Chapter 5

Water treatment

> "We never know the worth of water until the well is dry."
>
> **Thomas Fuller, English churchman and historian (1608–1661).**

The gap between available water resources and our domestic, municipal and industrial needs is becoming wider. Key causes are climate change and population growth. The number of people living in regions affected by severe water stress is expected to increase by a billion to almost four billion in the next two decades. The most severely affected regions will be North Africa, the Middle East, northern China, southern India, Pakistan and certain parts of the United States and Mexico. At the same time almost 40% of the global population live less than 100 *km* from the sea and 60% of the world's biggest cities in coastal areas do not have access to fresh water.

The available groundwater or surface water in remote regions may have a low quality and the contaminants need to be eliminated or reduced. The water must be cleaned to an acceptable quality, which depends on the final use. Naturally, drinking water needs to satisfy much higher quality standards than water for cleaning or for irrigation. In 5.1 an overview of water treatment technologies is presented. Filtering is often the first step in water purification, Section 5.2. Desalination is a

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often the first step in water purification, Section 5.2. Desalination is a key technology to produce clean fresh water, Section 5.3. Disinfection, 5.4, is another important means of removing pathogens and protecting human health.

5.1 PRODUCING CLEAN WATER

The required energy to clean water depends on the quality of the raw water supply. Often, available water sources in developing countries are contaminated and consequently there is a high demand on energy use by volume of water (such as kWh/m^3) to treat the water to an acceptable quality.

5.1.1 Underground water resources

Groundwater is the major source of water in many parts of the developing world and there is a serious problem in that in many places the water table is declining. As mentioned in Section 4.2, underground water has been pumped in an unsustainable way in many regions. There are two consequences: water sources are dwindling and the pumping energy to reach them is increasing. In many areas water that has been pumped from aquifers has been underground for thousands of years and is now being used far in excess of the rate at which the water is replenished. It may take generations or centuries to refill these aquifers via rainwater. Such a resource is non-renewable and this kind of practice can be called mining of groundwater. Irrigation will of course influence groundwater resources. Since the irrigation is mostly done in dry or arid areas there is a large risk that the groundwater levels will decrease, since the groundwater will not recover as quickly as it is consumed.

5.1.2 Saline water

The need to use seawater as a source for fresh water has increased dramatically because of both population growth and climate change. Many dry regions have become drier. Using seawater as a source represents an important possibility in coastal areas. The salt concentration in seawater is typically 3.5% or 35,000 *ppm* (parts per million or *mg/l*). Many underground aquifers or other groundwater sources have brackish water that needs to be made drinkable by eliminating the salt. Another increasing water supply problem is the invasion of seawater into groundwater. Sometimes the groundwater resources have been exhausted. In other cases, the rising sea level caused by climate change will intensify the problem. Table 5.1 indicates typical salinity for various water qualities.

Table 5.1 Salinity for different kinds of waters.

	Salinity (ppm = mg/l)
Seawater	35,000
Highly saline water	10,000–35,000
Brackish water	1,000–10,000
Fresh water	<1,000

5.1.3 Contaminated water

It is crucial to make drinking water safe to drink. Many groundwater or surface water sources in remote areas have highly contaminated water, not only pollution from organic carbon (COD) or nutrients (ammonia and phosphorus) but also pathogenic bacteria, viruses, protozoa and worms. Many sources are highly contaminated due to the presence of harmful metals like fluoride and arsenic, which cause serious health hazards. Obviously, unsafe contaminants must be eliminated. The surface water sources are frequently used as dumping grounds and at the edges of the water bodies there is often defecation, which results in bacteriological contamination. This is a challenge not only to agricultural production and rural livelihoods, but also to food safety.

Treating contaminated water requires more energy.

To remove contaminants requires energy. Biological treatment to remove COD typically requires a certain energy per *kg* of COD. Disinfection of water can be done in several ways. One principal way is disinfection via UV light. Another is via filters of various sizes. Both of them require electric energy to provide the UV light or to produce a pressure to operate membrane filters.

5.1.4 Water treatment technologies

The protection of human health is among the most important goals of water treatment systems. Any type of treatment must aim to reduce or inactivate potentially pathogenic organisms. Membrane separation is one methodology to remove harmful substances from the water. This aspect is emphasised in 5.2. Another technology to remove pathogens is by disinfection, as described in 5.4.

Having saline or brackish water as the water source means that small molecules have to be removed in order to make the water drinkable or useable for irrigation. This is called desalination, and is discussed in 5.3. There are two main technologies to produce fresh water from seawater or brackish water:

- Distillation, or thermal methods (heat treatment), and
- Reverse osmosis (membrane process).

Distillation is the oldest technology to obtain salt-free water. It uses a heat source to evaporate the water into steam and a cooling source to condense the steam into desalinated water. Regardless of the salt levels in the incoming water, the produced water will generally have a final salinity of less than 10 *mg/l*.

The phenomena of osmosis and reverse osmosis (RO) have been known for about 100 years but only in the 1960s, with the development of synthetic membranes, did these principles become an industrial reality. The first membranes were made from cellulose acetate. Since then a large number of organic membranes, made of polymers, and even mineral membranes have been added to the list. An RO membrane only allows water to pass through and retains the solutes. Membrane desalination uses high pressure from electrically powered pumps to separate fresh water from seawater or brackish water using a membrane. In other words: the RO process is electric power driven. Membrane technology, mainly reverse osmosis (RO), is used for almost 60% of installed capacity. Membrane technologies continue to dominate the desalination market. For example, according to the International Desalination Association (www.idadesal.org), in 2017 membrane technology accounted for 2.2 million m^3/day of annual contracted capacity while thermal processes accounted for just 0.1 million m^3/day during the same period.

5.2 MEMBRANE SEPARATION

Membrane technology has a huge impact on water purification. Semi-permeable membranes are used to physically separate substances. Using pressure across the membrane can drive the process. Then the smallest molecules or particles in a given solution are pushed through the membrane while larger molecules or particles are kept back. Pressure-driven membrane separation can be divided into four different types:

- *Microfiltration* (MF) screens particles from 0.1 to 0.5 microns ($10^{-6}\ m$);
- *Ultra-filtration* (UF) screens particles from 0.005 to 0.05 microns;
- *Nanofiltration* (NF) screens particles from $0.5 \cdot 10^{-3}$ to $1 \cdot 10^{-3}$ microns;
- *Reverse osmosis* (RO) ranging molecular size down to about 1 angstrom (10^{-4} microns). At this size the "particles" are individual molecules.

MF can remove suspended solids, high molecular weight species, bacteria, pathogens such as cryptosporidium and giardia in drinking water. Cryptosporidium is a parasite that commonly occurs in lakes and rivers, particularly when these water systems are contaminated with sewage or animal waste. The MF and UF techniques do not require any chemicals to inactivate the microbes.

Water purification by UF can remove macromolecules, colloids, viruses, proteins and pectins. The UF does not remove all the natural minerals, such as calcium (Ca^{2+}) or – more important – the salinity of seawater.

NF can remove small molecules and polyvalent ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), while RO is needed to remove soluble salts, smaller ions, colour and low molecular weight species.

Another parameter that distinguishes the four types of membrane filtration from one another is the pressure under which they normally operate. The flux (the capacity of purified water, permeate, measured in litres per m^2 of membrane per hour) depends on the feed pressure. MF and UF need relatively low pressures, while NF and RO require much more. Typically, NF would need 1–4 MPa (10–40 bar), while RO would require 1.5–8 MPa (15–80 bar). Above the optimum pressure clogging of "pores" occurs and the membrane is compacted.

Membranes can be used to treat various kinds of contaminated water, like greywater, blackwater and urine. This is further examined in 7.2.

5.3 DESALINATION

Worldwide about 300 million people get some fresh water from more than 19,300 desalination plants in 150 countries. Middle Eastern countries have the highest investment in desalination, but the technology is increasingly used around the world in water-scarce regions. According to the International Desalination Association, around 87 million m^3 of fresh water is produced every day via desalination. If that amount of water could be equally shared between the world's 7.6 billion people, then everybody would have more than 11 litres every day. The annual growth of desalination is projected to be 12% over the five years from 2018 to 2022.

Global desalination capacity today is sufficient to supply each person with 11 litres/day.

5.3.1 Energy supply for desalination

Today most of the energy supply for desalination is produced from fossil fuels and less than 1% comes from renewables (IEA-ETSAP & IRENA, 2013). Fossil-fuelled desalination has its problems, including the fact that electric power generated from coal and gas plants consumes water. Using a water-intensive resource to produce water is not sustainable. Therefore, we need to think about water as an energy resource and energy as a water resource.

The fact that fossil fuel for water production is not sustainable from an economic and environmental point of view has also been recognised in oil-rich Saudi Arabia, where King Abdullah's Initiative for Solar Water Desalination was announced in 2010 (IRENA, 2015b). The project has the goal of increasing water security for the country but will also contribute to the development of low-cost solar-based desalination technology. Increasing scale of deployment will make the solar desalination affordable in the long term. The cost of input energy is the dominating cost of desalination and is more than 50%. Considering continuously rising energy costs and with the impending exhaustion of conventional energy resources, it is a very attractive and promising prospect to use renewable energy to produce clean water. This is particularly true in the case of solar energy since regions with great water shortages tend to be those with higher solar radiation.

The water supply source for desalination is not always seawater, as shown in Table 5.2. Brackish groundwater is common in many water-scarce regions in the world.

Table 5.2 Potable water sources (globally) for desalination.

Desalination From	Percentage
Seawater	59
Brackish water	21
River water	9
Pure water for industrial applications	5
Used water for reuse	<5

Source: Wikipedia.

In many parts of the developing world there is plenty of both brackish water and solar energy. The use of solar energy to supply power for local desalination of brackish water is an interesting option where potable water is scarce.

5.3.2 Distillation – thermal methods

By heating up the water it is possible to separate the salt and dissolved minerals from the water in seawater or brackish water. This is called distillation. The basic principle of distillation is simply to heat up the water, let it evaporate and then condense it, producing fresh water. This principle has been used in warm and dry countries over the centuries by using sunlight. In ancient times sailors at sea obtained drinking water from primitive distillation systems. Inventors like Leonardo da Vinci and Thomas Jefferson experimented with seawater desalination. Aristotle, as early as the fourth century BC, described a method to evaporate impure water and then condense it to obtain potable water (Kalogirou, 2005).

Distillation requires a substantial amount of heat energy and must be coupled with other heat-producing applications. Distillation has mainly been developed in oil- and gas-producing countries, where it can be linked to thermal power facilities and thus use the heat they emit to produce evaporation. The advantage of this technique is that it does not require special pre-treatment of the water before its evaporation.

Today distillation is done more elaborately, and the most common method is *multistage flash distillation* (MSF) where the water is heated and the pressure decreased so that the water "flashes" into steam. MSF requires large amounts of energy to produce fresh water (typically 12–15 *kWh* and sometimes as much as 25 *kWh* per m^3). Two types of energy are required for the operation of a thermal desalination plant:

- Low-temperature heat, which is the main portion of energy input,
- Electricity, which is used to drive the system's pumps. Solar PV or wind power can be used to power the pumps. This may require 3–5 *kWh* per m^3.

The other thermal desalination process is *multiple effect distillation* (MED). Here the water passes through several evaporators in series. Vapour from one series is subsequently used to evaporate water in the next.

The MSF and MED technologies are industrial processes suitable for large-scale operations. They are very expensive for small-scale operations. MED is more efficient than MSF.

Thermal desalination is still the dominating technology in the Gulf countries and North Africa, but globally membrane-based methods are now the most common ways to desalinate seawater.

Distillation plants generate less waste (called brine) than membrane-based methods like reverse osmosis (RO), and there are no filters or membranes to get clogged. The brine issue is further examined below.

The energy used by desalination systems may be in the form of either work (such as electricity) or heat (normally as low-temperature steam). These forms of energy are distinct and cannot simply be added to find a "total" energy requirement. Because of the second law of thermodynamics electric energy can be converted to heat, but low-temperature heat cannot be converted to electric power.

5.3.3 Reverse osmosis

RO units are available in a wide range of capacities due to their modular design. The RO technology is used in applications from family size to as large as 600,000 m^3/day. This scalability together with similar scalability properties of solar PV and wind energy makes this combination extremely interesting.

Large plants are built up with hundreds of units that are accommodated in racks. A large plant's capacity far exceeds 100,000 m^3/day or 1 m^3/second, while very small units are made for flow rates as small as 0.1 m^3/day or about 4 litres/hour. The small units are used for single households, marine purposes or hotels and are suited to and used in rural areas or islands where there is no other water supply available.

Natural osmosis (or direct osmosis) governs how water transfers between solutions with different concentrations. It is the basis for the way in which human skin and organs function, and how flora and fauna maintain water balance. The osmosis process can be explained when there is a semi-permeable barrier such as a membrane located between two solutes with different salt content, as in Figure 5.1. In natural osmosis the water tends to flow from a solution with a lower concentration to a solution with a higher concentration if no external pressure is applied.

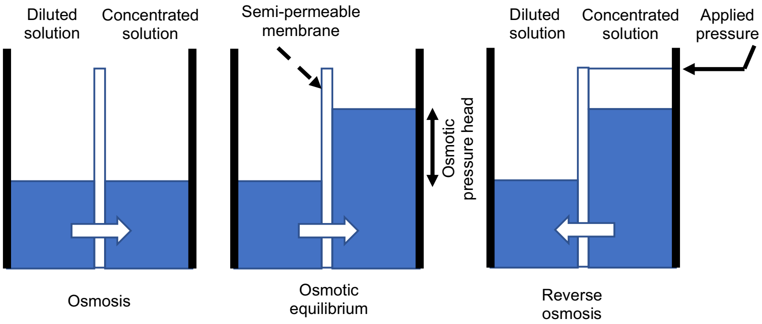

Figure 5.1 Illustration of osmosis and reverse osmosis. The arrows denote the water flow direction.

In RO the water will flow in the opposite direction compared to natural osmosis, Figure 5.1. This will require that a pressure is created.

The salty water is given a high pressure (Δp) that exceeds the osmotic pressure ($\Delta\pi$). Then the water from the concentrated solution will pass through a semi-permeable membrane and leave the solid salt particles behind. The osmotic pressure for seawater with 3.5% salt is 2.6 *MPa* (or ≈26 bar). Brackish water needs less energy since the osmotic pressure is lower. This means that a RO system for salty water only begins to produce water when a pressure higher than the osmotic pressure is achieved. In fact, the flux of the water through the membrane is proportional to the difference in pressure between the applied pump pressure Δp and the osmotic pressure $\Delta\pi$:

$$J_w = C \cdot (\Delta p - \Delta\pi)$$

where J_w is the flux (ℓ/m^2 membrane per hour) and C the so-called permeability constant. Consequently, the flow rate is

$$Q = J_w \cdot A = C \cdot (\Delta p - \Delta\pi) \cdot A$$

where A is the surface area of the membranes. The permeability depends on temperature. The higher the water temperature the higher the permeability will be. The change in permeability is about 3% per °C. As a result, the required pressure to achieve or keep a certain flux or capacity will be lower at higher temperatures.

A small part of the dissolved substance also goes through the membrane with the water. Some 2% of common salt (NaCl) may go through the filter in RO.

The actual required pressure and subsequent energetic cost of desalination is 2–3 times higher than the osmotic pressure due to inefficiency, material losses and membrane fouling. Typical operating pressure for seawater desalination is in the range *5.5–6.2 MPa* (or 55–62 bar) but pressures in the range *6.9–8.3 MPa* (69–83 bar) can be found.

Brackish water desalination needs less energy since the osmotic pressure is lower. It decreases almost linearly with decreasing salt content. The osmotic pressure (in bar) can be estimated with a rule of thumb formula:

$$\Delta\pi \approx 0.7 \cdot 10^{-3} \cdot C$$

where C is the salt concentration (mg/ℓ). For 1% salinity the osmotic pressure is around 0.75 *MPa* (or 7.5 bar).

Energy for desalination decreases almost linearly with decreasing salt content.

Brackish water reverse osmosis (BWRO) systems typically require pressures in the range 1.5–2.5 *MPa* (or 15–25 bar). Consequently, less power is needed for brackish water desalination (BWRO) compared to seawater desalination (SWRO). Also, the lower pressures found in BWRO systems permit the use of low-cost plastic components. Therefore, the total cost of water from brackish water is considerably less than that from seawater, and systems are beginning to be offered commercially.

The required pressure-pump power is proportional to the flow rate of the feed and to the pressure difference between the exit and inlet pressure of the primary pump. The RO plants are sensitive to the feedwater quality, such as salinity, turbidity and temperature. Energy is consumed not only to achieve a sufficiently high pressure for the RO process; it is also needed for the pumping that pulls the water into the desalination facility as well as for the filters for the pre-treatment. Up to 72% of the total energy required for seawater desalination with RO membranes is consumed by the high-pressure pumps (Voutchkov, 2012). Therefore, it is essential to make sure that the pressure pump has a high efficiency.

5.3.4 Reverse osmosis membranes

In an RO membrane the water moves by flowing through the polymer structure, which is always hydrophilic and “swelled” by the water. The RO membranes are arranged in spiral-wound modules so that the membrane unit looks like a tube.

It is very important to pre-treat the feedwater. Suspended particles need to be removed via pre-filters and chemicals may be added ahead of the RO filters. A well-functioning pre-treatment is the key to reliable fresh water production. This will minimise membrane washes and will give the RO modules a longer life. Still membranes can be affected by fouling that can be caused by high-turbidity feedwater where membranes are clogged with suspended solids, marine organisms and their metabolic products. Fouling is also a result of the sedimentation of natural organic material (NOM) and mineral particles on the membrane surface.

Fouling restricts water flow and ultimately affects the water recovery of the membrane system. It can also damage membranes. Fouling can be prevented by adding special chemical agents or anti-scalants. The presence of fouling increases energy use. Frequent cleanings and chemical injection reduce the RO membrane life.

Even with good pre-treatment design it is vital to provide for periodic washing of the modules. If washing is inadequate, it generally must be repeated quickly.

The desalination process produces two streams of water, one with the fresh water (having low salinity) and one with more salt. From the feedwater flow about half the volume is converted to drinkable water and the other half will be about twice as salty as the incoming water. The second stream is called brine, and its disposal is a key issue. The brine is denser than the seawater. As noted before, chemicals like anti-scaling agents and coagulants are added to the seawater in the desalination process. The chemicals do not pass through the membrane and are left in the brine.

As soon as the brine is released, biological activities will begin, and microorganisms will feed on the chemicals. This consumes dissolved oxygen in the receiving water. Phosphate and nitrate are also released when chemicals in the reject water break down, causing eutrophication of the receiving water. So, if the brine is discharged into the sea, there is a risk for marine life. Too much salt can be just as deadly for sea life as seawater is for land animals and crops. Furthermore, the brine is often quite hot, so its disposal can have a negative impact both on land and in water. One way to minimise the potential negative effects of the salts and the chemicals in the brine is to mix the reject water rapidly with the surrounding water.

A desalination plant located at the ocean has practically unlimited access to seawater. Inland desalination plants, on the other hand, can be used for water reuse and drinking water production from used water where traditional sources are inadequate. For inland plants the disposal options must be carefully considered. The primary environmental concern with the disposal of concentrate to surface water, to sewers or by land application, is salt-loading the receiving waters, whether they be surface water or groundwater.

Sometimes it is possible to collect the brine in an evaporation pond. In a hot climate the water in the brine evaporates and the salt can be collected and used for other purposes.

5.3.5 Renewable energy for desalination

The energy required for desalination has three functions: to perform the pre-treatment, supply the high-pressure pump for the RO and overcome the membrane's resistance to the flow of the water. The energy is electrical and can come from a wide range of sources. Desalination based on the use of renewable energy sources can provide a sustainable way to produce fresh water. Currently an estimated 1% of desalinated water comes from energy from renewable sources, mainly in small-scale facilities. But larger plants are starting to add renewables to their energy portfolio.

Typically, the energy requirement for RO of seawater is 3–5 kWh/m^3 (IEA-ETSAP & IRENA, 2013) for the whole process. Some sources say that 1.5–2 kWh/m^3 is achievable to desalinate seawater. The theoretical limit for RO is around 1 kWh/m^3, while the practical limit seems to be around 1.5. For brackish water the energy required is in the range 0.5–2.5 kWh/m^3.

Solar PV and wind power can provide necessary energy, but electric energy storage is an important challenge, considering the intermittent nature of the production (Chapter 10). An important aspect is that excess energy can be stored as produced desalinated water, which can be a cost-effective storage solution when generation exceeds demand.

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Thermal desalination requires both electricity and thermal energy, and – in total – more energy than the membrane process. Seawater desalination via MSF consumes typically 80 kWh/m^3 of heat energy (or 290 mJ/m^3) plus 2.5–3.5 kWh_e/m^3 of electricity (IEA-ETSAP & IRENA, 2013).

Bearing in mind the remarkable cost reduction of renewable technologies, desalination via renewables can already compete with conventional systems in remote regions where the cost of energy transmission and distribution is higher than the cost of off-grid generation. Desalination based on renewable energy is mostly based on the RO process, followed by the thermal MSF process. In existing applications solar PV is the energy source for almost half of the installed capacity, followed by solar thermal and wind. The best combination of renewable energy source and desalination technology will depend on the geographical location, the salinity of the water, the available renewable energy source and plant size. Of course, the requirements to pump and to pre-treat the feedwater are other factors to consider.

The cost for the solar cells is still the largest part of the cost, but batteries for electricity storage should also be considered (see Chapter 10). The batteries need maintenance. Any advances in storage capacity will have a profound impact on solar PV operations. On the other hand, the "fuel" is free, so the renewables will pay off with time, in contrast to diesel or grid electric power.

Solar energy is the most readily applicable source of renewable energy to be integrated with desalination technology. It can produce the heat and electricity required by all desalination processes. Worldwide, various renewable energy sources are used for desalination, as illustrated in Figure 5.2.

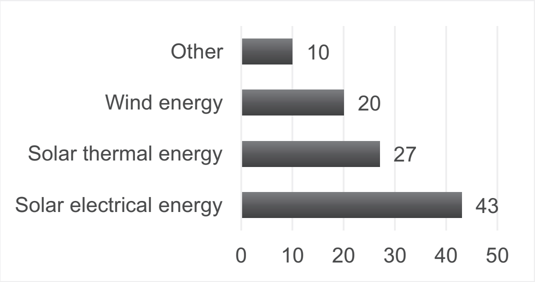

Figure 5.2 Renewable energy sources for desalination worldwide (in %). Data from Alkaisi *et al.* (2017).

Solar PV powered reverse osmosis has been proven commercially viable with significant reduction in production cost. One example is from Abu Dhabi. The levelised cost of large-scale desalination

(>100,000 m^3/day) is 0.91 USD/m^3 (3.3 Emirati dirham AED/m^3), compared to the current average water production cost of 1.42 USD/m^3 (5.16 AED/m^3) (Masdar, 2018).

Energy is the largest variable cost for seawater RO (SWRO) plants, varying from a third to more than half of the cost of produced water. According to Voutchkov (2016) there are no major technology breakthroughs expected in the next few years to dramatically lower the cost of seawater desalination. However, there is a steady reduction of production costs and technology advances. As Table 5.3 demonstrates, the cost will decrease significantly in the next few years.

Table 5.3 Reverse osmosis costs for medium and large best-in-class projects (Voutchkov, 2016).

	Year 2016	**By 2021**	**By 2035**
Cost of water USD/m^3	0.8–1.2	0.6–1.0	0.3–0.5
Electric energy use kWh/m^3	3.5–4.0	2.8–3.2	2.1–2.4

As mentioned, the source of energy, the water source salinity, the plant size and cost of land are factors that will affect the desalination cost. Typical desalination costs can vary from 0.5 to 3 USD/m^3.

Example 5.1: *Required Power for Small-Scale Desalination*

Assume that we wish to produce 1 m^3 of desalinated seawater per day. To be conservative, this will require 8 kWh using RO technology. Assuming that a solar PV-based array can deliver power for six hours, this will require an electric power of 1.3–1.4 kW. In a subtropical or tropical country, a solar array of 2 kW_p would be sufficient to provide this average power during the day.

If the plant were downsized to 0.1 m^3 per day the required power would be 0.2 kW_p.

5.3.6 Operation and maintenance issues

There were some important lessons learnt from early installations of RO desalination powered by renewable energy (Cipollina *et al.*, 2015). Solar PV will only produce electric power in daylight. This has consequences both for the design of the renewable energy source and for the operational life of the membranes (see also Chapter 10).

The main maintenance issues are the cleaning of the solar panels and the difficulty of replacing RO pumps and modules. The most essential operational problems reported are:

- Fouling in membrane modules that requires cleaning or replacement;
- The booster pumps in the RO system (producing the high pressure).

The most common failures reported are electronic device breakdowns and sensor failures.

5.4 DISINFECTION

Disinfection is a key operation in any water supply. Here we emphasise the potential of using UV light as a potentially important and realistic opportunity to meet the challenge of pathogens in the water.

5.4.1 Disinfection technology

Eliminating harmful organisms in the water is essential to protect people's health. In water disinfection pathogenic microorganisms are deactivated or killed. Pathogens cause waterborne diseases such as cholera, polio, typhoid, hepatitis and several other bacterial, viral and parasitic diseases. Naturally it is of the utmost importance to substantially reduce the total number of viable microorganisms in the water.

Disinfection can be achieved by using either physical or chemical disinfectants. The most common physical disinfectants are ultraviolet (UV) light, electronic radiation and heat. Common chemical agents for disinfection are chlorine (Cl_2), chlorine dioxide (ClO_2) and ozone (O_3). In municipal water supply systems chemical inactivation of microbial contamination in the raw water supply is commonly used as one of the last steps to reduce pathogens in drinking water. Traditionally, chlorination is widely used for disinfecting water supplies in most western countries. For small water flow rates (household to village size) the primary treatment methods are ozone, UV radiation and chlorine. Techniques such as filtration may remove infectious organisms from water. However, filtering is no substitute for disinfection.

5.4.2 UV light disinfection

One major advantage of using UV light in remote areas is that it does not require any consumable chemicals. Maintenance is straightforward and there is no risk of overdosing. UV radiation does not leave any residuals in the water. UV light has been used quite extensively for water supply disinfection in small communities. It is one of the few affordable technologies for small-scale water supply that effectively kills most bacteria, viruses and other harmful microorganisms. A UV lamp will imitate sunlight. In nature sunlight will destroy some bacteria, purifying water naturally.

The efficiency of UV disinfection depends on the intensity and the wavelength of the radiation. If the water contains colour or turbidity, then the exposure of the microorganisms will decrease, and the disinfection becomes less efficient. This is of course a disadvantage. Therefore, some pre-filtering before UV radiation may be needed. Another problem is that there is no simple test of the disinfection result.

Disinfection with UV is usually done so that the water is passing though transparent pipes. It is sufficient to have a contact time of a few seconds. A UV dose (energy) is normally expressed in $mJ/cm^2 = mWs/cm^2$, the product of the UV intensity in mW/cm^2 and the contact time. A common dose is 20–40 mWs/cm^2 (EPA, 2011) to inactivate most waterborne pathogenic bacteria. The Department of Health and Human Services (U.S.) has established a minimum exposure of 16 mWs/cm^2 for UV disinfection systems. Most manufacturers provide a lamp intensity of 30–50 mWs/cm^2. In general, coliform bacteria, for example, are destroyed at 7 mWs/cm^2 (Oram, 2014).

The usual wavelength is 254 *nm*. A typical low-pressure UV lamp has a power rating of 40–85 *W* and will last for about 12,000 hours (15 months). It has an operating temperature of about 40°C (*ibid.*).

Typical power requirement to disinfect water with UV light is 10–20 $W/m^3 \cdot h$. For example, assume that we need to disinfect 1 m^3 of water, which is produced during six hours of sunlight. With a flow rate of 1/6 m^3/hour this will require a UV light power source of 1.7–3.4 *W*, a very small amount of power compared to the requirement for desalination.

The cost of a UV disinfection system is much lower than ozonation and membrane filtering. For ozonation the capital cost is roughly five times higher and the operating costs three times higher. Membrane filtration has a capital cost around ten times higher and an operating cost eight times higher (*ibid.*). Using RO technology is the best method to purify the water, since these membranes can remove all particles down to small molecules, but it comes at a price.

5.5 FURTHER READING

There is a lot of literature on desalination. For the non-specialist there is a good description of desalination and disinfection in Varadi *et al.* (2018) Chapter 5.3. Burn and Gray (2014) present a comprehensive description and analysis of reverse osmosis.

The American Membrane Technology Association (AMTA) has produced several easy-to-read fact sheets concerning RO membranes, filtration and desalination, including planning, operation and maintenance (AMTA, 2018).

The book Liehr *et al.* (2018) documents an ambitious decade-long project in Namibia. The book records experiences of rainwater and floodwater harvesting, groundwater desalination, sanitation and water reuse. Not only technology solutions but also social aspects, management and governance issues, economic viability and sustainability evaluation are described.

Bazargan (2018) presents a broad introduction to and overview of desalination and covers both technical and non-technical issues.

Drioli *et al.* (2011) describe the basics of RO and desalination. Bundschuh and Hoinkis (2012) discuss the applicability of renewable energy for fresh-water production, the various barriers and how to overcome them. Mahmoudi *et al.* (2017) present a comprehensive report on renewable energy and desalination. Shatat *et al.* (2013) review the global opportunities for solar desalination.