Technological Educational Institute
Msc Post graduate course in the
Environmental Management

Basic Principles of
Water Quality Control

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Foreword

The purpose of this handout is to provide a text for the postgraduate student attending the courses of Environmental Management at the Technical Educational Institute (TEI) of Larissa, in Quality Control of potable Water.

The text is referred on my lecture courses, based on the indicative content and the learning strategies applied by the Staffordshire University in co-operation with the TEI of Larissa, for this module.

A lot of effort has been disbursed to cover fundamental demands of knowledge in a simple and easily understood way, since the content of this sector is really huge.

Wherever possible, simple illustrations or examples have been used to clarify the text. Reproduction of detailed working drawings has been avoided, since these are often confusing to the student until the fundamentals of the subject are fully understood.

In the hope that a large part of my targets has been realised, I hand over this textbook to the postgraduate students attending the courses of this module, accepting every criticism of good faith which could be proved useful in the future.

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Chapter 1

Introduction

In engineering, water supply is a large and growing field, which, until the second half of twentieth century was rather simple. In that period, water was abstracted from a reservoir or from wells and after generally minimal treatment was put into the distribution network.

Some supplies derived from rivers required more treatment. When poor quality lowland rivers were used as a source, the water was stored to allow self-purification and the subsequent treatment was often slow sand filtration.

Distribution systems were also simple. The water was generally pumped to towers located at high points, and from there served the supply zones by gravity. There was little or no flow measurement and leakage was generally not a major concern.

In practice the only quality standards were microbiological and testing of chlorine levels. In the UK, universal chlorination of public drinking water was introduced after the Croydon typhoid outbreak of 1936.

The major concern during the first half of the 20th century was to cover the ever-increasing demand for water, as the number of consumers were increased, they acquired indoor toilets, baths, washing machines, cars and garden hoses.

Water supply was a public service and was seen as a public right. Of course, in the developing world there are often high rates of demand growth associated with increasing urbanization and wealth, resulting to more water-using appliances.

Common problems include high per capita water production, a shortage of economic water resources and low water prices.

In Europe there were some complaints about the cost of water, but it is recognised as essential, to have the highest quality of water, almost regardless of cost.

1.1 – Fresh water

Water is the most vital natural resource to all life forms and indeed to social and economic activity. Although people can live for many days without food, the absence of water for just a few days has fatal consequences.

In the past the fresh water supply has been considered inexhaustible and, like fresh air, it has been treated as virtually 'free' good. Now, however, there are signs that the demand for fresh water is approaching the limits of supply. According to some estimates, the global supply crisis is expected to occur between 2025 and 2050, although much earlier for some individual countries.

This is the reason why attention is starting to focus on the prudent use of water and on more effective methods for treating and recovering it after use. Today, since fresh water is no longer free, nor freely available, it is clear that we can no longer afford to discard it as a waste product.

In Europe the demand for water has increased from 100 km^3 a year in 1950 to 650 km^3 in 2000. It is therefore obvious that over abstraction from surface and underground supplies may be short-term solutions but they are not sustainable in the long run.

About 7% of the earth's mass is water, which totally occupies the earth and its surrounding atmosphere. However, 96.5% of this water occurs as seawater and much of the remaining fresh water is incorporated into the polar icecaps and glaciers.

Only about 0.7% of the earth's water exists as fresh water in lakes, rivers, shallow aquifers and in the atmosphere. If this available water were distributed on the earth's surface in the same way as its population density there would be no problem for all predicted needs.

In practice, however, the distribution of precipitation varies widely from many meters a year in mountainous tropical rain forests, to essentially nil in major desert areas. In fact 20% of the fresh water of the earth is found in the Amazon Basin which has only a slight percentage of the earth's population.

Even within a continent there is a large variation between rainfall and population density. Heavy rainfall, which produces high runoff and ground water recharge, is found in mountainous regions with low population. Flat lowland areas, which are ideal for both urban development and agriculture, are often in the rain shadow of mountains, having low precipitation.

In the UK, for example, the Scottish Highlands has a population density of about 2 persons per km^2 with precipitation exceeding 3 m a year, while in South East England the population density exceeds 500 persons per km^2 with a rainfall only about 0.6 m a year.

The supply of fresh water on land is dependent on the hydrological or water cycle, which eventually is driven by the heat of the sun. The major steps of this cycle start with evaporation of water from seas, oceans and open water areas. This water vapour collects in the atmosphere and is precipitated as rain, snow, sleet, hail or dew. At this stage the water can be considered 'fresh' and largely free from contamination.

On reaching the land surface, however, this fresh water percolates through soils and rock layers, or runs off directly to watercourses and eventually returns to the sea. It is continuously abstracted directly from land, from these watercourses, or from wells or boreholes, to sustain natural vegetation or animal life along with human, domestic, agricultural and industrial needs.

1.2 – Sustainable development

Many environmental problems arose in the developed countries due to a lack of appreciation, concern and understanding of the causes of environmental pollution.

International discussions, aiming at preventing the earlier mistakes of the developed countries being repeated throughout the rest of the world, resulted in the introduction of the concept of sustainable development.

The Brundland report, *Our Common Future*, published in 1987, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In fact this definition implies:

- recognition of the essential needs – particularly of the world's poor
- concern for social equity between generations and within generations
- recognition of the limitations of technology and social organizations on the ability of the environment to meet the present and future demands.

With respect to water the above concepts can be interpret as follows:

1. Water is a scarce resource, which should be viewed as both a social and an economic resource.
2. Water should be managed by those who most use it, within a comprehensive framework, taking into account its impact on all aspects of social and economic development.

The European Commission defines the objectives of a sustainable water policy as

- provision of a secure supply of a safe drinking water in sufficient quantity
- provision of water resources of sufficient quality and quantity to meet other economic requirements of industry and agriculture
- quality and quantity of water resources sufficient to protect and sustain the good ecological state and functioning of the aquatic environment
- Management of water resources to prevent or reduce the adverse impact of floods and minimise the effects of droughts.

Although decisions may eventually be taken on political or philosophical grounds, it is essential that the fullest engineering and scientific information is available to assist the decision-makers.

1.3 – The role of engineers and scientists

Water engineering is probably the largest single branch of the civil engineering profession. Public works, such as water supply and sewage disposal schemes have traditionally been seen as civil engineering activities.

The relation with civil engineering is due to the fact that most water engineering works involve large structures and require a good understanding of hydraulics.

Water science and technology involve the application of biological, chemical and physical principles along with engineering techniques.

A major objective in the research of water quality control is to reduce the incidence of water-related diseases. This depends on the ability to develop water sources, which provide an ample supply of healthy water, i.e. water free from

- visible suspended matter

- excessive colour, taste and odour
- objectionable dissolved matter
- aggressive constituents
- bacteria indicative of faecal pollution

Having provided water of suitable quality and quantity, it becomes necessary to convey the supply to consumers through a distribution system, consisting of water mains, pumping stations etc.

Big cities produce large volumes of solid wastes, which may create major environmental problems in their disposal.

1.4 – The hydrological cycle

The total volume of water in the world remains constant. What changes is its quality and availability. Water is constantly being recycled, a system known as the hydrological cycle.

Within this cycle, the water is constantly moving, driven by solar energy. The sun causes evaporation from the oceans, which forms clouds and precipitation (rainfall). Evaporation also occurs from lakes rivers and the soil, with plants contributing significant quantities of water by evapo-transpiration.

While about 80% of precipitation falls back into the oceans, the remainder falls on to land. It is this water that replenishes the soil and ground water, feeds the streams and lakes, and provides all the water needed by plants, animals and, of course, humans.

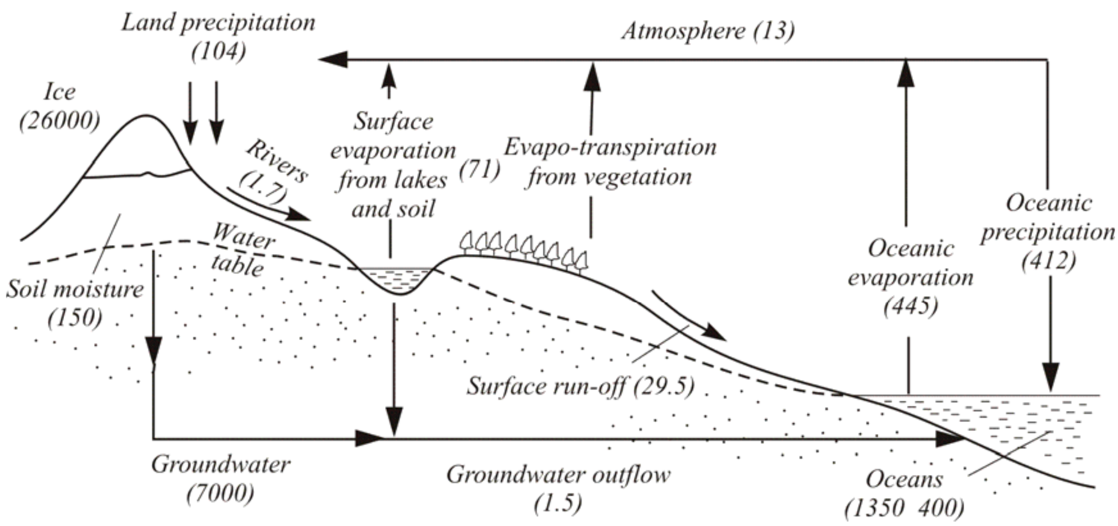

Figure 1.1 Hydrological cycle

The cycle is a continuous one and so water is a renewable resource. In essence, the more it rains the greater the flow in the rivers and the higher the water table rises as the underground storage areas (i.e. the aquifers) fill with water as it percolates downwards into the earth.

Hydrological cycle is presented in figure 1.1 along with the volume of water that is stored and the amount of it, which is cycled annually. All volumes are expressed as 10^3 km^3.

Water supplies depend on rain and when this amount decreases, the volume of water available for supply will decrease, and in cases of severe drought will fall to nothing. Thus a careful management of resources is required for sufficient water supply all year round.

Nearly all freshwater supplies come from precipitation which falls on to a catchment's area. Also known as watershed or river basin, the catchment is the area of land, often bounded by mountains, from which any water that falls into it will drain into a particular river system. A major river catchment will be made up of many smaller sub-catchments each draining into a tributary of the major river.

Each sub-catchment usually has different rock and soil types, and consequently different land use activities, which also affect water quality. So the water draining from each sub-catchment may be different in terms of chemical quality.

As the tributaries enter the main river, they mix with water from other sub-catchments upstream, and alter continuously the chemical composition of the water. Therefore water from different areas will be chemically uniquely different.

When precipitation falls into a catchment, one of the following 3 possible events will occur:

1. It may remain on the ground as surface moisture, returning eventually to the atmosphere by evaporation. Alternatively it may be stored as snow on the surface until the temperature rises sufficiently to melt it. Storage as snow is an important source of drinking water in some regions. For example throughout Scandinavia lagoons are constructed to collect the run-off from snow as it melts, and this provides the bulk of their drinking water during the summer.

2. Precipitation flows over the surface into small channels to become surface run-off into streams and lakes. This is the basis of all surface water supplies and will eventually evaporate into the atmosphere, percolate into the soil to become ground water, or continue as surface flow in rivers back to the sea.

3. The third route is for precipitation to infiltrate the soil and slowly percolate into the ground to become ground water, which is stored in porous sediments and rocks. Ground water may remain in these porous layers for periods ranging from just a few days to possibly millions of years. Eventually ground water is removed by natural upward capillary movement to the soil surface, plant uptake, ground-water seepage into surface rivers, lakes or directly to the sea, or artificially by pumping from wells and boreholes.

The water in the oceans, icecaps and aquifers is all ancient, acting as sinks for pollutants. All pollution eventually ends up in the cycle and will ultimately find its way to one of these sinks.

1.5 – Fresh water habitats

There is a wide range of fresh water habitats. Lakes, ponds, springs, mountain torrents, lowland rivers are just some of them and the hydrological, physico-chemical and biological characteristics may vary enormously between them.

In the most basic classification, water can be separated into surface and ground water. Surface waters are further divided into flowing systems (lotic) and standing systems (lentic).

In reality lotic and lentic systems often grade into each other and may be difficult in practice to differentiate. Some systems are a mixture of the two.

Lotic systems have a more open system than lentic ones, with a continuous and rapid throughput of water and nutrients, resulting in a unique flora and fauna.

Chapter 2

Characteristics of water

Water has several properties, which can not be explained in a simple way. At low temperatures water behaves as if its molecular form was H_6O_3 or H_8O_4 held together by hydrogen bridges. As the temperature approaches freezing, these structural links become more important than the thermal agitation, which results in a looser association of molecules.

The effect that ice is less dense than water and the fact that the water density increases as the temperature rises from 0°C to 4°C is due to the interaction of the two molecular forces, internal and external. Then, the decrease of density with further increases in temperature is because thermal agitation has greater effect at higher temperatures.

This density effect results in two main consequences:

1. Bursting of pipes during freezing conditions
2. Thermal stratification of lakes.

In the second case, seasonal warming of a body of water forms a density barrier to mixing, so that in deep lakes, a large volume of water may be virtually stagnant and of poor quality. When the air temperature falls, the water on the surface cools, increasing the density, which eventually reaches that of the lower level, with the result that the surface and lower layer are mixed together.

This overturn is usually realised by wind and gives rise to serious quality problems as stagnant bottom water is mixed with the good quality water from the surface.

All natural waters contain different amounts of other materials, in concentrations ranging from minute traces at the ng/l level of organics in rainwater, to around 35000 mg/l in seawater.

Wastewaters usually contain most of the dissolved materials of the water supply with additional impurities, arising from the waste processes.

The human metabolism releases about 6 g of chloride each day, so that with a water consumption of 150 l/person day, domestic sewage will contain at least 40 mg/l more chloride than the water supply to the area.

A typical raw sewage contains around 1000 mg/l of solids in solution and suspension and consequently is 99.9% pure water. Seawater at 35000 mg/l of impurities is obviously much more contaminated than raw sewage. This anomaly highlights the fact that a simple measure of the total solids of a sample is insufficient to specify its character. The prospect of swimming in seawater is rather more attractive than the same activity in raw sewage!

To have a true understanding of what is the nature of a particular sample, it is necessary to measure different properties by analysing different physical, chemical or biological characteristics.

2.1 – Tastes and odours

Algae may exist in surface waters, particularly those coming from lakes or reservoirs. These can lead to objectionable tastes and odours in treated water and are particularly associated with chlorination.

The removal of algae is essential and often difficult. Some substances may also cause taste even when they are in extremely low concentration, such as 1 μg/l.

After chlorination, phenols may give rise to taste from chlorophenols when present in concentration down to as low as 0.01 μg/l.

2.2 – Hardness

The soluble salts of calcium (Ca) and magnesium (Mg), commonly found in water cause hardness. Hardness forms insoluble precipitates with soap and requires more soap for lather. It also causes boiler scale.

In the past it was common to soften hard waters. However, it is somehow believed that soft water causes hart disease, so today, softening is less common.

In the UK there is sometimes a legal requirement to soften supplies in some areas for promoting water supply schemes.

2.3 – Iron and manganese

Iron and manganese impart colour and may have staining results in washing. Iron is derived either from raw water or from corrosion of iron water mains. Manganese exists in raw water.

These elements are common in some ground waters or waters taken from lower levels of reservoirs.

2.4 – Sulfates, chlorides, bromides, and fluorides

When the sulfates of magnesium and sodium exist largely in water act as laxatives.

Chlorides in concentration above 600 mg/l tend to give the water a salty taste.

Bromides have only recently become recognized as a raw-water-quality problem, because when bromide is ozonated, there is a risk of bromates forming, for which the allowable concentration is very low.

Fluorides in low concentration of approximately 1.0 mg/l provide protection from tooth decay and fluoride is dosed in some areas for this reason. However, levels of higher concentration (1.5 mg/l) are undesirable and may affect bones and cause mottling of teeth.

2.5 – Corrosiveness and plumbosolvency

Waters with high concentration of CO_2, low pH and low alkalinity are generally corrosive. Corrosive waters can attack materials of the distribution network and domestic plumbing systems, and may result in higher concentration of iron, copper and lead.

A commonly used measure of weather water is corrosive is the **Langelier Saturation Index** (LSI). This is the difference between the actual pH of the water and the pH value at which the water would be saturated with calcium carbonate (pH_s). However it is only a crude indicator of corrosion problems. Corrosion is far more complex than this.

Plumbosolvency is the tendency of water to dissolve lead, which exists in many older domestic plumbing systems (lead pipes, lead joints in cast iron pipes, and in the solder used to join copper pipes).

High lead concentrations are associated with health problems, particularly in infants and young children. Due to the lead standards in the 1998 EU Drinking water Directive, pH adjustment and the dosing of phosphate-based chemicals to reduce corrosion has become very common.

Chapter 3

The impurities

It is impossible to find absolutely pure water in nature and it is rare to encounter a source of water that requires no treatment before its use for potable water supply.

Water contains both inorganic and biological matter and it is normal to classify the impurities found in water in one of the three – progressively finer states – suspended, colloidal and dissolved.

The method of treatment required for the removal of impurities, or their reduction to acceptable limits, depends basically on the fineness of the material. While the matter found in raw water may result to make it inappropriate for human consumption, treatment could also badly affect water quality, by introducing pollutants, or by modifying chemicals that were harmless before.

3.1 – Suspended matter

Running water usually carries floating debris, but it also can pick up and transport solid particles of greater density than water. The higher the velocity the heavier the particle that can be transported.

Rivers are normally at a high turbid during flood. Table 3.1 shows the sizes of solids that are transported at different velocities.

Table 3.1. Transportation velocities of particles

Material	Particle's diameter (mm)	Water Velocity (m/s)
Fine sand	0.4	0.15
Medium sand	1.1	0.23
Coarse sand	2.5	0.30
Gravel	2.5 – 25	0.76
Shingle	25 – 75	1.20

Large rivers often run at velocities much higher than those indicated in the table and therefore may carry high quantities of suspended material.

3.2 – Colloids

These are fine articles that do not settle, which are electrically charged. They have a similar electrical charge, normally negative, which prevents them from joining together to form larger settle able particles.

They are invisible to the naked eye, but can give colour and turbidity to the water.

3.3 – Dissolved solids

The water, passing over or through the ground, may dissolve a wide variety of chemicals.

Common cations of metals are aluminium, calcium, sodium, potassium, iron and manganese.

Common anions are bicarbonate, chloride, sulfate and nitrate.

A soft upland water, usually has a **Total Dissolved Solids** (TDS) of 70 – 150 mg/l and a hardness of 30 – 100 mg $CaCO_3$/l.

Lowland rivers have a TDS of 200 – 400 mg/l and a hardness of 100 – 250 mg $CaCO_3$/l.

Ground waters can have a TDS of up to 500 mg/l or even higher and a hardness of 400 mg $CaCO_3$/l or more.

Gasses may also exist in ground waters, particularly carbon dioxide, CO_2, oxygen, nitrogen and ammonia.

Dissolved Solids (DS) that exist naturally in low concentrations are not usually harmful.

3.4 – Organic pollution

Pollution from organic matters may be dangerous, particularly for ground water sources, which usually receive little treatment. Faecal pollution, either from animals or from humans is very serious, since there are many risks of disease transmission. The presence of ammonia, nitrates or nitrites, which are decomposition products of organic wastes, indicates the possibility of faecal contamination. This is confirmed by the presence of bacterial indicators.

Water derived from peaty upland catchments may have high levels of organic colour, usually coming from humic acids. Treatment in such cases is not easy and chlorination may result in the production of **TriHaloMethanes** (THMs). Waters with algae may also tend to form high levels of THMs after chlorination. Chloroform is the most common THM.

3.5 – Algal toxins

When water is taken out from lakes or reservoirs, there is a risk of algal toxins produced by blue-green algae (cyanobacteria). There are three classes of toxins, which are important for drinking water:

- hepatotoxins – which affect the liver
- neurotoxins – which affect the nervous system (respiratory arrest)
- lipopolisaccharides – some of which are irritants.

In this environment, another kind of toxins, which may cause severe dermatitis to swimmers, is dermatotoxins.

3.6 – Microbiological parameters

The greatest threat to human health from drinking water derives from pathogenic micro-organisms. Our first concern of water treatment is therefore to produce water free from such organisms.

One way would be to analyse for organisms causing specific diseases. However, it is difficult to cultivate such bacteria, and it is not practicable to analyse directly for viruses. So the approach is to look if there are easily identified bacteria that are known to exist in human faeces, and to treat them as an indication of possible faecal contamination.

If there are not such organisms, then water is assumed to be free from human pathogens and consequently suitable for consumption.

There are three or four main bacteriological parameters used to assess the quality of drinking water:

- coliform bacteria
- faecal coliforms
- colony/plate counts and
- faecal streptococcus

The 1998 European Union (EU) Drinking water Directive included a standard for surface waters for the sulphate reducing bacterium

Clostridium perfringens, which is another indicator of faecal pollution. British Standards also include a standard for *Cryptosporidium parvum* (commonly known as crypto). This was introduced because recently there was an anxiety on the presence of protozoan oocysts, notably *Cryptosporidium* and *Giardia lamblia*, both of which cause severe gastroenteritis.

Of course the transmission of viruses is a problem, but it seems that viruses are inactivated by disinfection. So far there is little evidence for viral transmission in properly treated water.

Coliform bacteria are widely found in nature and do not necessarily indicate faecal contamination.

In practice all surface waters and surface sources have coliforms, and most have faecal coliforms. However, ground waters are often pure from the bacteriological point of view.

Plate counts give an indicator of the overall level of bacterial activity in a sample and do not directly relate to faecal contamination.

Chapter 4

Health and water

In the developed world, water-related diseases are rare because there is efficient water supply and waste water disposal systems. However in the developing world more than 1 billion people are without safe water supply and almost 2 billion do not have adequate sanitation. Millions of people die each year due to unsafe water or inadequate sanitation.

At any time there are likely to be 400 million people suffering from gastroenteritis, 200 million with schistosomiasis, 160 million with malaria and 30 million with onchocerciasis. All these diseases may be water-related although some environmental factors may also play an important role.

4.1 - Diseases

A brief outline of the main features for the water-related diseases is given below.

Each case of disease requires for its spread a source of infection, a transmission route, and the exposure of a susceptible living organism. A control of disease would therefore aim at curing sufferers, breaking the route of transmission or protecting the susceptible population.

The measures taken by engineering in disease control essentially break the transmission route. The two other parts of the infection chain, (source and exposure) are covered by medical measures.

Depending on the way the pathogen spends its life in the human body, there are 2 basic types of diseases:

a. Contagious, when the pathogen remains mainly in the human body. It can live only for a short time in the unfavourable environment outside the body. Direct contact, droplet infection or similar means transmits this type of disease.

b. Non-contagious, when the pathogen spends part of its life cycle outside the human body, so that direct contact is not of great significance. This type of disease may involve simple or more complex transmission routes with extra corporeal development of the organism in soil or water.

When a disease is always present in a population at a low level of incidence, it is termed *endemic*. If it has widely varying levels of incidence, the peak levels are called *epidemics* and worldwide outbreaks are termed *pandemics*.

4.2 – Water – related disease

The next table shows the most important infectious diseases, which can be transmitted by water. These diseases may be due to viruses, bacteria, protozoa or worms.

Table 4.1 The main water – related diseases

Disease	**Relationship**	**Annual deaths**
Cholera	Waterborne	4 million
Amoebic dysentery	Waterborne or water-washed	1 million
Ascariasis	Water – washed	Few deaths, many cases
Dracunculiasis	Water – based	200 thousand
Malaria	Water related insect vector	1 million

Although their control and detection is partly based on the type of the agent, it is often helpful to consider the water – related aspects of the spread of infection.

4.2.1 – Waterborne disease

The contamination of water by human faeces or urine is the most common form of water-related disease, that causes most harm on a global scale. This type of infection, occurs in the scheme which follows,

… Infected person … Pathogens in excreta … Contaminated water source … Consumption of untreated water … Susceptible person … Infected person… ,

when the pathogenic organism enters in water, which is then consumed by a person who does not have immunity to the disease.

This category comprises cholera, typhoid, bacillary dysentery etc. They follow a classical faecal – oral transmission route and result in a simultaneous illness for a number of people who use the same source of water.

There are other waterborne diseases in which the infection scheme is more complicated. Weil's disease (leptospirosis) is transmitted in the urine of infected rats and the causative organism is able to penetrate the skin so that external contact with contaminated sewage or flood water can spread the disease.

4.2.2 – Water – washed disease

This type of disease includes a number of skin and eye infections, which normally are not fatal, but have a serious debilitating effect on sufferers.

The main reason is usually the poor hygiene, due to inadequate water supply for washing.

The diseases of this form comprise bacterial ulcers, scabies and trahoma and usually occur in hot dry climates. Their incidence can be reduced if ample water is available for personal washing.

4.2.3 – Water – based disease

This type of disease depends on the pathogenic organisms. These organisms spend a part of their life either in water or in an intermediate host, which lives in water.

Worms that infest the sufferers cause many of these diseases and produce eggs which are discharged in faeces or urine. Infection often occurs by penetration of the skin rather than by consumption of water.

Schistostomiasis (also called bilharzia) is the most important example. The infection occurs in a relatively complex scheme and comprises two cycles: one in water and one in man.

Dracunculiasis (guinea worm) is another water – based disease, which is spread in the tropics. The intermediate host here is *Cyclops* and infection occurs by ingestion of water containing infected *Cyclops*.

4.2.4 – Water – related insect vectors

Many diseases are spread by insects, which feed near water. Infection with these diseases is not connected with human consumption or contact with the water. Mosquitoes, which transmit malaria and other diseases, prefer shallow stagnant water, i.e. in pools, around the edges of lakes.

From this point of view it is important to ensure that water supply and drainage works do not allow the existence of mosquitoes. If this is not possible, effective screens should prevent mosquitoes.

Simulium flies, which transmit onchocerciasis (river blindness), breed in turbulent waters associated with waterfalls or created by engineering structures. Control may be by use of insecticides injected upstream of the point of turbulence.

4.2.5 – Water – related diseases in developed countries

Many water-related diseases, especially those of a gastrointestinal nature, like cholera and typhoid, were widespread in Europe and North America last century, but have disappeared in developed countries due to improvements in public water supply and sanitation.

However, a waterborne disease is always possible. Recently pathogenic protozoans present in public water supplies have caused a number of intestinal infections in the UK and North America. These outbreaks caused by microorganisms of the *Cryptosporidium* and *Giardia* families, which exist as cyst forms and can be spread in the environment, since they exist in the faeces of many animals. The cysts are usually removed by sand filtration, but this cannot be guaranteed. They are resistant to chlorine as well.

Legionnaires' disease has been recently related to hot water supplies, showerheads, cooling waters and systems that produce droplets of fine sprays. So the disease appears not by drinking contaminated water but breathing in a contaminated spray.

The causative micro organism occurs naturally in water sources, often underground, and, resisting the normal water treatment, it can colonize the service systems in buildings, specially in warm surroundings.

Chapter 5

Control on water pollution

All natural waters contain a variety of contaminants. To this natural contamination is added that, arising from domestic and industrial wastewaters, which may be disposed of into the sea, on to land, or, most commonly, into surface water.

Paracelsus, in his classic book published in the 1500s, quoted that all substances are poisons, only the dose makes a distinction between one that is a poison and one, which is a remedy.

Any body of water is capable of assimilating a certain amount of pollution without serious effects because of the dilution and self-purification factors that are present.

If additional pollution occurs, the nature of the receiving water will be altered and therefore its suitability for various uses may be impaired.

5.1 – *Sources of water pollution*

The demand for water varies depending on the use and also on the country concerned. For instance, the average daily per capita water consumption in Europe is approximately 225 litres, with some countries in Northern Europe (e.g. Denmark and Germany) consuming less than 200 litres (Kiely, 1997).

The UK consumption averages 340 litres per capita per day (Water UK, 2000) while the USA average varies from 130 to 2000 litres per capita per day.

Table 5.1 shows that industry consumes 78% of fresh water in the UK while 1% is consumed by agriculture and 21% by domestic and commercial activities.

However, these proportions are quite different in less developed countries with hotter climates (e.g. India and Egypt), where water usage is dominated by agricultural irrigation practices.

Table 5.1 Use of fresh water in selected countries

(Saeijs and van Berkel, 1995)

Country	Agricultural	Industrial	Domestic and Commercial
China	87%	7%	6%
Egypt	88%	5%	7%
India	93%	3%	4%
France	12%	71%	17%
Netherlands	32%	63%	5%
United Kingdom	1%	78%	21%

Agricultural practice is considered to be the largest contributor to water pollution, due to run-off into watercourses from farmyard wastes, slurry, and under-utilised fertiliser and pesticide applications. Industry, on the other hand, is not considered to be such a large polluter because industrial effluents are closely monitored by the regulatory agencies, which in most cases require on-site waste water treatment prior to its discharge into water courses or sewerage systems.

Furthermore, for economic reasons, industry is now recycling progressively higher proportions of its process water on site, thereby reducing its need for new supplies. For example, a UK power station operator has reduced its fresh water purchases at one of the sites by 90%, thus saving £800,000 per year in water purchase and treatment costs.

By contrast, wastewater or *sewage* from domestic and commercial activities is normally not treated at source, but fed through the piped sewerage system to be purified at a **Sewage Treatment Works** (STW). There are over 6000 STW in the UK, catering for communities ranging in size from a few hundred to over 6 million people. The key objective of an STW is to remove or render harmless substances, which could be harmful to health or the environment: notably toxic materials and compounds and disease-bearing organisms. Following successful treatment of the pollution, the treated water should be fit for return to reservoirs or other watercourses, and from there, for further use.

5.2 – Measures of water pollution

Typical physical, chemical and microbiological characteristics of domestic and commercial wastewater are shown in Table 5.2.

The main indicators of water pollution are **Biochemical Oxygen Demand** (BOD), **Chemical Oxygen Demand** (COD), **Total Suspended Solids** (TSS) and the amount of nutrients, primarily nitrogen and phosphorus. Both BOD and COD are measures of water pollution caused by organic substances – the higher the BOD and COD, the more polluted the water.

The BOD is a measure of the organic carbon in the wastewater, which is biodegradable, while COD is a measure of the total organic carbon, both biodegradable and non-biodegradable. BOD is expressed as the amount of dissolved oxygen in milligrams per litre (mg/l) of wastewater, consumed by micro-organisms when a sample is incubated, usually for 5 days at 20 °C. Therefore, it is usual to refer to the biochemical oxygen demand as BOD_5.

COD is the amount of oxygen consumed from a specified oxidising agent (usually potassium permanganate) for complete oxidation of the organic carbon to carbon dioxide and water. For typical urban sewage, the COD may be two or three times higher than the BOD (see Table 5.2).

Total solids comprise suspended, *colloidal* and dissolved solids. They are mainly organic in composition, contributing some 60% of the total BOD of typical wastewater influents into STWs

Table 5.2 Typical characteristics of a raw urban waste water

Class	**Parameter**	**Total (mg/l)**
Physical	Total solids (TS)	740
	Total suspended solids (TSS)	300
	Temperature	10-20 °C
	Colour	Fresh-grey; old-black
Chemical	Fats, oils, grease	100
	BOD-Biological oxygen demand	250
- Organic	COD-Chemical oxygen demand	500
	TOC-Total organic carbon	160
	Alkalinity	100
- Inorganic	Nutrients N, P	N = 40; P = 9
Microbiological	Viruses	1000 -10000 units/l
	Coliforms	100 –1,000 million /l

Total Suspended Solids (TSS) is a measure of the amount of suspended material (i.e. the material that cannot settle-out), mostly of organic content. TSS makes up about 40% of the total solids in typical raw sewage water and their percentage reduction is a measure of the efficiency of the wastewater treatment plant.

Nitrogen and phosphorous compounds can also be present in wastewater. They are classified as nutrients. If discharged with wastewaters, they can cause over fertilisation of the water and the stimulation of 'blooms' of algae. The growing algal biomass depletes the watercourse of its naturally occurring dissolved oxygen, threatening higher life forms such as fish. This process is known as *eutrophication*.

The quality of the treated water leaving the STW is defined by the values of all of the above parameters. They are dependent on the efficiency of the systems that supply oxygen and on the amount of oxygen available in the process.

5.3 – How is the wastewater treated

The contaminants in urban wastewater are primarily organic and a significant number of industries including chemical, pharmaceutical and food industries have high organic waste loads. This means that the main treatment processes are directed at removal of organics. In a typical treatment plant, the wastewater is directed through a series of physical, chemical and biological processes with the following tasks:

- Pre-treatment: physical and/or chemical
- Primary treatment: physical
- Secondary treatment: biological
- Tertiary treatment: physical and/or biological

Wastewater pre-treatment is used to remove floating debris, oils and greases, while primary treatment allows water to settle for several hours in a settling tank, mainly to remove suspended solids. Biological treatment in most sewage treatment works is carried out by oxidising the polluting organic substances into CO_2 and H_2O, through exposing waste water to appropriate strains of bacteria in the presence of oxygen. These processes are known as 'aerobic' and they are designed to reduce organic pollution expressed as BOD and COD. Anaerobic processes also exist whereby, in the absence of oxygen, different strains of bacteria reduce carbon-based pollutants to methane.

5.4 – Biological waste water treatment

As shown in Figure 5.1, wastewater entering a typical STW is first screened to remove larger solid objects such as wood, plastic and grit, and then fed to a primary settlement tank. Here, any remaining solids settle by gravity and are removed as 'primary sludge'.

The wastewater is then ready for secondary, biological treatment in an aeration tank. Biodegradation is the dominant mechanism for removal of organics in wastewaters. The 'activated' sludge system is used for these purposes in most STWs. The aeration tank (biological reactor), which can have various configurations, retains water for a number of hours or days in a well-mixed environment in the presence of oxygen.

During that time, the micro-organisms, i.e. 'activated sludge', use organic matter in the water as the food source to generate more microbial cells, CO_2 and water, while at the same time reducing the organic pollution:

$$\text{Organic matter} + O_2 + \text{nutrients} \xrightarrow{\text{Microorganisms}} \text{new biomass} + CO_2 + H_2O$$

This is an oxidation reaction, which consumes dissolved O_2 from the water body. If the oxygen demand (BOD) of the waste is high enough, it may deplete all the O_2 and the worst-case scenario is an anaerobic water body.

The limiting factor in the growth of the biomass and the breakdown of the pollutants is the availability of dissolved oxygen in the waste water-activated sludge mix. Digestion proceeds, and the mass of activated sludge is continuously washed through the aeration tank into a sludge separation tank.

After settlement, the clarified water is drawn off for further treatment or is returned directly to the environment. As shown in the Figure part of the settled sludge is removed for disposal, but the majority of it is recycled as **Returned Activated Sludge** (RAS).

This ensures that sufficient biomass will be available at the aeration stage to ensure full digestion of the pollutants in the new influent wastewater. The microorganisms in the sludge progressively die off and are themselves digested, but the nutrients in the new influent sustain the growth and activity of the biomass as a whole.

Pumps recirculate the sludge continuously, for mixing with new pollution-bearing influent and further oxygenation. At each pass of the RAS, a proportion of the pollutants associated with it is broken down or digested, purifying the wastewater, renewing the RAS and releasing inert products. The amount of RAS in circulation remains roughly constant for the constant composition of the incoming wastewater.

However, if the composition of the wastewater changes, so must the amount of RAS. This is one of the tasks of the STW operators, who must adjust and control the amount and flow rate of the RAS and the aeration process so that they match the BOD and flow rate of the incoming wastewater.

At the same time, they must take account of the regulator's requirements regarding the quality of the treated water on its final release.

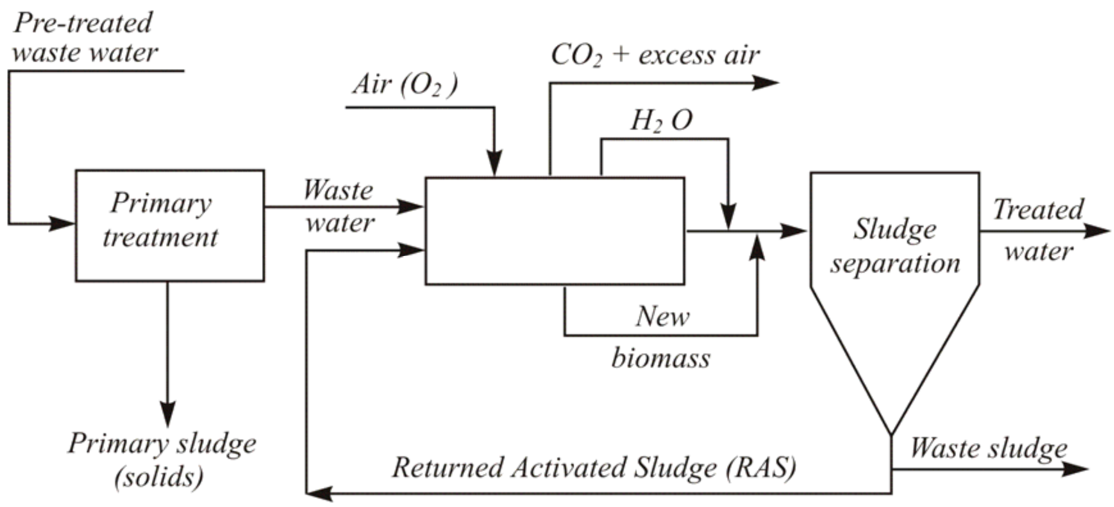

Figure 5.1 - Typical layout of activated sludge system

5.5 – Sludge disposal

The disposal of sewage sludge is itself a challenge to environmental management. For example, in 1997/98 the following sludge disposal methods were used in the UK (Water UK, 2000):

Spreading on farmland	52%
Dumping at sea	26%
Incineration	8%
Dumping in landfill sites	7%
Other	7%

Up to 1998, standard practice for sludge disposal in many parts of the UK was dumping at sea, but an EU Directive has banned this practice and alternative methods of disposal have had to be found for over 1 million tonnes of sludge per year. As the above table shows, the possibilities include use of sludge on agricultural land as a fertiliser and soil conditioner, and incineration of sludge for energy recovery. For example, the large STW in Bacton in east London has an associated **Combined Heat and Power** (CHP) plant which generates 4.3 MW of energy from the sewage sludge incinerated daily.

5.6 – The alternatives for aeration

As noted previously, the key limiting factor in wastewater treatment is the provision of a sufficient amount of oxygen dissolved in water in the aeration stage, to ensure complete breakdown of the polluting organic material by the activated sludge. There are several aeration techniques for doing this, and for each there is a balance between the effectiveness of the process, its cost, and the associated environmental and social impacts. The methods available for aeration in activated sludge process can be classified as mechanical aeration, coarse bubble aeration and fine bubbles or jet aeration. These are explained next.

5.6.1 – Mechanical aeration

Mechanical aeration by surface agitators is the simplest aeration method, and is still widely used. In the most common systems, paddles are fixed on a horizontal spindle mounted at or just below the surface of the aeration tank (see Figure 5.2). The spindle is rotated causing the paddles to stir the top layers of wastewater and sludge. The paddles entrap air bubbles, which they submerge below the surface. Some of the oxygen in this air dissolves in water and is available for the aerobic process.

5.6.2 – Bubble aeration: coarse bubbles

Aeration by agitating the surface layers of the sludge and the overlying water is less efficient than methods which involve greater mixing throughout the whole body of the aeration tank and so allow more time for oxygen to dissolve from air bubbles. One method for achieving this, is to pump in air through perforated pipe work located at the bottom of the tank (Figure 5.3). As the air rises through the tank to the surface in the form of a stream of bubbles (of around 3-5 mm diameter), it sets up circulation patterns in the water which aid better mixing. The bubbles spend several tens of seconds in the liquid enabling a proportion of the oxygen in the bubbles to dissolve in the solution and allowing the digestion process to proceed.

5.6.3 – Jet aeration: fine bubbles

A further improvement to the aeration process is to extract a stream of the liquid from the reactor tank, and then pump it back into the bottom layers of the water-sludge mix under higher pressure (see Figure 5.4). As the stream passes through the surface of the tank it entrains air which is forced into the bulk of the tank in the form of fine bubbles with diameter of 1.5–2 mm.

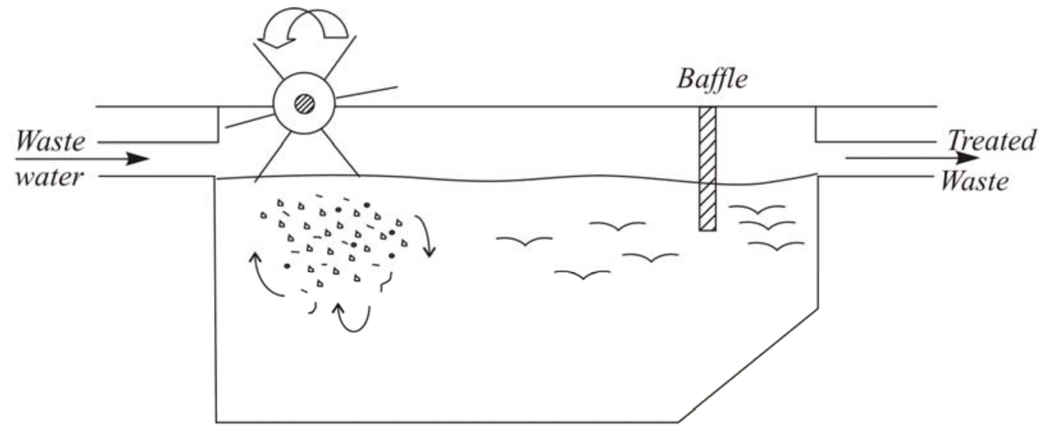

Figure 5.2 - Paddle aerator

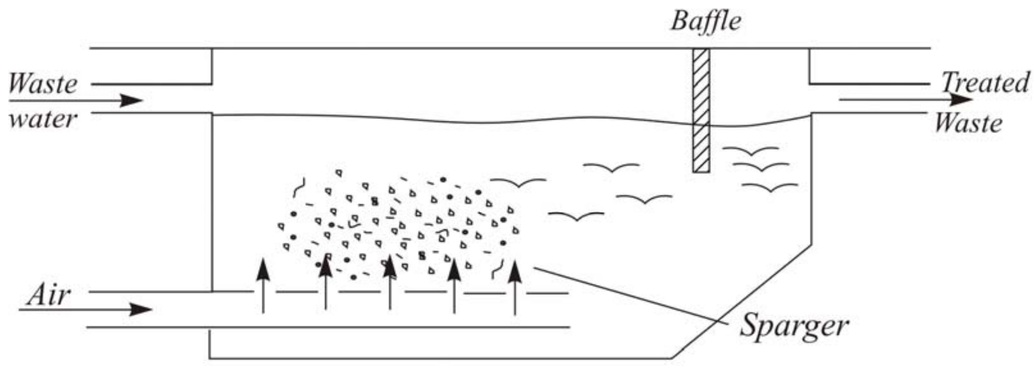

Figure 5.3 - Bubble aerator

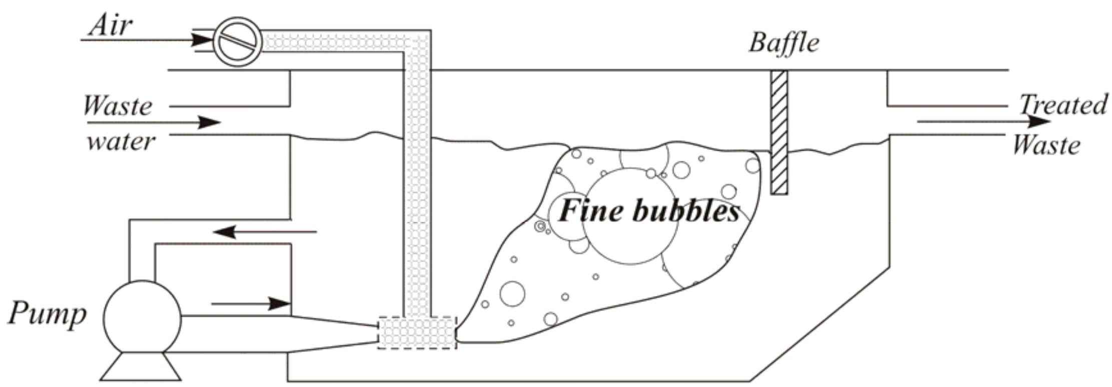

Figure 5.4 - Bubble aerator or diffusion: jet aeration (fine bubbles)

This has two advantages: more air and hence oxygen, can be delivered per unit time, and the smaller bubble size leads to an increased area of contact between the air and the water. The rate of the transfer of oxygen in gaseous form to the oxygen in solution depends on the surface area of the contact between gas and liquid: the finer the bubble size, the greater the contact area per unit mass of O_2.

5.7 – Modern water treatment

Water treatment process passed recently a period of development. In the UK and Europe modern treatment processes include:

- improved coagulation control
- dissolved air flotation (DAF)
- advanced clarifiers
- ozonation
- granular activates carbon (GAC) adsorption
- membrane-based processes
- air stripping of volatile organic chemicals and
- advanced disinfection (ultraviolet, ozonation and chlorine dioxide).

Most of the above processes are used to deal with organic chemicals present in water, either naturally occurring compounds that give rise to colour, taste or chlorination, or pollutants arising from human activities.

The introduction of computer-based systems has led to great improvements in the monitoring and control of the traditional processes, leading to higher and more consistent quality of water produced from traditional plants.

5.8 – Typical process streams

In practice there are many ways to treat a particular water. The next three Figures are typical process streams for a selection of waters.

Figure 5.5 represents the treatment water from the lower reaches of a large English river such as the Thames or the Severn. Such water requires extensive treatment to remove in particular the pollutants derived from upstream human activities and the treated wastewater that has been discharged upstream. Despite the number of processes shown, the water is relatively easy to treat.

Figure 5.6 is an alternative approach to figure 5.5, using bankside storage of raw water and slow sand filters.

Figure 5.7 represents a possible treatment process for water extracted from the upper reaches of a river draining upland moors.

Such waters are likely to be low in pollutants derived from human activities, but could well be soft with high natural colour and be of concern with respect to *cryptosporidium* oocysts. These waters are difficult to coagulate, forming a light flock that does not settle well.

Chlorination may lead to THM formation and is delayed as long as possible. If the source was assessed at high risk of animal-derived *cryptosporidium* oocysts been present in high numbers, the poor-coagulation characteristics of such waters may lead to the addition of an extra treatment stage, only for *cryptosporidium* removal.

Figure 5.8 represents a possible treatment process for water extracted from boreholes or reservoir waters containing iron and manganese. The key problem is to remove both iron and manganese, which require different chemical environments for most effective removal.

The process shown includes two-stage filtration, but this is not always necessary.

5.9 – Raw and treated water quality

Conventional water treatment is appropriate for most surface or ground waters that are free of serious organic contamination derived from human activities, as well as for many waters that are not.

A conventional treatment plant might well have produced water that had long been considered potable, but might now no longer be acceptable because of, for example, a failure to comply with the colour of THM standards.

There have been many attempts to codify conventional water treatment, particularly for surface waters. These take into account key quality parameters of raw water and define the required treatment process.

Such broad approaches are of limited use. They may define a suitable starting point but often in practice the water engineer is either working within constraints that may severely limit the applicability of the solutions produced by such an approach, or the raw-water quality may be more complex than allowed for by a simple approach.

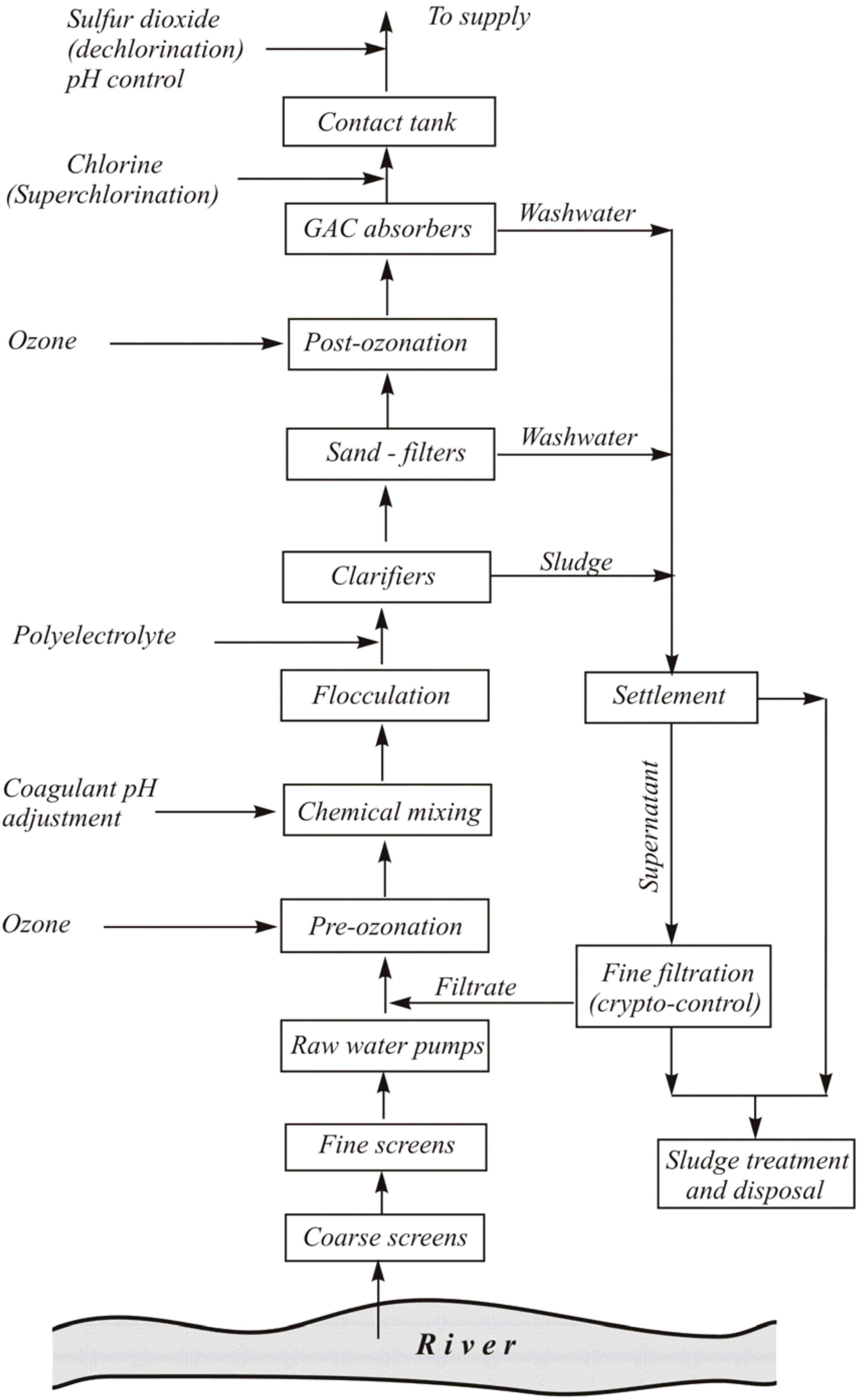

Figure 5.5 -Treatment schematic for lowland river water

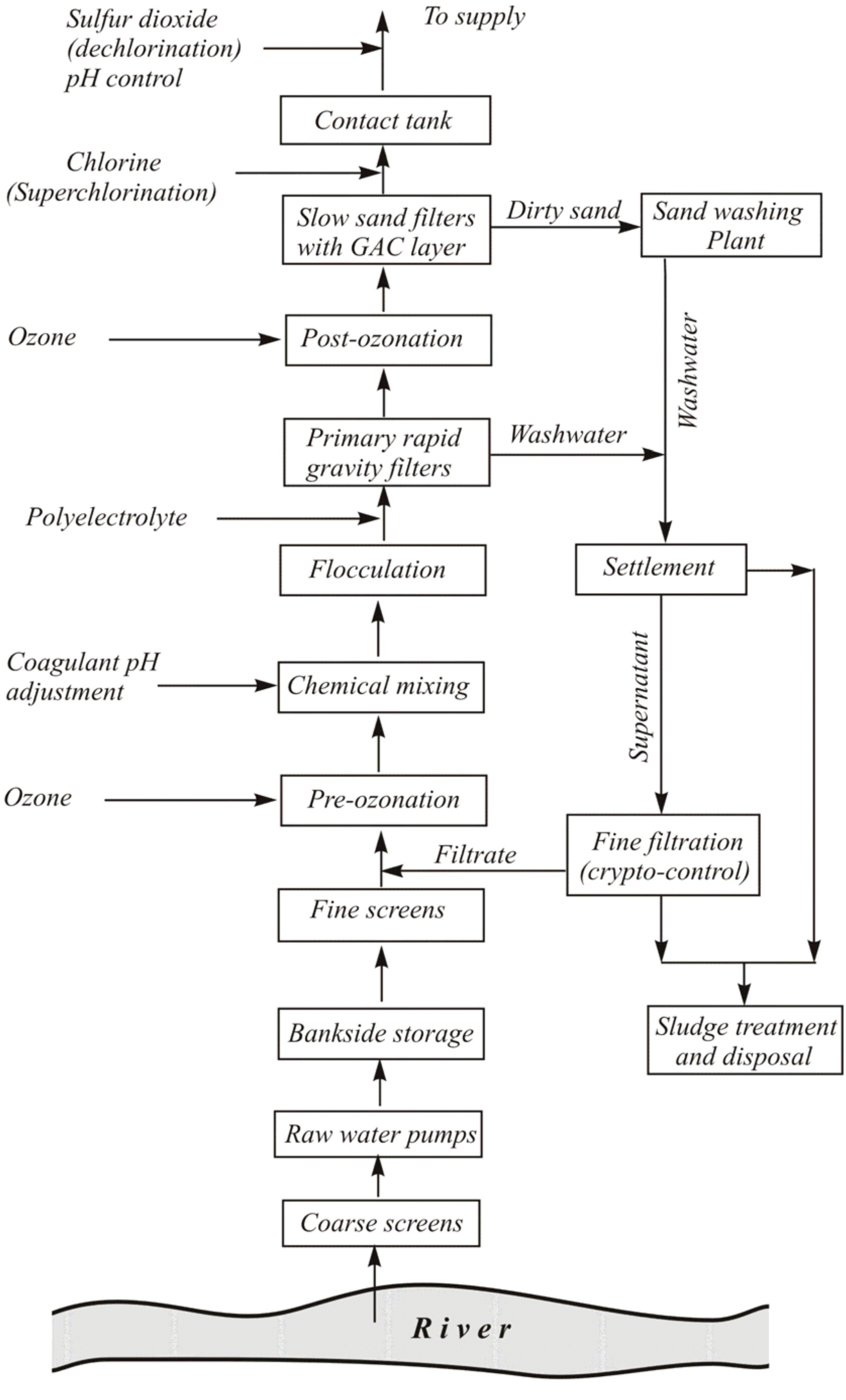

Figure 5.6
Treatment schematic for lowland river water using slow sand filters

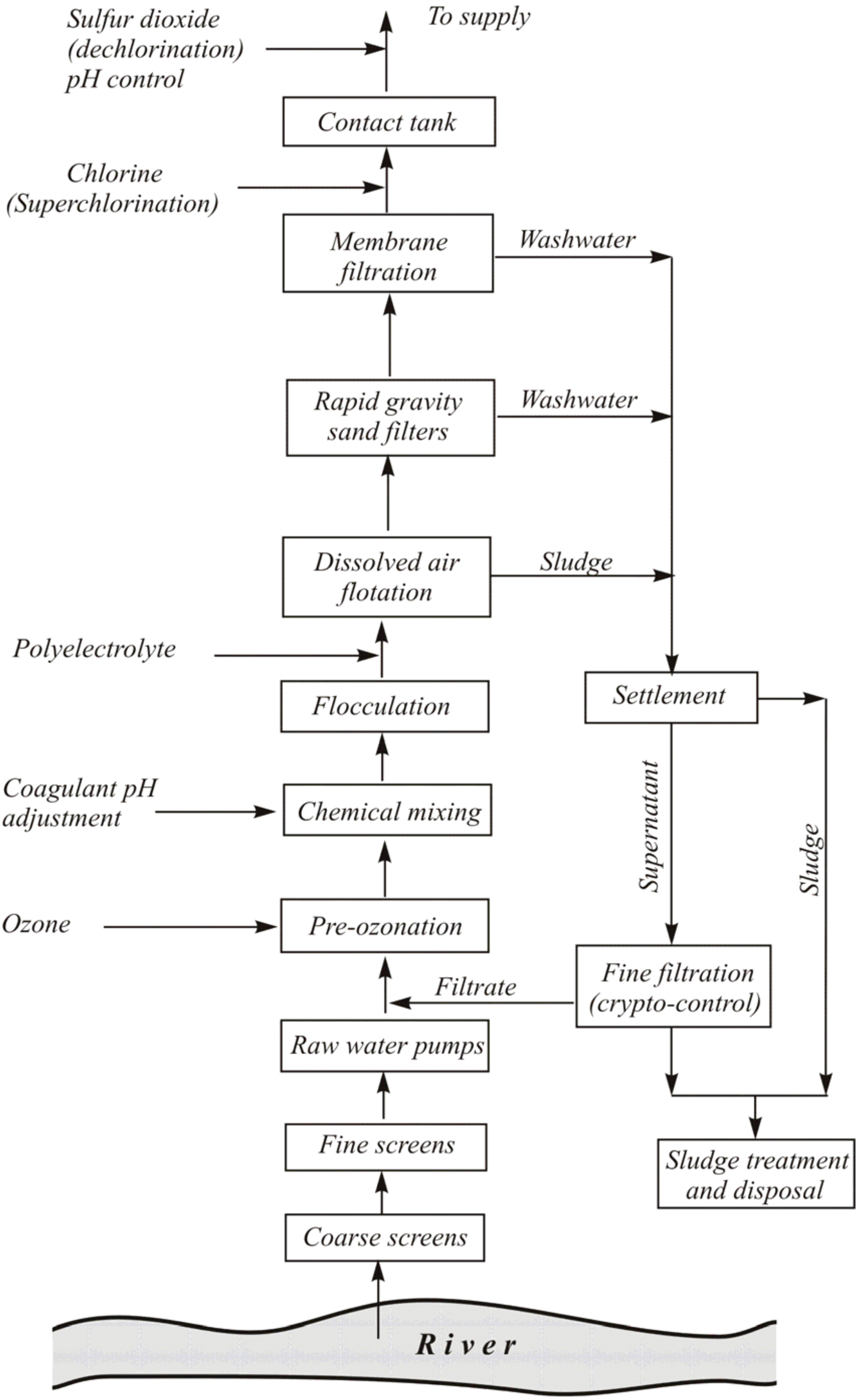

Figure 5.7 - Treatment schematic for upland river water

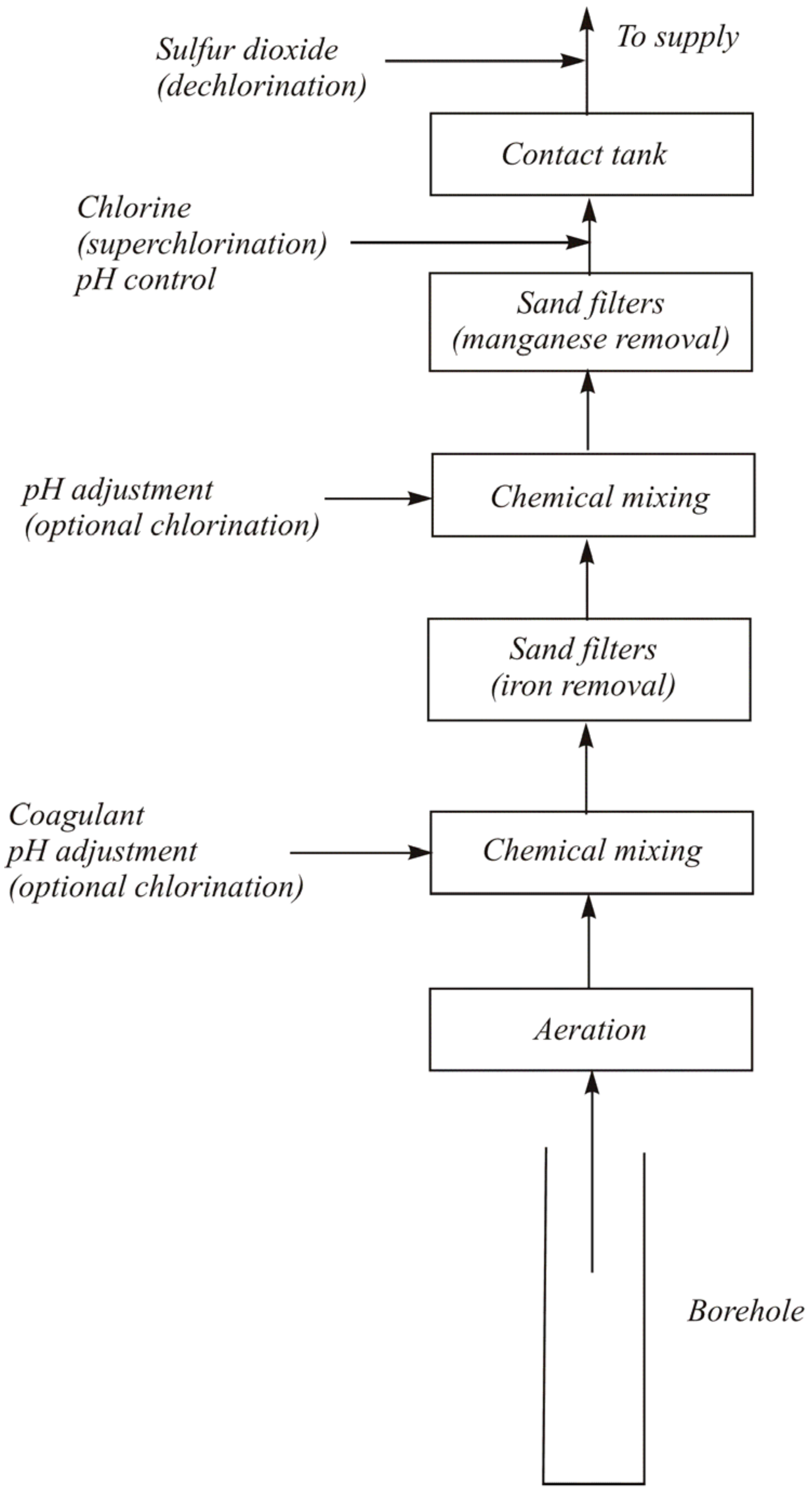

Figure 5.8 - Treatment schematic for borehole water

Chapter 6

Membrane process

This chapter gives an overview of the various membrane processes, introducing some of the key concepts involved and discussing the reasons for their increasing use.

The term applies to processes that use membranes to remove either very small particles or molecules and ions from water.

Figure 6.1 shows the range of particle sizes associated with membrane treatment along with the corresponding processes used for different sizes of particles.

It should be noted that definitions concerning the sizes of particles are only indicative. It is common to specify the approximate molecular weight of the molecules retained by the coarser membranes; this reflects better their performance.

Reverse osmosis is the process that removes essentially all particles and dissolved chemicals from water. However, small dissolved undissociated molecules and dissolved gasses do pass through membranes.

The mechanism of separation is a mix of physical straining and diffusion. Reverse osmosis is often considered to remove particles below 1 nm (0.001 μm).

Nanofiltration is reverse osmosis but refers to the use of leakier membranes that allow a high proportion of monovalent ions and a small proportion of bivalent ions.

With the wide range of membranes available, reverse osmosis membranes can be optimized to remove particular sizes of dissolved molecules and ions. The use of the term nanofiltration implies only that the smallest and most mobile ions will pass through.

Ultrafiltration is largely a straining process, which essentially comprises a very fine sieve. It removes suspended matter, colloidal material and, where the pore sizes are at the lower end of the range, some organic molecules. It removes particles in the range of 0.001 to around 0.1 μm.

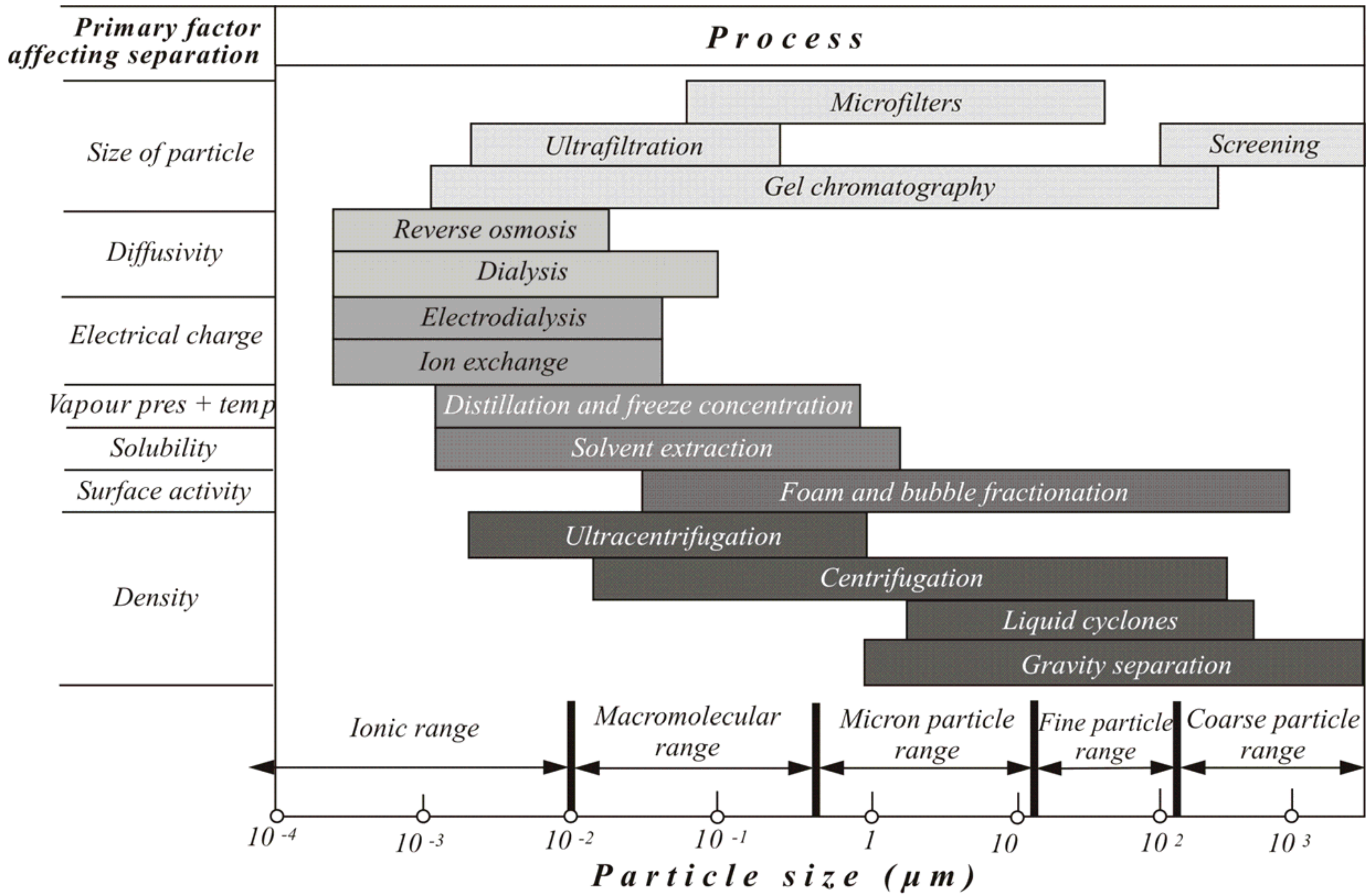

Figure 6.1 - Particle sizes with applicable separation process

Microfiltration is a pure straining process, removing particles in the range of 0.1 – 100 μm without affecting the soluble materials in the water.

Another membrane process is electrodialysis. The key difference here is that it is an electrical-based process that only removes ions and charged particles, although there may be some secondary straining.

6.1 – Reverse osmosis

Osmosis is the term for the phenomenon whereby if a semi-permeable membrane separates two salt solutions of different concentration, water will migrate from the weaker solution through the membrane to the stronger solution, until the solutions are of the same concentration. The salt will be retained by the membrane and will not cross from one side to the other.

Reverse osmosis involves applying a differential pressure to reverse this natural flow, forcing water to move from the more concentrated solution to the weaker. The pressure required to do this has two components:

1) The first is the pressure needed to prevent water moving to the more concentrated solution. This is the osmotic pressure which is a function of the difference in ionic strength either side of the membrane.

Assuming a temperature of 27°C and pure water on one side of the membrane, the pressure varies linearly from approximately 0.4 bar for water with a sodium chloride concentration of 1000 mg/l to approximately 14.8 bar for water with a sodium chloride concentration of 35,000 mg/l (approximately equivalent to seawater).

This pressure is the minimum required and needs to be added the second component.

2) The head losses through the membrane. The pressure due to head loss through a membrane depends on the membrane used and the flow rate per unit of area through the membrane.

For a given membrane material it is inversely proportional to the thickness of the membrane. It is of the order 15-60 bar, with more saline waters requiring higher pressures.

Combining the two components it follows that the flow of water through a membrane is given by:

$$Q_w = K_w \times (A/t) \times (\Delta P - \Delta \pi)$$

where:

Q_w is the water flow rate
K_w is the membrane permeability coefficient for water
A is the area of membrane
t is the thickness of the membrane
ΔP is the pressure across the membrane
$\Delta \pi$ is the osmotic pressure

Membranes used in reverse osmosis are not completely efficient semi-permeable membranes. They also allow some diffusion of salt. This depends on diffusion and the flow rate is given by:

$$Q_s = K_s \times (A/t) \times \Delta C_s$$

where:

Q_s is the salt-flow rate
K_s is the membrane permeability coefficient for water
A is the area of membrane
t is the thickness of the membrane
ΔC_s is the difference in salt concentration across the membrane.

The two important points that follow from the above two equations are that:

- increasing the differential pressure increases water flow across the membrane
- the rate of salt movement across the membrane is independent of pressure.

Therefore minimizing treated-water salt concentration, it is better to operate at high differential pressures (which maximize water flow) and low differential salt concentrations (which minimize salt flow across the membrane).

6.2 – Membranes

There is a variety of membrane materials while new materials are under development.

Initially membranes were based on cellulose acetate. This was developed into a range of cellulose-based polymers. A notable advantage of these membranes is that most are tolerant of chlorine at low levels, which means that bio fouling can be avoided. This is very important because they can be biologically degraded.

Other materials, mainly polyamide-based, have been developed so far. There is now a wide range of them with properties, which can be optimised for particular applications. Of special note are thin film polyamide-based materials which, being thinner, therefore with less head loss across the membrane, operate at much lower pressures. These materials are resistant to biological degradation, but chemically attacked by chlorine.

The two most common forms of membranes used are spiral wound modules and hollow fibre modules. In both cases the material comprises the membrane itself and a more porous supporting material to provide the necessary strength for the module to be manufactured.

Spiral wound modules are of a Swiss-role construction, consisting of three layers:

- a high pressure layer which contains the feed water which is going to be treated
- the membrane layer
- a low pressure layer which contains the treated water.

The high and low-pressure layers contain spacers with permit flow to pass through them. Normally the permeate flows to a collection tube in the centre of the module. Feed water is introduced at the outside of the module and the concentrated feed water is collected at one end of the module.

Hollow fibre modules have the membrane in the form of a hollow fibre. These have the membrane layer on the outside of a hollow fibre of supporting material.

Flow is from the outside of the fibre into the hollow centre. The fibres are sealed into pressure bulkheads, forming a 'U' tube within the module. The feed water and the concentrate are on the outside of the fibres and the permeate is collected from where the fibres are sealed into the pressure bulkhead.

6.3 – Nanofiltration

A type of reverse osmosis is nanofiltration. As a method, it has been developed after the improvements in membrane materials to remove larger molecules and ions.

It operates at lower pressures, partly because the membranes let through most monovalent ions, leading to smaller osmotic pressure, but mainly because the membranes themselves are more permeable with a much lower head loss.

Nanofiltration is not used for the production of drinking water from brackish water or seawater but is used to soften water and remove nitrates. It can also be used to treat waters to remove organic matter that would react with chlorine to form THMs (see Section 3.4) along with colour removal.

6.4 – Microfiltration and ultrafiltration

Ultrafiltration is a process using very fine pores, able to remove all suspended mater and large organic molecules. The process also removes all microorganisms, keeping possibly smaller viruses, which will be removed only by membranes with a small pore size.

Microfiltration has a larger pore size than ultrafiltration.

Most ultrafiltration membranes use hollow fibres. They normally form a thin skin of membrane on a supporting structure.

The membrane may be either on the outside of the fibre, filtering from the outside to the inside of the tube, or on the inside of the fibre, filtering from inside to the outside.

The membranes operate at far lower pressures than **Reverse Osmosis** (RO) membranes, typically between 2 and 5 bar.

Ultrafiltration is a cross-flow filtration process. In a conventional process, flow is perpendicular to the filter medium passing through it. In a cross-flow process the main flow is **parallel** to the medium, with only a proportion of the flow passing through it. In this way rejected material is carried with the reject water. This process is easier to visualise where the flow of feed water is in the centre of a hollow fibre.

Due to the low pressures at which the membranes operate, a wide choice of materials is available, and the use of more resistant materials assist in cleaning. Apart from flushing and backwashing, chemicals can be used for membranes' cleaning to dissolve material attached to them.

In the UK, ultrafiltration is now used, often as the only treatment, of high-quality ground waters for *Cryptosporidium* removal.

Microfiltration may use either hollow fibres or some form of filtration mat.

6.5 – Future developments

There is no doubt that membrane processes will be increasingly used in the future. The reasons for the increasing popularity of these processes are:

- an increasing need to provide potable water from saline or brackish water (using reverse osmosis)
- their ability to soften water and remove nitrates (reverse osmosis and nanofiltration)
- their use for single-stage treatment of soft upland waters containing colour, iron, manganese and micro organisms (nanofiltration and ultrafiltration)
- their ability to effectively remove protozoan oocysts (ultrafiltration).

In all the above examples the membrane process is one of the options available and the decision for the process to be used depends on local circumstances and, at least in part, on personal preferences.

On the other hand reverse osmosis is an energy-intensive process with high CO_2 emissions. This may be an important factor as carbon taxes become significant.

In addition disposal of the wastes from membrane plants, particularly Reverse Osmosis plants, is difficult and this may limit their adoption in some locations.

Chapter 7

Tertiary treatment

As the water resources approach their limits, it is not surprising that in addition to conventional water and waste treatment processes a lot of effort has been focused on additional or **alternative** ways to achieve new objectives.

Although conventional sewage treatment can realise a high degree of purification, this may be not enough in situations with little dilution or where potable water abstractions occur downstream.

In such cases the authorities often stipulate an additional stage of treatment to remove most of the remaining **Suspended Solids** (SS) and the associated **Biochemical Oxygen Demand** (BOD). This type of additional removal is usually termed as tertiary treatment.

In areas where water resources are limited, it may be necessary to utilize wastewater effluents, brackish ground waters or even seawater to satisfy the demands for domestic and industrial consumers.

Many domestic uses of water, such as toilette flushing, do not need potable water and recycled effluent may be appropriate for a dual supply.

Some industrial uses of water can be easily satisfied by tertiary treated sewage effluent and such sources can be perfectly acceptable for irrigation use under carefully controlled conditions.

For more demanding uses it may be necessary to utilize treatment processes designed to remove particular impurities, which are not affected by conventional ways. The conversion of saline waters into potable supplies requires the removal of dissolved inorganic constituents that are unaffected by conventional water treatment processes.

7.1 – Tertiary treatment

Although a conventional sewage- treatment plant may be able to produce an effluent of better than 30 mg/l SS and 20 mg/l BOD, the reliable production of an effluent much better than 30:20 requires some form of tertiary treatment. The suggested 4 mg/l BOD as limiting level of pollution is rather unrealistic. The need for tertiary treatment in a particular situation should be assessed in relation to dilution, reaeration characteristics, downstream water use and water quality objectives.

The main reason for limiting SS in effluents is that they may settle on the stream bed and inhibit certain forms of aquatic life. Flood flows may resuspend these bottom deposits and exert sudden oxygen demands. In any case, settlement does not occur in waters, which are naturally turbid. Although the SS level influence the BOD of the effluent, it is not of great significance.

Most forms of tertiary treatment used in the UK aim at removal of some of the excess SS in the effluent from a well operated conventional process.

Tertiary treatment should be considered as a technique for improving the quality of a good effluent and not as a method of trying to convert a poor effluent into one of a very good quality.

Removal of SS from an effluent gives an associated removal of BOD due to the BOD exerted by the suspended matter. There is evidence showing that the removal of 10 mg/l SS from normal sewage effluents is likely to remove about 3 mg/l BOD.

There are several methods of tertiary treatment, based on processes used in water treatment.

7.1.1 – Rapid filtration

This process is frequently used in large plants. Most installations are based on the down flow sand filter which has been used in water-treatment for many years. More efficient forms of filter, including mixed media beds and up flow units, have been used with some success, but in many cases the down flow unit is adopted because of its simplicity and reliability.

The variable nature of the SS present in the effluent from final settling tanks makes prediction of the performance of any tertiary treatment unit difficult. Because of the wide variation in filtration characteristics of suspended matter it is always better to carry out experimental work on a particular effluent before proceeding with design work.

It is generally assumed that rapid gravity filters operated at a hydraulic loading of about 200 m^3/m^2 day should remove 65 – 80 % SS and 20 – 35 % BOD from a 30:20 standard effluent.

Due to relatively short time between backwashes (24-48 h), there is little biological activity and rapid filters are not able to achieve significant oxidation of ammonia. The SS removal is not highly affected by the hydraulic loading and there is little benefit in using sand smaller than 1.0 – 2.0 mm grading.

7.1.2 – Slow filtration

Slow sand filters are sometimes employed on small works for tertiary treatment at loadings of 2 – 5 m^3/m^2 day. Slow filters have low operation and maintenance costs, but the large area that they require exclude them for large installations.

They expect to remove 60-80 % SS and 30-50 % BOD. Slow filters provide a significant amount of biological activity, encouraging BOD removal and providing a degree of nitrification.

In addition they can provide significant removals of bacteria and other microorganisms.

7.1.3 - Microstraining

Microstrainers have been utilized for tertiary treatment since 1948 and a number of installations are in operation. They have the advantage of small size and can easily be placed under cover.

Removals of SS and BOD depend upon the mesh size of the fabric used and the filtrability characteristics of the suspended matter.

Reported removals range from 35 to 75 % SS and 12 to 50 % BOD. Microstraining should reliably give an effluent of 15 mg/l SS. 10 mg/l SS should be possible with a good final tank effluent.

Typical filtration rates are 400 – 600 m^3/m^2 day. Ultra Violent lamps can control biological growths on the fabric, which could cause clogging and excessive head loss.

7.1.4 – Upward-flow clarifier

This technique was developed to obtain better quality effluents from conventional humus tanks on small bacteria bed installations.

The process is based on passing the tank effluent through a 150 mm layer of 5-10 mm gravel supported on a perforated or wedge-wire plate near the top of a horizontal flow humus tank with surface overflow rates of 15-25 m^3/m^2 day.

Passage through the gravel bed facilitates flocculation of the suspended matter and the flock settles on top of the gravel. Accumulated solids are removed by drawing down the liquid level below the gravel bed.

Removals of 30-50 % SS can be achieved, dependent upon the size of gravel and the type of solids. Similar results have been achieved with wedge wire instead of gravel and there is evidence that many types of porous materials can be used to facilitate flocculation.

7.1.5 – Grass plots

Land irrigation on grass plots can provide an effective form of tertiary treatment, particularly suitable for small communities.

Effluent is distributed over grassland, ideally with a slop of 1:60, and collected in channels at the bottom of the plot. Hydraulic loadings should be in the range of 0.05-0.3 m^3/m^2 day and 60-90 % SS and up to 70 % BOD removals can be achieved.

Short grasses are preferable, but the sowing of special grass mixtures does not seem to be worthwhile. The area should be divided into a number of plots to access for grass and weed cutting, since growth is likely to be prolific due to the nutrients, which exist in effluents.

7.1.6 – Reed beds

The use of reed beds for tertiary treatment on small wastewater treatment plants is becoming common and they are capable of producing good quality effluents under the right conditions.

At loadings of 1 m^2/person after **Rotating Biological Contactors** (RBC) or conventional filtration should reliably produce effluents with average SS and BOD levels of around 5 mg/l and with significant removals of ammonia.

7.1.7 – Lagoons

Storage of effluents in lagoons or maturation ponds gives a combination of sedimentation and biological oxidation depending upon the retention time.

With short retention times (2-3 days) purification is mainly due to flocculation and sedimentation, with SS removals of 30-40 %. With longer retention (14-21 days), the improvement in quality is evident, with 75-90 % SS, 50-60 % BOD and 99 % coliform removals. The improvement in bacteriological quality in lagoons is greater than that provided by most other forms of tertiary treatment.

In UK conditions it seems that a retention time of about 8 days gives the best performance, since longer retention times usually give rise to excessive algal growths.

7.2 – Physicochemical treatment of wastewater

In the discussion of tertiary treatment of water it has been assumed that conventional processes using physical and biological operations have initially treated wastewaters.

A considerable amount of research has been undertaken in the USA to determine the performance capabilities of physicochemical treatment plants using chemical coagulation and precipitation followed by filtration and adsorption. Such plants can produce effluents of around 10 mg/l BOD and 20 mg/l COD from relatively weak US wastewaters.

In countries like UK, where small water consumptions produce stronger wastewaters, there is little evidence to suggest that physico-chemical plants could produce effluents of similar quality to those obtained from conventional plants and at the same cost.

Physicochemical treatment does have some potential in the case of partial treatment requirements, where discharge is made to coastal or estuarial waters with relaxed effluent standards.

Raw sewage dosed with a coagulant and then flocculated prior to sedimentation in an upward-flow sludge blanket settling tank can be transformed into an effluent with low SS and BOD.

The effluent contains bacteria concentrations several orders of magnitude lower than in the raw sewage.

The relatively small size occupied by this type of plant can be an advantage for resort areas. However, it remains a question if environmental legislation will permit the somehow lower effluent quality than would be achieved by a conventional biological system.

Chapter 8

Disinfection

As water passes through a treatment plant, the various processes remove or inactivate many of the organisms present in the water.

The final treatment in a water-treatment plant is disinfection of the treated water. The correct meaning of 'disinfection' is under threat and the world often uses it incorrectly.

Disinfection is not sterilisation, which means the inactivation of all organisms. It is rather the killing of pathogenic organisms, those, which cause disease. Disinfection is normally the most critical process for supplying safe water.

There are two aspects of disinfection:

1. to kill all the pathogens that have passed through the various treatment stages and
2. to apply a residual disinfectant, so that the water leaving the treatment works remain safe as it passes through the distribution system to the point of use.

There are 3 sorts of pathogenic micro-organisms that are of greatest concern in water treatment. Viruses, bacteria and protozoa. Instead of classifying micro-organisms it would be useful to understand some of their key differences.

Viruses are the smallest. They are simple organisms, consisting of a core containing nucleic acid surrounded by an envelope of protein.

They are obligate parasites able to multiply only in other living cells. It is quite possible to argue that viruses are not living organisms at all. Viruses are responsible for diseases such as polio, AIDS, rabies, and the common cold. Some pathogenic viruses can be transmitted in water.

Bacteria and **protozoa** are both single cell organisms. They are both normally heterotrophic, using organic matter as a source of energy.

Some of the difference between bacteria and protozoa are that bacteria are smaller and lack a clear nucleus. They evolve much earlier than protozoa and tend to be less complex.

Bacteria of concern in water treatment include *Salmonella typhi*, which causes typhoid, and *E. coli*, which is the key indicator of faecal contamination of water.

Protozoa of concern include *Cryptosporidium parvum* and *Giardia lamblia*. A key factor of some of the parasitic protozoa, specially the fist of the above two, is that they have a complex reproductive cycle, which includes the production of oocysts. These are the infective bodies that transmit the organism from host to host. The oocysts can be very resistant to chemical attack and can exist dormant for many months.

All disinfection processes discussed here are effective against pathogenic bacteria and viruses. They may not be effective against some spore-forming bacteria, but these are not pathogenic. The processes are considered by the regulation authorities in the UK to be ineffective against *Cryptosporidium* oocysts at acceptable dosages. Such organisms have therefore to be physically removed. In the USA, ozonation and **Ultra Violent** (UV) disinfection under specified conditions are considered effective for inactivation of *Cryptosporidium* oocysts.

The need for a residual disinfectant to be carried into the distribution system is taken for granted in the UK and over much of the world. However, in some countries, there is increasing public resistance to the use of chlorination as a residual disinfectant under normal conditions.

If a distribution system is in good condition and clean, and the circulating water is stable and low in dissolved assimilable organic carbon, then there will be little bacterial growth within the distribution system. It is quite possible that there will be increasing objections to chlorination in the future and this view may become more widely held.

8.1 – Disinfection during treatment

In any case the disinfectant must kill the organisms of concern while not being toxic to humans. Disinfection within the treatment plant may utilise one or more of the following processes:

- chlorination
- ozonation
- UV disinfection
- Chlorine dioxide

Chlorination is mainly used only for disinfecting fully treated water or high-quality ground waters to reduce the formation of THMs. These are chemicals formed from methane (CH_4) in which 3 of the hydrogen atoms have been replaced by halogens (primarily chlorine). The compound of most concern is chloroform ($CHCl_3$), which is a known carcinogen. THMs are formed by reactions between halogens and organic matter in water, in particular the humic and fluvic acids found in peaty coloured water.

In the past it was common to pre-chlorinate water at the point of entry to the treatment works. This controlled the attached growths of algae that otherwise occur and also killed algae present in the raw water, making them easier to remove.

Nowadays, it is unusual to pre-chlorinate. However, pre-chlorination may be acceptable if an assessment of THM formation indicates that there will be no problems with THMs. Chlorine dioxide may be used for waters that are particularly prone to THM formation.

Ozonation has been widely used in Europe for many years for disinfection in water-treatment plants. Now it is also becoming common on large plants in the UK and North America. In the UK it is used primarily for oxidation of pesticides, but it also disinfects.

UV disinfection may be favoured where an existing plant does not have a contact tank for chlorination.

8.2 – Chlorination

The most common form of disinfection is chlorination. It consists of two different types;

- the use of gaseous chlorine, which is dissolved in water before being added to the water under treating
- the use of a solution of hypochlorite, normally sodium hypochlorite

Chlorine, when added to the water, reacts rapidly to form hypochlorous acid and hydrogen and chloride ions (effectively dissolved hydrochloric acid):

$$Cl_2 + H_2O \Leftrightarrow HClO + H^+ + Cl^-$$

The hypochlorous acid may then dissociate:

$$HClO \Leftrightarrow H^+ + OCl^-$$

Where a solution of sodium or calcium hypochlorite is used they dissociate as follows:

$Ca(OCl)_2 \Leftrightarrow Ca^{2+} + 2OCl^-$

$NaOCl \Leftrightarrow Na^{2+} + OCl^-$

The other important set of reactions in relation to chlorination is the reaction between chlorine and ammonia. These are important because:

a) they remove hypochlorous acid and

b) the compounds formed are disinfectants and are often used to provide residual disinfection in distribution systems.

Chlorine or hypochlorous acid reacts with ammonium ion to successively replace the hydrogen atoms with chlorine:

$NH_3 + HOCl \Leftrightarrow NH_2Cl + H_2O$

$NH_2Cl + HOCl \Leftrightarrow NHCl_2 + H_2O$

$NHCl_2 + HOCl \Leftrightarrow NCl_3 + H_2O$

The reactions lead to the successive formation of monochloramine, dichloramine and trichloramine. However, chlorination of water containing ammonia also leads to the production of nitrogen gas as follows

$2NHCl_2 + HOCl \rightarrow N_2 + 3HCl + H_2O$

This releases nitrogen and converts hypochlorite to hydrochloric acid. There is also some production of nitrate, but this is a minor reaction.

Hypochlorious acid and the hypochlorite ion together are called 'free chlorine'. The chloramines are known as 'combined chlorine'.

8.3 – Ultraviolet disinfection

UV disinfection means passing water through high-intensity UV radiation. The radiation kills or inactivates bacteria and viruses at a wavelength of around 260 nm.

Water is passed through a chamber or channel containing UV lamps, which expose the water to a controlled dose of UV radiation for a minimum period. The UV radiation penetrates organisms and initiates photochemical reactions within the cells inhibiting or killing the organisms.

The method is very effective against bacteria and viruses but less effective or ineffective against larger protozoa. The key parameter in UV disinfection are the power intensity (mW/cm^2) and the dose applied (mWs/cm^2), the intensity by the exposure time.

A minimum dose is 15 mWs/cm^2, which normally produces water of acceptable bacteriological quality, but 25-40 mWs/cm^2 is desirable.

For UV disinfection to be effective, the water has to be of high adsorbence, which is measured to assess the suitability of UV use and estimate the level of the required dose.

Normally there are no problems with potable water but where iron levels are above 0.1 mg/l or water is hard, there may be problems with scaling of lamps. Usually a water sample should be tested before using UV disinfection due to scaling.

UV disinfection is particularly useful for groundwater sources which pump directly into supply and which do not have a chlorine contact tank. As a method provides assurance that the water living the site is safe, with a residual disinfectant required only to maintain the safety of the water.

8.4 – *Ozonation*

Ozonation is a powerful disinfectant but is not normally used solely for disinfection in the UK. The dosages and contact times required for effective disinfection are lower than those needed for treatment of organic chemicals. Therefore where ozone is used for other purposes it also provides very effective disinfection.

For disinfection, an ozone residual of 0.4 mg/l and a contact time of 4 min will effectively kill all bacteria and viruses of concern, provided there is either plug flow or two cells to prevent short-circuiting.

8.5 – Other Methods

Other methods of disinfection that may be encountered are:

- bleaching powder – including calcium hypochlorite
- boiling water – suitable for emergency use only
- use of metal ions – the use of silver ions is suitable for only emergency short-term use for potable water
- potassium permanganate – can be used though is not very effective
- membrane processes – ultra filtration and reverse osmosis remove micro-organisms
- bromine or iodine – emergency use only.

Chapter 9

Water supply in developing countries

In developed countries the public expects, and usually gets, a high standard water-supply service and efficient collection, treatment and disposal of wastewaters. The techniques for pollution control are, in general, well developed and since populations are in low or zero-growth, public demands on water resources are usually manageable.

The picture is very different in developing countries where some 1.3 thousand million people are without safe water and more than 2 thousand million do not have adequate sanitation. This means that about 70 % of the population in these parts of the world lack basic facilities.

9.1 – The current situation

As a result of the **World Health Organisation** (WHO) research, large numbers of people in developing countries were provided with water and sanitation but rapid population growth has masked the improvements in many areas, as shown in table 9.1.

Table 9.1 Water and sanitation in the International Drinking Water Supply and Sanitation Decade, 1981 – 90

	Millions of people without			
	Safe water supply		Adequate sanitation	
	1981	1990	1981	1990
Urban	213	243	292	377
Rural	1613	989	1442	1364
Total	**1826**	**1232**	**1734**	**1741**

In its monitoring of the decade 1981-90, WHO concluded that during this period a total of around 135 US$ thousand million had been invested in water supply and sanitation, 55% on water supply and 45% on sanitation.

To achieve safe water and adequate sanitation for all in the year 2000 an annual investment of around 50 billion US$ has been required which is 5 times that achieved during the decade.

Although for urban areas throughout the world the ultimate aim is to provide a higher level of service, the provision of services at this level for the millions in rural areas of developing countries is unrealistic.

If the aim is really to reduce the toll of water-related disease, improvements must be made in both water supply and sanitation.

Unfortunately sanitation is often neglected in favour of the more attractive water-supply activities. It is equally important to understand that the construction of sophisticated style water and wastewater treatment facilities is of little value if the appropriate operation and maintenance back up is not also provided.

Many successful schemes have achieved their objectives by a combination of appropriate technologies and self-help by the communities served.

9.2 – Sources of water

In the developed countries it is normal to provide at least some degree of treatment for water from any source, whereas for rural areas in developing countries treatment will not be feasible in many circumstances.

It is thus necessary to consider water sources in relation to what is likely to be the most important quality parameter, which is that of bacteriological quality.

9.2.1 – Rainwater

The collection and storage of runoff from roofs can give a quite satisfactory source of water provided that the first flush of water from a storm, which is likely to be contaminated by bird droppings etc., can be diverted away from the storage tank.

With irregular rainfall, the size and cost of storage tanks may be large and, unless the tanks are protected from contamination and the entry of mosquitoes, health problems may arise.

Depending upon the intensity of the rainfall and the efficiency of the gutter and downpipe system, 50-80 % of the rainfall may be collected.

9.2.2 – Springs

Spring water is normally of good quality provided that it is derived from an aquifer without being the discharge of a stream, which was underground for a short distance.

It is important to maintain this good quality by protecting the spring and its surroundings from contamination by humans and animals. A collecting tank should be constructed to cover the eye of the spring and prevent debris being washed into the supply.

9.2.3 – Tube wells

Ground waters are usually of good bacteriological quality, because of the natural purification, which removes suspended matter, such as bacteria. However, care must be taken to ensure that the absence or the existence of sanitation practices does not cause any groundwater contamination.

Bored wells can be produced by hand auger or by machines. Small diameter wells (40-100 mm) are normally fitted with simple hand pumps at ground level when the water table is sufficiently close to the surface. For deeper water table sites, where a surface pump has insufficient lift, it must be placed down the well. This usually requires a larger diameter bore and thus increases the cost.

The head of a tube well should be suitably covered to prevent entry of contaminated surface water.

9.2.4 – Hand-dug wells

Hand-dug wells, 1-3 m diameter, are in many parts of the world the traditional sources of water in rural areas. Depending upon the depth of the water table these wells may be as much as 30 m deep and during construction there are many hazards since the risk of collapse is often high. This risk can be greatly reduced by the use of precast concrete rings, which sink as excavation proceeds and provide a permanent lining.

It is important that the site of the well is such to avoid the entry of contaminated groundwater and that a watertight lining extents 3-6 m below the surface.

The well head should have a headwall and drainage apron. These features are particularly important in areas where guinea-worm infections are endemic. Where possible, a pump with a fixed cover on the well should be used for water abstraction to reduce the risk of contamination.

9.2.5 – Surface water abstraction

The traditional developed-country sources of water, in the form of rivers and lakes exist in many parts of the world, but in tropical countries the quality of surface waters is often poor. Hence for rural supplies it is advisable to use surface water only as a last resort.

The basic characteristics of suitable rural water sources are shown in Figure 9.1. The undoubted attractions of groundwater supplies, as far as bacteriological quality is concerned, have resulted in many rural water schemes based on tube wells.

Through these schemes it is possible to abstract ground water at a rate which will not exceed the natural recharge. If this basic principle is disregarded the consequence will be falling of groundwater tables and exhaustion of wells.

9.3 – Sanitation

Here the term sanitation refers to the relationships between a number of water-related diseases and the presence in the environment of excreta from people suffering from these diseases.

It could be argued that the sanitary disposal of human excreta – in a health context – is more important than the provision of a safe water supply. Even in the presence of good-quality water, direct faecal – oral contact can maintain many disease-cases such as typhoid and cholera.

It would therefore be important to make every effort to prevent faecal contamination of water sources as a primary objective. This is because the treatment of already polluted water can be costly and, if it is on a small scale, it does not usually have high reliability.

Excretion is inevitably a high personal process. A vital first step in any sanitation programme is to fully understand the current excretion practices and the likely acceptability of possible alternatives.

There are two types of sanitation systems:

a. The dry system, which essentially handles only faeces, possibly with some urine and
b. The wet system which handles faeces, urine and sullage (the liquid wastes from cooking, washing and other household operations

A simple classification of sanitation methods, is:

- dry, on-site treatment and disposal – trench and pit latrines, composting latrines

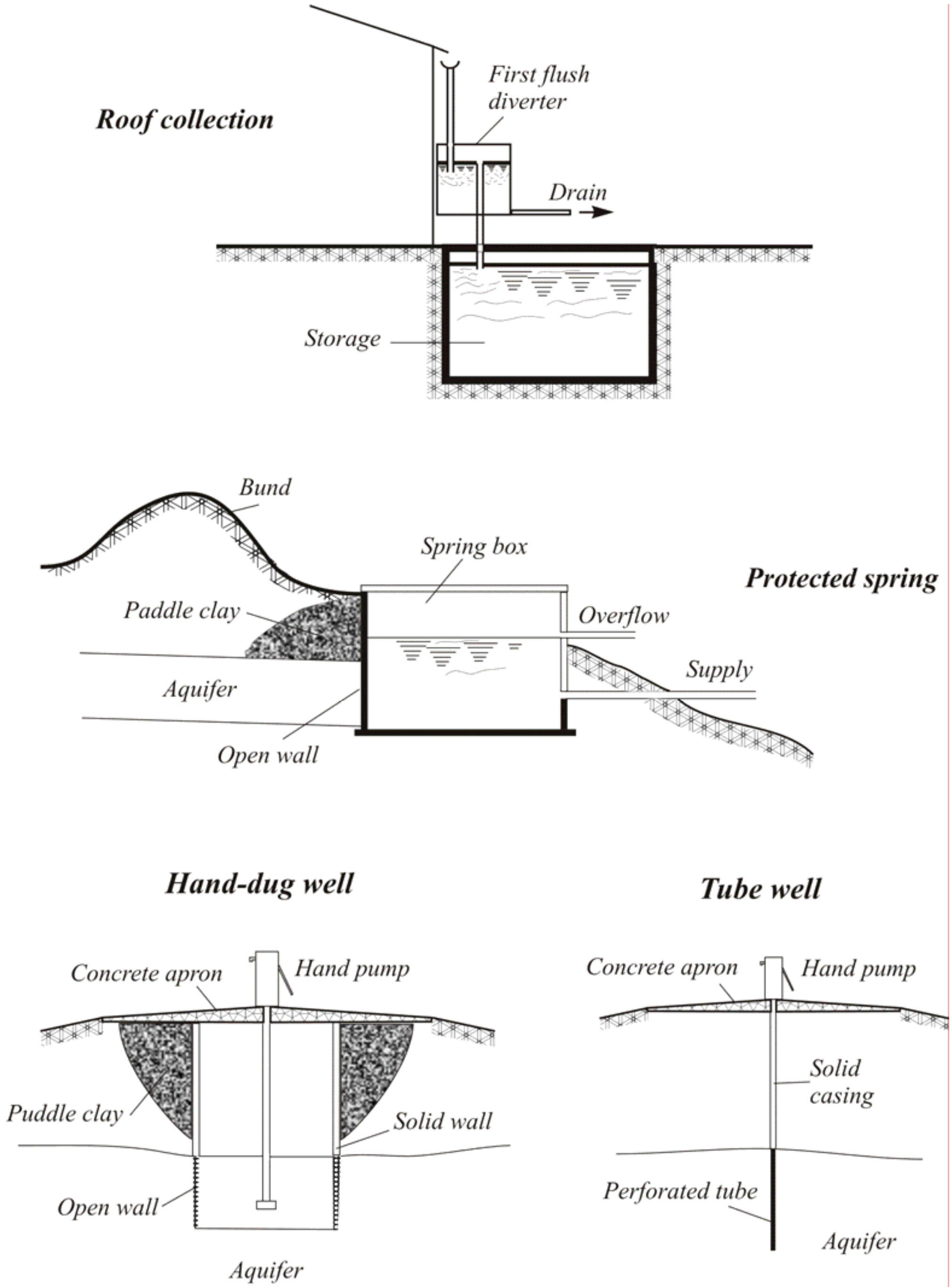

Figure 9.1 Rural water sources

- dry, off-site treatment and disposal – bucket or vault latrine with collection service and central treatment facility
- wet, on-site treatment and disposal – wet pit, aqua privy, septic tank, biogas, land disposal
- wet, off-site treatment and disposal – conventional or modified sewerage and central treatment facility.

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Glossary

Adsorption

Unlike absorption, in which solute molecules diffuse from the bulk of a gas phase to the bulk of a liquid phase, in adsorption molecules diffuse from the bulk of the fluid to the surface of the solid adsorbent, forming a distinct adsorbed phase. Examples of adsorbents include silica gel (for drying gases), zeolites (for adsorption of oxygen from air) and activated carbon (for water purification).

Colloids

Colloids are distinguished from true solutions by the presence of particles that are too small to be observed with a normal microscope yet are much larger than normal molecules. Colloids are the systems in which there are two or more phases, with one (the dispersed phase) distributed in the other (the continuous phase). At least one of the phases has small dimensions (in the range 10-9-10-6 m). Some examples of colloids include oil-in-water emulsions and gelatine.

Distillation

The process of partially evaporating a liquid and condensing and collecting the vapour. It is used to purify liquids and to separate liquid mixtures.

Economies of scale

The economies of scale refer to the relationship between the size of a chemical plant and its capital and operating costs. (Capital costs are costs incurred to build the plant while the operating costs are those incurred by running the plant. The latter include the costs of raw materials, energy and workforce.) Normally, the larger the capacity of an industrial plant, i.e. the larger the economies of scale, the lower the capital and operating costs.

Eutrophication

It is defined as the potential to cause over-fertilisation of water and soil, which can result in increased growth of biomass. Species that can cause eutrophication include NOx, NH_4^+, N, PO_4^{3}-, P. Eutrophication is usually expressed relative to PO_4^{3}-.

Sewage

Waste water and other refuse such as faeces, carried away in sewers.

Sparger

A sparger (see figure 5.3) is a device for introducing a stream of gas in the form of small bubbles into a liquid. A sparger can be simply an open tube located at the bottom of the tank, through which gas issues into the liquid. However, it can also have several orifices to ensure better distribution.

Venturi

A simple venturi consists of a duct with a reduced cross-sectional area, known as venturi throat, in the middle. At the throat, the velocity is much higher than at the inlet or outlet of the venturi and the pressure is therefore lower than upstream or downstream of the throat. In contact with the high-speed water flow at the venturi throat, oxygen gas is broken down into small bubbles, which become even finer in the higher-pressure region downstream of the throat.

Volatile Organic Compounds (VOC)

VOCs are gaseous organic compounds and they include alkanes, halogenated hydrocarbons, alcohols, ketones, olefins and aromatics. Examples include methane (CH_4) and ethylene (C_2H_4). VOCs are often blamed for causing photochemical smog and contributing to global warming.