12 Water treatment

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12.1 Introduction

There are many situations where treatment of raw water is necessary to render it fit for drinking and domestic use. The problems of affordability and technical complexity associated with small to medium water treatment facilities are relevant for all high, medium and low income country economies. In more densely populated areas in the North, these problems have been reduced by encouraging large cities to extend water services to smaller communities, or, in areas with no large cities, by stimulating small communities to form regional water companies. In 1996, the 31 drinking water companies in the Netherlands supplied water to 15.5 million people, an average of 500,000 consumers per company. In contrast, the network for supplying drinking water in the United States of America (USA) is fragmented. In 1996 there were 54,728 community water systems (CWSs) in the USA serving 248 million people, i.e. an average of 4,500 consumers per company.

Box 12.1 Fragmentation of drinking water supply sector in the USA

They were distributed in 46,827 small systems (supplying water to a range of 25-3300 people) serving a total of 25 million people; 4332 medium (in the range of 3301-10,000 people) serving 25 million people in total; and 3569 large (range >10,000 people) serving 198 million people. While the small systems serve around 10% of the population covered by the USA CWSs, they account for an inordinate percentage of the violations under the USA Safe Drinking Water Act, SDWA.

Source: Stout and Bik, 1998

Small communities in the USA face great difficulty in continuously supplying water of adequate quality and quantity. This is because at the salary levels that the national economy requires they often lack the economies of scale needed to hire experienced operators and managers.

In Canada and the USA in the 1990s, special attention was given to the development and promotion of treatment technologies for small to medium-sized communities. The 1996 Safe Drinking Water Act (SDWA) Amendments in the USA contain provisions related to water supply systems serving less than 10,000 people, recognising their differences in costs, technology, management capacity, and risk characteristics. The Environmental Protection Agency (EPA) developed a list of water treatment technologies that smaller companies can apply to comply with the US regulations. In this list, the EPA suggests that rapid filtration should be used only in systems with full-time access to a skilled operator. It considers that slow sand filtration may be the most suitable filtration technology for small systems, when used with source water of appropriate quality (EPA, 1998).

In spite of changes originating from decentralisation of the water supply and sanitation (WSS) sector, the water supply companies' field is also fragmented in most developing countries. In some countries solutions have been found in the formation of strong regional water companies. They make it feasible to introduce and sustain more complex technologies and systems. Smaller towns and rural communities are not able to run complicated water systems that surmount local capacity and feasible regional support structures. When planning and designing a small water treatment plant, the construction and running costs, and the operational and maintenance needs are key factors that must be considered carefully.

12.2 Multiple barriers strategy and basic water treatment concepts

Applying different barriers is important to reduce the sanitary risks from drinking water due to microbial, physical and chemical contaminants. Barriers include: watershed and land use management to protect surface and ground water; selection and protection of the best available water sources; on-site or off-site wastewater treatment and reuse; water treatment; adequate and well-maintained distribution systems; and safe water practices by consumers (Geldreich and Craun, 1996). Water source protection programmes are considered particularly relevant to small systems, where community participation is likely to be more effective.

Because water contamination is associated with so many variables, a good drinking water quality depends on more than water quality enhancement or stream self-purification capacity or the water treatment processes. Water treatment is viewed as just one of the barriers needed to ensure that water produced from a given source complies with the national drinking water quality standards or the World Health Organization (WHO) guidelines. This is particularly important in regions where the majority of the systems rely on surface water sources.

The level of water treatment technology should be in harmony with the types of risk existing in the supply source and the institutional and socio-economic conditions prevailing in the target community. This includes the availability of skilled O&M and management staff. Since infectious diseases caused by pathogens are the most common health risks associated with drinking water, priority in water treatment should be given to reducing this type of contaminants, but without ignoring the risks associated with chemical contaminants in the source water.

Some basic concepts can be identified to make water treatment more reliable and efficient:

- **Multi-stage water treatment.** This concept has a long history and has evolved gradually with the increased attention to water quality. Successive stages progressively remove contaminants from the raw water and consistently produce safe and wholesome final water. Ideally, the safe state should be achieved before the final treatment stage, so that failure of any one process does not result in significant risk of waterborne disease transmission. Consequently the system should be robust and close to fail-safe.
- **Integrated water treatment**. In applying the multistage water treatment concept it is important to understand that each unit process may not be equally effective in removing different types of pollutants. Integrated water treatment is therefore also an important concept. It requires that the strengths and weaknesses of each treatment stage be quantified and balanced, as well as the combination of the different treatment stages, so that all contaminants are effectively removed at a feasible cost. In general it is convenient to separate the heaviest and larger material first and gradually proceed by separating or inactivating the smaller material represented by particles that include colloidal solids and microbes.
- **Terminal water disinfection.** The last stage of treatment providing protection from waterborne pathogens is usually called terminal or safety disinfection. However, this stage will only be effective if the previous stages have efficiently removed most of the waterborne pathogens and reduced solids or other contaminants that may either interfere with the mechanisms involved in the disinfection process or contribute to unacceptable levels of disinfection by-products in the distribution system.

Application of a multiple barriers strategy should contribute significantly to reducing the cost and complexity of water treatment. The appropriate selection and combination of the different treatment stages should allow the use of only a small and fairly constant dose of disinfectant as final safety barrier. In this way, application of multistage and integrated water treatment concepts should contribute substantially to avoiding both customer complaints and excessive disinfection by-products. In turn, it will make the final treatment stage easier to operate and more reliable.

The benefit of applying multistage treatment is illustrated by the fact that the incidence of waterborne diseases in the USA is eight times higher in communities using surface water sources without filtration, than in those using filtration (Craun et al., 1994). Reinforcing the argument, the use of multistage treatment plants to produce safe and bio-stable effluents, together with good materials and engineering practices in the distribution systems, are allowing the Dutch water industry to maintain the quality of treated surface water without disinfectant residuals.

12.3 Health risks associated with drinking water

The main health risk related to water supply systems that use surface water from unprotected catchment areas stems from the discharge of untreated wastewater from human settlements and industries. Contamination of a water source with human and animal excreta introduces a great variety of bacteria, viruses and protozoa. The health risks associated with microbiological contamination are so important that their control is the highest priority. Poor water quality may be particularly harmful to children, old people or members of the community with compromised immune systems. For these groups, infectious doses are significantly lower than for the rest of the population.

There are a few chemical compounds that pose an acute health risk to the users such as high levels of nitrate leading to methaemoglobinaemia (*blue baby syndrome*) in infants. Other high-risk chemicals include heavy metals, fluoride, arsenic and organic compounds that enter the environment via industrial discharges, mining activities or spraying of pesticides and herbicides. But chemicals like fluoride and arsenic may also be present in geological formations and be dissolved in the groundwater as a result of chemical and physical processes. Chemical pollution may pose a chronic health risk associated with long periods of exposure. Its control is therefore important, but is a secondary concern in water supply systems that are subject to severe bacteriological contamination.

Understanding that chlorine reacting with organic matter can cause oxidation by-products (OBPs) that may represent a chronic health risk, raised concerns about its application in controlling the transmission of cholera in Latin America. However, it has been established that the health risk associated with these by-products is very small, compared with the risk related to inadequate disinfection. In reality, the chronic risks must not be ignored, but the acute risks from microbiological contamination are clearly much more important, especially in the case of systems drawing water from polluted sources. This is the situation in many countries with a poor sanitary situation and a low level of socio-economic development. In the search for possible alternatives to chlorine (such as ozone and ultraviolet radiation), it is necessary to know if they produce OBPs, as well as assessing whether they are equally effective, economically competitive, and easy to dose and supply. Specific techniques have been developed for home-based disinfection including solar disinfection.

Consumers accept or reject drinking water mainly using aesthetic considerations. Issues such as turbidity, colour, taste (for instance caused by high salt content) and odour can make them turn to other water sources that may be more contaminated and involve a higher health risk. So, aesthetic aspects need to be taken into account in the development of water supply systems. Aesthetic standards vary with local culture. National standards can therefore not be applied as a matter of routine. They need to be cross-checked with local women in particular, to ensure acceptability of any quality norms that will be applied.

With increasing life expectancy, enhanced institutional capacities and improved economic conditions, water treatment has progressively combined technologies to reduce initially the acute health risks, often of microbiological nature, and later the chronic health risks, usually of physical, chemical origin. This is illustrated in figure 12.1, based on the work of Coffey and Reid (1982).

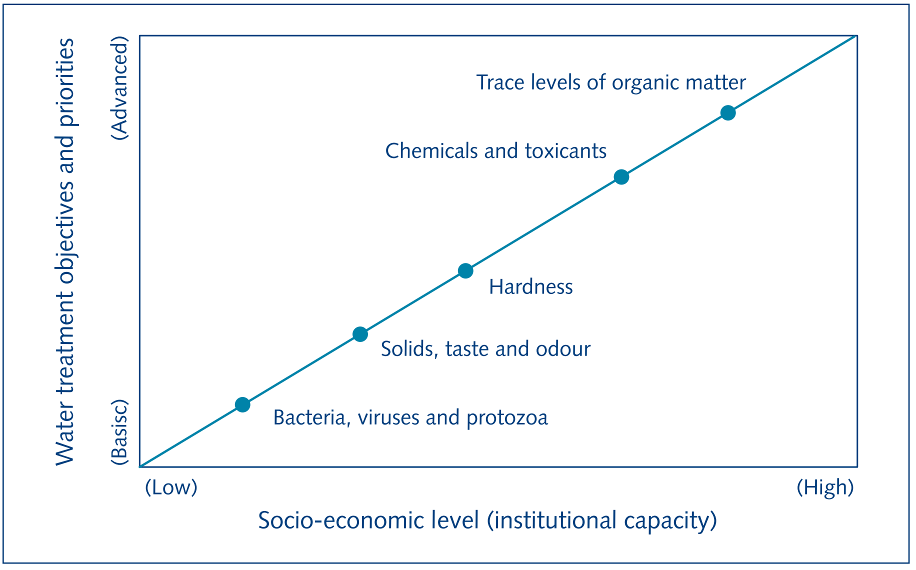

Fig. 12.1. Conceptual relation between socio-economic level and water treatment objectives

In summary, the most important criterion in the treatment of domestic water is the removal of all pathogenic organisms as well as high risk chemical substances such as heavy metals, fluoride, arsenic, nitrate and organic constituents. Other substances may also need to be removed or at least considerably reduced. These include suspended matter causing turbidity, iron and manganese compounds imparting a bitter taste or staining laundry, and excessive carbon dioxide corroding concrete and metal parts. For small community water supplies, other water quality characteristics such as hardness, total dissolved solids and organic content would generally be less important. The aim is a reduction to levels that are acceptable to the consumers so that use and sustainability are not affected negatively, although the extent to which the water is treated will be limited by economic and technical considerations. The quality guidelines for drinking water presented in chapter 4 should be a guide when the extent of the necessary treatment is determined.

12.4 Historical background of water treatment plants

The Romans made great strides in building and organising water supply systems. The water commissioner of Rome around 100 AD was the head of a well developed organisation run by the government. According to books describing the system, it included a settling reservoir at the head of one of the aqueducts supplying the city, and the piscanae, pebble catcher facilities built into most of the roman aqueducts (Baker, 1981; Coffey and Reid, 1982).

During the Middle Ages in Europe, after the decline of the Roman civilisation, WSS principles were widely ignored. Monasteries came to be leaders in providing water services. When the urban populations resumed their growth, municipalities took over leadership. By 1810 there were several private companies serving London. Due to the growth of towns and the increasing popularity of water closets in the early 1800s, sewage and other wastes were dumped into drains that discharged to the rivers being used as drinking water sources. Early water mains supplied water only intermittently and in some poor areas one well pump and a privy would serve many houses.

In 1831 the first recorded cholera epidemic reached Britain. At that time no one knew the cause or origin of diseases such as cholera, typhoid, and dysentery. Frequent complaints and difficulties arising from the poor quality of the water supplied in London led to successive political decisions and reforms. In 1842 Edwin Chadwick produced an important Report on the Sanitary Conditions of the Labouring Population of Great Britain. Although Chadwick did not make any specific connection between water and disease, clean water was considered part of the environmental improvements desirable for health. In 1848, an Act of Parliament charged government for the first time with the responsibility for safeguarding public health. According to this Act, water supplies had to be “pure, safe, and constant”. It was another fifty years before this sanitary ambition was practically fulfilled. A metropolitan water act of 1852 required that domestic water from the Thames River had to be filtered. London’s population was close to 2.5 million then. However, the water companies were often not fulfilling these requirements.

It was in 1849, during the second epidemic of cholera in Britain, that John Snow’s first essay on the waterborne nature of cholera appeared. It was based on evidence collected and analysed on fatal cases around a well on Broad Street in London. Still, it was not until the third epidemic in 1854, that John Snow’s views on the dissemination of cholera were vindicated. After Snow's work and the events of 1854 and 1856, the connection between water supply and waterborne disease was firmly established.

In the second half of the 19th century it was generally accepted that solutions to the prevailing public health problems depended on improvements in the sanitary infrastructure, requiring large engineering projects. Towards the end of the century scientific developments in the medical world started to become influential. With the development of bacteriology, after the discoveries of Pasteur and Koch in the 1880s, the germ theory became important in the fight against contagious diseases. This stimulated interest in other issues such as water source protection, water supply, basic sanitation, hygiene education and water treatment.

Pioneering work in water treatment by filtration

Plain sedimentation improves the clarity of surface water, but filtration gives much better results. In Paris, sand filters in copper containers were used for two centuries. The first water filter patent was granted in France around 1750. These filters were to be constructed of lead, pewter or earthenware. The filtering material of sand (or sponge) was packed between two plates, the lower one to serve as a false bottom to the filter, the upper to prevent disturbance of the sand when the water was poured into the vessel.

Towards the end of the 18th century, the first British patent was granted on a process and apparatus for water filtration, with ascending flow to clarify the water and reverse flow to clean the filter medium. To accomplish this, the patent proposed either three tanks or one tank with three compartments. The first received the turbid water from a service pipe, the second contained a stratified medium for filtration, and the third received the clarified water. The coarse filter material was placed at the bottom of the filter with regularly decreasing sizes above it, so that interstitial spaces would increase in geometric ratio.

Crude versions of slow sand filters (SSF) were used for industrial water supplies in Britain before the end of the 18th century. A Scottish industrialist started to sell water from his industrial plant to city dwellers. The muddy and industrially polluted river water flowed to a well through a coarse filter 23 m long, 2.4 m wide and 1.2 m deep. A steam engine placed over the well lifted the water to an *air chest* about 5 m above the river, from which it flowed to the plant. The plant had sedimentation and double filtration stages with lateral flow as shown in figure 12.2. Due to its radial layout, maintenance problems are likely to have been a serious limitation for long-term operation.

The early filters were never completely successful because an adequate cleaning procedure was not available to the operators. Two filter cleaning methods were gradually developed by testing and learning. The first was the self-cleaning filter, washed by reverse flow. The other was achieved by scraping off the thin dirty top layer, removing, washing, and restoring it at intervals. Both were based on the fact that surface clogging caused the filtration process to fail. The common filter material arrangement was from coarse at the bottom to fine material at the top of the filter.

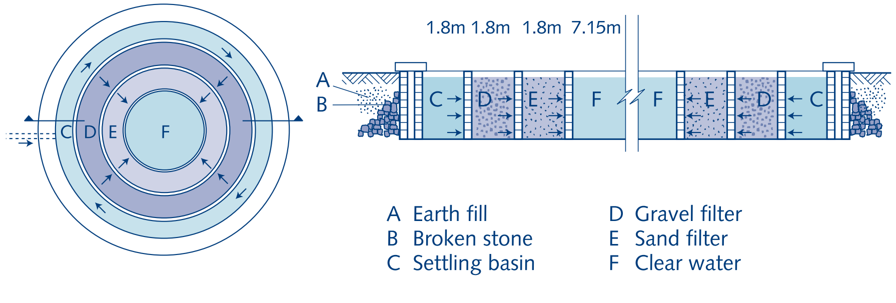

Fig. 12.2. Water treatment plant at Paisley, Scotland, 1804 (Adapted from Baker, 1981)

The experimental slow sand filter plant in London had two settling reservoirs working in parallel, followed by a filter (fig. 12.3). The filter was 13.4 m^2 at the top and 1.8 m deep. The plant filtered 3.9 l/s^{-1}, at a rate of 0.15 m/h^{-1}. During tests the filter was being scraped about once a fortnight. This scraping procedure was seen as the best way of overcoming cleaning limitations.

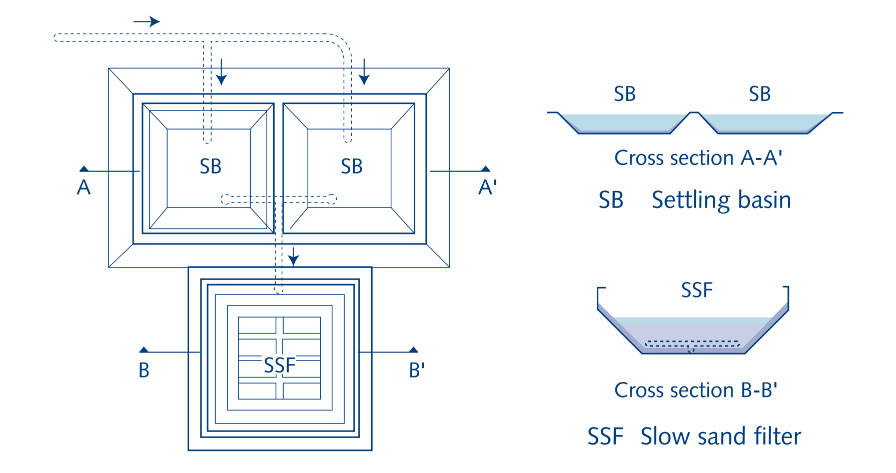

Fig. 12.3. Simpson's London experimental slow sand filter, 1827-1828 (Adapted from Baker, 1981).

Based upon this experimental SSF, a first English SSF with a size of one acre was put into operation at Chelsea in 1829. This became the classical model of SSF. The other filter design with the elements of reverse-flow wash and a false bottom were to become principal features of the rapid filter developed in the USA during the 1880s.

In France, Darcy patented a filter that included all of the elements of the American rapid filter except one – coagulation. Darcy made an innovative combination of previously developed filtration principles with sound hydraulic considerations about flow through porous media, now known as Darcy's Law. This law states that the flow per unit of area of filtering bed is proportional to the hydraulic gradient in the porous media.

Over the years, disinfection processes associated with water treatment have included heat, copper, silver, chlorine, ozone, ultraviolet radiation, and membranes. The most popular has been chlorine. Chlorine, as hypochlorite solution, started to be used at treatment plant level in Belgium in 1902, the United States in 1904, Britain in 1911, and London in 1916. Chlorine as a liquid (compressed in metal cylinders) was applied first in the USA in 1913, and in Britain (London) in 1917. Recent regulation concerning the control of disinfection by-products has led to a better sequential application of the multiple stage and integrated water treatment concepts, in which chlorination is logically the final treatment stage. Additionally, there is a growing awareness that some pathogens (e.g. giardia cysts and cryptosporidia) are best removed by filtration at an earlier stage, as they are resistant to chemical disinfection.

Though SSF technology has been successfully applied in northwest Europe since the 19th century, in other regions the use and the impact of this technology has been rather limited. The growing application of rapid filtration (RF) and chemical disinfection in the 20th century contributed significantly to the reduction of waterborne diseases and to the improvement of productivity and quality of life in urban settlements that had the opportunity to install and sustain these technologies. Today, a large number of different types of treatment exist for the purification of water. However, selection of the most suitable option for a given community remains a major challenge, particularly if it is a low-income community with limited institutional, organisational and financial capacity.

There needs to be a systematic partnership approach involving representatives of the different user groups and the availability and use of all relevant information on robust, efficient treatment technologies. The goal is to arrive at a solution that includes selection and protection of the best available water resources combined with a treatment system that is economically sound and easy to operate, manage and maintain. For small communities, the partners need to compare the technical, managerial and institutional feasibility of potential central water treatment systems with other water treatment and water supply options. The other options could include home-based water treatment and family-based small systems such as private, protected wells.

12.5 General effectiveness of water treatment process for contaminant removal

Some water treatment processes serve a single purpose and others have multiple applicability. Often a treatment result can be obtained in different ways. The removal of some water contaminants by various well-designed and properly maintained and operated treatment processes is illustrated in table 12.1. The comparison is necessarily general, due to the multiple factors affecting water treatment efficiency.

Storage of water can be regarded as treatment. For example, Schistosoma cercariae are normally unable to survive 48 hours of storage. The number of faecal coliforms and faecal streptococci will be considerably reduced when the raw water is subjected to storage. Storage also allows sedimentation to take place, reducing the settleable solids content of the water. Storage, however, may promote algal growth in the water. Loss of water through evaporation is often another drawback.

By exposing water to air (aeration), volatile dissolved components that are in excess of their saturation concentration can be removed from the water while gases from the atmosphere can be transferred to the water. Carbon dioxide (CO_2) and some volatile toxic organic and taste- and odour- causing compounds may be removed to satisfactory levels. The addition of oxygen (O_2) will enhance the oxidation of metals (e.g. iron and manganese) to higher and more insoluble oxidation states.

In chemical coagulation, colloidal particles are destabilised, to be subsequently agglomerated or flocculated to form larger particles that are easier to filter (direct filtration) or settle. In sedimentation, water is exposed to relatively quiescent conditions and suspended solids (SS) may be removed by the action of gravity.

Filtration usually fulfils the role of "polishing" the treated water. SSF and RF are the main filtration alternatives in common use. Only high quality raw water can be directly filtered (without pre-treatment) to remove small quantities of suspended solids. Other raw waters must be conditioned before reaching the main filtration stage. Coarse media (e.g. sand or gravel) filters can be used to reduce concentration of contaminants such as algae, micro-organisms or suspended solids. The combination of coarse media and slow sand filtration units can be used to treat polluted surface water, without dosing it with chemical coagulants. Influent water to RF must have a coagulant agent added to it first.

There are some typical operational differences between SSF and RF units. Filtration rates are around 50-150 times lower for SSF. Flow retention periods are about 30-90 times longer for SSF. Filter run lengths are about 30-90 times longer for SSF, and the surfaces of SSF units are usually scraped at the end of the filter runs, whereas RF units are cleaned by backwashing. These differences originate from the most relevant and distinctive feature of SSF, the biological life at the sandbed surface. In fact, the main treatment mechanisms in RF are of a physical-chemical nature and the water treatment in SSF is the result of a combination of physical-chemical and biological mechanisms that interact in a complex way. For a more detailed discussion of multi-stage filtration including SSF see chapter 16. RF is described in detail in chapter 17.

Table 12.1 General effectiveness of water treatment processes for contaminant removal

Water quality parameters Treatment processes	Aeration and stripping					
	Sedimentation	Coagulation,	Flocculation, sedimentation, and filtration	Slow Sand filtration	Multistage filtration[1]	Chemical oxidation: disinfection
Bacteria	0	0	+++	+++	++++	++++
Viruses	0	0	+++	+++	++++	++++
Giardia cysts	0	0	+++	+++	++++	++
Cryptosporidium oocysts	0	0	+++	+++	+++	+
Turbidity	0	+	++++	+++	++++	0
Suspended solids	0	+++	++++	+++	++++	0
Taste and Odour	++	0	+++	++	+++	+
Iron and manganese	++[2]	+	+++	+++	+++	++
Fluoride	0	0	+	0	0	0
Arsenic	0	0	++	+	+	0
Heavy metals	++[2]	0	++	+	++	+
Dissolved Oxygen	+	0	0	-	-	0
Carbon Dioxide	-	0	0	+	+	0
Colour and organics	0	0	++	++	++	+

0, no effect; ++++, increasing positive effect; -, negative effect

1 Multistage filtration: Combinations of one or more stages of gravel filtration in series with slow sand filtration

2. Aeration in combination with sedimentation.

Disinfection removes pathogenic micro-organisms or renders them inactive. Water must be in contact with the dose of disinfectant agent for a time long enough to assure the required reductions of indicator micro-organisms, usually bacteria. Disinfection processes are described in chapter 19.

12.6 Groundwater quality and treatment

For the most part, groundwater originates from rainwater that infiltrates through the soil and is stored in aquifers. During infiltration the water can pick up impurities such as in-organic and organic soil particles, debris from plant and animal life, micro-organisms, natural or man-made fertilisers, pesticides, etc. During its flow underground, however, a great improvement in water quality will usually occur. Suspended particles are removed by filtration, organic substances are degraded by oxidation, and micro-organisms die away because of lack of nutrients. The dissolved mineral compounds, though, are not removed. In fact, the mineral content of the water can increase considerably through the leaching of salts from the underground layers.

Groundwater, if properly withdrawn, will be free from turbidity and pathogenic organisms. When it originates from a clean sand aquifer, other hazardous objectionable substances will also be absent. In these cases, disinfection as a safety barrier is desirable, but direct use of the water as drinking water may be permitted without any treatment. When the water comes from an aquifer containing organic matter, oxygen will have been consumed and the carbon dioxide content of the water is likely to be high. The water will then be corrosive unless calcium carbonate in one form or another is present. When the amount of organic matter in the aquifer is high, the oxygen content may be completely depleted. Water containing no oxygen (anaerobic water) will dissolve iron, manganese and heavy metals from the underground strata. These substances can be removed, i.e. by aeration and filtration. It depends on the type of aerator whether the carbon dioxide content of the water will be reduced or left unchanged. A reduction is desirable if the water is corrosive but in other cases it can result in troublesome deposits of calcium carbonate.

Sometimes groundwater contains excessive amounts of iron, manganese and ammonia, but also fluoride, arsenic and salts. Groundwater may also sometimes be polluted by industrial and other hazardous waste. These compounds may be dissolved in the groundwater and they can pose a very high health risk even in small concentrations. Where alternative water is scarce, even these polluted groundwater sources may have to be used and the source water treated with chemical coagulation and flocculation, ion exchange and different filtration technologies (including GAC[1]) to render them fit for drinking and domestic purposes.

Many of these treatment processes involve expensive technologies. They are also technically very complicated to manage and the O&M is expensive. For small community water supplies in the South many of these processes are too complicated and they should be avoided whenever possible. New small-scale water treatment techniques and methods have been and still are being developed which are appropriate for the specific conditions in poor communities in the South. Table 12.2 summarises the treatment processes described above. If groundwater is under the direct influence of surface water, it should be protected or treated as surface water. For chemicals such fluoride, arsenic and salts (dissolved solids) more complicated treatment processes are required. They are described in chapters 22 ("Fluoride"), 23 ("Arsenic and Iron") and 18 ("Desalination").

1 GAC = granular active carbon used as a filter medium

Table 12.2 Treatment of groundwater

Water quality parameters	Treatment processes				
	Aeration for		Plain sedimentation	(Rapid) filtration	Safety disinfection (chlorination)
	Increasing O_2	Reducing CO_2			
Aerobic, fairly hard and not corrosive					0
Aerobic, soft, and corrosive		X			0
Anaerobic, fairly hard, and not corrosive	X				0
Anaerobic, fairly hard, not corrosive with iron and manganese	X		0	X	0
Anaerobic, soft, corrosive no iron and manganese	X	X			0
Anaerobic, soft corrosive with iron and manganese	X	X	0	X	0

(X, necessary; 0, optional)

12.7 Surface water quality and treatment

Surface water can be taken from streams, rivers, lakes or irrigation canals (see chapter 11). Water in such surface sources originates partly from groundwater outflows and partly from rainwater that has flowed over the ground to the receiving bodies of surface water. The groundwater outflows will bring dissolved solids into the surface water; the surface run-off is the main contributor of turbidity and organic matter, as well as pathogenic organisms. In surface water bodies, the dissolved mineral particles will remain unchanged but the organic impurities are degraded through chemical and microbial processes. Sedimentation in impounded or slow-flowing surface water results in the removal of suspended solids. Pathogenic organisms will die off due to lack of suitable food. However, new contamination of the surface water is likely to take place as a result of waste influents and algal growth.

The criteria for the degree of treatment recommended by WHO (1993) to produce drinking water from surface sources with a negligible risk of containing viruses are summarised in table 12.3. Although pre-disinfection is recommended in this table, other treatment stages such as storage or coarse filtration should be preferred to reduce the required doses of chemical disinfectants and risks associated with oxidation by-products. WHO (1993) considers that "the attainment of the bacteriological criteria [absence of E. coli or thermotolerant coliform bacteria] and the application of treatment for virological reduction [table 12.3] should, except in extraordinary cases of extreme contamination by parasites, ensure that the water has a negligible risk of transmitting parasitic diseases". However, the guidelines published by WHO (1993) do not include information on performance of the treatment steps to facilitate process selection and combination to fulfil water treatment objectives with different levels of contamination in the water sources.

Table 12.3 Treatment steps recommended by WHO to produce water with negligible virus risk from surface water sources (WHO, 1993)

Type of surface water source	Recommended treatment
• Protected, impounded upland water; essentially free of faecal contamination	• Disinfection[1]
• Protected, impounded water; or upland river; faecal contamination	• Filtration[2] and disinfection
• Unprotected lowland rivers; faecal contamination	• Pre-disinfection[3] or storage, filtration, disinfection
• Unprotected watershed; heavy faecal contamination	• Pre-disinfection[3] or storage, filtration, additional treatment[4], and disinfection
• Unprotected watershed; gross faecal contamination	• Not recommended for drinking water supply

1. Before terminal disinfection median turbidity < 1 NTU and < 5 NTU in single samples. Residual of free chlorine > 0.5 mgl-1 after at least 30 minutes of contact time at pH < 8.0, or an equivalent disinfection process for > 99.99% of enterovirus inactivation.
2. Slow sand filtration (SSF), [Multi-stage filtration (a combination of gravel filtration and SSF)] or rapid filtration (RF) preceded by coagulation-flocculation, or an equivalent filtration process for > 90% enterovirus reduction.
3. Although pre-disinfection is recommended in this table, other treatment stages, such as storage or coarse filtration, should be preferred to reduce the required doses of chemical disinfectants and risks associated with oxidation by-products
4. Additional treatment may consist of SSF, granular activated carbon adsorption with ozonation, or any other process demonstrated to achieve > 99 % enterovirus reduction.

Unpolluted surface water of permanently low turbidity may be purified by slow sand filtration (SSF), or by direct rapid filtration followed by chlorination. SSF has the great advantage of relatively low operational requirements, and local communities can build the filters if required materials and appropriate supervision are available.

When the turbidity of the water to be treated is high, or when algae are present, SSF units would rapidly clog. Pre-treatment is needed, such as sedimentation, coarse (gravel) media filtration, rapid filtration or a combination of two or more of these processes. For colloidal suspended particles, the removal by settling or filtering can be greatly improved through chemical coagulation and flocculation. All these processes are required in most instances where the organic content of the raw water is high. Water from rivers and lakes is of a very wide variety in composition and it is impossible to describe in detail all the treatment systems required in every case. Leaving complicated processes out, table 12.4 shows the systems most applicable to small community water supplies.

Table 12.4 Treatment of surface water

Water quality	Treatment processes			
	Plain sedimentation	Rapid filtration	Multi-stage[1] filtration	Disinfection (chlorination)
Clear and unpolluted			O	O
Slightly polluted and low turbidity		X	X	X
Slightly polluted and medium turbidity	O	X	X	X
Slightly polluted and high turbidity	X	X	X	X
Slightly polluted and many algae	O	X	X	X
Heavily polluted and little turbidity	O	X	X	X
Heavily polluted and much turbidity	X	X	X	X

(X, necessary, 0, optional)

1. Multi-stage filtration: Combinations of one or more stages of gravel filtration in series with slow sand filtration

Water treatment plant efficiencies are meaningless without reference to the quality of the raw and treated water. For this reason it is important not only to have an assessment of the raw water quality but also performance efficiencies and treatment objectives for the treatment plant. Table 12.5 illustrates this situation based on data from pilot and full-scale multi-stage filtration projects treating water from tropical Andean rivers.

Table 12.5 An example of performance objectives for removal of turbidity and faecal coliform bacteria in multistage filtration water treatment plants (adapted from Lloyd et al., 1991 and Galvis 1999)

Stage and process	Turbidity			Thermotolerant coliform bacteria		
	Removal1 (%)	Average loading (NTU)	Maximum[2] loading (NTU)	Removal[1] (%)	Average loading (Per 100 ml)	Maximum loading (Per 100 ml)
Screening	NA[3]	NA	NA	NA	NA	NA
Plain Sedimentation	50	60	600	50	2000	10,000
Dynamic gravel filter	30	30	300	40	1000	5000
Coarse (Gravel) filters[4]	80	21	210	90	600	3000
Slow Sand Filter	>90	<5	42	95	60	300
Disinfection	NA	<1	<5	>99.9	3	15
Distributed Water	NA	<1	<5	NA	<1	<1

1 Required performance

2 Maximum loading corresponds to turbidity peaks of short duration (< one day)

3 NA, not applicable. Process not designed to remove turbidity and/or bacteria

4 Three stages of coarse up-flow gravel filtration

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http://www.who.int/water_sanitation_health/GDWQ/GWDWQindex.html

Web sites

IRC Portal: http://www.irc.nl/

PAHO/WHO. Virtual Library in Health and Environment:
Water Treatment: http://www.cepis.ops-oms.org/index.html

Cost-Effective Technologies in Water Supply and Sanitation: http://www.skat.ch/htn/ and http://waternet.com/

Roughing Filtration Technology: http://www.sandec.ch/water/roughfilter.html

For arsenic and fluoride removal and disinfection, also see the specific chapters.

GARNET discussion groups

Water and Sanitation Applied Research:
http://www.jiscmail.ac.uk/cgi-bin/wa.exe?SUBED1=water-and-san-applied-research&A=1

Iron and manganese removal:
http://info.lut.ac.uk/departments/cv/wedc/garnet/tncironm.html

Water quality monitoring: http://info.lut.ac.uk/departments/cv/wedc/garnet/tncwq.html