and either comparing it with the colours of solutions of a known standard chemical composition or measuring the absorption of light using a spectrophotometer. A widely used standard for such colour grading is the Hazen scale, one Hazen colour unit (HU) being the colour produced by a standard solution containing platinum (BSI, 1976). Colour may be pH-dependent, so this also has to be recorded.

Turbidity

Turbidity gives a rough indication of the quantity of undissolved matter in water and is easily measured. The presently preferred method is to use a nephelometer, which measures the scattering of light of a specified wavelength by a sample of water. The turbidity is quoted in nephelometric turbidity units (NTU).

6.3.14 Coliforms

Coliforms are generally non-pathogenic microorganisms, often of faecal origin. *E. coli* is a coliform found in the intestines of humans and other mammals (see Section 3.6.2); its presence in water indicates possible faecal contamination and the possible presence of human pathogens from faeces.

Coliforms are deemed to be present in a sample (in a test tube) if bacterial growth occurs in a medium containing bile salts, and if the sample is shown to be capable of fermenting lactose within 48 hours at 37 °C with the production of acid and carbon dioxide gas. Gas production can be demonstrated using Durham tubes (miniature test tubes, inserted upside down in the sample test tube, that trap any gas produced). This is a 'presumptive test', because it is presumed that all the tubes that show acid and gas production contain coliform organisms.

A confirmatory test for *E. coli* is normally carried out after coliforms are found in the presumptive test. A loopful of culture from each positive tube in the presumptive test is transferred to each of two tubes; one contains tryptone water, the other usually contains lactose ricinoleate broth. Both tubes are then incubated in a water bath at 44.5 °C for 24 hours. *E. coli* is the only coliform that produces indole from tryptophan and ferments lactose at 44.5 °C, so to confirm the presence of *E. coli*, both tubes must give a positive reaction.

An alternative confirmatory test is to plate out a loopful of culture from each presumptive positive tube on eosin methylene blue agar. After incubation for 24 hours at 37 °C, colonies of *E. coli* exhibit a green metallic sheen.

Quantifying faecal coliforms

Membrane techniques are often used to quantify faecal coliforms. A measured volume of sample, or an

appropriate dilution of it, is filtered through a 0.45-µm membrane filter. Microorganisms are retained on the filter surface, which is then incubated in a petri dish on a medium containing lactose. The visible colonies that develop (Figure 71) after 24 hours' incubation at 44.5 °C are counted and expressed in terms of the number present in 100 ml of the original sample.
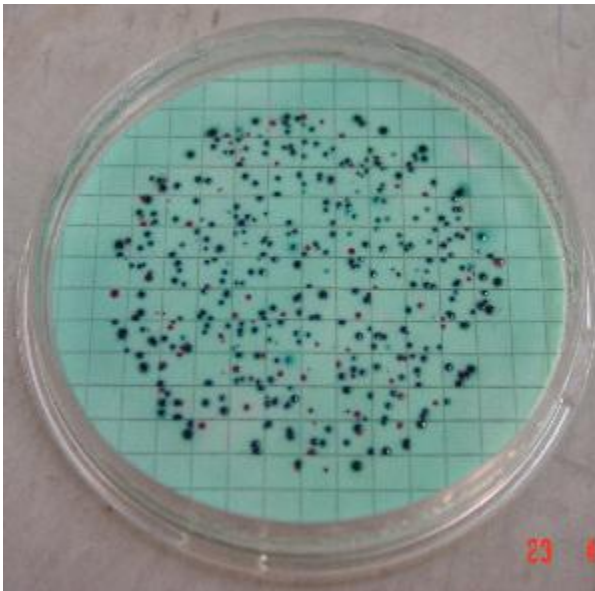
Figure 71 A membrane filter with bacterial colonies

View description

Samplers have been developed that comprise 0.45-µm membranes bonded to absorbent pads containing dehydrated nutrient media (Figure 72). Each sampler (called a dipslide) is contained in a transparent plastic

case. The entire assembly is sterilised at manufacture. When the dipslide is immersed in the water to be analysed, it absorbs 1 ml of sample. The dipslide is then put back into its plastic case and the case is put into an incubator maintained at 44.5 °C. After 24 hours, the faecal coliform colonies that develop are counted. The surface of the dipslide has grid squares to ease the process of counting.

Figure 72 Membrane-type samplers

View description

Multiple tube fermentation is an older method of enumerating faecal coliforms. It involves adding

measured volumes of sample to sets of sterile test tubes containing a liquid medium with lactose and bile salts, then incubating at 44 °C for 24 hours. The production of gas indicates that faecal coliforms are present. The numbers of tubes showing positive and negative reactions are recorded, and an estimate of the most probable number (MPN) of faecal coliforms present in the original sample is obtained by using appropriate statistical tables relating to the volumes of sample inoculated.

Portable battery-powered incubators enable analysis for faecal coliforms to be undertaken in remote locations where laboratory facilities are not at hand.

Other coliforms

Other coliform organisms, closely related to *E. coli*, can also occur in water, especially under tropical conditions. They need not be of faecal origin, but their presence indicates the existence of some pollution, even though at the time of sampling typically faecal organisms were not present.

Simple colour change test kits for coliforms are available. These consist of standard bacterial media with enzymes that react to the presence of certain chemicals in the bacteria. One millilitre of the sample water is put into a sterilised bottle and a sachet of media is added. After 18–24 hours of incubation, the presence of coliforms will be shown by a colour change. Faecal coliforms will be indicated by fluorescence. A special

counting tray can be used to estimate the number of bacteria present.

6.3.15 Other microorganisms

Faecal streptococci

A presumptive test for *Streptococcus* uses multiple tube fermentation. It needs a five-day incubation period using glucose azide broth. The tubes are incubated for a maximum period of 72 hours at 37 °C. As soon as acidity is observed in a tube through a colour change (purple to yellow) of the pH indicator in the medium, three loopfuls of the culture are transferred to a fresh tube of the same medium, which is incubated in a water bath at 44 °C for 48 hours. Tubes showing acidity at this temperature are deemed to contain faecal streptococci and are used to calculate the MPN.

The confirmatory test for faecal streptococci involves plating out a loopful of culture from a positive second-stage MPN tube onto MacConkey's agar. Minute magenta-coloured colonies should be formed after incubation at 37 °C for 24 hours.

Clostridium perfringens

This organism is an indicator of faecal pollution. A two-stage MPN technique is generally used to measure *C. perfringens* in water.

1. The sample is heated to 75–80 °C in a water bath and held at this temperature for 10–15 minutes, then cooled.
2. Different volumes of the sample are then used to inoculate differential reinforced clostridial broth, which is transferred to screw-capped bottles containing double-strength medium. The bottles are topped with single-strength medium to leave only a small air space. The cap is screwed on tightly to ensure sufficiently anaerobic conditions. The medium also contains a reducing agent.

After incubation for 48 hours at 37 °C, bottles containing *Clostridium* turn black due to the precipitation of iron sulfides resulting from the reaction between iron salts in the medium and the sulfite produced by the action of the organisms on sulfate in the medium. Each positive black bottle is then examined for the presence of *C. perfringens*, since blackening can be produced by any *Clostridium*.

All strains of *C. perfringens* produce zones of opalescence round their colonies on egg yolk agar. This is used to confirm its presence in a sample.

Viruses

Detecting and measuring viruses is a complex and time-consuming operation, so it is not routinely undertaken. It is, however, carried out when there is an outbreak of disease.

A representative sample is first acquired and the viruses concentrated through a technique such as absorption to, and removal (elution) from, a microporous filter. The concentrated viruses can then be identified using sensitive biological assays to detect viral genetic material or protein. This test involves the polymerase chain reaction (PCR) and takes only a few hours. If virus particles are detected, quantification using tissue culture techniques and plaque formation (where areas of cell destruction in a tissue culture monolayer preparation are measured) is employed. This process can take about a week!

Virus detection poses several difficulties. Viruses are very small in size (20–100 nm), they are often at very low concentrations, and they can be of varied types. They are also inherently unstable as biological entities. To compound matters, the various dissolved and suspended impurities in water and wastewater can interfere with the analytical procedures to detect and quantify viruses.

The results of assays for viruses are expressed using the number of plaque-forming units (PFU) per unit volume (e.g. 5 PFU per litre).

6.4 Toxicity testing

The number of chemicals on the market is constantly growing, and their effects on the environment are not always known. In conventional toxicity testing,

organisms are exposed to different dilutions (0–100%) of a chemical under standard conditions in a laboratory. Table 18 gives an indication of the test species at different trophic levels that can be used for freshwater and marine/estuarine environments.

Table 18 Species commonly used in toxicity testing

Trophic level	Fresh water	Marine/estuarine
1	*Selenastrum* (alga)	*Skeletonema* (alga)
2	*Daphnia magna* (crustacean)	*Crassostrea* (oyster embryo larva)
3	Juvenile trout	Juvenile turbot

The EC_{50} is the concentration of the effluent at which 50% inhibition or elimination occurs compared with the control (see Section 4.7.2); the accepted exposure time for a test organism is 48 hours. This makes assessing the impact of a sample a very long process, especially when one takes into account the time taken to prepare the sample and process the data. There is also the complication that the test organisms may not be available when the test is required. Further, the sample (of, say, river water) tested may not be representative of the true situation.

In order to overcome these problems, 'on-line' toxicity measuring devices that can be installed at potential 'trouble spots' have been developed. They can use bacteria, algae, marine invertebrates or fish as the test

organisms. The devices provide a real-time result for the effect of a chemical or an effluent.

Two toxicity measuring methods are described below.

Microtox®

The Microtox® test uses the marine bacterium *Vibrio fischeri*, which is bioluminescent. When it is exposed to a toxic sample, the amount of light emitted diminishes. Thus a measure of the diminution of the light is a direct assessment of the toxicity of the sample. The test organism is supplied in freeze-dried form; it has to be reconstituted for the test, using the sterile diluent and reagents that are also supplied.

Amtox™

Amtox™ is an on-line nitrification inhibition monitor that uses nitrifying bacteria immobilised in a polyvinyl alcohol matrix. The bacteria are held in an aerated reactor at 30 °C and pH 6.5–8.5 for optimum nitrification conditions. The sample is added to the reactor, where a built-in ammonia probe measures the conversion of ammonia to nitrate by recording the residual ammonia in the reactor. This provides an indication of inhibition or death of the bacteria and, hence, the toxicity of the sample.

6.5 Further SAQs

SAQ 51

Identify which of the following statements is true, and give reasons why the others are false.

a. Where chemical tests such as hardness, pH value and chloride concentration can be carried out, physical tests such as colour and turbidity need not be performed because these tests do not measure true pollutants.

b. An analyst could distinguish river water from groundwater simply by measuring the chloride concentration.

c. Hardness, pH value, acidity and alkalinity are related to each other in water possessing hardness.

d. The Hazen scale is useful for measuring the concentrations of specific substances in water.

e. Odour detection and control is important in sewage treatment, but in water treatment odour tests are a luxury.

View answer

SAQ 52

Which test would be most useful in initially characterising the organic matter in water polluted with:

- a. dairy wastes
- b. wastes from a petroleum refinery?

Choose from dissolved oxygen, BOD, TOC, pH and ammonia.

View answer

SAQ 53

What inferences can be made from bacteriological tests on samples of river water that show the following?

- a. There are no bacteria that thrive at 22 °C.
- b. There are bacteria present that thrive at 45 °C.

SAQ 54

What might be the likely 'trouble spots' at which to install an on-line toxicity monitor?

6.6 Summary

The testing of water quality covers a range of different aspects – physical, chemical and biological. The two major parameters in the monitoring of effluent discharges are the oxygen demand and the suspended solids content.

Table 19 summarises the analytical methods for the various water quality parameters discussed in this section.

Table 19 Some important water quality tests, their chief significance and their general means of measurement

Quality parameter	Significance	General method of analysis

Dissolved oxygen	Quantity of oxygen in water sample indicates quality of water	Electrode (per cent saturation or $g\,m^{-3}$)
Biochemical oxygen demand (BOD)	Quantity of biodegradable organic matter is an indicator of pollution	Measurement of dissolved oxygen before and after incubation for five days at 20 °C (grams of oxygen consumed per cubic metre of sample)
Chemical oxygen demand (COD)	Estimate of organic and inorganic matter, which is an indicator of pollution	Oxidation with strongly acidic dichromate solution for two hours, then oxygen consumption determined (grams of oxygen consumed from standard

		dichromate solution per cubic metre)
Total organic carbon (TOC)	Estimate of organic matter, which is an indicator of pollution	Combustion, followed by measurement of CO_2 by infrared absorption (grams of organic carbon per cubic metre)
Temperature	Measure of heat pollution	Thermometer or temperature probe (°C)
pH value	Intensity of acid or alkali present affects many chemical and biological properties	Ion-selective probe, titration or test strips (pH value 0–14)
Suspended solids	Cause turbidity; treatment efficiency may be affected	Gravimetric estimate $(g\,m^{-3})$

Dissolved solids	Cause salinity; may affect ecosystems and domestic/ agricultural usefulness	Gravimetric estimate $(g\,m^{-3})$ Conductivity meter $(mS\ cm^{-1}$, converted to $g\,m^{-3})$
Total solids	General polluting potential	Gravimetric estimate $(g\,m^{-3})$
Hardness	Affects soap consumption and scale formation	Titration $(g\ CaCO_3\ m^{-3})$
Alkalinity	Important parameter in industrial water uses	Titration $(g\ CaCO_3\ m^{-3})$
Ammonia	Toxic; provides an estimate of decomposition of nitrogenous	Colour comparator, spectrophotometry, test strip or ion-selective electrode

	compounds (proteins)	(grams of ammonia as nitrogen per cubic metre)
Nitrites	Toxic to fish and other aquatic organisms	Colour comparator, test strip, ion-selective electrode or spectrophotometry (grams of nitrite as nitrogen per cubic metre)
Nitrates	Provide an estimate of oxidation of NH_3; plant nutrient; may serve as source of O_2; toxic	Colour comparator, test strip, ion-selective electrode or spectrophotometry (grams of nitrate as nitrogen per cubic metre)
Phosphates	Plant nutrient	Colour comparator, test strip or spectrophotometry (grams of phosphate as

		phosphorus per cubic metre)
Chlorides	Indicate degree of pollution with sewage and/or degree of salt water intrusion; affect taste; cause corrosion in hot water systems	Titration, spectrophotometry or colour comparator (g Cl$^-$ m^{-3})
Iron	Causes taste, discoloration and turbidity; encourages growth of iron bacteria	Atomic absorption spectroscopy or colour comparator (mg Fe m^{-3})
Magnesium	Affects hardness and taste; may cause gastrointestinal irritation	Atomic absorption spectroscopy or colour comparator (mg Mg m^{-3})
Zinc	Affects taste and turbidity	Atomic absorption spectroscopy or colour comparator (mg Zn m^{-3})

Copper	Causes taste and discoloration	Atomic absorption spectroscopy or colour comparator $(mg\ Cu\ m^{-3})$
Oil	Reduces rate of O_2 transfer; causes taste, odour and toxicity	Spectroscopy $(g\ oil\ m^{-3})$
Pesticides	Cause toxic pollution	Chromatography and mass spectroscopy $(g\ pesticide\ m^{-3})$
Phenols	Cause toxic pollution, odour and taste	Titration, colour comparator or spectrophotometry $(g\ phenol\ m^{-3})$
Radiation	Carcinogenic	Liquid scintillation spectrometer $(Bq\ l^{-1})$

Odour	Unaesthetic indicator of pollution	– Subjective perceived odour (threshold number)
Colour (true)	Indicates presence of suspended and dissolved solids and organic matter	Spectrophotometry or comparison with platinum–cobalt standard (Hazen units)
Turbidity	Provides an estimate of suspended matter	Nephelometer (NTU)
Faecal coliforms	Indicate faecal pollution	Membrane techniques or multiple tube fermentation (MPN) (number per 100 ml) or membrane dipslides (number per 1 ml)

		or
		colour change tests
Faecal streptococci	Indicate faecal pollution	Multiple tube fermentation followed by confirmatory test
		(number per 100 ml)
Clostridium perfringens	Indicate faecal pollution	Two-stage test (heating, then incubating for 48 hours)
		(number per 100 ml)
Viruses	Indicate faecal pollution	Concentration, PCR and tissue culture
		(PFU per unit volume)
Toxicity	Causes elimination of	Decrease in activity levels in

species in watercourse	bacteria, algae, invertebrates

Section 7: Industrial wastewater treatment

7.1 Introduction

As indicated in Section 4.7, industrial wastewaters or trade effluents tend to be characterised by great variability in flow rate and composition.

Very large installations, such as refineries, tend to produce a consistent-quality effluent due to their objective of producing a consistent product from well-characterised feedstocks to comply with market demand. However, the majority of industries worldwide are small to medium-sized and do not operate continuously, so they do not produce a continuous effluent or even one of consistent quality. In such small industries (e.g. a dairy), the effluent-producing operations (such as tank cleaning) are discontinuous, giving rise to variability of both flow and load for treatment. If the dairy manufactures different products (a range of milks, yoghurts, cheeses, etc.) then the different processes will produce effluents of different volume and composition.

The short sewer lengths through which industrial wastewater is conveyed to an in-house treatment plant accentuate the variability in effluent quality. In comparison, in a municipal sewerage system, the effluent would have been subjected to considerable

mixing, dilution and attenuation due to the extensiveness of the sewerage network.

Industrial effluents may contain chemicals that are toxic, corrosive or of extreme pH. Small amounts of these effluents can be tolerated in a treatment plant, but large quantities may cause disruption, especially to biological treatment systems. There are also likely to be sudden loads in the form of erratic discharges of specific chemicals or waste that may be dumped into the factory drainage system.

Consequently, an industrial wastewater treatment plant must be able to accommodate a range of flow and composition variations. Facilities for flow balancing and neutralisation (to achieve a uniform flow rate) are often included in such plants. Prior to any treatment, however, effluent streams will be segregated for reuse – for instance, final rinse water from a washing process can be reused in the initial washing stages, while streams with high-value components (e.g. metals) will be separated out for recovery of the material.

7.2 Trade effluent control

There are several legal measures available to control pollution of the aquatic environment by trade effluents. For direct industrial discharges, strict consent conditions have to be met. These conditions may be such that expensive treatment plants have to be installed before discharge can take place to a river or estuary. If the cost

of this is high then it is often cheaper to discharge to the sewer and have the wastewater treated at the local sewage works, although this will also incur costs. The receiving sewage works may insist that the industry pretreat the effluent so that biological treatment units at the works are not adversely affected. For example, a high heavy metal content will have to be reduced by precipitation.

One formula to calculate the cost of discharging trade effluent to the sewer, which was first developed for use at the Mogden Sewage Treatment Works in west London, is as follows (Walker, 2000):

$$C = R + V + \left(\frac{O_t}{O_s}\right)B + \left(\frac{S_t}{S_s}\right)S \qquad (22)$$

where

> C is the total charge per cubic metre of trade effluent
> R is the reception and conveyance charge per cubic metre of sewage
> V is the volumetric and primary treatment cost per cubic metre of sewage
> O_t is the COD (in mg l^{-1}) of the trade effluent after one hour of quiescent settlement
> O_s is the COD (in mg l^{-1}) of settled sewage (standard strength)
> B is the biological oxidation cost per cubic metre of settled sewage

S_t is the total suspended solids content (in mg l^{-1}) of the trade effluent

S_s is the total suspended solids content (in mg l^{-1}) of crude sewage (standard strength)

S is the treatment and disposal cost of primary sludge per cubic metre of sewage.

SAQ 55

A trade effluent from a sugar beet factory is discharged to the sewer. The effluent has a COD of 1150 mg l^{-1} and a suspended solids content of 800 mg l^{-1}, and is discharged at a flow rate of 200 m^3 d^{-1}. Using the Mogden formula (Equation 22), calculate the total daily charge for discharge of the effluent to the sewer, given the following information:

$R = 20.00$p m^{-3}
$V = 22.56$p m^{-3}
$O_s = 355$ mg l^{-1}
$B = 14.94$p m^{-3}
$S_s = 268$ mg l^{-1}
$S = 17.42$p m^{-3}

View answer

SAQ 56

A trade effluent from a chemical plant is discharged to the sewer at a flow rate of 300 $m^3\,d^{-1}$. The COD and suspended solids content of the effluent are 1500 mg l^{-1} and 250 mg l^{-1} respectively. Trade effluent charges are based on the Mogden formula (Equation 22), with:

$R = 21.89p\ m^{-3}$
$V = 22.28p\ m^{-3}$
$O_S = 542.8\ mg\ l^{-1}$
$B = 13.31p\ m^{-3}$
$S_S = 347.6\ mg\ l^{-1}$
$S = 9.92p\ m^{-3}$

Calculate:

a. the total daily charge for discharging the trade effluent to the sewer
b. the total daily charge for discharging the trade effluent to the sewer, if uncontaminated cooling water equivalent to 30% of the flow is removed prior to discharge.

View answer

7.3 Summary

Trade effluents can be variable in flow rate and composition. While some industries may have in-house

treatment plants, others may discharge their effluent to the sewer to be treated at the local sewage works. The sewage works will impose a cost on the industry concerned.

The Mogden formula is one way of arriving at such a cost. This formula takes into account the flow rate of the trade effluent and its chemical oxygen demand and suspended solids concentration.

Section 8: River quality modelling

8.1 Introduction

So far this text has covered water pollution and how effluents can be treated to ensure they have minimal impact on receiving waters. We can use mathematical modelling of river quality to predict the impacts that effluents will have on watercourses. Thus this final section considers the modelling of biochemical oxygen demand, dissolved oxygen, plant nutrients and total coliforms in a river.

The equations used in the examples are introductory and form the basis of river quality modelling. When investigating real-life pollution problems, more sophisticated models that consider a host of parameters affecting degradation and dispersion are used.

8.2 Dispersion of pollutants in water

Pollutants generally enter a watercourse via a point source, but can also enter diffusely.

When a point-source effluent enters a water body such as a river, it is initially diluted at the point of entry and

then diluted even further downstream. The initial dilution will depend on:

- the method used to discharge the effluent into the river
- the volume, momentum, buoyancy and velocity of the discharge
- the difference in density between the effluent and the river water.

The discharged effluent usually has a higher velocity than that of the river, and this results in turbulent mixing of the effluent with the water in the river. The higher the velocity of discharge, the greater the degree of mixing.

The dispersion of a pollutant is due to the process of *molecular diffusion*. This is the random motion of the pollutant molecules at the interface with the river water. The molecules of pollutant constantly collide with the molecules of river water, moving sometimes towards a region of higher concentration and sometimes towards a region of lower concentration without having a preference for one or the other. Eventually, a net transfer of the molecules of pollutant from the region of higher concentration to that of lower concentration results. This explains the dispersion that is observed.

The effluent forms a *plume*, which moves downstream. The density of the effluent will determine the rate of rise and the position of the plume in the *water column* of the river. If the effluent is warmer than the river, it will be less dense than the river water and will rise in it. This will cause the effluent plume to break the water surface.

Eventually it will mix with the river water, at which point the plume mixture will move down to the level of the river where the water is of the same density.

Initial dilution continues until the energy in the effluent discharge is dissipated and the velocity of the plume matches that of the river. Once this happens, the natural turbulence in the river causes further dilution of the effluent.

The plume is diluted downstream by horizontal and vertical mixing. Generally, horizontal mixing is more rapid, and the plume will be dispersed horizontally for some distance without being fully mixed in the river.

The velocity of the river will be a major factor in dispersion. Generally the velocity will be higher in the upper reaches of the river. Fluctuations in river water flow may occur seasonally, and this will affect the level of dilution of the effluent. If the river is tidal, the water level will fluctuate daily, and also the change in density due to salinity will influence mixing and dilution.

Climatic conditions such as wind can significantly affect effluent dispersion and also influence plume behaviour. In cold regions, ice in rivers can drastically affect the degree of mixing.

Pollutants entering a river generally have a short residence time (compared to pollutants entering a lake). The rapid dispersion and transport of the pollutants in a river aids the recovery of the river from the impacts of

those pollutants. However, if a pollutant ends up in the sediment, it will take a long time to be removed.

Dispersion of effluents can be modelled mathematically, and such models are used when designing discharge points for effluents from industry, etc. Models can also be used to predict the fate of pollutants; this is what I will be doing in the rest of this section, for a limited number of parameters.

8.3 Biochemical oxygen demand

As described in Section 1.3.2, the BOD (expressed in mg O_2 l^{-1} or g O_2 m^{-3}) of an effluent is the amount of oxygen required for the biodegradation of the pollutants in the effluent by microorganisms. Most often this is the carbonaceous BOD (CBOD – the biochemical oxygen demand due to the oxidation of carbon-containing compounds), where the effect of nitrifying bacteria (and hence nitrification) is inhibited using allylthiourea (ATU).

The equations used to model river quality in this section refer to the carbonaceous BOD, because this is likely to be much more significant than the oxygen demand due to nitrification.

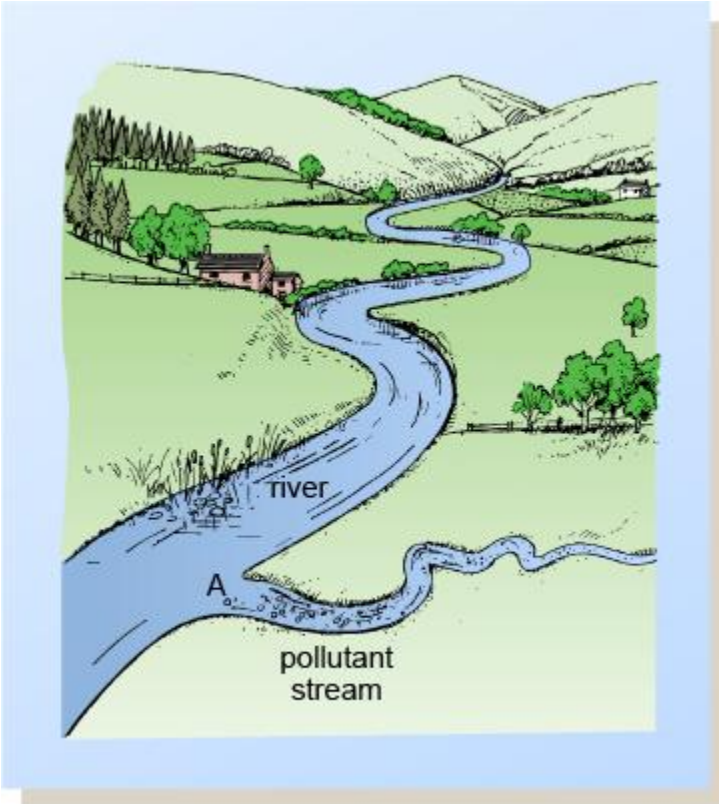Consider a river into which a pollutant stream enters at point A (Figure 73).

Figure 73 River scenario

View description

If the cross-sectional area of the river is considered to be constant, then under steady-state conditions, the BOD distribution down the river will be given by the expression:

(23)

$$L = L_0 \exp\left[\frac{-k_L x}{U_0}\right]$$

where

> L is the ultimate carbonaceous BOD (or CBOD) in the river at a distance x from point A
> L_0 is the ultimate BOD at point A after the pollutant stream enters the river (in g m^{-3})
> k_L is the rate of decay of the BOD in the river (in d^{-1}), i.e. the BOD decay rate constant
> x is the distance from point A (in m)
> U_0 is the velocity at point A (in m d^{-1}).

Mass balance can also be used to determine L_0. If:

> L_{up} is the ultimate CBOD of the river upstream of point A (in g m^{-3})
> Q_{up} is the volumetric flow rate of the river upstream of point A (in m^3 s^{-1})
> L_e is the ultimate CBOD of the effluent stream (in g m^{-3})
> Q_e is the volumetric flow rate of the effluent stream (in m^3 s^{-1})

then assuming perfect mixing:

$$L_{up}Q_{up} + L_e Q_e = L_0(Q_{up} + Q_e) \tag{24}$$

$$L_0 = \frac{L_{up}Q_{up} + L_e Q_e}{Q_{up} + Q_e}$$

Conversely, 5-day BOD values for the effluent and river can be used to find the 5-day BOD of the mixture, and this can be converted to the ultimate BOD using the expression:

$$\frac{\mathrm{BOD}_5^{20}}{\left(1 - e^{-5k_{20}}\right)} = L_0 \tag{25}$$

(Note that this is essentially a rearrangement of Equation 21 (Section 6.2.2), with L_0 being used instead of L_u to indicate that we are considering the ultimate oxygen demand at the point at which the effluent enters the river.)

The rate of decay of BOD is temperature dependent, with the relationship between k_{20} (the value of k_L at 20 °C) and k_T (the value of k_L at any other temperature T °C) for sewage normally being given by:

$$k_T = 1.047^{(T-20)}k_{20} \tag{26}$$

The value of k_L reflects both the biological oxidation of organic matter and the settling of that matter on the river bed.

8.3.1 Use of equations

Exercise 15 shows how the equations in Section 8.3 can be used to derive answers to a particular problem.

Exercise 15

A steady flow of partially treated sewage with a BOD_5^{20} of 60 mg l^{-1} enters a river that has a BOD_5^{20} of 2 mg l^{-1}. The temperature of the river ranges from 8 °C to 15 °C over the year.

The following data are known:

> flow rate of river upstream of discharge point = 36 000 $m^3 h^{-1}$
> flow rate of treated effluent = 18 000 $m^3 h^{-1}$
> k_{20} = 0.25 d^{-1}
> velocity of river = 0.05 m s^{-1}

and you can assume that the cross-sectional area of the river is constant.

a. Determine the BOD decay rate constant for each of the temperatures from 8 °C to 15 °C.

View answer

b. Estimate the distance downstream of the discharge point at which the ultimate CBOD of the river will be an acceptable 6.3 mg l^{-1} for freshwater fish life for each of the temperatures from 8 °C to 15 °C, and show these values in a graph.

View answer

SAQ 58

A water intake is to be constructed downstream of a sewage treatment works outlet.

a. If a water treatment plant of category A1 is to be built (where the raw water has a BOD_5^{20} of less than 3.0 mg l^{-1}), calculate how far downstream of the outlet the water intake must be, given the following data:

flow rate of river upstream of treated sewage discharge = 720 $m^3 h^{-1}$

BOD_5^{20} of river upstream of treated sewage discharge = 2 mg l^{-1}
velocity of river flow = 0.1 m s^{-1}
flow rate of treated sewage = 90 m^3 h^{-1}
BOD_5^{20} of treated sewage = 30 mg l^{-1}
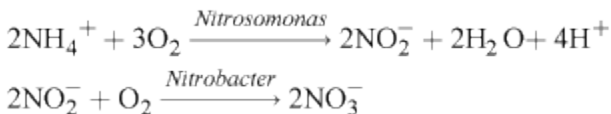temperature of river water ranges from 6 °C to 14 °C
k_L at 20 °C = 0.25 d^{-1}.

View answer

b. Plot a graph relating river water temperature to the positioning of the water intake.

View answer

8.3.2 Oxygen demand due to nitrification

As discussed in Section 4.9.2, ammonia is oxidised to nitrate in two stages:

$$2NH_4^+ + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+$$
$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2NO_3^-$$

It can be seen that the oxidation of two atoms of nitrogen in the first stage of nitrification requires six atoms of oxygen, while in the second stage of oxidation

a further two atoms of oxygen are used. In all, then, two atoms of nitrogen require eight atoms of oxygen for oxidation. Since:

two atoms of nitrogen = 2 × 14 = 28 atomic mass units
eight atoms of oxygen = 8 × 16 = 128 atomic mass units

the ratio of oxygen demand to nitrogen is equal to 128/ 28 = 4.57. This leads to the following equation:

nitrogenous biochemical oxygen demand = 4.57 × total oxidisable nitrogen

where total oxidisable nitrogen = organic nitrogen + nitrogen as ammonia.

The equation for nitrogen removal is analogous to that for BOD depletion (Equation 23):

$$N = N_0 \exp\left[\frac{-k_N x}{U_0}\right] \tag{27}$$

where

N is the ultimate nitrogenous biochemical oxygen demand (NBOD) at a distance x from the point of entry of the contaminant stream
N_0 is the ultimate NBOD at the point of mixing between the river and the contaminant stream
k_N is the NBOD decay rate constant, typically 0.3 d^{-1}

U_0 is the velocity of the river (in m d^{-1}).

N_0 may be obtained by mass balance.

Since, in general, the carbonaceous oxygen demand is satisfied first, the modelling of CBOD has taken priority in the analysis of pollution incidents.

8.4 Dissolved oxygen

Dissolved oxygen content is frequently used as an indicator of water quality in streams and rivers. The dissolved oxygen concentration downstream from a point source of BOD can be modelled using Equation 28, the Streeter–Phelps equation (Streeter and Phelps, 1925). Assuming a constant cross-sectional area for the river, the dissolved oxygen deficit D can be determined by:

$$D = D_0 \exp\left(\frac{-k_a x}{U_0}\right) + \frac{L_0 k_L}{k_a - k_L}\left[\exp\left(\frac{-k_L x}{U_0}\right) - \exp\left(\frac{-k_a x}{U_0}\right)\right] \quad (28)$$

where

D is the dissolved oxygen deficit (in mg l^{-1}) at a distance x from the point of contamination
D_0 is the dissolved oxygen deficit (in mg l^{-1}) at $x = 0$
k_a is the reaeration coefficient (in d^{-1})
U_0 is the river velocity (in m d^{-1})
L_0 is the ultimate CBOD (in mg l^{-1}) at $x = 0$
k_L is the BOD decay rate constant (in d^{-1}).

You may recall from Section 1 Equation 1 that the dissolved oxygen deficit D can also be calculated from:

$$D = C_s - C$$

where C_s is the saturation concentration of oxygen and C is the concentration of oxygen actually present. Alternatively, this can be written as:

$$D = DO_{sat} - DO \tag{29}$$

This equation can be used in conjunction with the Streeter–Phelps equation to plot levels of dissolved oxygen along the river downstream of the contamination point, as you will see shortly.

Dissolved oxygen saturation concentration

The saturation concentration of dissolved oxygen (C_s or DO_{sat}) is a function of temperature (T), salinity and barometric pressure. The effect of salinity becomes important in estuarine systems and, to a lesser extent, in rivers with high irrigation return flows. However, by far the most important parameter determining the concentration of dissolved oxygen in water is temperature. The value of C_s at zero salinity at temperature T (in °C) and one atmosphere pressure is given by:

$$C_s = 14.65 - 0.410\ 22\ T + 0.007\ 91\ T^2 - 0.000\ 077\ 74\ T^3 \tag{30}$$

Two further parameters of the Streeter–Phelps equation, the initial dissolved oxygen deficit (D_0) and the reaeration coefficient (k_a), will be discussed further in Sections 8.4.1 and 8.4.2 respectively.

8.4.1 Initial dissolved oxygen deficit

The initial dissolved oxygen deficit (D_0) is calculated from:

$$D_0 = \frac{D_{up}Q_{up} + D_eQ_e}{Q_{up} + Q_e} \qquad (31)$$

where

> D_{up} is the dissolved oxygen deficit upstream of the contamination (in mg l^{-1})
> Q_{up} is the flow rate of the river upstream of the contamination (in m^3 s^{-1})
> D_e is the dissolved oxygen deficit in the effluent stream (in mg l^{-1})
> Q_e is the flow rate of the effluent stream (in m^3 s^{-1}).

Equations 28 and 31 disregard the oxygen production due to photosynthesis, the oxygen use due to respiration, and the benthic oxygen demand. Photosynthesis is affected by several factors, e.g. turbidity of the water and intensity of sunlight. Similarly, respiration rates vary widely, ranging from 0.5 g m^{-2} d^{-1} to greater than 20 g m^{-2} d^{-1}.

Exercise 16

The following data are known for a watercourse:

D_0 = 5.0 mg l^{-1}
dissolved oxygen saturation level = 10.6 mg l^{-1}
k_a = 2.5 d^{-1}
U_0 = 0.5 m s^{-1}
L_0 = 98 mg l^{-1}
k_L = 0.25 d^{-1}.

Use these data and the Streeter–Phelps equation (Equation 28) to do the following.

a. Plot a graph of dissolved oxygen against distance downstream for x from 0 to 600 km in steps of 1.0 km.

View answer

b. From the graph, determine the maximum dissolved oxygen deficit (called the critical deficit, D_c) and the point in the river (the critical distance, x_c) at which it occurs.

View answer

An industrial effluent is accidentally discharged into a river.

a. The following values are known for the relevant factors in the Streeter–Phelps equation (Equation 28):

$D_0 = 8.0$ mg l^{-1}
dissolved oxygen saturation level = 9.8 mg l^{-1}
$k_a = 2.0$ d^{-1}
$U_0 = 0.1$ m s^{-1}
$L_0 = 80$ mg l^{-1}
$k_L = 0.25$ d^{-1}.

Generate a graph showing the dissolved oxygen concentration for 150 km from the point of discharge.

b. Determine D_c and x_c.

View answer

8.4.2 Reaeration coefficient

The atmosphere is the major source for the replenishment of dissolved oxygen in rivers. There are several correlations for the reaeration coefficient. Three favoured expressions are given below for a river water

temperature of 20 °C. Each expression is valid for a given range of depth and river water velocity, as shown in Figure 79.
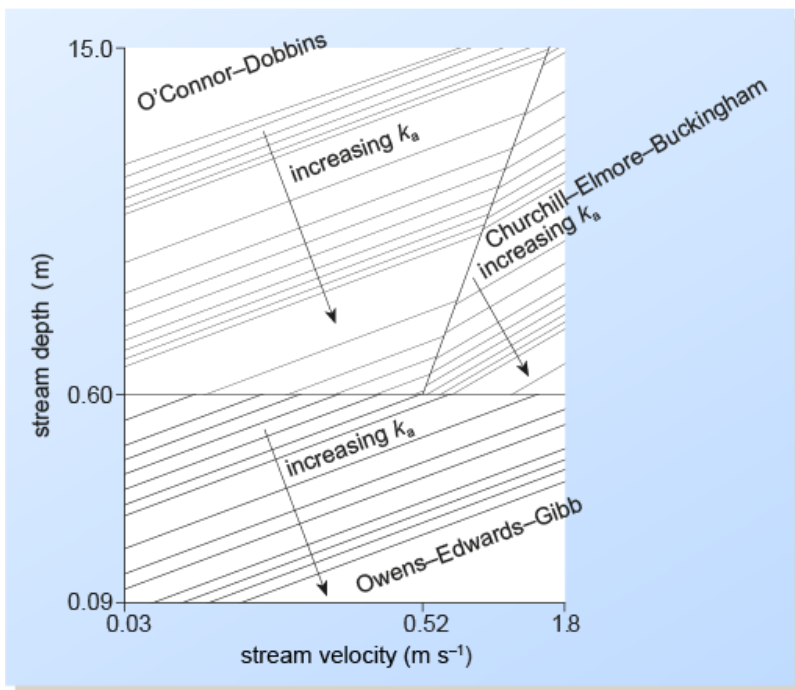

Figure 79 The regions of validity for the different correlations for the reaeration coefficient k_a (EPA, 1985)

View description

The O'Connor–Dobbins correlation

(32)

$$k_a = 3.93 \frac{U_0^{0.5}}{H^{1.5}}$$

where

k_a is the reaeration coefficient (in d^{-1}) for river water of temperature 20 °C
U_0 is the average stream velocity (in m s^{-1})
H is the average stream depth (in m).

The Churchill–Elmore–Buckingham correlation

$$k_a = 5.03 \frac{U_0^{0.969}}{H^{1.673}}$$ (33)

with U_0 and H as before.

The Owens–Edwards–Gibb correlation

$$k_a = 5.34 \frac{U_0^{0.67}}{H^{1.85}}$$ (34)

with U_0 and H as before.

The reaeration rate is affected by temperature. At a river temperature T (°C), the reaeration rate $(k_a)_T$ is approximated by the expression:

$$(k_a)_T = 1.024^{(T-20)}(k_a)_{20}$$ (35)

8.4.3 Critical distance and critical deficit

You have already seen that at the critical distance, x_c, the dissolved oxygen deficit will reach a maximum called the critical deficit, D_c. The travel time (t_c) to this critical deficit is given by:

$$t_c = \frac{1}{k_a - k_L} \ln\left[\frac{k_a}{k_L}\left(1 - D_0\frac{(k_a - k_L)}{k_L L_0}\right)\right] \qquad (36)$$

where

k_a is the reaeration coefficient (in d^{-1})
k_L is the BOD decay rate constant (in d^{-1})
D_0 is the dissolved oxygen deficit (in mg l^{-1}) at $x = 0$
L_0 is the ultimate CBOD (in mg l^{-1}) at $x = 0$.

Once the travel time and river velocity are known, the critical distance can be computed:

$$x_c = U_0 t_c \qquad (37)$$

The critical deficit can be found from:

$$\qquad (38)$$

$$D_c = \left[D_0 - \frac{L_0 k_L}{k_a - k_L} \right] \left[\frac{k_a}{k_L} \left(1 - D_0 \frac{(k_a - k_L)}{k_L L_0} \right) \right]^{-\frac{k_a}{k_a - k_L}}$$

$$+ \left[\frac{L_0 k_L}{k_a - k_L} \right] \left[\frac{k_a}{k_L} \left(1 - D_0 \frac{(k_a - k_L)}{k_L L_0} \right) \right]^{\frac{k_L}{k_a - k_L}}$$

Exercise 17

A river of 0.8 m average depth and 1.5 m s^{-1} velocity receives a flow of treated effluent at 2.0 m^3 s^{-1} from an industrial plant. A mechanical failure in the plant results in an effluent with a BOD_5^{20} of 1500 mg l^{-1} entering the river. Calculate the critical dissolved oxygen deficit and the distance from the effluent discharge point at which it occurs, given that:

effluent and river temperature = 10 °C
effluent dissolved oxygen concentration = 0 mg l^{-1}
k_L = 0.15 d^{-1} in the river
BOD_5^{20} of river upstream of effluent discharge = 3 mg l^{-1}
river is 80% saturated with oxygen upstream of the effluent discharge
river flow rate = 10 m^3 s^{-1}.

Assume that the saturation concentration of oxygen in the effluent and in the river is given by Equation 30.

SAQ 60

An illegal discharge of farmyard slurry with a BOD_5^{20} of 450 mg l^{-1} enters a river. The following data are known:

    average river depth = 0.7 m
    river flow rate = 2.0 m^3 s^{-1}
    average river velocity = 0.2 m s^{-1}
    BOD_5^{20} of river upstream of farm = 1.5 mg l^{-1}
    flow rate of slurry = 0.4 m^3 s^{-1}
    k_L at 20 °C = 0.3 d^{-1}
    dissolved oxygen concentration in river upstream of effluent discharge = 7.0 mg l^{-1}.

Determine the critical dissolved oxygen deficit and its location with reference to the entry point of the slurry into the river. Assume that the saturation concentration of dissolved oxygen in the river and the effluent is that of clean water. The effluent and river water are both at 20 °C and the effluent has a dissolved oxygen content of 0.1 mg l^{-1}.

8.4.4 Effect of nitrification

Nitrification can be significant in rivers where nitrifying bacteria have become established due to, say, N-bearing pollutant streams discharging into a river in which a stable river substrate facilitates their attachment and colonisation.

If nitrogenous BOD is to be taken into account, the expression for the dissolved oxygen deficit becomes:

$$D = D_0 \exp\left(\frac{-k_a x}{U_0}\right) + \frac{L_0 k_L}{k_a - k_L}\left[\exp\left(\frac{-k_L x}{U_0}\right) - \exp\left(\frac{-k_a x}{U_0}\right)\right] \qquad (39)$$
$$+ \frac{N_0 k_N}{k_a - k_N}\left[\exp\left(\frac{-k_N x}{U_0}\right) - \exp\left(\frac{-k_a x}{U_0}\right)\right]$$

where

> N_0 is the ultimate nitrogenous BOD (NBOD) in the river after entry of the pollutant stream
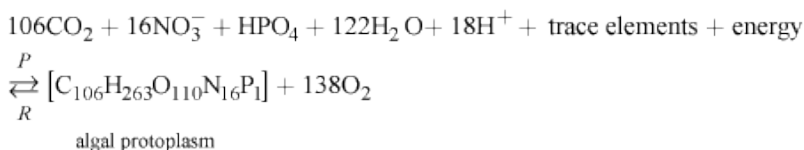> k_N is the decay rate constant of NBOD in the river.

Nitrification is very much pH dependent, with an optimum pH range of 8.0–8.5. It is unlikely to be significant below pH 7.0.

The value of k_N at temperature T is the same as that of k_L, i.e. (Equation 26):

$$k_N = 1.047^{(T-20)} \times (k_N)_{20}$$

8.5 Nutrients and eutrophication potential

The presentation of excess plant nutrients can lead to eutrophication. A possible representation for the stoichiometry of algal growth is:

$$106CO_2 + 16NO_3^- + HPO_4 + 122H_2O + 18H^+ + \text{trace elements} + \text{energy}$$
$$\underset{R}{\overset{P}{\rightleftarrows}} [C_{106}H_{263}O_{110}N_{16}P_1] + 138O_2$$

algal protoplasm

where

P is the process of photosynthesis
R is the process of respiration.

The ratio of C:N:P in the algae in terms of atoms can be seen to be 106:16:1; converted to mass, this comes to 41:7.2:1. Thus only a small amount of phosphorus is needed, in relation to the amounts of carbon and nitrogen, to support algal growth. Conversely, if the phosphorus is not present in the amount required then algal production will be curtailed, regardless of how much of the other nutrients is available. In this situation, phosphorus is termed the growth-limiting element.

Nitrogen uptake by algae is generally in the form of nitrate, if any is available. Different types of freshwater algae, however, can use organic nitrogen, or inorganic nitrogen in the form of ammonia. Algal uptake of phosphorus is usually in its inorganic form as the orthophosphate ion.

Plotting the ratio of total nitrogen (TN) to total phosphorus (TP), the TN:TP ratio, can give an indication as to which element is limiting growth of the algae. Conversely, it can give information on what control measures to take to prevent eutrophication.

This assumes that other factors such as temperature and river velocity are favourable to algal growth in the given watercourse.

8.5.1 Estimating in-stream nutrient concentrations

If TN and TP can be considered conservative (i.e. not reactive and remaining in either solution or suspension), a mass balance approach can be formulated for these constituents. In reality this assumption may not be met for a variety of reasons, e.g. algae use nutrients, die and settle to the bottom. Assuming TN and TP to be conservative, however, should give an estimate of the upper limit of the in-stream concentrations of these elements.

The in-stream concentration of TN (TN_0) resulting from a point discharge (e.g. an effluent stream) is given by:

$$TN_0 = \frac{TN_{up}Q_{up} + TN_eQ_e}{Q_{up} + Q_e} \qquad (40)$$

where

TN_0 is the resulting in-stream TN concentration (in mg N l^{-1})

TN_{up} is the in-stream TN concentration upstream of the discharge (in mg N l^{-1})

Q_{up} is the flow rate of the river upstream of the point of discharge (in m^3 s^{-1})

TN_e is the concentration of TN in the point discharge (in mg N l^{-1})

Q_e is the flow rate of the point discharge (in m^3 s^{-1}).

For a diffuse or distributed discharge (say run-off from a field of crops), and assuming no removal of N by bacterial or other action, in-stream concentration of TN would be given by:

$$TN = TN_0 + \frac{\Delta Q\,x}{Q}\,(TN_r - TN_0) \qquad (41)$$

where

TN_0 is the in-stream TN concentration at $x = 0$ (in mg N l^{-1})

ΔQ is the incremental flow increase per unit distance (in m^3 s^{-1} km^{-1})

x is the distance downstream from the reference point (in km)

Q is the stream flow rate at x (in $m^3\,s^{-1}$)

TN_r is the concentration of TN entering with the distributed flow (in mg N l^{-1}).

Equations for TP are analogous to those for TN. Thus for a point source of P:

$$TP_0 = \frac{TP_{up}Q_{up} + TP_eQ_e}{Q_{up} + Q_e} \tag{42}$$

and for a diffuse discharge of P:

$$TP = TP_0 + \frac{\Delta Q\, x}{Q}(TP_r - TP_0) \tag{43}$$

Exercise 18

Inappropriate application rates of chemical fertiliser result in N and P being washed into a river flowing for 10 km across an agricultural area. The following data are known:

initial flow rate of river (i.e. without contribution of run-off) = 20 $m^3\,s^{-1}$

flow rate of run-off over the 10 km length of river = 4 $m^3\,s^{-1}$

initial concentration of TN in river = 0.05 mg l^{-1}

initial concentration of TP in river = 0.02 mg l^{-1}

concentration of TN in run-off = 1.0 mg l^{-1}
concentration of TP in run-off = 0.25 mg l^{-1}.

a. Determine the concentration profiles of total-N and total-P along the length of the river through the farmland.

View answer

b. Plot the ratio TN:TP as a function of distance.

View answer

SAQ 61

A 15 km stretch of river flows across agricultural land on which wheat is grown. Nitrate and phosphate from artificial fertilisers are leached out of the fields and enter the river. The following data are known:

flow rate of river upstream of wheat fields = 10 m^3 s^{-1}

flow rate of run-off along the 15 km stretch of river = 5.0 m^3 s^{-1}

concentration of TN in river upstream of wheat fields = 0.3 mg N l^{-1}

concentration of TP in river upstream of wheat fields = 0.03 mg P l^{-1}

concentration of TN in run-off = 1.5 mg l^{-1}

concentration of TP in run-off = 0.25 mg l^{-1}.

a. Determine the concentration profiles of TN and TP along the length of the river.
b. Determine the point in the river where the limiting element changes from one plant nutrient to the other, assuming the native species of algae has an N:P ratio of 7.5:1.

Assume that the input of run-off and the concentration of the compounds in it are uniform along the length of the river, and that all other elements (apart from N and P) needed for algal growth are present in excess.

View answer

8.6 Total coliform bacteria

Coliform bacteria are considered an indicator of the presence of pathogenic organisms and, as such, relate to the potential for public health problems. The allowable levels of total coliform bacteria in a waterway vary with the intended use of the water – for example, in water for bathing, in a river or in the sea.

A major source of coliforms is treated sewage, but the contribution from urban stormwater run-off can also be significant, especially through combined sewer overflows.

For a point source of coliforms, such as a partially treated effluent, the equation representing total coliforms is:

$$TC = TC_0 \exp\left(-\frac{k_{tc}x}{U_0}\right)$$

(44)

where

TC is the total coliform number (MPN per 100 ml) at a point x m from the point of discharge
TC_0 is the initial total coliform number (MPN per 100 ml)
k_{tc} is the decay coefficient for total coliforms (in d^{-1})
x is the distance downstream from the point of discharge (in m)
U_0 is the velocity of the river (in m d^{-1}).

The initial total coliform number is given by (assuming perfect mixing):

$$TC_0 = \frac{TC_{up}Q_{up} + TC_eQ_e}{Q_{up} + Q_e}$$

(45)

where

TC_{up} is the total coliform number upstream of the discharge point (MPN per 100 ml)
Q_{up} is the flow rate of the river upstream of the discharge point (in $m^3 s^{-1}$)
TC_e is the total coliform number in the effluent stream (MPN per 100 ml)

Q_e is the flow rate of the effluent (in $m^3 \ s^{-1}$).

The decay coefficient varies with temperature according to the equation:

$$k_{tc} = 1.0 + 0.02(T - 20) \qquad (46)$$

where T is the water temperature in °C.

Exercise 19

A sewage treatment works discharges a poor effluent with a total coliform level of 4×10^6 per 100 ml. The effluent is discharged into a river with a background total coliform count of 800 per 100 ml, and the following data are known:

river flow rate = 20 $m^3 \ s^{-1}$
effluent flow rate = 5 $m^3 \ s^{-1}$
river and effluent temperature = 10 °C
river velocity = 0.15 $m \ s^{-1}$.

a. Estimate the distance downstream from the sewage treatment works outfall where the level of total coliforms would be down to 500 per 100 ml (which has been identified as a safe level for recreational water).

View answer

b. Plot a graph showing the decrease in the total coliform number against the distance down the river.

SAQ 62

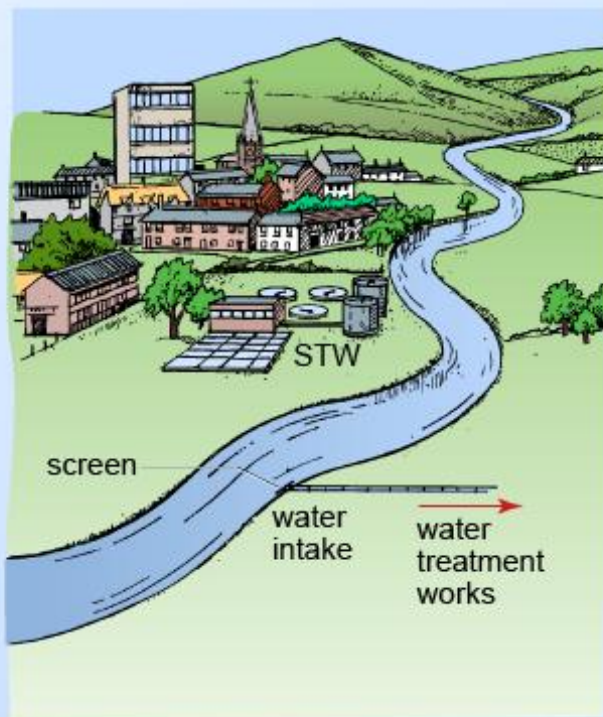Figure 87 shows a water intake point 15 km downstream of the outlet from a sewage treatment works (STW).

Figure 87 River and sewage works diagram

The following data are known:

flow rate of treated sewage = 50 m^3 h^{-1}
river flow rate = 200 m^3 h^{-1}
river velocity = 1 m s^{-1}

k_{tc} = 0.70 d^{-1} at existing river temperature
total coliforms in river water = 1000 per 100 ml.

a. Calculate the level of total coliforms that can be allowed in the outlet from the sewage treatment works such that the level at the water intake point is a maximum of 50 000 (MPN) per 100 ml.

View answer

b. Determine the required removal of total coliforms at the sewage treatment works if the raw sewage has a total coliform count of 4.0 × 10^8 per 100 ml.

View answer

c. Generate a graph showing the total coliform level in the river against distance, and find the point at which the river water would be suitable for abstraction for a new water treatment plant that can handle a total coliform level of 5000 per 100 ml. Assume the coliform removal rate is that derived in part (b).

View answer

d. Verify the location of the abstraction point in part (c) by calculation.

View answer

8.7 Summary

River quality modelling allows us to predict the impacts that pollutants can have on a watercourse. The basic models introduced in this section have covered the following variables:

- biochemical oxygen demand
- plant nutrients (nitrogen and phosphorus)
- coliforms.

Glossary

accumulative
Growing by gradual increase.

activated sludge process
(activated sludge system) A wastewater treatment process by which bacteria that feed on organic wastes are continuously circulated and put in contact with organic waste in the presence of oxygen to increase the rate of decomposition.

acute
Having a rapid onset and/or a short course (opposite of chronic).

advanced wastewater treatment
The wastewater treatment undertaken after tertiary treatment, with the aim of removing remaining pollutants such as trace organics or pathogens.

algal bloom
A rapid increase in the population of algae in an aquatic system.

bioaccumulation
The accumulation of a substance, such as a pesticide or another organic chemical, in the tissues of a living organism.

bioavailability
Of a substance, the degree to which or rate at which that substance is absorbed or becomes available at the site of physiological activity, i.e. the extent to which it can be taken up by living organisms.

biochemical oxygen demand
(BOD) The amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down the organic material present in a given water sample at a certain temperature over a specific time period.

biodegradable
Capable of being broken down into innocuous products by the action of microorganisms or other living creatures.

biological filtration
A wastewater treatment process where the effluent is distributed over a fixed bed of rocks or other media. The wastewater flows downward and causes a layer of microbial slime to grow, covering the bed of media. Aerobic conditions are usually maintained by natural convection of air.

biomagnification
The sequence of processes in an ecosystem by which higher concentrations of a particular chemical are reached in organisms higher up the food chain.

biota
The total collection of organisms in a geographic region or time period.

blue corridors
A network of watercourses and wetlands linking urban and rural areas that allows wildlife to move through urban areas into the wider countryside, permitting genetic transport and exchange.

blue-green algae
(cyanobacteria) Also known as blue-green bacteria and Cyanophyta. A phylum of bacteria that obtain their energy through photosynthesis.

brackish
Term referring to water that has higher *salinity* than freshwater but lower than seawater. Brackish water can be found in aquifers, or when seawater mixes with freshwater (as in estuaries). It contains between 0.5 and 30 grams of salt per litre (i.e. between 500 and 30 000 ppm). This is often expressed in parts per thousand (ppt), i.e. between 0.5 and 30 ppt.

catalyst
A substance that increases the rate of a chemical reaction without itself undergoing any permanent chemical change.

cations
Ions or groups of ions that have a positive charge and characteristically move toward the negative electrode in electrolysis.

chemical oxygen demand
(COD) The oxygen needed to chemically oxidise all the carbonaceous material present.

chemical speciation
The chemical form or compound in which an element occurs in both non-living and living systems.

chronic
Of a condition or disease, persistent or otherwise long-lasting in its effects.

colloidal
Term referring to a system in which finely divided particles, which are approximately 10×10^{-10} m to $10\,000 \times 10^{-10}$ m in size, are dispersed within a continuous medium in a manner that prevents them from being filtered easily or settled rapidly.

comminution
The action of reducing a material to minute fragments.

cyanobacteria
See *blue-green algae*.

denitrification
A process where the oxygen in nitrate is used up, and nitrogen gas is produced as a result.

diffuse sources
Sources of pollution (often small) that have no specific point of discharge.

diffusion
The movement of atoms or molecules from an area of high concentration to one of low concentration.

dissociate
In reference to ionic compounds (complexes or salts), to separate or split into smaller particles, ions or radicals, usually in a reversible manner.

dry weather flow
(DWF) The average flow during seven consecutive days without rain following seven days during which the rainfall did not exceed 0.25 mm on any one day.

ecosystem services
Services provided by the natural environment that benefit people.

emulsion
A mixture of two or more liquids that are normally immiscible.

enzyme
A substance produced by a living organism that acts as a catalyst to bring about a specific biochemical reaction.

equilibrium
The condition of a system in which all competing influences are balanced. In chemistry, an equilibrium arrow (a combination of two half-headed arrows facing in opposite directions) denotes that the chemical reaction is a reversible reaction – in equilibrium.

eutrophication
The enrichment of a water body with inorganic plant nutrients such as nitrates and phosphates. Eutrophication may occur naturally but can also be the result of human activity (from fertilizer run-off and sewage discharge), and is particularly evident in slow-moving rivers and shallow lakes.

facultative anaerobes
Organisms, such as certain bacteria and fungi, that are able to alter their metabolism to grow in either the presence or absence of oxygen.

flocculent
Having the appearance of small puffballs.

green algae
The large group of algae (more than 7000 species) from which the embryophytes (higher plants) emerged.

green infrastructure
The planned network of multi-functional green spaces capable of delivering environmental and quality of life benefits for local communities. It also includes 'blue' spaces or *blue corridors*.

green roofs
Roofs with plants growing on them. The plants provide a degree of retention, attenuation and treatment of rainwater, and promote evapotranspiration.

greywater
See *sullage*.

heat island effect
As urban areas develop, changes occur in their landscape, with buildings, roads and other infrastructure replacing open land and vegetation. Surfaces that were once permeable and moist become impermeable and dry. These changes cause urban regions to become warmer than their rural surroundings, forming 'islands' of higher temperatures in the landscape.

homeostasis
Maintenance of a constant internal environment.

hydrological cycle
The natural water cycle that describes the continuous movement of water on, above and below the surface of the Earth.

indicators
Species that can be used to monitor the health of an environment or ecosystem.

ionic
Related to *ions*.

ions
Atoms or molecules in which the total number of electrons is not equal to the total number of protons, giving a net positive or negative electrical charge.

leachate
Any liquid that, in passing through matter, extracts solutes, suspended solids or any other component of the material through which it has passed.

lethal
Related to or causing death.

macroinvertebrates
Organisms that are large (macro) enough to be seen with the naked eye and lack a backbone (invertebrate).

molecular diffusion
The thermal motion of all liquid or gas particles at temperatures above absolute zero (-273 °C or 0 K).

mutagenicity
The capacity to induce mutation.

nephelometric
Relating to a method for determining the amount of cloudiness, or *turbidity*, in a solution based upon

measurement of the effect of this turbidity upon the transmission and scattering of light.

nitrification
The process by which ammonia is converted to nitrites (NO^{2-}) and then nitrates (NO^{3-}). This process is carried out by specialised bacteria in nature.

nitrogen fixation
The process by which nitrogen gas (N_2) in the atmosphere is converted into ammonia (NH_3).

oligotrophic
Having low levels of plant nutrients and high levels of dissolved oxygen.

permanent hardness
Hardness (mineral content) that cannot be removed by boiling. It is usually caused by the presence of calcium sulfate and/or magnesium sulfates in the water, which precipitate out as the temperature increases. Ions causing permanent hardness of water can be removed using a water softener or ion exchange column.

persistent organic pollutants
(POPs) Organic compounds that are highly toxic, persist in the environment, bioaccumulate in human and animal tissue, and can be transported by wind and water. Most POPs are pesticides.

plume
A spread-out shape resembling a feather.

point sources
Single identifiable sources of pollution from which pollutants are discharged, such as a pipe.

preliminary treatment
The initial stage within a wastewater treatment plant where solids from the incoming influent are removed to enhance further treatment processes and prevent damage to equipment.

primary production
The production of organic compounds from atmospheric or aquatic carbon dioxide. It may occur through the process of photosynthesis, using light as a source of energy.

primary treatment
The stage in wastewater treatment where screens and sedimentation tanks are used to remove most of the material that floats or will settle.

radionuclides
Atoms with an unstable nucleus, characterised by excess energy available to be imparted either to newly created radiation particles within the nucleus or via internal conversion.

salinity
The saltiness or dissolved salt content (such as sodium chloride, magnesium and calcium sulfates, and bicarbonates) of a water body or in soil.

saturation concentration
The point of maximum concentration, when no more of the solute can be dissolved in the solvent.

secondary treatment
The phase in a wastewater treatment process where bacteria are used to digest organic matter in the wastewater.

solution
A homogeneous mixture composed of only one phase. In such a mixture, one substance (the solute) is dissolved in another substance (the solvent).

solvent
A substance, usually a liquid, capable of dissolving another substance.

sublethal
Having an effect less than lethal, with changes in physiological processes, growth, reproduction behaviour, development, etc.

substratum
Any layer or stratum lying underneath another.

sullage
(greywater) The wastewater from baths, showers, hand basins, dishwashers and washing machines.

supernatant
The liquid lying above a solid residue after crystallisation, precipitation, centrifugation or other similar process.

suspension
A heterogeneous mixture containing solid particles that are sufficiently large for sedimentation – usually larger than 1 micrometre in diameter. The internal phase

(solid) is dispersed throughout the external phase (fluid) through mechanical agitation.

swales
Linear grass-covered depressions that lead surface water overland from the drained surface to a storage or discharge system, typically using road verges.

synergism
Condition in which the interaction of two or more substances results in a combined effect that is greater than the sum of their separate effects.

tailings dam
Dam in which tailings – the materials left over after the process of separating the valuable fraction from the uneconomic fraction of an ore – are deposited. Tailings are distinct from overburden, which is the waste rocks or materials overlying an ore or mineral body that are displaced during mining without being processed.

temporary hardness
The type of water hardness caused by the presence of dissolved bicarbonate minerals (calcium bicarbonate and magnesium bicarbonate). Temporary hardness can be reduced either by boiling the water, or by the addition of lime (calcium hydroxide) through the softening process of lime softening.

tertiary treatment
Wastewater treatment beyond the secondary or biological stage of treatment. It includes the removal of nutrients such as phosphorus and nitrogen and a high percentage of suspended solids.

trade wastes

Any wastewater produced on trade premises (and in pursuit of a trade or business).

trophic system

The sequential stages in a food chain, occupied by producers at the bottom, and in turn by primary, secondary and tertiary consumers.

turbidity

A measure of the degree to which water loses its transparency due to the presence of suspended particulates (which are generally invisible to the naked eye).

water column

A conceptual column of water from the surface to the bottom sediments. This concept is used chiefly for environmental studies evaluating the stratification or mixing (e.g. by wind-induced currents) of the layers in a lake, stream or ocean.

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Acknowledgements

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Answer

Flowing water in a river will disperse plant nutrients, whereas in the standing water of a lake the nutrients are more likely to accumulate. Eutrophication will cause excessive plant growth that could eventually lead to parts of the lake becoming choked with plants.

Back

Answer

From Table 1, at 10 ºC the saturation concentration of dissolved oxygen in pure water would be 11.26 g m^{-3}.

Since the water contains dissolved salts, a correction is needed. From Table 3, the correction factor to use (for a conductivity of 16 000 µS cm^{-1}, with water at 10 ºC) is 0.942.

Hence, the saturation concentration of dissolved oxygen will be 0.942 × 11.26 = 10.6 g m^{-3} (to 3 significant figures).

Back

Answer

We need to use Equation 1. From Table 1, C_S = 11.3 g m^{-3} at 10 °C, and from the information given above, C = 8.1 g m^{-3}. Thus Equation 1 gives:

$$D = 11.3 - 8.1 \text{ g m}^{-3} = 3.2 \text{ g m}^{-3}$$

Back

Answer

Correct:

A slight breeze blowing over the water

Wrong:

Doubling the oxygen deficit

Large amounts of salts being discharged into the water

The water flowing over a weir

Raising the temperature of the water by 10 °C

Only if the wind is strong enough to cause turbulence will it result in an increase in the rate of oxygen transfer across the water–air interface; otherwise it will not significantly affect the rate of transfer. The atmosphere contains approximately 21% oxygen by volume so there is always plenty of oxygen in the air immediately above the interface, even when the air is not moving.

Back

Answer

In warm weather when aquatic plants are growing rapidly, their photosynthetic processes usually result in a diurnal variation in the concentration of dissolved oxygen; it is high during the day and low at night. During summer days the water may become supersaturated with dissolved oxygen, especially during the afternoon. After sunset, photosynthesis ceases but respiration by aquatic organisms continues and the concentration of dissolved oxygen declines, generally reaching its lowest levels early in the morning.

In temperate countries, the oxygen demand as a result of bacterial decay of leaves and other organic matter that have fallen into the water means that levels of dissolved oxygen will also be very low in the autumn.

Back

Answer

Group	Family	Points scored
mayfly nymphs	Ephemeridae	10
	Baetidae	4
stonefly nymphs	three families	10 × 3 = 30
cased caddis larvae	two families	7 × 2 = 14
freshwater shrimps	Gammaridae	6
freshwater limpets	Ancylidae	6
alderfly larvae	Sialidae	4
snails	three families	3 × 3 = 9
Total		**83**

The relatively high score and the presence of clean water indicators (i.e. sensitive species) show that the river is clean and only slightly impacted.

Back

Answer

Correct:

> d. Permanent and temporary hardness both contribute to scaling, but for permanent hardness the scaling is due to decreased solubility, while for temporary hardness the scaling is due to the formation of new insoluble compounds.

Wrong:

> a. 'Sewage fungus' is a single species of fungus.

False: 'sewage fungus' is a mixture of different species of bacteria, fungi, algae and protozoa.

> b. Carbon dioxide and oxygen both react with water.

False: oxygen does not react with water but with the substances contained in the water.

> c. With reference to the bicarbonate–carbonate equilibrium, in a water with high pH, any carbon dioxide that is present will remain as carbon dioxide.

False: high pH values correspond to low H^+ alkaline conditions. From Equation 2, this will mean a decrease in hydrogen ions and thus the equilibrium moves to the right, increasing the concentration of carbonate and reducing the concentration of dissolved carbon dioxide.

Statement (d) is true.

Statement (a) is false: 'sewage fungus' is a mixture of different species of bacteria, fungi, algae and protozoa.

Statement (b) is false: oxygen does not react with water but with the substances contained in the water.

Statement (c) is false: high pH values correspond to low H^+ alkaline conditions. From Equation 2, this will mean a decrease in hydrogen ions and thus the equilibrium moves to the right, increasing the concentration of carbonate and reducing the concentration of dissolved carbon dioxide.

Back

Answer

According to Equation 2, the removal of carbon dioxide by plants causes the reaction to shift to the left to compensate. The concentration of hydrogen ions then drops and so the pH rises.

Back

Answer

a. From Table 2, the salinity of the water is 10 621 mg l^{-1}.

b. Table 1 shows that at 25 °C, the saturation concentration of dissolved oxygen in pure water will be 8.12 g m^{-3} or 8.12 mg l^{-1}. From Table 3, the correction factor for saline water of 18 000 µS cm^{-1} is 0.941. Therefore the dissolved oxygen level of the underground water will be 0.941 × 8.12 = 7.64 mg l^{-1} (to 3 s.f.). This is well above the minimum value needed for *Tilapia*, and so there should be healthy growth of the fish, provided all other requirements are met.

Back

Answer

Using the information given in Table 4:

Group	Family	Points scored
mayfly nymphs	Baetidae	4
snails	two families	3 × 2 = 6
leeches	two families	3 × 2 = 6
fly larvae	Chironomidae	2
	Culicidae	1
true worms	three families	1 × 3 = 3
Total		**22**

The BMWP score is 22. The low score and the absence of clean water indicators signify that the effluent discharge is having a detrimental effect on the river quality.

Back

Answer

Correct:

b. The phosphate content in sewage can largely be attributed to detergents, food wastes and excretion from the human body.

c. The BOD of tannery effluent is approximately 10 times that of domestic sewage.

Wrong:

a. Any input of pollutants into a river is undesirable.

False: low concentrations of organic pollutants can serve as nutrients for the river organisms.

d. The only concern with antibiotics being discharged with effluents into rivers is the fact that antibiotic-resistant bacteria will emerge.

False: antibiotics can also cause mutagenicity and bring about allergic responses.

e. Surface water run-off contains a wide variety of pollutants that can all be said to originate from our current lifestyle (e.g. heavy vehicle use, keen

interest in gardening and hence fertiliser and pesticide use, etc.).

False: surface water run-off, while carrying mostly pollutants that can be traced to motor transport, often contains pollutants from historic use of materials such as lead in old plumbing systems, paint, etc.

Statements (b) and (c) are true.

Statement (a) is false: low concentrations of organic pollutants can serve as nutrients for the river organisms.

Statement (d) is false: antibiotics can also cause mutagenicity and bring about allergic responses.

Statement (e) is false: surface water run-off, while carrying mostly pollutants that can be traced to motor transport, often contains pollutants from historic use of materials such as lead in old plumbing systems, paint, etc.

Answer

a. The effluent flow rate is 600 m^3 per hour, which equates to 14 400 m^3 per day. The final temperature in the river will be:

$$\frac{(14\ 400 \times 40) + (20\ 000 \times 15)}{14\ 400 + 20\ 000} = 25.47\ °C$$

b. The higher temperature will:
  - increase the metabolic rate of the aquatic organisms in the river
  - decrease the level of dissolved oxygen, affecting organisms and plants in the water
  - cause species more suited to waters warmer than the ambient to become established
  - prevent fish from migrating upstream past the entry point of the heated effluent.

Back

Answer

Correct:

> d. A reduction of dissolved oxygen in both cases causes the depletion of species.

> e. Once the dissolved oxygen content is decreased, only the removal of the offending pollutant can allow an increase in species.

Wrong:

> a. Depletion of oxygen occurs because of an increase in the activities of primary producers in both cases.

False: depletion of oxygen occurs in both cases due to the activities of decomposers. An increase in primary producers (plants) would increase oxygen levels.

> b. In both cases it is the presence of plant nutrients (nitrates and phosphates) that causes the death of green plants and depletion of oxygen.

False: only in eutrophication are plant nutrients present, and these will usually encourage plant growth.

> c. The difference in the proportion of producers and consumers between organically polluted waters and eutrophic waters is negligible.

False: in organically polluted waters the producers are only a small proportion of the ecology, making up less than 25% of the population, whilst in eutrophic waters they constitute more than 75%. The proportion of consumers, on the other hand, is similar in both situations (though slightly greater in organically polluted waters).

Statements (d) and (e) are true.

Statement (a) is false: depletion of oxygen occurs in both cases due to the activities of decomposers. An increase in primary producers (plants) would increase oxygen levels.

Statement (b) is false: only in eutrophication are plant nutrients present, and these will usually encourage plant growth.

Statement (c) is false: in organically polluted waters the producers are only a small proportion of the ecology, making up less than 25% of the population, whilst in eutrophic waters they constitute more than 75%. The proportion of consumers, on the other hand, is similar in both situations (though slightly greater in organically polluted waters).

Back

Answer

Correct:

> c. Effluents from fish farms can be badly polluted. Concern has arisen about these effluents mainly because they contain unconsumed food and faecal matter from fish.

> e. Metals that are water soluble are able to bioaccumulate by diffusing across the biological membranes of organisms.

Wrong:

> a. Continuously flowing organic pollutants such as domestic sewage cannot cause long-term damage to a watercourse in the way that toxic pollutants can.

False: heavy organic loads on a watercourse can cause long-term damage to the water in the vicinity of the effluent outfall. However, recovery is more likely if pollution ceases than would be the case for toxic chemicals.

> b. A temperature rise in a waterway leads to higher productivity but doesn't affect the BOD.

False: the BOD will increase, as the metabolic rates of the microorganisms will be higher at a higher temperature.

> d. Pesticide pollution of watercourses is due solely to large-scale use of these compounds by farmers.

False: householders use a large quantity of pesticides in the form of herbicides and insecticides, and these can also contribute to water pollution.

Statement (e) is true. Statement (c) is also true, though concern has also arisen because fish farm effluents contain antibiotics (see Section 2).

Statement (a) is false: heavy organic loads on a watercourse can cause long-term damage to the water in the vicinity of the effluent outfall. However, recovery is more likely if pollution ceases than would be the case for toxic chemicals.

Statement (b) is false: the BOD will increase, as the metabolic rates of the microorganisms will be higher at a higher temperature.

Statement (d) is false: householders use a large quantity of pesticides in the form of herbicides and insecticides, and these can also contribute to water pollution.

Answer

Correct:

> b. In toxicity tests for a proposed discharge, the most sensitive species in the receiving watercourse should be used as the test organism.

> e. *Clostridium perfringens* is a pathogenic bacterium that lives in the human gut and can cause food poisoning.

Wrong:

> a. The toxicities of individual chemicals in a mixture can be summed up to give an overall toxicity figure. This is simpler than testing a complex mixture.

False: there may be synergistic effects between the individual chemicals in the mixture.

> c. When suspended solids settle on the river bed, it is only benthic plants that are affected, as the light will not reach the leaves.

False: fish spawning and the ecology of invertebrates are also disrupted.

> d. *E. coli* is a species of bacterium that inhabits human intestines and is always harmless.

False: certain strains of *E. coli* (e.g. *E. coli* O157:H7) are pathogens and can cause fatalities.

> f. Controlling the discharge of the culprit chemicals from industry will overcome the problem of endocrine disruptors.

False: the discharge of oestrogens, often at high levels, due to the use of contraceptive pills will still contribute to the problem.

Statements (b) and (e) are true.

Statement (a) is false: there may be synergistic effects between the individual chemicals in the mixture.

Statement (c) is false: fish spawning and the ecology of invertebrates are also disrupted.

Statement (d) is false: certain strains of *E. coli* (e.g. *E. coli* O157:H7) are pathogens and can cause fatalities.

Statement (f) is false: the discharge of oestrogens, often at high levels, due to the use of contraceptive pills will still contribute to the problem.

Back

Answer

Cholera	bacterium
Poliomyelitis	virus
Typhoid	bacterium
Bilharzia	helminth
Anthrax	bacterium
Cryptosporidiosis	protozoan

Back

Answer

We have 250 m^3 of sewage:

$$\text{density} = \frac{\text{mass}}{\text{volume}} \quad \text{and} \quad \text{mass} = \text{density} \times \text{volume}$$

So:

$$\text{mass of sewage} = 1000 \text{ kg m}^{-3} \times 250 \text{ m}^3$$
$$= 2.5 \times 10^5 \text{ kg}$$

Sewage is up to 99.9% water. So, the amount of water will be:

$$\frac{99.9}{100} \times 2.5 \times 10^5 = 249\ 750 \text{ kg}$$

The remaining 0.1% (250 kg) will be made up of 70% organic material and 30% inorganic material. Thus the mass of organic material is:

$$\frac{70}{100} \times 250 = 175 \text{ kg}$$

This will consist of:

65% proteins = 113.75 kg

25% carbohydrates = 43.75 kg

445

10% fats = 17.5 kg

The remaining 30% of the 250 kg will be inorganic (grit, metals and salts). This would be 75 kg.

Thus $250\,m^3$ of domestic sewage is made up of 249 750 kg water, 175 kg organic material (made up of 113.75 kg protein, 43.75 kg carbohydrate and 17.5 kg fat), and 75 kg inorganic material.

Back

Answer

Correct:

> Size

Wrong:

> Gravity flow

> Pipe material

> Jointing

Sewers may receive the flow from several underground drains, so they should be larger. The pipe materials and jointing are usually similar for both drains and sewers, as there are the same constraints on both. Also, both drains and sewers are laid to exploit gravity wherever possible.

Note that although a distinction has been drawn in this text, in common usage the terms 'drain' and 'sewer' are interchangeable.

Back

Answer

Correct:

Diameter

Pressure

Gradient

Speed of flow

Wrong:

Type of effluent

All will differ except the type of effluent.

The diameter of a rising sewer main will be smaller than that of a gravity sewer.

The pressure in a gravity sewer is just local atmospheric pressure. A rising main flowing full is under greater than atmospheric pressure because of the pump pressure.

A gravity sewer slopes downwards. A rising sewer main, as its name suggests, slopes upwards.

The flow velocity in a rising main will be higher for a given flow rate than in a gravity sewer, because of the reduced flow area (since the diameter of the rising main would be smaller than that of the gravity sewer).

Back

Answer

Since there are 1000 litres in a cubic metre, the domestic and trade effluent flow is:

$$20\,000 \times 0.25 = 5000 \text{ m}^3 \text{ d}^{-1}$$

Then, since the infiltration rate = 0.2 × *DWF*:

$$DWF = 5000 + 0.2\,DWF$$
$$0.8\,DWF = 5000$$
$$DWF = \frac{5000}{0.8}$$
$$= 6250 \text{ m}^3 \text{ d}^{-1}$$

The maximum flow to the treatment plant (given by 3 × *DWF*) will be:

$$3 \times 6250 = 18\,750 \text{ m}^3 \text{ d}^{-1}$$

Back

Answer

From Table 11, the volume of sewage generated each day will be as follows:

from the offices, 600 × 60 = 36 000 litres
from the hotel, 0.75 × 200 × 230 = 34 500 litres.

This gives a total of 70 500 litres of sewage per day, or 70.5 m^3 per day.

Back

Answer

When a storm occurs, the early part of the storm cleanses the roads and streets (see Section 2.2.5), and also flushes out the combined sewer system where a certain amount of sedimentation may have taken place. Thus the early flow of a storm can be considerably contaminated by oil and other materials from roads that have settled in the sewers; even in a river swollen by the storm it could prove to be a problem.

Answer

A combined sewerage system will collect grit, sand, oil and rubbish from gutters, roads and paved areas. This can lead to increased wear of equipment in the sewage treatment works and also cause problems with the disposal of the resulting sludge. Oil can affect treatment of the sewage and can also cause blockage in filter cloths used in sludge presses. The flows arriving are much more variable in a combined system, and this can complicate treatment as well as necessitate storm overflows and storm tanks. Combined systems also need bigger sewers. However, a separate system needs more pipe-laying.

Back

Answer

a. By Equation 7, the retention time is:

$$\frac{75 \text{ m}^3}{20 \text{ m}^3 \text{ h}^{-1}} = 3.75 \text{ h}$$

b. If the depth is 1 m, the area must be 75 m^2. Say the width is w; then the length is $3w$. Thus $3w^2 = 75$. This means $w^2 = 25$, so $w = 5$.

So the dimensions of the tank are length 15 m, width 5 m and depth 1 m.

Answer

The mass of BOD added to the biological stage per day is equal to flow rate × BOD:

$$2500 \times 0.2 = 500 \text{ kg d}^{-1}$$

Thus, rearranging Equation 8:

a. biomass needed for low-rate process = 500/ 0.07 = 7140 kg
b. biomass needed for high-rate process = 500/ 1.8 = 278 kg

Answer

We need to use Equation 9 with the following values:

$Q = 5 \text{ m}^3 \text{ d}^{-1}$

$$A = \pi r^2 = \pi \left(\frac{2.5}{2}\right)^2 \text{m}^2$$

$H = 2 \text{ m}$

$Y = 0.21 \text{ kg m}^{-3}$

Therefore the organic loading rate is:

$$\frac{5 \times 0.21}{\pi \times \frac{6.25}{4} \times 2} \text{ kg BOD m}^{-3} \text{d}^{-1} = \frac{1.05}{9.82} \text{ kg BOD m}^{-3} \text{d}^{-1}$$

$$= 0.11 \text{ kg BOD m}^{-3} \text{d}^{-1}$$

Answer

Correct:

> b. In a biological filter, nitrification takes place due to the bacterial activity of *Nitrosomonas* and *Nitrobacter*.

Wrong:

> a. Comminutors (where used) are always placed after coarse screens but before grit removal in the preliminary treatment of sewage.

False: in situations where a high proportion of grit is present, comminutors are placed after the grit removal system so that the grit does not wear out the comminutor blades.

> c. One advantage of using biological filters is that they do not require final sedimentation tanks.

False: biological filters require final humus tanks.

> d. In a biological filter, bacteria and algae reduce the BOD of the settled sewage.

False: only the bacteria would reduce the BOD of the settled sewage.

> e. High-rate biological filters remove a greater portion of the BOD compared to low-rate filters.

False: low-rate filters remove 80–90% of the BOD, while high-rate filters only remove 50–80%.

Statement (b) is true.

Statement (a) is false: in situations where a high proportion of grit is present, comminutors are placed after the grit removal system so that the grit does not wear out the comminutor blades.

Statement (c) is false: biological filters require final humus tanks.

Statement (d) is false: only the bacteria would reduce the BOD of the settled sewage.

Statement (e) is false: low-rate filters remove 80–90% of the BOD, while high-rate filters only remove 50–80%.

Back

Answer

Correct:

c. The surface-area-to-volume ratio of the filter medium.

Wrong:

a. Whether the medium is to be used in a high-rate or a low-rate filter.

b. Whether the filter is to be used for crude sewage or a sewage that has been partially treated by screening and primary sedimentation.

d. The regularity of shape of the particles of the medium.

e. The size of the particles of the medium.

Consideration (c) is most important, since this determines the extent to which oxidation will take place.

Consideration (a) can be relevant in choosing between plastic and conventional media.

Considerations (b), (d) and (e) are secondary.

It is also important that the medium does not deteriorate significantly while being used.

Back

Answer

Again using Equation 9, the organic loading rate is:

$$\frac{QY}{AH} = \frac{1200 \times 0.18}{\pi \times 20^2 \times 1.8}$$

$$= \frac{216}{2262}$$

$$= 0.095 \text{ kg BOD m}^{-3}\text{d}^{-1}$$

The BOD removal rate is:

$$1200 \times (0.18 - 0.02) = 192 \text{ kg BOD d}^{-1}$$

Back

Answer

$$SVI = \frac{150 \text{ ml l}^{-1}}{1.85 \text{ g l}^{-1}}$$
$$= 81.08 \text{ ml g}^{-1}$$

Back

Answer

Using Equation 12:

$$\text{sludge age} = \frac{13.5 \times 10^3 \times 1850}{320 \times 7500} = 10.4 \text{ days}$$

Back

Answer

a. Rearranging Equation 14:

$$L_i - L_e = \frac{k_a X V}{Q}$$

$$= \frac{0.28 \times 2 \times 25 \times 5 \times 4}{1500} \text{ kg m}^{-3} \text{ BOD}$$

$$= 0.18667 \text{ kg m}^{-3} \text{ BOD}$$

$$= 186.67 \text{ g m}^{-3} \text{ BOD}$$

Therefore, the overall percentage BOD removal is:

$$\frac{186.67}{200} \times 100\% = 93.3\%$$

b. By Equation 7, the retention time is equal to the volume of the tank divided by the flow rate (i.e. *V/Q*), so:

$$\text{retention time} = \frac{25 \times 5 \times 4}{1500} \text{ days}$$

$$= 0.33 \text{ day}$$

c. From Equation 13, the aeration tank loading rate is given by the BOD entering the tank per day divided by the volume (i.e. *QL_i/V*), so:

$$\text{aeration tank loading rate} = \frac{1500 \times 0.2}{25 \times 5 \times 4} \text{ kg BOD m}^{-3} \text{d}^{-1}$$
$$= 0.6 \text{ kg BOD m}^{-3} \text{d}^{-1}$$

d. From Equation 10:

$$F/M = \frac{QL_i}{VX}$$
$$= \frac{1500 \times 0.2}{25 \times 5 \times 4 \times 2} \text{ kg BOD kg}^{-1} \text{MLSS d}^{-1}$$
$$= 0.3 \text{ kg BOD kg}^{-1} \text{MLSS d}^{-1}$$

Back

Answer

Using Equation 11a:

$$SVI = \frac{280 \text{ ml l}^{-1}}{1.05 \text{ g l}^{-1}}$$

$$= 267 \text{ ml g}^{-1}$$

This sludge would have a tendency not to settle and could possibly be carried over in the effluent.

Back

Answer

a. Rearranging Equation 14:

$$X = \frac{Q(L_i - L_e)}{k_a V}$$
$$= \frac{1000 \times (0.25 - 0.02)}{0.3 \times 250} \text{ kg m}^{-3}$$
$$= 3.07 \text{ kg m}^{-3}$$

b. There are two alternatives:
   i. Divert some of the entering sewage into temporary storage to await repair of the primary treatment plant.
   ii. Increase the concentration X of activated sludge in the aeration tanks by recirculating a larger quantity of sludge in the return loop (see Figure 31). This action is also likely to require increased aeration to cope with the increased organic loading in the tanks.

The second of these two options would not be possible with a biological filter. It is this additional flexibility in operation that gives activated sludge plants an important advantage.

Answer

Activated sludge process	Biological filter
Treated effluent quality can be controlled through the sludge recycle in the event of a poorer quality influent entering the works	Treated effluent quality not easily controlled
Fly nuisance is avoided	Flies can be a problem
Negligible loss of head in effluent flow	Significant loss of head in effluent flow
Low space requirement	Significant space requirement
Requires continuous attention	Requires little attention
Energy consumption high	Energy consumption low
Can be upset by surges in flow or high organic loading	Can tolerate surges in flow and high organic loading
Noisy	Quiet

Limited nitrification	Nitrification efficiency high
Relatively complex to monitor and control	Simple to monitor and control
Vulnerable to toxic substances	Not so vulnerable to toxic substances

Back

Answer

Industrial activity	Pollutant(s)	Pre-treatment option
a. Ceramic works	china clay	sedimentation
b. Distillery	spent grain	microstraining
c. Chicken processing plant	oil and fat	flotation
d. Electroplating works	chromium (VI)	chemical reduction (to chromium (III))
e. Copper mining	acid mine waters	neutralisation

Back

Answer

For part (a), use Equation 15:

Concentration of trade effluent (%)	Percentage inhibition (%)
20	8.2
40	18.2
60	38.2
80	44.1
100	55.5

For parts (b) and (c), see the plot of data in Figure 36. The EC_{50} is about 90%. The concentration of the trade effluent that will result in 15% inhibition of biological activity is approximately 34%, which is equivalent to roughly one volume of trade effluent being mixed with two volumes of domestic sewage (assuming the latter doesn't contain any toxic chemicals itself).
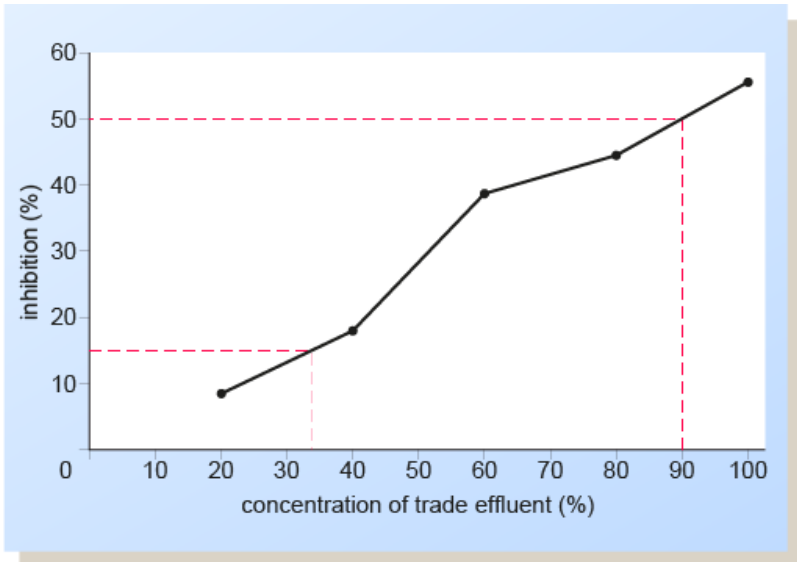
Figure 36 Percentage inhibition against dilution for the treatment plant in SAQ 29

View description

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Answer

a. The culture should be thermotolerant and able to survive in the presence of toxic material that might be present in the refinery effluent.
b. It might be found in the pipes transporting crude oil or in the soil around oil wells.

Answer

a. It is able to do so because it holds a much higher concentration of biomass.
b. Ultrafiltration removes suspended solids and microorganisms (including pathogens).

Answer

Using Equation 17:

$$Q = 72 \times \frac{150}{1000} = 10.8 \text{ m}^3 \text{ d}^{-1}$$
$$C_0 = 230 \text{ mg l}^{-1} = 230 \text{ g m}^{-3}$$
$$C_1 = 20 \text{ mg l}^{-1} = 20 \text{ g m}^{-3}$$
$$k_i = 0.08 \text{ m d}^{-1}$$
$$A = 10.8 \left(\frac{\ln(230) - \ln(20)}{0.08} \right)$$
$$= 10.8 \left(\frac{5.4381 - 2.9957}{0.08} \right)$$
$$= 10.8 \times 30.53$$
$$= 329.72$$

So the required land area for the reed bed is approximately 330 m^2.

Back

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Answer

Effluent	Treatment technique(s)
a. Domestic sewage from a single cottage in the countryside	Septic tank or rotating biological contactor
b. Domestic and farm wastewaters in a sparsely populated rural area with a lot of land available	Waste stabilisation ponds; possibly reed beds
c. A high-BOD effluent from a food-processing plant in a built-up area with little available land	Deep Shaft™ process; possibly pure oxygen activated sludge process
d. Domestic effluent from a remote group of houses in an area of low soil permeability	Rotating biological contactor (a septic tank would not be appropriate as the effluent would not soak away easily)
e. An effluent with high ammonia content from a fertiliser plant that has extensive land available	Oxidation ditch; possibly rotating biological contactor
f. An industrial effluent with traces of mixed organics not easily degraded in a conventional mechanical plant	Reed beds; possibly waste stabilisation ponds

g. A mixed industrial–sanitary wastewater with a high and fluctuating organic load, in a city site	Pure oxygen activated sludge process; possibly Deep Shaft™ process
h. Domestic sewage that has to be treated for reuse in watering a golf course	Membrane bioreactor

Back

Answer

In water with a good supply of oxygen, nitrate and phosphate, there is a strong possibility of algal growth, which could be beneficial to the receiving watercourse for the following reasons.

- Algae can contribute to the oxygenation of the receiving water if they can continue photosynthesising.
- They could increase the productivity of the receiving water; for instance, algae could be food for shellfish in coastal waters.
- Non-toxic algae may be able to multiply and out-compete toxic algal species such as blue-greens present in the receiving waterway.

Also, the lagoons can be used for fish cultivation and can develop into attractive semi-natural habitats that can be valuable for wildlife.

Back

Answer

Correct:

Grass plots

Lagoons

Reed beds

Wrong:

Microstrainers

Rapid-gravity sand filters

Grass plots, lagoons and reed beds are likely to remove nitrogen and phosphorus as well.

Back

Answer

Correct:

> Air stripping

Wrong:

> Nitrification

In nitrification, ammonia is converted to nitrate.

> Denitrification

In denitrification, nitrates are converted to nitrogen gas.

> The oxidation ditch system

In the oxidation ditch system, nitrification (and denitrification) takes place.

> Breakpoint chlorination

In breakpoint chlorination, the ammonia is oxidised to nitrogen gas.

Air stripping is the only process listed where ammonia gas is produced.

Back

Answer

Taking the average inlet P level in domestic sewage as 20 mg l^{-1} (from), 10% of this will be removed in primary settlement.

This leaves 18 mg l^{-1}.

If the final level is to be 2.0 mg l^{-1}, 16.0 mg l^{-1} has to be removed.

If the effluent flow is 100 000 m^3 d^{-1}, this is 100 000 × 10^3 l d^{-1}.

So, in one day, the amount of P that has to be removed is:

$$16.0 \text{ mg l}^{-1} \times 100\,000 \times 10^3 \text{ l d}^{-1} = 1.6 \times 10^9 \text{ mg d}^{-1}$$
$$= 1600 \text{ kg d}^{-1}$$

Answer

a. Tertiary treatment will be required when a quality better than 30 g m^{-3} BOD and 20 g m^{-3} suspended solids is needed.

b. If space is at a premium then a possible choice is microstraining or rapid sand filtration.

Back

Answer

Correct:

> b. It will conform to standards depending on the needs of the watercourse receiving it.

Wrong:

> a. It will contain at most 30 g m^{-3} of suspended solids and have a BOD of 20 g m^{-3}.

This will only be true for secondary-treated effluent.

> c. It will not be a risk to public health.

Unless treatment included disinfection, it would be a risk to public health.

> d. It will be potable.

The treated effluent would not be potable until all toxic and pathogenic matter was removed.

> e. It will not contain any polluting substances.

Only if advanced wastewater treatment were applied would the effluent be free of polluting substances, suspended solids, toxic chemicals and BOD.

Statement (b) is correct. The 30/20 standard is not always enforced, since greater pollution loads may be acceptable in some circumstances. Where a watercourse is used for direct abstraction for domestic and industrial supplies as well as effluent discharge, the treatment may aim for a higher standard. Higher standards will of course apply if the dilution is less than 8:1.

Statement (a): this will only be true for secondary-treated effluent.

Statement (c): unless treatment included disinfection, it would be a risk to public health.

Statement (d): the treated effluent would not be potable until all toxic and pathogenic matter was removed.

Statement (e): only if advanced wastewater treatment were applied would the effluent be free of polluting substances, suspended solids, toxic chemicals and BOD.

Back

Answer

Percentage difference = $(35 - 25)/25 \times 100\% = 40\%$

So the activated sludge unit produces 40% more solids by mass than the biological filter.

Back

Answer

From Table 16, the volume of sludge produced per person per day from primary sedimentation and biological filters will be 1.80 + 0.63 = 2.43 litres.

Thus, for a population of 20 000, the amount of sludge produced will be:

$2.43 \times 20\ 000 = 48\ 600$ litres per day

or 48.6 m^3 per day.

Back

Answer

Favourable conditions are as follows:

- a temperature of 35 °C
- a pH of 7.0
- adequate alkalinity (1000–5000 g m^{-3} as $CaCO_3$)
- minimal toxic material (e.g. heavy metal content should be less than 1 g m^{-3}).

Back

Answer

Sludge is generated through primary and secondary sedimentation in biological filter and activated sludge systems. In primary sedimentation it is the solid matter in the incoming crude sewage that is removed, while in secondary sedimentation it is the biomass produced in the biological oxidation stage that is separated. Sludge is also produced where chemical precipitation of phosphates is carried out.

Back

Answer

Since density = mass/volume, the mass of sludge produced will be given by density × volume.

From , the volume of primary sludge produced will be $1.8 \times 50\,000 = 90\,000$ litres per day. Since the density of primary sludge is given as 1.03 kg l^{-1}, the mass of primary sludge will be:

$1.03 \times 90\,000 = 92\,700$ kg or 92.7 tonnes

In the activated sludge unit, the volume of sludge produced will be $5 \times 50\,000 = 250\,000$ litres per day. Since the density of the sludge is 1.0 kg l^{-1}, the mass of sludge will be 250 000 kg or 250 tonnes.

Thus the total mass of sludge produced is 92.7 + 250 = 342.7 tonnes per day.

Answer

Benefits include:

- a 35–40% reduction in the total solids content of the sludge
- production of methane gas, which can be used as a fuel for heating
- removal of offensive odours
- a reduction in the number of pathogens
- breakdown of organic nitrogen compounds to ammonia or ammonium salts, increasing the availability of nitrogen to crops when the wet digested sludge is applied to land.

Back

Answer

When an effluent is diluted with clean water, the ultimate oxygen demand of the resulting mixture is less than that of the original effluent. However, the principle of mass conservation applies to the oxidisable material present both before and after dilution, i.e. mass of oxidisable material *before* dilution = mass of oxidisable material *after* dilution.

Since mass of material = volume × concentration, if L_u is the 'concentration' of oxidisable material in the sample after dilution then the mass balance gives:

$$1 \times 50 \text{ g m}^{-3} = (1 + 9)L_u$$
$$L_u = 5 \text{ g m}^{-3}$$

which is the ultimate oxygen demand of the diluted sample.

Answer

Rearranging Equation 18:

$$C_u = C_0 - L_u$$
$$= 8.2 - 5 \text{ g m}^{-3}$$
$$= 3.2 \text{ g m}^{-3}$$

Back

Answer

a. Using Equation 18, the ultimate oxygen demand of the diluted sample is:

$$L_u = 7.6 - 1.3 \text{ g m}^{-3}$$
$$= 6.3 \text{ g m}^{-3}$$

b. The principle of mass conservation applies. If x is the 'concentration' of oxidisable material in the original effluent then

$$1 \times x = (1 + 49) \times 6.3 \text{ g m}^{-3}$$
$$x = 315 \text{ g m}^{-3}$$

So this is the ultimate oxygen demand of the original effluent.

Back

Answer

If $C_t = C_u$, $e^{-kt} = 0$. This can happen only if t is infinitely large. So Equation 19 predicts that the dissolved oxygen concentration never actually falls to the ultimate value C_u. Of course, the equation is just a mathematical model for the oxidation reaction and we cannot expect real reactions to behave in precisely this way. Nevertheless, we might expect to have to leave the sample for a very long time to ensure that the reaction is complete. It would obviously be expedient to set a fixed time after the start of a test at which to measure the oxygen demand of a sample, and then standardise on that time.

Back

Answer

Using Equation 19, the dissolved oxygen concentration C_t after 14 hours or 0.58 days is given by:

$$\frac{C_t - 2.3}{8.0 - 2.3} = e^{-0.2 \times 0.58} \text{ g m}^{-3}$$

$$= 0.89 \text{ g m}^{-3}$$

$$C_t = 2.3 + 5.7 \times 0.89 \text{ g m}^{-3}$$

$$= 7.4 \text{ g m}^{-3}$$

Back

Answer

Using Equation 21, and from the information given:

$$7000 \text{ g m}^{-3} = L_u(1 - e^{-5\times0.3})$$

Rearranging the equation:

$$
\begin{aligned}
L_u &= \frac{7000}{1 - e^{-5\times0.3}} \text{ g m}^{-3} \\
&= \frac{7000}{0.78} \text{ g m}^{-3} \\
&\approx 9000 \text{ g m}^{-3}
\end{aligned}
$$

Back

Answer

$$L_u = \frac{150}{1 - e^{-5 \times 0.4}} \text{ g m}^{-3}$$
$$= \frac{150}{0.86} \text{ g m}^{-3}$$
$$\approx 170 \text{ g m}^{-3}$$

Back

Answer

a. The BOD–time curve is shown in Figure 66.
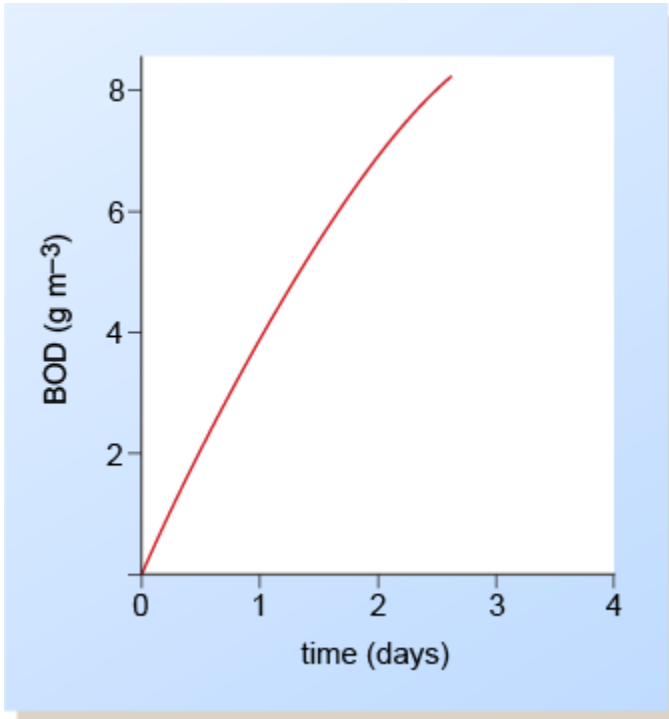
Figure 66 BOD–time curve for SAQ 48(a)

View description

b. From Equation 21, a plot of BOD_t versus $(1 - e^{-kt})$ should give a straight line through the origin of slope L_u. This is shown in Figure 67, from which $L_u = 12.9$ g m^{-3}.
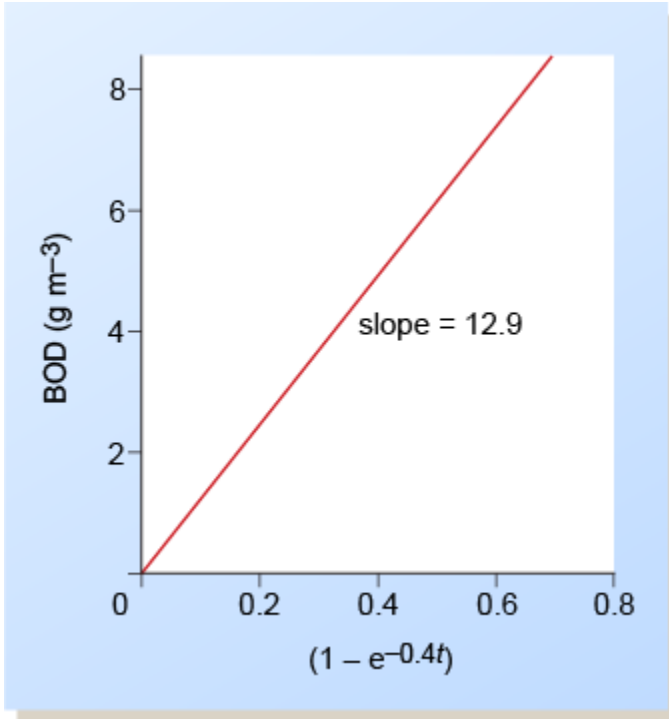
Figure 67 BOD_t versus $(1 - e^{-kt})$ for SAQ 48(b)

View description

c. Using Equation 21:

$$BOD_5^{20} = 12.9(1 - e^{-2}) \text{ g m}^{-3}$$
$$= 11.2 \text{ g m}^{-3}$$

Back

Answer

Since the COD represents oxidation of both organic and inorganic portions, in the first effluent the proportion of organic pollutant (amenable to biodegradation) would be 1/2 = 0.5, whilst in the second effluent it would be 1/3.5 = 0.29.

Back

Answer

From Section 2 Table 5, the BOD:COD ratios are as follows:

Sewage (using average figures) = 200:275 or 0.73:1

Pulp and paper mill effluent = 1400:7000 or 0.2:1

This shows that a greater proportion of the sewage is biodegradable compared to pulp and paper mill effluent.

Back

Answer

Correct:

> c. Hardness, pH value, acidity and alkalinity are related to each other in water possessing hardness.

Wrong:

> a. Where chemical tests such as hardness, pH value and chloride concentration can be carried out, physical tests such as colour and turbidity need not be performed because these tests do not measure true pollutants.

False: physical parameters are the manifestations of pollutants and are useful in characterising the general nature of pollutants.

> b. An analyst could distinguish river water from groundwater simply by measuring the chloride concentration.

False: while clean freshwaters are generally low in chloride, sewage or sewage-like pollution increases chloride concentrations. The chloride levels vary in different groundwaters depending on the geochemical nature of the aquifer and the intrusion of seawater.

> d. The Hazen scale is useful for measuring the concentrations of specific substances in water.

False: the Hazen scale is based on the colours produced by specific substances in water, but the presence of a particular colour does not imply that those substances are necessarily present – other substances may produce similar colours.

> e. Odour detection and control is important in sewage treatment, but in water treatment odour tests are a luxury.

False: human operators are used in some water treatment plants to detect the presence of odoriferous compounds.

Statement (c) is true: these parameters are all related through the carbonate, bicarbonate, carbonic acid system.

Statement (a) is false: physical parameters are the manifestations of pollutants and are useful in characterising the general nature of pollutants.

Statement (b) is false: while clean freshwaters are generally low in chloride, sewage or sewage-like pollution increases chloride concentrations. The chloride levels vary in different groundwaters depending on the geochemical nature of the aquifer and the intrusion of seawater.

Statement (d) is false: the Hazen scale is based on the colours produced by specific substances in water, but the presence of a particular colour does not imply that those substances are necessarily present – other substances may produce similar colours.

Statement (e) is false: human operators are used in some water treatment plants to detect the presence of odoriferous compounds.

Answer

Of those listed, only the BOD and TOC tests give a measure of organic matter.

a. The BOD test would be most useful for water polluted with dairy wastes, because the organic matter in dairy wastes is biodegradable.

b. The much more severe TOC test would be more appropriate for water polluted with wastes from a petroleum refinery, because the organic matter in petroleum refinery effluent is not easily biodegradable due to the presence of toxic components such as cyanides and heavy metals.

Back

Answer

a. Since this is extremely unlikely, we suspect that something in the water has killed the bacteria that are normal inhabitants of river water, or that the test was not carried out properly.
b. This is evidence that faecal pollution is present and it is possible that pathogens are also present.

Back

Answer

An intake point for a water treatment plant or a fish farm.

A discharge point for an effluent treatment plant, particularly one treating industrial effluent.

Back

Answer

$$C = 20.00 + 22.56 + \frac{1150}{355} \times 14.94 + \frac{800}{268} \times 17.42$$
$$= 20.00 + 22.56 + 48.40 + 52.00$$
$$= 143.0p$$
$$= £1.43$$

Total daily charge $= £1.43 \times 200$
$$= £286$$

Answer

$$C = 21.89 + 22.28 + \frac{1500}{542.8} \times 13.31 + \frac{250}{347.6} \times 9.92$$
$$= 21.89 + 22.28 + 36.78 + 7.13$$
$$= 88.08p$$

a. $$= £0.8808$$

$$\text{Total daily charge} = £0.8808 \times 300$$
$$= £264$$

b. If the volume of discharge is reduced by 30%, the flow will be:

$$\frac{70}{100} \times 300 = 210 \, m^3 \, \text{per day}$$

If the pollutant load remains the same, the COD and suspended solids concentration will increase.

Say the new COD concentration is x. Then:

$$210x = 300 \times 1500$$
$$x = \frac{300 \times 1500}{210}$$
$$= 2143 \, mg \, l^{-1}$$

Similarly for the suspended solids, if the new concentration is y, then:

$$210y = 300 \times 250$$
$$y = \frac{300 \times 250}{210}$$
$$= 357.1 \text{ mg l}^{-1}$$

Therefore:

$$C_{new} = 21.89 + 22.28 + \frac{2143}{542.8} \times 13.31 + \frac{357.1}{347.6} \times 9.92$$
$$= 21.89 + 22.28 + 52.55 + 10.19$$
$$= 106.9\text{p}$$
$$= \pounds\,1.069$$

$$\text{Total daily charge} = \pounds\,1.069 \times 210$$
$$= \pounds\,225$$

This shows that a reduction in volume of the discharge will be beneficial.

Back

Answer

Using Equation 26, and given that k_{20} = 0.13 d^{-1}:

$$k_{10} = 1.047^{(10-20)} \times 0.13$$
$$= 1.047^{-10} \times 0.13$$
$$= 0.0821$$

So at 10 °C the rate of decay would be approximately 0.08 d^{-1}.

Back

Answer

Given that $k_{20} = 0.25 \, \text{d}^{-1}$, we use Equation 26 to calculate k_T for $T = 8 \, °\text{C}$ to $T = 15 \, °\text{C}$:

$$k_T = 1.047^{(T-20)} \times 0.25$$

Substituting relevant values of T into the above equation gives:

$T \, (°\text{C})$	$k_T \, (\text{d}^{-1})$
8	0.144
9	0.151
10	0.158
11	0.165
12	0.173
13	0.181
14	0.190
15	0.199

We can plot this graph (Figure 74).
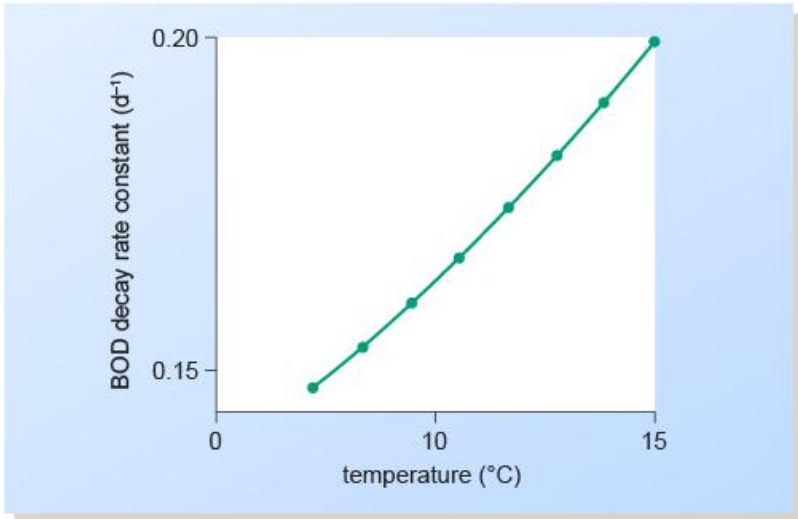
Figure 74 BOD decay rate constant against temperature for Exercise 15(a)

View description

Back

Answer

We need to use Equation 23.

First, however, we have to calculate the BOD_5^{20} of the effluent–river water mixture and convert it to the ultimate oxygen demand (L_0) of the mixture.

Now, the BOD_5^{20} of the river water is:

$$\mathrm{BOD}_{5,\mathrm{up}}^{20} = 2 \text{ mg } l^{-1} \, (= 2 \text{ g m}^{-3})$$

and the BOD_5^{20} of the treated effluent is:

$$\mathrm{BOD}_{5,\mathrm{e}}^{20} = 60 \text{ mg } l^{-1} \, (= 60 \text{ g m}^{-3})$$

Also, from the data given, we know that:

Q_up = 36 000 m^3 h^{-1} = 10 m^3 s^{-1}
Q_e = 18 000 m^3 h^{-1} = 5 m^3 s^{-1}

Using the equivalent version of Equation 24, the BOD_5^{20} of the effluent–river water mixture can be calculated as:

$$BOD_5^{20} = \frac{BOD_{5,up}^{20} Q_{up} + BOD_{5,e}^{20} Q_e}{Q_{up} + Q_e}$$

$$= \frac{2 \times 10 + 60 \times 5}{10 + 5}$$

$$= \frac{320}{15}$$

$$= 21.33 \text{ g m}^{-3} (= 21.33 \text{ mg l}^{-1})$$

This BOD_5^{20} can be converted to an ultimate oxygen demand using Equation 25:

$$L_0 = \frac{21.33}{1 - e^{-0.25 \times 5}}$$

$$= 29.90 \text{ mg l}^{-1}$$

Given also that $U_0 = 0.05 \text{ m s}^{-1} = 4320 \text{ m d}^{-1}$, and that we are looking for $L = 6.3 \text{ mg } 1^{-1}$, we can use Equation 23 to calculate the distance x for different values of k_L (covering the temperature range 8–15 °C):

$$L = L_0 \exp\left[\frac{-k_L x}{U_0}\right]$$

$$6.3 = 29.90 \exp\left[\frac{-k_L x}{4320}\right]$$

$$\frac{6.3}{29.90} = \exp\left[\frac{-k_L x}{4320}\right]$$

$$0.2107 = \exp\left[\frac{-k_L x}{4320}\right]$$

Taking natural logarithms of both sides:

$$-1.557 = -\frac{k_L x}{4320}$$

$$1.557 = \frac{k_L x}{4320}$$

$$x = \frac{1.557 \times 4320}{k_L}$$

$$= \frac{6726}{k_L}$$

From part (a), we already have the values of k_L for $T = 8\,°C$ to $T = 15\,°C$. Substituting these into the equation above and dividing by 1000 to convert the values to km, we obtain:

T (°C)	k_L (d^{-1})	x (km)
8	0.144	46.7
9	0.151	44.5
10	0.158	42.6
11	0.165	40.8
12	0.173	38.9
13	0.181	37.2
14	0.190	35.4
15	0.199	33.8

A plot of x against T will show the distance downstream of the effluent discharge at which the conditions are

acceptable for fish life, at different values of the water temperature (Figure 75).
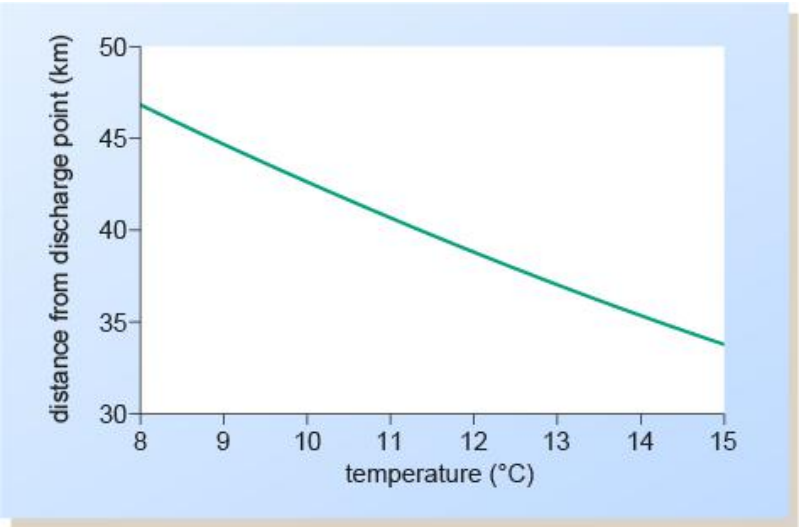
Figure 75 Distance from discharge point against temperature for Exercise 15(b)

View description

Back

Answer

From the data given:

$$Q_{up} = 720 \text{ m}^3 \text{ h}^{-1} = 0.2 \text{ m}^3 \text{ s}^{-1}$$

$$Q_e = 90 \text{ m}^3 \text{ h}^{-1} = 0.025 \text{ m}^3 \text{ s}^{-1}$$

$$\text{BOD}^{20}_{5,up} = 2 \text{ mg l}^{-1} = 2 \text{ g m}^{-3}$$

$$\text{BOD}^{20}_{5,e} = 30 \text{ mg l}^{-1} = 30 \text{ g m}^{-3}$$

$$U_0 = 0.1 \text{ m s}^{-1} = 8640 \text{ m d}^{-1}$$

$$k_{20} = 0.25 \text{ d}^{-1}.$$

Using the equivalent version of Equation 24, the BOD^{20}_5 of the river water/effluent mixture is given by:

$$
\begin{aligned}
\text{BOD}^{20}_5 &= \frac{2 \times 0.2 + 30 \times 0.025}{0.2 + 0.025} \\
&= \frac{1.15}{0.225} \\
&= 5.11 \text{ mg l}^{-1}
\end{aligned}
$$

Then, using Equation 25:

$$
\begin{aligned}
L_0 &= \frac{5.11}{1 - e^{-(0.25 \times 5)}} \\
&= 7.16 \text{ mg l}^{-1}
\end{aligned}
$$

For A1 treatment, the BOD_5^{20} of the raw water should be less than 3.0 mg l^{-1}. By Equation 25, this is equivalent to an ultimate oxygen demand of:

$$\frac{3}{1 - e^{-(0.25 \times 5)}} = 4.20 \text{ mg l}^{-1}$$

so L = 4.20 mg l^{-1}. Substituting these values into Equation 23:

$$4.20 = 7.16 \exp\left[-\frac{k_L x}{8640}\right]$$

$$\frac{4.20}{7.16} = \exp\left[-\frac{k_L x}{8640}\right]$$

$$0.587 = \exp\left[-\frac{k_L x}{8640}\right]$$

Taking natural logarithms of both sides:

$$-0.533 = -\frac{k_L x}{8640}$$

$$x = \frac{0.533 \times 8640}{k_L}$$

$$= \frac{4605}{k_L}$$

Using Equation 26, the k_L value for different temperatures from 6 °C to 14 °C can be calculated:

T (°C)	k_L (d^{-1})

6	0.131
7	0.138
8	0.144
9	0.151
10	0.158
11	0.165
12	0.173
13	0.181
14	0.190

We have already established that the (theoretical) safe distance x at which the water intake could be located is given by:

$$x = \frac{4605}{k_L}$$

Thus for each of the temperatures $6\,°C$ to $14\,°C$, a value of x can be calculated (again dividing by 1000 to convert the units to kilometres):

T (°C)	k_L (d^{-1})	x (km)
6	0.131	35.2
7	0.138	33.4
8	0.144	32.0
9	0.151	30.5
10	0.158	29.1

11	0.165	27.9
12	0.173	26.6
13	0.181	25.4
14	0.190	24.2

The values of *x* calculated are the theoretically safe distances downstream from which water could be abstracted at various river water temperatures. Therefore, to cater for the worst case, the intake should be at least 36 km downstream of the effluent discharge.

Back

Answer

The plot of river water temperature against the location of the water intake is shown in Figure 76.
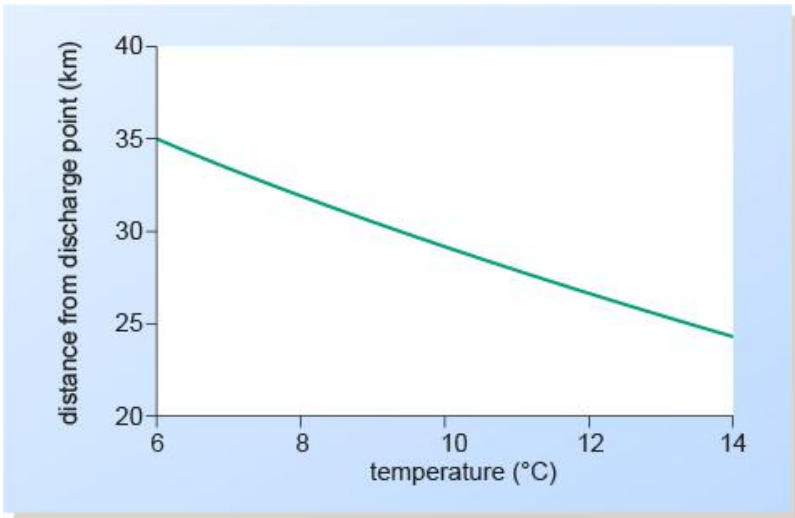
Figure 76 Distance from discharge point against temperature for SAQ 58

View description

Back

Answer

To find the dissolved oxygen level along the river, we use Equation 29:

$$DO = DO_{sat} - D$$

$$= 10.6 - \left\{ D_0 \exp\left(\frac{-k_a x}{U_0}\right) + \frac{L_0 k_L}{k_a - k_L}\left[\exp\left(\frac{-k_L x}{U_0}\right) - \exp\left(\frac{-k_a x}{U_0}\right)\right] \right\}$$

Substituting in the data given (and noting that U_0 = 0.5 m s^{-1} = 43 200 m d^{-1}), we can generate a plot of dissolved oxygen against distance down the river (Figure 77a).
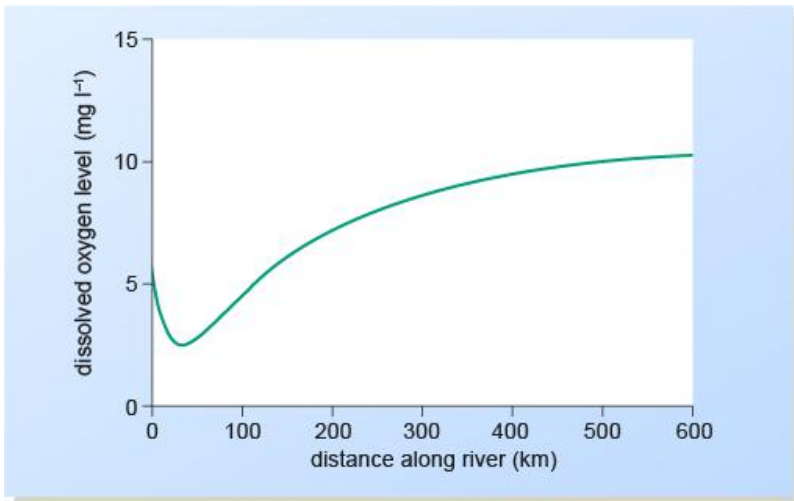
Figure 77a Dissolved oxygen level against distance for Exercise 16

View description

Back

Answer

Figure 77b focuses on the region of the graph around the minimum dissolved oxygen level, which gives the maximum dissolved oxygen deficit (the critical deficit, D_C) and its location (the critical distance, x_C).
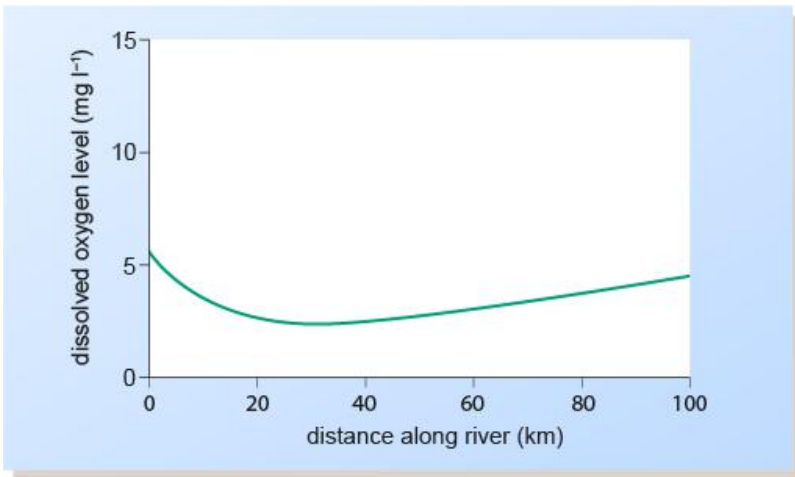
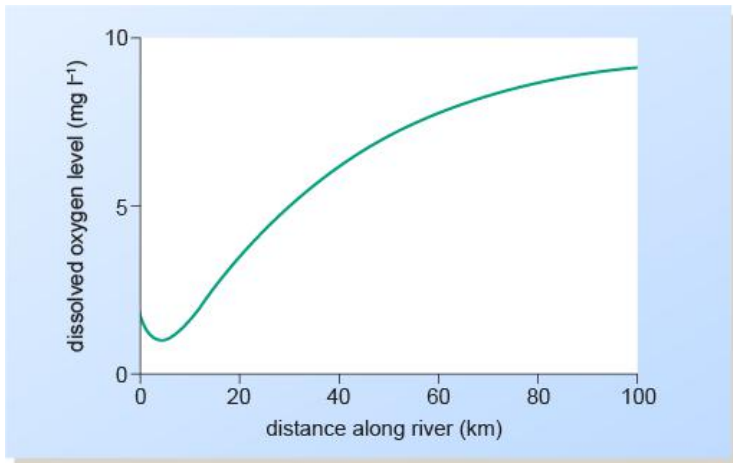**Figure 77b** Dissolved oxygen level against distance (close-up on minimum region)

View description

The minimum dissolved oxygen level is about 2.5 mg l^{-1}; therefore the critical deficit is 10.6 − 2.5 = 8.1 mg l^{-1}. The critical distance is about 32 km from the discharge point.

Back

Answer

a. Using Equations 28 and 29:

$$DO = DO_{\text{sat}} - D$$

$$= 9.8 - \left\{ D_0 \exp\left(\frac{-k_a x}{U_0}\right) + \frac{L_0 k_L}{k_a - k_L}\left[\exp\left(\frac{-k_L x}{U_0}\right) - \exp\left(\frac{-k_a x}{U_0}\right)\right] \right\}$$

Substituting in the data given (and noting that U_0 = 0.1 m s^{-1} = 8640 m d^{-1}), we can generate the required graph (Figure 78a).
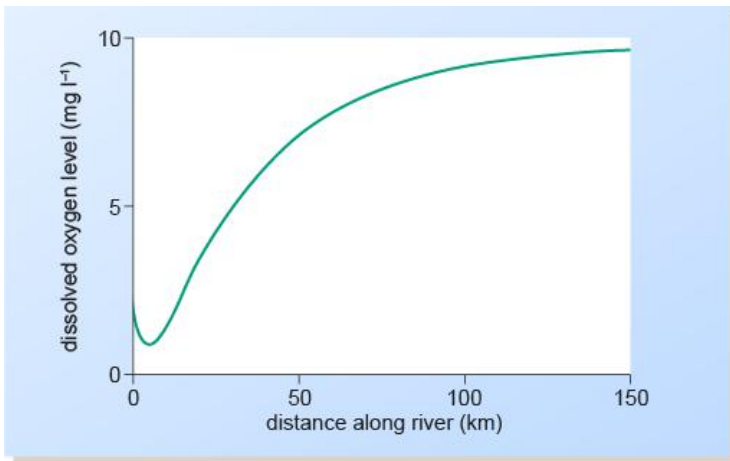
Figure 78a Dissolved oxygen level against distance for SAQ 59

View description

b. Figure 78b plots the values around the minimum of the graph in Figure 78a, from which the minimum dissolved oxygen level is seen to be about 0.98 mg l^{-1}. (You may find it helpful to add gridlines when estimating this value.)

Figure 78b Dissolved oxygen level against distance (close-up on minimum region)

View description

Therefore, the critical dissolved oxygen deficit is 9.8 − 0.98 = 8.82 mg l^{-1}. The critical distance is about 4.0 km from the discharge point.

Back

Answer

To calculate the critical oxygen deficit, we use Equation 38.

Determination of D_0

Equation 31 states that:

$$D_0 = \frac{D_{up}Q_{up} + D_e Q_e}{Q_{up} + Q_e}$$

The river temperature is 10 °C, so the saturation concentration of dissolved oxygen is (by Equation 30):

$$14.65 - 0.410\,22 \times 10 + 0.007\,91 \times 10^2 - 0.000\,077\,74 \times 10^3$$
$$= 11.26 \text{ mg l}^{-1}$$

Since the river water is 80% saturated, the dissolved oxygen concentration in the river water is:

$$0.80 \times 11.26 = 9.01 \text{ mg l}^{-1}$$

So we have:

> D_{up} = 11.26 − 9.01 = 2.25 mg l^{-1}
> D_e = 11.26 mg l^{-1} (since the dissolved oxygen concentration in the effluent is 0 mg l^{-1})
> Q_{up} = 10 m^3 s^{-1}
> Q_e = 2 m^3 s^{-1}

So by Equation 31:

$$D_0 = \frac{2.25 \times 10 + 11.26 \times 2}{10 + 2}$$
$$= 3.75 \text{ mg l}^{-1}$$

Determination of L_0

Using the equivalent version of Equation 24, the BOD_5^{20} of the river water/effluent mixture is:

$$\frac{3 \times 10 + 1500 \times 2}{10 + 2} = 252.5 \text{ mg l}^{-1}$$

By Equation 26, $k_T = 1.047^{(T - 20)} k_{20}$. We know that at $T = 10\ °C$, $k_L = 0.15\ \text{d}^{-1}$. Therefore:

$$k_{20} = \frac{k_T}{1.047^{(T-20)}}$$
$$= \frac{0.15}{1.047^{-10}}$$
$$= 0.24\ \text{d}^{-1}$$

and from Equation 25:

$$L_0 = \frac{252.5}{1 - e^{-(0.24 \times 5)}}$$
$$= 361.3 \text{ mg l}^{-1}$$

Determination of k_a

We know that depth $H = 0.8$ m and velocity $U_0 = 1.5$ m s^{-1}. Thus from Figure 79, k_a is best estimated using the Churchill–Elmore–Buckingham correlation (Equation 33):

$$k_a = 5.03 \frac{U_0^{0.969}}{H^{1.673}}$$

$$= 5.03 \times \frac{1.5^{0.969}}{0.8^{1.673}}$$

$$= 10.82 \text{ d}^{-1}$$

This is for 20 °C. For 10 °C (the temperature in the river), Equation 35 gives:

$$(k_a)_{10} = 1.024^{(10 - 20)} \times 10.82 = 8.54 \text{ d}^{-1}$$

Determination of D_c

We now have:

$D_0 = 3.75$ mg l^{-1}
$L_0 = 361.3$ mg l^{-1}
$k_L = 0.15$ d^{-1}
$k_a = 8.54$ d^{-1}.

Substituting these values into Equation 38, the critical dissolved oxygen deficit becomes:

$$D_c = \left[D_0 - \frac{L_0 k_L}{k_a - k_L} \left| \frac{k_a}{k_L} \left(1 - D_0 \frac{(k_a - k_L)}{k_L L_0}\right)\right|^{-\frac{k_a}{k_a - k_L}} \right] + \left[\frac{L_0 k_L}{k_a - k_L} \left| \frac{k_a}{k_L} \left(1 - D_0 \frac{(k_a - k_L)}{k_L L_0}\right)\right|^{-\frac{k_L}{k_a - k_L}} \right]$$

$$= \left[3.75 - \frac{361.3 \times 0.15}{8.54 - 0.15} \left| \frac{8.54}{0.15} \left(1 - 3.75\frac{8.54 - 0.15}{0.15 \times 361.3)}\right)\right|^{-\frac{8.54}{8.54 - 0.15}} \right] + \left[\frac{361.3 \times 0.15}{8.54 - 0.15} \left| \frac{8.54}{0.15} \left(1 - 3.75\frac{8.54 - 0.15}{0.15 \times 361.3}\right)\right|^{-\frac{0.15}{8.54 - 0.15}} \right]$$

$$= -2.71 \times 0.0396 + 6.46 \times 0.945$$

$$= 6.0 \text{ mg l}^{-1}$$

Determination of x_c

The distance at which the critical dissolved oxygen deficit occurs is given by Equation 37. We already know that $U_0 = 1.5$ m s^{-1} = 129 600 m d^{-1}. To find t_c we use Equation 36, with:

$k_a = 8.54$ d^{-1}
$k_L = 0.15$ d^{-1}
$D_0 = 3.75$ mg l^{-1}
$L_0 = 361.3$ mg l^{-1}.

Substituting these values into Equation 36 gives:

$$t_c = \frac{1}{8.54 - 0.15}\ln\left[\frac{8.54}{0.15} \left(1 - 3.75\frac{8.54 - 0.15}{0.15 \times 361.3}\right)\right]$$

$$= 0.378$$

Therefore, by Equation 37, x_c = 129 600 × 0.378 = 49 000 m or 49 km.

From above, the critical dissolved oxygen deficit is 6.0 mg l^{-1}. This equates to a dissolved oxygen level of 11.26 − 6.0 = 5.26 mg l^{-1}. The critical deficit occurs 49 km downstream of the effluent discharge point.

Back

Answer

We need to use Equation 38.

Determination of D_0

Equation 31 states that:

$$D_0 = \frac{D_{up}Q_{up} + D_eQ_e}{Q_{up} + Q_e}$$

The river temperature is 20 °C, so the saturation concentration of dissolved oxygen is (by Equation 30):

$$14.65 - 0.410\ 22 \times 20 + 0.007 \qquad 91 \times 20^2 - 0.000 \qquad 077$$
$$74 \times 20^3 = 8.99\ \text{mg l}^{-1}$$

We are told the dissolved oxygen concentration in the river upstream of the discharge is 7.0 mg l^{-1}, and that of the effluent is 0.1 mg l^{-1}. So we have:

$\quad D_{up} = 8.99 - 7.0 = 1.99$ mg l^{-1}
$\quad D_e = 8.99 - 0.1 = 8.89$ mg l^{-1}
$\quad Q_{up} = 2.0$ m^3 s^{-1}
$\quad Q_e = 0.4$ m^3 s^{-1}

So by Equation 31:

$$D_0 = \frac{1.99 \times 2.0 + 8.89 \times 0.4}{2.0 + 0.4}$$
$$= 3.14\ \text{mg l}^{-1}$$

Determination of L_0

Using the equivalent version of Equation 24, the BOD_5^{20} of the river water/effluent mixture is:

$$\frac{1.5 \times 2.0 + 450 \times 0.4}{2.0 + 0.4} = 76.25 \text{ mg l}^{-1}$$

From Equation 25:

$$L_0 = \frac{76.25}{1 - e^{-(0.3 \times 5)}}$$
$$= 98.15 \text{ mg l}^{-1}$$

Determination of k_a

We know that depth $H = 0.7$ m and velocity $U_0 = 0.2$ m s^{-1}. Thus from Figure 79, k_a is best estimated by the O'Connor–Dobbins correlation (Equation 32):

$$k_a = 3.93 \frac{U_0^{0.5}}{H^{1.5}}$$
$$= 3.93 \times \frac{0.2^{0.5}}{0.7^{1.5}}$$
$$= 3.0 \text{ d}^{-1}$$

Determination of D_c

We now have:

$D_0 = 3.14$ mg l^{-1}
$L_0 = 98.15$ mg l^{-1}
$k_L = 0.3$ d^{-1}
$k_a = 3.0$ d^{-1}.

Substituting these values into Equation 38, we obtain:

$$D_c = \left[D_0 - \frac{L_0 k_L}{k_a - k_L} \right] \left[\frac{k_a}{k_L} \left(1 - D_0 \frac{(k_a - k_L)}{k_L L_0} \right) \right]^{-\frac{k_a}{k_a - k_L}} + \left[\frac{L_0 k_L}{k_a - k_L} \right] \left[\frac{k_a}{k_L} \left(1 - D_0 \frac{(k_a - k_L)}{k_L L_0} \right) \right]^{-\frac{k_L}{k_a - k_L}}$$

$$= \left[3.14 - \frac{98.15 \times 0.3}{3.0 - 0.3} \right] \left[\frac{3.0}{0.3} \left(1 - 3.14 \frac{3.0 - 0.3}{0.3 \times 98.15)} \right) \right]^{-\frac{3.0}{3.0 - 0.3}} + \left[\frac{98.15 \times 0.3}{3.0 - 0.3} \right] \left[\frac{3.0}{0.3} \left(1 - 3.14 \frac{3.0 - 0.3}{0.3 \times 98.15} \right) \right]^{-\frac{0.3}{3.0 - 0.3}}$$

$$= -7.77 \times 0.113 + 10.9 \times 0.804$$

$$= 7.89 \text{ mg l}^{-1}$$

Determination of x_c

The distance at which the critical dissolved oxygen deficit occurs is given by Equation 37. We already know that $U_0 = 0.2$ m s^{-1} = 17 280 m d^{-1}. To find t_c we use Equation 36, with:

$k_a = 3.0$ d^{-1}
$k_L = 0.3$ d^{-1}
$D_0 = 3.14$ mg l^{-1}
$L_0 = 98.15$ mg l^{-1}.

Substituting these values into Equation 36 gives:

$$t_c = \frac{1}{3.0 - 0.3} \ln \left[\frac{3.0}{0.3} \left(1 - 3.14 \frac{3.0 - 0.3}{0.3 \times 98.15} \right) \right]$$

$$= 0.727 \text{ d}$$

Therefore, by Equation 37, x_C = 17 280 × 0.727 = 12 600 m or 12.6 km.

The critical dissolved oxygen deficit is thus 7.89 mg l^{-1}, and it occurs 12.6 km after the point of entry of the slurry into the river.

Back

Answer

The concentration profile for total-N in the river is given by Equation 41. We have:

$$TN_0 = 0.05 \text{ mg l}^{-1}$$
$$\Delta Q = 4/10 = 0.4 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$$
$$Q = 20 + 0.4x \text{ m}^3 \text{ s}^{-1}$$
$$TN_r = 1.0 \text{ mg l}^{-1}$$

Substituting these values into Equation 41:

$$TN = 0.05 + \frac{0.4x}{20 + 0.4x}(1.0 - 0.05)$$
$$= 0.05 + \frac{0.38x}{20 + 0.4x}$$

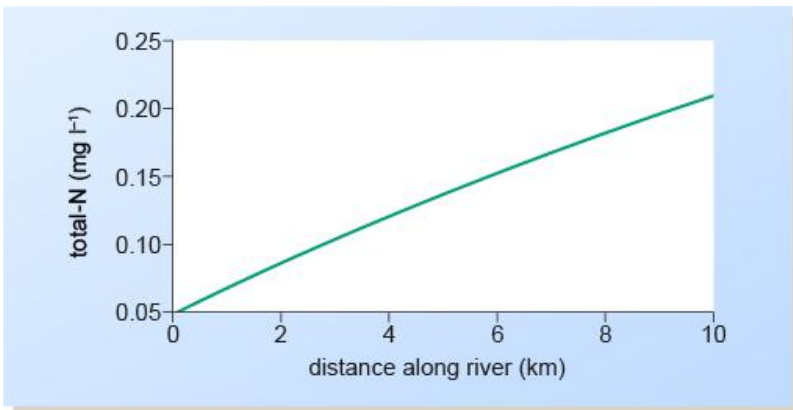We can plot a graph of TN against distance for the 10 km stretch of river (Figure 80).

Figure 80 Total-N against distance

The concentration of TP in the river can be calculated using Equation 43. We have:

$TP_0 = 0.02$ mg l^{-1}
$\Delta Q = 0.4$ m^3 s^{-1} km^{-1}
$Q = 20 + 0.4x$ m^3 s^{-1}
$TP_r = 0.25$ mg l^{-1}.

Substituting these values into Equation 43:

$$TP = 0.02 + \frac{0.4x}{20 + 0.4x} (0.25 - 0.02)$$

$$= 0.02 + \frac{0.092x}{20 + 0.4x}$$

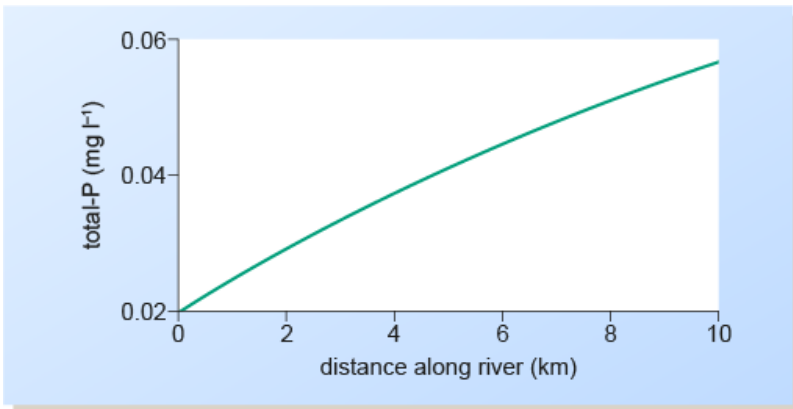As in the case of TN, we can plot a graph of TP against distance (Figure 81).

Figure 81 Total-P against distance

View description

Back

Answer

A plot of the ratio TN:TP for points along the river can be generated (Figure 82). From this graph, the TN:TP ratio at a given point can be ascertained. (Conversely, the location of a given TN:TP ratio can be found. For instance, the TN:TP ratio of 3.0:1 occurs at a distance of about 2 km from the start point ($x = 0$).)
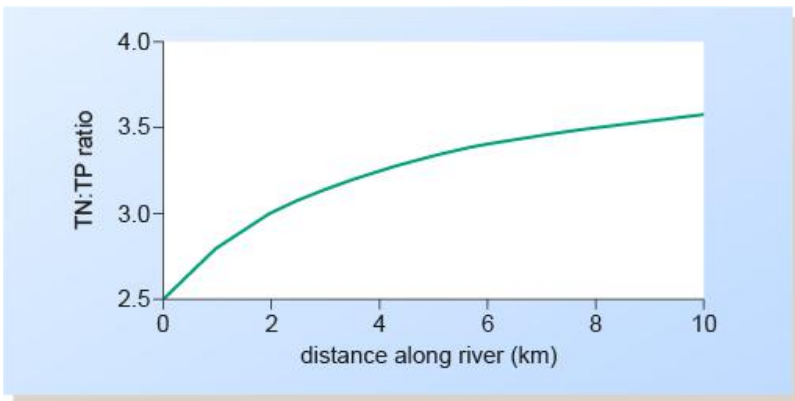

Figure 82 TN:TP ratio against distance

View description

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540

Answer

a. The concentration profile for total-N is given by Equation 41. We have:

$$TN_0 = 0.3 \text{ mg l}^{-1}$$
$$\Delta Q = 5/15 = 0.33 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$$
$$Q = 10 + 0.33x \text{ m}^3 \text{ s}^{-1}$$
$$TN_r = 1.5 \text{ mg l}^{-1}.$$

Substituting these values into Equation 41:

$$TN = 0.3 + \frac{0.33x}{10 + 0.33x}(1.5 - 0.3)$$
$$= 0.3 + \frac{0.396x}{10 + 0.33x}$$

A plot of TN against distance is shown in Figure 83.

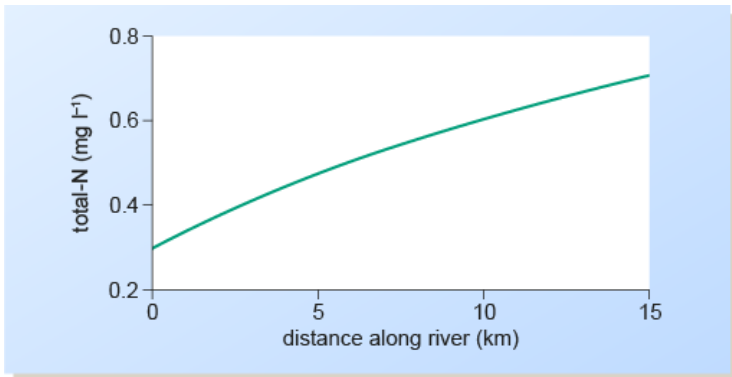**Figure 83** TN against distance

View description

The concentration of TP in the river is given by Equation 43. We have:

TP_0 = 0.03 mg l^{-1}
ΔQ = 0.33 m^3 s^{-1} km^{-1}
Q = 10 + 0.33x m^3 s^{-1}
TP_r = 0.25 mg l^{-1}.

Substituting these values into Equation 43:

$$TP = 0.03 + \frac{0.33x}{10 + 0.33x}(0.25 - 0.03)$$
$$= 0.03 + \frac{0.0726x}{10 + 0.33x}$$

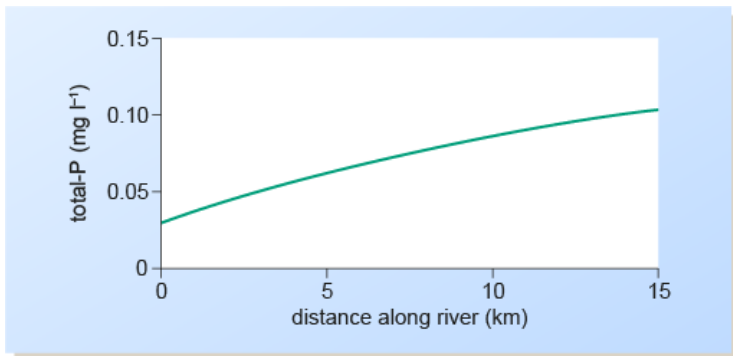Again, a plot of TP against distance can be generated (Figure 84).

Figure 84 TP against distance

View description

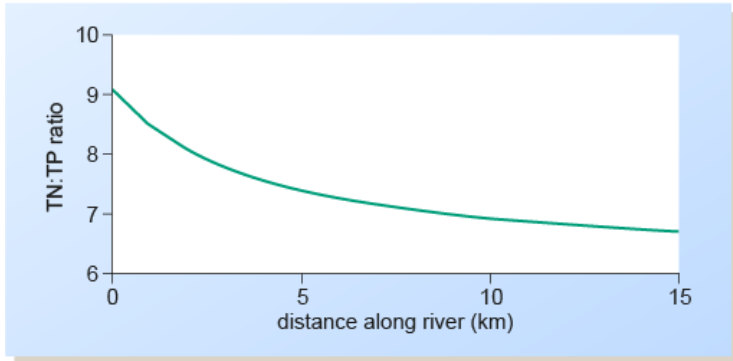b. The plot of the ratio TN:TP can be generated as in Figure 85.

Figure 85 TN:TP ratio against distance

View description

The point at which the TN:TP ratio is 7.5:1 is about 4.0 km along the river. After this point, the deficiency in N limits growth of the algae.

Back

Answer

Determination of TC_0

Putting the following data into Equation 45:

TC_{up} = 800 per 100 ml
Q_{up} = 20 m^3 s^{-1}
TC_e = 4 × 10^6 per 100 ml
Q_e = 5 m^3 s^{-1}

we get:

$$TC_0 = \frac{800 \times 20 + 4 \times 10^6 \times 5}{20 + 5}$$
$$= 8.0064 \times 10^5 \text{ per } 100 \text{ ml}$$

Determination of k_{tc}

T = 10 °C, so from Equation 46:

$$k_{tc} = 1.0 + 0.02(10 - 20) = 0.8 \text{ d}^{-1}$$

Determination of x

We are looking for the point at which TC = 500 per 100 ml. We also have:

TC_0 = 8.0064 × 10^5 per 100 ml
k_{tc} = 0.8 d^{-1}
U_0 = 0.15 m s^{-1} = 12 960 m d^{-1}

We can now determine the location at which the water should be safe for recreation using Equation 44:

$$500 = 8.0064 \times 10^5 \times \exp\left(\frac{-0.8x}{12\,960}\right)$$

$$6.245 \times 10^{-4} = \exp\left(-6.173 \times 10^{-5}x\right)$$

Taking natural logarithms of both sides:

$$-7.379 = -6.173 \times 10^{-5}x$$
$$x = 119\,500$$

Therefore it will be safe to use the river for recreational purposes after going about 120 km downstream of the discharge.

Back

Answer

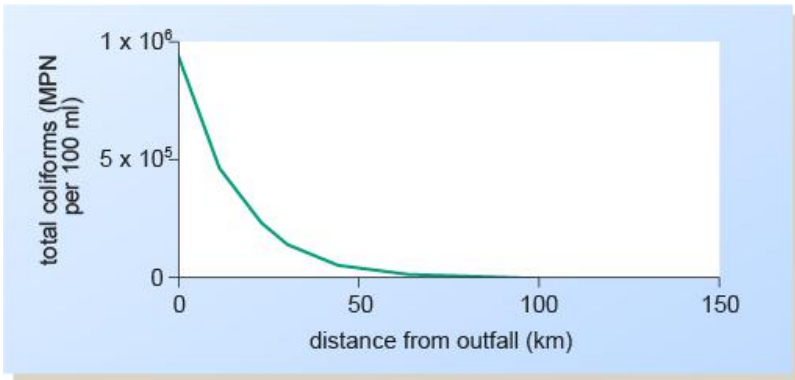The graph showing the decrease in total coliforms with distance is shown in Figure 86.

Figure 86 Total coliforms against distance

View description

Back

Answer

Equation 44 relates the total coliforms at the water intake (TC) to that at the point in the river where the treated effluent enters (TC_0). We have:

TC = 50 000 per 100 ml
k_{tc} = 0.70 d^{-1}
x = 15 km = 15 000 m
U_0 = 1 m s^{-1} = 86 400 m d^{-1}.

Substituting these values into Equation 44:

$$50\,000 = TC_0 \exp\left(\frac{-0.70 \times 15\,000}{86\,400}\right)$$
$$50\,000 = TC_0 \exp(-0.1215)$$
$$TC_0 = \frac{50\,000}{\exp(-0.1215)}$$
$$\approx 56\,460 \text{ per } 100 \text{ ml}$$

TC_0 can be related back to the total coliforms in the river and those in the treated effluent by Equation 45. Substituting in the following values:

TC_0 = 56 460 per 100 ml
TC_{up} = 1000 per 100 ml
Q_{up} = 200 m^3 h^{-1}
Q_c = 50 m^3 h^{-1}

we obtain:

$$56\,460 = \frac{1000 \times 200 + 50TC_e}{200 + 50}$$

$$56\,460 = \frac{200\,000 + 50TC_e}{250}$$

$$56\,460 \times 250 = 200\,000 + 50TC_e$$

$$TC_e = \frac{56\,460 \times 250 - 200\,000}{50}$$

$$= 278\,300 \text{ per } 100 \text{ ml}$$

So the level of total coliforms permissible in the treated effluent is approximately 3×10^5 per 100 ml.

Answer

If the raw sewage has a total coliform count of 4×10^8 per 100 ml, the required removal rate is:

$$\left(\frac{4 \times 10^8 - 3 \times 10^5}{4 \times 10^8} \right) \times 100\% = 99.925\%$$

Back

Answer

We can use Equation 44 to plot a graph of *TC* against *x* (Figure 88a).
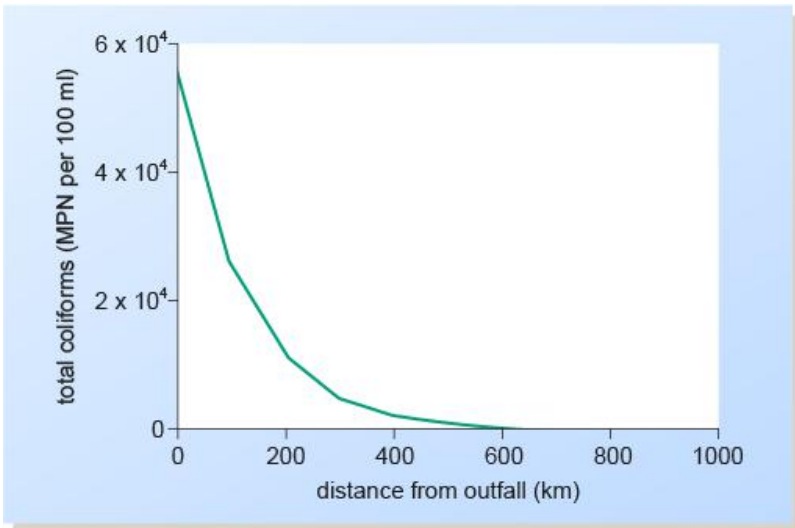
Figure 88a Total coliforms against distance

View description

We can then determine the point at which *TC* is 5000 by concentrating on the region around *TC* = 5000 (Figure 88b).
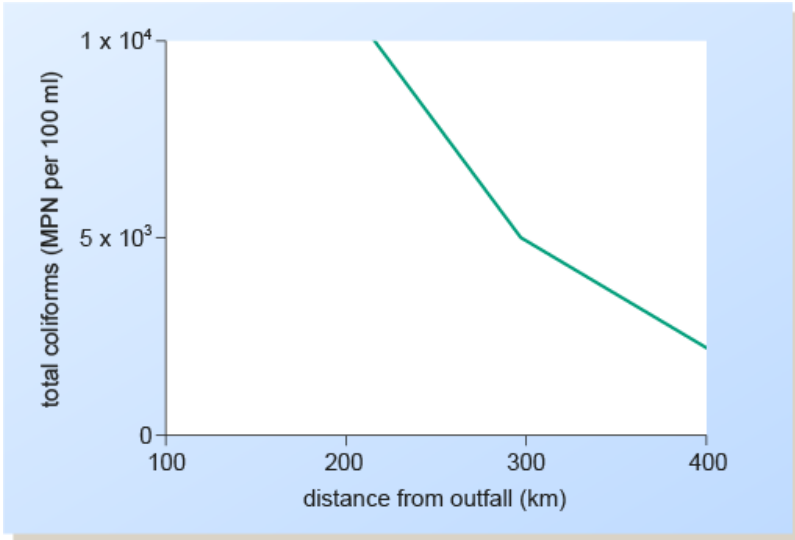
Figure 88b Total coliforms against distance, focused on a TC of 5000 MPN per 100 ml

From Figure 88b, the location of the new water abstraction point could be around 300 km downstream of the treated effluent outlet. This is assuming that no other coliform-carrying effluents enter the river after the sewage treatment plant referred to. This is unrealistic, as there are likely to be other sewage treatment works along the river, as well as discharges from farms, etc. along the river.

Answer

Using Equation 44 with:

> TC = 5000 per 100 ml
> TC_0 = 56 460 per 100 ml
> k_{tc} = 0.70 d^{-1}
> U_0 = 86 400 m d^{-1}

gives:

$$x = -\frac{U_0}{k_{tc}} \ln\left(\frac{TC}{TC_0}\right)$$

$$= -\frac{86\ 400}{0.70} \ln\left(\frac{5000}{56\ 460}\right)$$

$$\approx 299 \text{ km}$$

Back

Description

Figure 1 shows a group of cavemen with spears sitting on the ground in front of a large boulder. The boulder has a drawing of the sun, mountains, clouds, fields and animals. In front of the boulder, a caveman, using a spear as a pointer, is explaining the hydrological cycle to those gathered.

Back

Description

Figure 2 is a drawing showing clouds, the wind, mountains, snow and ice, a river, fields, a forest, houses, a lake, groundwater flow, and the sea. There are volumes in tera cubic metres (10^{12} m^3) against certain items:

atmosphere – 13

snow and ice – 26 000

infiltration – 150

lakes – 230

rivers – 1.7

groundwater flow – 7000

oceans – 1 350 400.

There are upward-pointing arrows indicating loss to atmosphere: evaporation from the lake; transpiration from the forest and fields; evaporation from precipitation (rain); and evaporation from the sea.

There are downward-pointing arrows for precipitation, surface run-off from the mountains and oceanic precipitation.

Back

Description

Figure 3 depicts the water temperature in a lake, in winter and in summer, in different shades of blue. In winter, the temperature is uniform from top to bottom. In summer, there is a layer of warm water at the top. The water temperature in the cold part (called the hypolimnion) is shown as 6 degrees Celsius, while the surface layer (called the epilimnion) has a temperature of 15 degrees Celsius.

Back

Description

Figure 4, showing the variation of dissolved oxygen concentration with depth in a water body, is in two parts. Part (a) indicates, with a straight line from the bottom to the top, that where there is no consumption of oxygen, the dissolved oxygen is at saturation value (C_s).

In part (b), where there is consumption of oxygen in the water body, the line indicates saturation value (C_s) at the water surface. The line then curves as it goes below the surface, and reaches a steady value (C), which is less than the saturation value. This difference is written as $D = C_s - C$, the oxygen deficit.

Description

Figure 5 is a set of three curves. The x-axis depicts time, while the y-axis is dissolved oxygen concentration. From a point C_O on the y-axis, a smooth curve, representing oxygen demand, slopes downward with time. Also from C_O, another curve (termed the sag curve) starts going downwards but reaches a trough quite soon and then goes upwards, eventually reaching a value C_S, the saturation concentration. A third curve (labelled the reaeration curve), from the point C_O, goes upwards and reaches the value C_S. The difference between C_S and C_O is labelled 'initial oxygen deficit'. The difference between C_S and the lowest point of the sag curve is labelled 'critical oxygen deficit'.

Back

Description

Figure 6 shows a graph of dissolved oxygen (percentage of average) against time of day. The graph starts at midnight with about 75% dissolved oxygen, goes to a low point at about 7 a.m. with about 45% dissolved oxygen, then rises to nearly 180% dissolved oxygen at about 3 p.m. It then drops back to about 75% dissolved oxygen at midnight.

Back

Description

Figure 7 shows the months June to November along the x-axis, and mean dissolved oxygen in g m^{-3} along the y-axis. There is a fluctuating line with an overall downward trend from June to November; within that trend it has peak values of dissolved oxygen in mid-June (about 7.9 g m^{-3}), the end of August (about 6.2 g m^{-3}) and early November (about 3.4 g m^{-3}).

Back

Description

Figure 8 shows, in separate rectangular boxes, all the factors influencing aquatic life (represented by a circle in the centre of the figure). The boxes are connected by straight lines to the circle. The factors are depth, suspended solids, substratum, flow velocity, pH, hardness, nutrient levels, dissolved oxygen, temperature and light penetration. Sunlight affects temperature and light penetration. Suspended solids affect turbidity, which in turn affects light penetration; also, suspended solids and flow velocity affect substratum. Nutrient levels and temperature both affect dissolved oxygen. Depth affects light penetration, which affects temperature.

Description

Figure 9 is a photograph of an Atlantic salmon leaping out of turbulent water.

Back

Description

CO_2 (dissolved carbon dioxide) plus H_2O (water) becomes H^+ (hydrogen ion) plus HCO_3^- (bicarbonate ion), which in turn becomes $2H^+$ (hydrogen ions) plus CO_3^{2-} (carbonate ion). These reactions are represented by two-way arrows, indicating that they are reversible.

Back

Description

Figure 10 is a set of curves representing CO_2, CO_3^{2-} and HCO_3^-, set against an *x*-axis showing pH and a *y*-axis showing concentration as a percentage.

The CO_2 curve goes downwards from 100% at a pH of about 5.3, to 20% at a pH of about 9.4.

The CO_3^{2-} curve goes upwards from about 15% at pH 6.5, to about 90% at pH 9.8.

The HCO_3^- curve starts from about 20% at pH 5.5 and goes to a peak of 100% at pH 8. It then goes downwards to about 60% at pH 10.

Back

Description

With the application of heat, $Ca(HCO_3)_2$ (calcium bicarbonate) becomes H_2O (water) plus CO_2 (carbon dioxide) plus $CaCO_3$ (calcium carbonate in the form of scale).

Back

Description

Figure 11 shows some common algae. *Anabaena* is between 5 and 12 micrometres in length, and looks like a chain of small round pebbles. *Asterionella* looks like a star made of five sticks; an entire colony is 300 micrometres across. *Spirogyra* is between 15 and 100 micrometres in length, and looks like a snake with cross-hatching on it.

Back

Description

Under the action of aerobes, C, H, O, N, P, S, etc. (carbohydrates and proteins) plus O_2 (oxygen) becomes CO_2 (carbon dioxide) plus H_2O (water) plus NO_3^- (nitrates) plus PO_4^{3-} (phosphates) plus SO_4^{2-} (sulfates) plus new cells plus energy.

Back

Description

Under the action of anaerobes, C, H, O, N, P, S, etc. (carbohydrates and proteins) plus NO_3^- (nitrates) plus PO_4^{3-} (phosphates) plus SO_4^{2-} (sulfates) becomes CO_2 (carbon dioxide) plus CH_4 (methane) plus N_2 (nitrogen) plus PH_3 (phosphine) plus H_2S (hydrogen sulfide) plus new cells plus energy.

Back

Description

Figure 12 is a photograph of sewage fungus. It looks like a woolly mass.

Back

Description

Figure 13 is a collage of different creatures that can be found on or in a river bed. There are snails with different types of shells, a limpet, a worm, a leech, different types of larvae, different types of nymph, a flatworm, a freshwater shrimp, a water hog louse, different types of cased caddis, a water boatman, a diving beetle and a water mite.

Back

Description

Figure 14 is a photograph of a lake surrounded by trees. The surface of the water is covered in a bright green layer.

Back

Description

Figure 15 is a series of six rectangular boxes, one above the other, and connected by arrows pointing downwards. Starting from the top, they have the following wording: increase in organic material in river; increase in decomposers; respiratory oxygen demand; oxygen depleted and different species eliminated according to their tolerances; extent of recovery depends on load and ability for self-purification; oxygen increase, species recolonisation.

Description

Figure 16 is a series of five rectangular boxes, one above the other, and connected by arrows pointing downwards. Starting from the top, they have the following wording: increase in plant nutrients, NO_3^- and PO_4^{3-}; increase in primary producers; eutrophication – algal blooms, P usually limiting; depletion of oxygen (especially at night); depletion or death of other species.

Back

Description

Figure 17 shows three circles representing clean waters, organically polluted water and water suffering eutrophication. The proportions of producers, consumers and decomposers in each are shown by means of slices (as in a pie) as follows (approximately):

	Clean waters	Organically polluted waters	Waters showing eutrophication
Producers	80	15	87
Consumers	13	5	4
Decomposers	7	80	9

Description

Figure 18a shows a single *Salmonella typhi*, which looks like two rectangular tablets joined together at the ends, with long hair-like tendrils emanating from them.

Back

Description

Figure 18b shows several *Escherichia coli*, which look like rectangular tablets with short hair-like tendrils.

Description

Figure 18c shows a single *Streptococcus faecalis*, which looks like a shoe-print but with the bottom (heel) part only slightly smaller than the front part.

Back

Description

Figure 18d shows a single *Clostridium perfringens*, which looks like a rectangular tablet.

Back

Description

Figure 18e shows several smallpox viruses, which look oval in shape with a dumbbell-shaped structure inside.

Back

Description

Figure 19 shows a helminth, which looks like a long translucent worm.

Back

Description

Figure 20 shows a schematic of a house with all the possible effluent sources, and piping taking them to a sewer. One set of pipes and gulleys takes rainwater run-off from the roof, while the second set takes wastewaters from the toilets, sinks, baths and showers. Manholes are shown at intervals along the pipe network.

Back

Description

Figure 21 shows how the drainage pipe runs from a house to the public sewer. It has a slope so that the wastewaters run by gravity. The drainage pipe has a minimum cover of 0.76 m under gardens and 1.22 m under roads and paths. Manholes are positioned at intervals along it, with the final one being within 12.2 m of the sewer.

Back

Description

Figure 22 is a schematic of a sewage treatment plant. It shows that 1 to 3 times the dry weather flow goes through a comminutor, a crossflow grit extractor, primary settlement, an activated sludge unit and then secondary settlement. The treated effluent from here is discharged to a river.

Some of the sludge from the secondary settlement unit is returned to the inflow of the activated sludge unit, and the rest goes to a sludge digester.

Incoming flow that is 3 to 6 times the dry weather flow goes through a fine screen to a crossflow grit extractor and then to a storm water tank, from which it goes to a river.

Flows greater than 6 times the dry weather flow go through a fine screen and then straight to the river.

The composition of the effluent is given at various stages:

	Crude sewage	After primary settlement	After secondary settlement
Biochemical oxygen demand $(g\ m^{-3})$	250	175	<20

Suspended solids (g m^{-3})	250	75	<30
Ammonia (N) (g m^{-3})	30	20	<5
Nitrate (N) (g m^{-3})	<5	<5	5

Description

Figure 23 is a schematic of a comminutor. This is a U-shaped structure with a macerating device (comprising many blades) atop one of the arms of the 'U'. The incoming effluent encounters the rotating blades of the comminutor, which shred solid material in the effluent. The macerated items stay in the effluent, which flows down the bend of the 'U' and emerges from the other end into a pipe taking the effluent to the next stage of treatment.

Back

Description

Figure 24 is a photograph of three open concrete grit channels, side by side. Above the grit channels is a gantry with equipment on top, with pipes going down into the grit channels.

Back

Description

Figure 25 shows the plan and elevation of a circular Pista grit trap. It is set to one side of the effluent pipe, so that the effluent goes into it and then rejoins the main effluent pipe. The section view shows that the device narrows towards the middle, with the resultant lower circular section being of a smaller diameter than the top section of the device (which contains a rotating paddle). Grit that settles out at the bottom of the trap is pumped out to a drainage basin at the side of the device.

Back

Description

Figure 26 is a photograph of an empty crossflow grit extractor. It is a large tank with a rotating arm positioned vertically in the centre. The arm has three spokes at its base, reaching from the centre of the tank to the edges, with blades underneath to sweep the settled grit towards the centre of the tank. The arm is rotated by a motor positioned on a bridge that goes across the top of the tank.

Back

Description

Figure 27 shows a schematic of an upward-flow sedimentation tank. It is shaped like a 'V' with the base flat. Influent flows through a pipe into a stilling box in the middle part of the tank. The influent then fills the tank, and solids settle out at the bottom as sludge. This is withdrawn through a pipe running up the wall of the tank. The effluent leaves the tank at the surface (where a scum baffle is positioned).

Back

Description

Figure 28 shows two graphs of concentration against time. One graph is of food (organic matter), which decreases with time in a laterally inverted S-shaped manner from a high value to zero. The other graph is of the concentration of microorganisms. This starts from zero and is bell-shaped, with the maximum point aligned with the minimum point of the food curve. In the graph of microorganism concentration, the first 75% of the rising part of the graph depicts the situation for high-rate processes (A), while the remaining 25% of the rise represents the situation for low-rate processes (B). From the peak to the decline of the microbial concentration represents endogenous respiration processes (C).

Back

Description

Figure 29 shows a biological filter. This is a large, low, circular concrete tank, filled with clinker, which has a set of rotating arms over it that distribute raw effluent over the bed of the filter.

Back

Description

Figure 30 shows some different types of corrugated plastic sheets, in stacks.

Back

Description

Figure 31 is a schematic of an activated sludge system. It shows screened, degritted sewage going into a primary sedimentation unit. There is a waste sludge draw-off from this. The outflow from the unit goes to three aeration tanks, and the outflow from these goes to a secondary sedimentation unit. From this unit, some activated sludge is returned to the inflow of the aeration tanks, while the rest is taken away as waste sludge. The outflow of clean effluent from the secondary sedimentation unit is discharged.

Description

Figure 32 shows six different types of aeration system: (a) a coarse air diffuser (an open pipe); (b) a fine air diffuser (a ceramic device through which air is pumped and broken into tiny air bubbles); (c) a surface aerator (which looks like an upturned umbrella), which is rotated on the surface of an activated sludge tank; (d) a brush aerator (a long cylinder with short vanes along it, which is rotated on the surface of a ditch containing the effluent); (e) a turbine–sparger system in which air is introduced at the bottom of a tank of effluent and is broken into tiny droplets by two rotating mixer blades (on a shaft) located at different heights above the air outlet; (f) a jet aerator, which uses a tube of varying diameter to generate small bubbles.

Back

Description

Figure 33 shows a rectangular box with one arrow entering it and another arrow leaving it.

The first arrow represents the settled sewage influent, with a flow rate of Q m^3 d^{-1} and a BOD of L_i kg m^{-3}.

The central box represents the aeration tank, which has a volume of V m^3, a rate constant of k_a d^{-1} and a sludge concentration of X kg m^{-3}.

The final arrow represents the treated effluent, with a flow rate of Q m^3 d^{-1} and a BOD of L_e kg m^{-3}.

Description

Figure 34 shows the elevation and plan of an oil interceptor. It consists of three square tanks in series. Effluent enters at the top of the first tank and is drawn off at the bottom (where it is clean, since oil will have floated to the surface). This is repeated in the next two tanks before the effluent, now minus the oil, is discharged.

Description

Figure 35 is a photograph of a system used to undertake the activated sludge respiration inhibition test. A water bath holds the samples in bottles at a fixed temperature, and the samples have leads connecting them to a computer. Atop the computer is a monitor.

Back

Description

Figure 36 is a line graph of the percentage inhibition calculated from the data given in SAQ 29. Along the *x*-axis is the percentage concentration of trade effluent, from 20 to 100%, and along the *y*-axis is the percentage inhibition. At trade effluent concentrations of 20, 40, 60, 80 and 100%, the inhibitions are, respectively, 8.2, 18.2, 38.2, 44.1 and 55.5%. From this plot, the EC_{50} can be read off, as well as the dilution necessary to reduce the percentage inhibition to 15%.

Back

Description

Figure 37 shows a schematic of an oxidation ditch system, where screened, degritted sewage is fed into a racetrack-shaped tank. The tank has two brush aerators going fully across each side, and located diagonal to each other. The outflow from the oxidation ditch goes to a final settlement tank and is then discharged. Some of the sludge from this tank is returned to the inlet of the oxidation ditch, whilst the rest is sent for disposal as surplus sludge.

Back

Description

Figure 38 is a depiction of a pure oxygen activated sludge process. There is a large closed tank with three connected compartments. Pure oxygen is fed in at the headspace of the first compartment, and exhaust gas is withdrawn from the headspace of the last compartment. The compartments have surface aerators. The effluent moves in sequence through the compartments and exits from the last. Recycled sludge is added at the first compartment.

Back

Description

Figure 39 shows the Deep Shaft process in schematic form. The shaft looks like the letter 'T', with the base tapering to a point. Screened, degritted sewage is fed in at the top of the shaft. The shaft is divided into two compartments, with the compartment on the left called the downcomer and the one on the right called the riser. Air is pumped into the downcomer, and a circular flow of effluent results. The outflow from the shaft emerges from the top of the riser, from where it goes to a vacuum degasser and then to a settlement tank, where sludge settles out. Some of the sludge is recycled to the shaft (by being fed in at the top), and the rest is disposed of.

Description

Figure 40 is a photograph of a rotating biological contactor. It looks like a large drum, positioned horizontally, with a shaft running through the middle that rotates it. The contactor is made up of a multitude of corrugated circular plastic sheets on which bacteria can grow. The contactor is half-immersed in effluent, contained in a tank.

Back

Description

Figure 41 shows a schematic of the HYBACS system. Wastewater is indicated coming into a RBC-type unit (called a 'SMART' unit), and from this unit to an activated sludge system consisting of four aeration tanks. An air blower is shown feeding air into the aeration tanks. From the aeration tanks the effluent flows to a clarifier, where sludge settles out and treated effluent is discharged. Some of the effluent from the aeration tanks is recycled back to the inlet of the process.

Some of the sludge from the clarifier is recycled back to the inlet of the process, and some is taken away for disposal.

Description

Figure 42 is a schematic of a sidestream MBR system. The wastewater is fed into the top of a closed tank (called a bioreactor). The bioreactor is aerated by diffusers at the bottom. A portion of the effluent is continuously withdrawn from the tank and passed to ultrafiltration membranes, where the microorganisms (sludge) in the effluent are separated out. Some of this sludge is recycled back to the bioreactor, while the rest is sent off for disposal.

Back

Description

Figure 43 shows a schematic of four squarish ponds, with the first two labelled as facultative ponds and the second two labelled as maturation ponds. Raw or screened, degritted sewage enters the first facultative pond at one corner and leaves at the opposite corner, flowing into the second pond. This process is repeated until the effluent, now treated, leaves the fourth pond.

Description

Figure 44 is a photograph of jets of water (treated sewage) being sprayed over plants from an irrigation system.

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Description

Figure 45 is a schematic of a covered septic tank, comprising two compartments. The first compartment is rectangular, with a sloping floor and a sump at the bottom to allow sludge to accumulate. Raw sewage enters the tank and passes through slots into a second, square compartment, from which it flows under a deflector and out to a soakaway. The inlet end of the septic tank, and the square compartment, both have inspection covers. A scum layer forms at the surface of the effluent in the septic tank.

Description

Figure 46 shows some reeds growing. At the base of the reeds, a pipe distributes effluent. The effluent percolates through the soil to the roots of the reeds, where it gets treated. The soil under the reeds has a polypropylene lining, and the ground slopes such that the treated effluent can be collected at one end of the reed bed system.

Back

Description

Figure 47 is a schematic of a microstrainer. It consists of a drum with a stainless steel micromesh covering, placed horizontally in a tank. This is rotated and the water to be treated is fed in at one end of the drum. The water passes through the mesh screen, leaving the solid material on the inner part of the screen. There is a backwash spray on the drum that washes the retained solids into a collecting trough in the hollow of the drum, ready for discharge.

Back

Description

Figure 48 is a section through a rapid-gravity sand filter. Essentially, this is a rectangular tank in which is a bed of sand. Under the sand is a collecting channel. Water requiring treatment flows through the sand and out through the collecting channel, and solids from the water are trapped in the sand bed. For backwashing, air is required, and there is a piping system to allow air to be blown through the sand bed.

Back

Description

Figure 49 shows a cutaway of a DynaSand filter. It looks like a cylinder with a cone at the bottom. A pipe with a flange emerges from the right side of the cone.

In the middle of the filter is a long airlift pipe with an inverted cone about one-quarter the distance from the bottom.

From about a third of the way down the airlift pipe there is an annulus that leads to radial pipes above the cone. Another pipe comes in at the top of the filter and joins the annulus near the top. Arrows indicate that influent flows down this pipe into the annulus; when it reaches the radial pipes it flows upwards through the main body of the filter. At the top of the filter is a weir over which the clean water flows, before leaving through another pipe.

Around the airlift pipe is the sand bed, which is shown to be moving downward (i.e. against the flow of the influent). When the sand reaches the bottom of the filter it is carried upward through the airlift pipe to a sand washer (represented as a series of rings) and then to a circular reject compartment at the top of the filter.

Back

Description

Figure 50 is a schematic of the nitrification–denitrification process. The raw wastewater or primary influent goes first to an anoxic tank where denitrification takes place. It then goes to an aerobic tank where oxidation and nitrification occur. A portion of the outflow from this tank is returned to the anoxic tank for reduction of nitrate, while the rest goes to a secondary clarifier for sludge removal. The treated effluent is then discharged. Part of the sludge collected is recycled to the inlet of the anoxic tank, while the rest is disposed of.

Description

Figure 51 is a schematic of an oxidation ditch incorporating denitrification. The ditch has mechanical aerators only at one end. This results in anoxic and aerobic zones being created in the ditch. Influent enters at the anoxic zone and leaves from the aerobic zone. The treated effluent goes to a secondary clarifier, from which some of the sludge is recycled into the aerobic zone.

Back

Description

Figure 52 is a schematic of a packed tower for removal of ammonia from wastewaters. The effluent is fed in from the top of the tower, and air is blown in from the bottom. The emergent stream at the top is air and ammonia gas, while the outflow from the bottom is treated effluent.

Back

Description

Figure 53 is a schematic of a process to remove phosphorus biologically. Influent enters an anaerobic tank and then goes to an aerobic tank, before going to a secondary clarifier. Some of the sludge collected in the secondary clarifier is recycled to the inlet stream.

Back

Description

Figure 54 shows the principles of biological phosphate removal. In a bacterial cell under anaerobic conditions, the polyphosphates are used as an energy source and converted to orthophosphates, which are released into the effluent. Fatty acids, produced during anaerobic decomposition, are absorbed and stored as polyhydroxybutyrate in the cell. When the cell is under aerobic conditions, the absorbed polyhydroxybutyrate is oxidised to carbon dioxide and water, and orthophosphates are absorbed and stored as polyphosphates.

Description

Figure 55 shows the volumetric flow rates between the tanks in the anoxic–oxic process (referred to as the A–O process). There are three tanks in sequence – anaerobic, anoxic and aerobic – followed by a clarifier. The flow rate of sewage into the first (anaerobic) tank is Q. This tank also receives a return sludge flow of Q from the clarifier. The anoxic tank (the second in the series) receives a flow of 4–5 Q from the third (aerobic) tank.

Back

Description

Figure 56 shows in schematic form the Bardenpho process. This consists of five tanks in various conditions, as follows: anaerobic, anoxic, aerobic, anoxic and aerobic. These are followed by a sedimentation tank, from which some sludge is recycled to the beginning of the process while the rest is disposed of. Mixed liquor is returned from the third (aerobic) tank to the second (anoxic) tank.

Back

Description

Figure 57 shows the set-up for membrane filtration. The water needing treatment is pumped into a membrane module. Pure water (the permeate) emerges after passing through the membrane. The remainder, called retentate, is recycled back to the inlet stream.

Description

Figure 58 shows the construction of a spiral-wound membrane. There are two membranes with a porous layer between them. The clean water emerging from the membrane enters the porous layer and is spiralled to the central collecting tube.

Back

Description

Figure 59 is a flow diagram containing a number of unknowns. Raw sewage goes to preliminary treatment; from there, three streams emerge. One stream goes to primary treatment, one goes to a box marked 'a' and then to 'macerate/bury', and the last goes to a box marked 'grit' and then to a box marked 'b'.

From primary treatment, one stream goes to 'biological treatment by activated sludge process' and the other goes to a box marked 'c'.

From the box marked 'c', the stream goes to sludge treatment and from there to two further streams, one to 'dewatering' and one to a box marked 'd'.

From the biological treatment stage, one stream goes to 'secondary sludge' and then to a box marked 'e' before returning to the inlet to the biological treatment process. The other stream goes to a box marked 'f' and then is considered as treated effluent.

Back

Description

Figure 60 shows the anaerobic digestion process, which involves two covered tanks. In the first tank, sludge is mixed and heated. Digester gas rises to the top of the tank and is withdrawn. Sludge from the first tank goes to a second tank, where it settles out. Again, gas rises to the top and is withdrawn.

Back

Description

Figure 61 is a photograph showing several low rectangular enclosures, each containing an even layer of sludge.

Back

Description

Figure 62 shows the main components of a dissolved oxygen probe. It has a circular plastic body, a silver cathode, a lead anode and a semi-permeable membrane. The cathode and anode are connected to an amplifier and then to a meter.

Back

Description

Figure 63 shows how the dissolved oxygen concentration decreases during an oxidation reaction. The x-axis denotes time, while the y-axis records concentration. From an initial dissolved oxygen concentration of C_0, the concentration decreases to a value C_u. The dissolved oxygen concentration C_t at any time t can be read off from the smooth graph relating time and dissolved oxygen concentration.

Back

Description

Figure 64 shows how the BOD (along the *y*-axis) increases over time (shown on the *x*-axis), first rapidly and then more slowly, until it reaches a horizontal line representing the ultimate oxygen demand (L_u). At any time *t*, BOD_t is given by the distance between the *x*-axis and the graph line, while L_t is the distance between the graph line and the L_u line.

Description

Figure 65 shows the BOD versus time relationship for three different effluents with three different decay constants (k). The effluent with the highest k value (1.0 d^{-1}) decays rapidly, with the BOD rising rapidly with time. The effluent with the lowest k value (0.01 d^{-1}) follows a straight line of about 30 degrees. The third effluent, with a k value of 0.1 d^{-1}, shows a BOD-time profile between the other two situations.

Back

Description

Figure 66 shows an almost straight line for BOD against time, rising from 0 at 0 days to just over 8 after 2.5 days.

Back

Description

Figure 67 shows a plot of BOD against $(1 - e^{-0.4t})$. This is a straight line of slope 12.9, starting at the origin and rising to about 8.5 BOD for $(1 - e^{-0.4t})$ equal to approximately 0.7.

Back

Description

Figure 68 shows a diagram of a sample bottle for measuring BOD. Less than half the bottle is taken up by sample, with the rest being headspace. There is a stirring bar at the bottom, and a BOD sensor and NaOH tablets in the cap.

Back

Description

Figure 69 is a photograph of a test strip being compared against a standard strip. The standard shows a series of squares of different colours, each marked with a pH value.

Back

Description

Figure 70 is a photograph of a conductivity meter, a small hand-held device with a digital readout.

Back

Description

Figure 71 shows a circular membrane filter with red and green dots of colonies on it, held in a transparent dish. The membrane filter is marked with grid squares, making it easier to count the dots.

Description

Figure 72 shows several membrane-type samplers. Each one is rectangular in shape with a grid of squares on it, and has a small projection on the top by which it can be held. Each sampler is stored within its own plastic case.

Back

Description

Figure 73 shows a river meandering through a valley, with trees and shrubs to each side. A pollutant stream is seen to enter the river from the right, at a point marked A.

Back

Description

Figure 74 shows how the BOD decay rate constant (in units of d^{-1}, from 0 to 0.2 along the *y*-axis) varies with temperature (in degrees Celsius, from 0 to 15 along the *x*-axis). The graph is almost a straight line, with a positive slope, at an angle of about 45 degrees. Thus the BOD decay rate constant is seen to increase with temperature.

Back

Description

Figure 75 shows a graph that indicates the distance downstream of the discharge point where the CBOD will be at an acceptable level (6.3 mg l^{-1}) for freshwater fish life, for different river water temperatures. The graph is a straight line with a downward slope. At 8 degrees Celsius (on the *x*-axis) the acceptable distance is 46.7 km (on the *y*-axis), and at 15 degrees Celsius it is 33.8 km.

Description

Figure 76 shows where a water intake point should be located downstream of a sewage works discharge point, for different river water temperatures. It is a straight line with a downward slope, with distance from the sewage works discharge point on the *y*-axis and river water temperature on the *x*-axis. At a river water temperature of 6 degrees Celsius, the intake point should be 35.2 km from the discharge point, and at 14 degrees Celsius it should be at 24.2 km.

Back

Description

Figure 77a shows the dissolved oxygen level (in mg l^{-1} along the *y*-axis) at different points along a river (the distance shown in m along the *x*-axis). There is a dip when the dissolved oxygen level reaches a minimum, and then afterwards it rises.

Back

Description

Figure 77b zooms in on the area around the dip in the graph in Figure 77a, showing the minimum dissolved oxygen level to be about 2.5 mg l^{-1}, at a distance of about 32 km down the river.

Back

Description

Figure 78a shows the dissolved oxygen level in the river after the accidental discharge of industrial effluent. A minimum level of dissolved oxygen is reached before the level goes up.

Back

Description

Figure 78b is a similar graph to Figure 78a but with a larger scale. The minimum level of dissolved oxygen is seen to be about 0.98 mg l^{-1}, at a distance of about 4.0 km from the discharge point.

Back

Description

Figure 79 shows the regions of validity for three different correlations for the reaeration constant. The regions are bounded by different values of stream velocity (in m s^{-1}, along the *x*-axis) and stream depth (in m, along the *y*-axis). The regions are as follows:

Correlation	Stream velocity (m s^{-1})	Stream depth (m)
Owens–Edwards–Gibb	0.03–1.8	0.09–0.60
O'Connor–Dobbins	0.03–0.52 at a depth of 0.60 m, to 0.03–1.63 at a depth of 15.0 m	0.60–15.0
Churchill–Elmore–Buckingham	0.52–1.80 at a depth of 0.60 m, to 1.63–1.80 at a depth of 15.0 m	0.60–15.0

Each of the three regions contains parallel lines, showing increasing values of the reaeration constant as depth decreases and velocity increases.

Description

Figure 80 shows the level of total-nitrogen along the 10 km of the river detailed in the exercise. The total-nitrogen (shown along the y-axis) is 0.05 mg l^{-1} initially and rises in a smooth curve to a value of about 0.2 mg l^{-1} at a distance of 10 km (shown on the x-axis).

Back

Description

Figure 81 shows the level of total-phosphorus along the 10 km of the river detailed in the exercise. The total-phosphorus (shown along the y-axis) is 0.02 mg l^{-1} initially and rises in a smooth curve to a value of about 0.057 mg l^{-1} at a distance of 10 km (shown on the x-axis).

Back

Description

Figure 82 shows the total-nitrogen to total-phosphorus ratio along the 10 km of the river detailed in the exercise. The ratio (shown along the *y*-axis) is 2.5 initially, but rises steeply at first and then more gradually to a value of about 3.6 at a distance of 10 km (shown on the *x*-axis).

Back

Description

Figure 83 shows the level of total-nitrogen along the 15 km of the river detailed in the SAQ. The total-nitrogen (shown along the y-axis) is 0.3 mg l^{-1} initially and rises in a smooth curve to a value of about 0.7 mg l^{-1} at a distance of 15 km (shown on the x-axis).

Back

Description

Figure 84 shows the level of total-phosphorus along the 15 km of the river detailed in the SAQ. The total-phosphorus (shown along the y-axis) is 0.03 mg l^{-1} initially and rises in a smooth curve to a value of about 0.10 mg l^{-1} at a distance of 15 km (shown on the x-axis).

Back

Description

Figure 85 shows the total-nitrogen to total-phosphorus ratio along the 15 km of the river detailed in the SAQ. The ratio (shown along the *y*-axis) is 9.2 initially, but drops steeply at first and then more gradually to a value of about 6.8 at a distance of 15 km (shown on the *x*-axis).

Back

Description

Figure 86 shows the total coliforms (in MPN per 100 ml, along the *y*-axis) against the distance from the outfall (in m, along the *x*-axis). The MPN is about 9×10^5 at the outfall, but decreases steeply at first and then more gradually to become 0 at about 100 km away.

Back

Description

Figure 87 is a drawing showing a town with a sewage works on one side of a river, and a water intake (with a screen) further downstream on the other side of the river, leading to a water treatment works.

Back

Description

Figure 88a shows a graph of total coliforms (in MPN per 100 ml, along the *y*-axis) against the distance from the outfall (in m, along the *x*-axis). The MPN is about 5.5×10^4 at the outfall, but decreases at first steeply and then more gradually to become 0 at just over 600 km away.

Back

Description

Figure 88b is a graph focused on the region of Figure 88a where the total coliforms are around 5000 MPN per 100 ml. This reveals that the point in the river where the total coliforms are 5000 is about 300 km from the outfall.

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