Chapter 28. Desalinization

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1. Introduction

Desalinization of seawater is an essential process for the support of human communities in many places around the world. Seawater has a salt content of around 35,000 parts per million (ppm) depending on the location and circumstances: to produce the equivalent of freshwater (with around 1000 ppm (AMS, 2014) therefore requires the removal of over 97 per cent of the salt content. The main purpose of desalinization is to produce water for drinking, sanitation and irrigation. The process can also be used to generate ultra-pure water for certain industrial processes. This chapter reviews the scale of desalinization, the processes involved and its social and economic benefits. Issues relating to discharges from desalinization plants are considered in Chapter 20 (Coastal, riverine and atmospheric inputs from land).

2. Nature, location and magnitude of desalinization

As figure 1 shows, desalinization capacity has grown rapidly over the past half-century. About 16,000 desalinization plants were built worldwide between 1965 and 2011. About 3,800 of these plants are thought to be currently out of service or decommissioned. The current operational capacity is estimated to be about 65,200 megalitres per day (65,200,000 cubic metres per day (m^3/d) – in comparison, the public water supply of New York City, United States of America, delivers in total about 3,800 megalitres per day) (GWI, 2015; NYCEP, 2014).

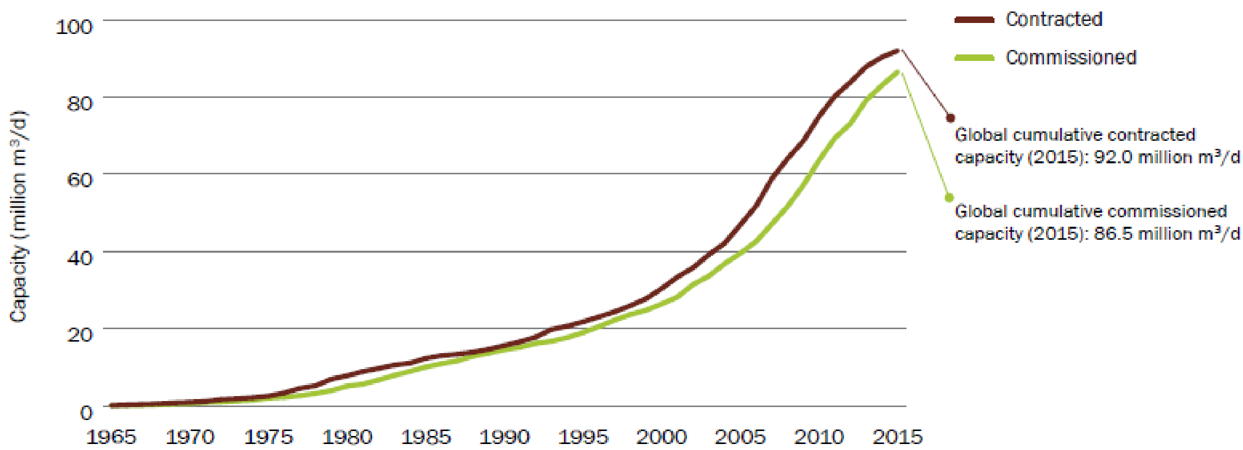
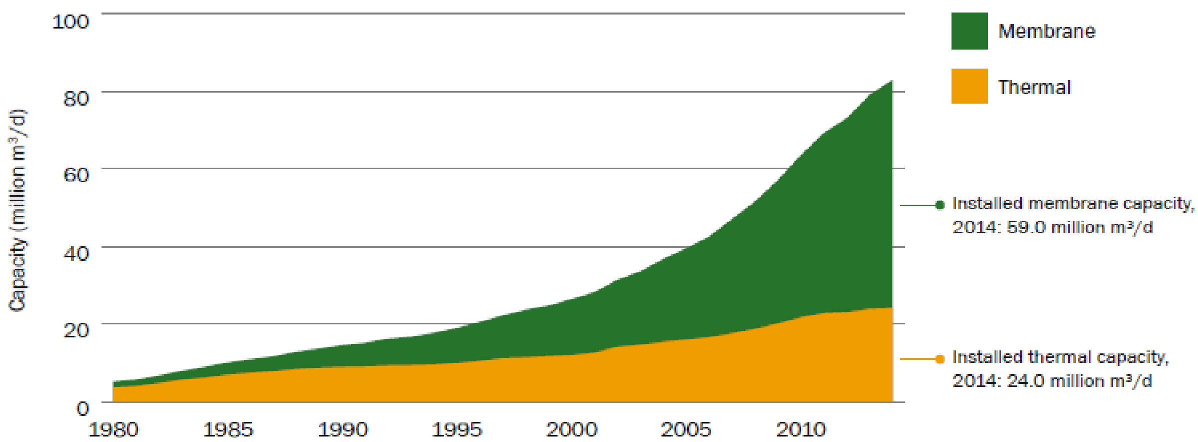


Figure 1. Global desalinization capacity 1965 – 2015. Source: GWI, 2015. "Contracted" covers plant that is complete or under construction; "commissioned" covers plant that is in operation or is available for operation.

Historically, human settlements have tended to grow up where freshwater was available, and their growth has been conditioned by freshwater availability and the possibilities of bringing it to serve the settlement. As long ago as 312 BCE, the Romans had had to build a 16.4-kilometre aqueduct to bring water to Rome in order to avoid this constraint (Frontinus). Desalinization represents an alternative technology for avoiding this constraint on the growth of human settlements in areas with very limited availability of freshwater. That capability, however, comes at the price of considerable capital investment and energy consumption. Gleick et al. (2009) give an overview of the worldwide distribution of desalinization capacity in 2009.

The nature of the industry, however, varies in many ways between the different regions, particularly in respect of the technology used: the Middle East has relied more on thermal processes, while the United States has relied more on membrane processes. Thermal processes (mainly Multi-Stage-Flash (MSF) and Multiple-Effect-Distillation (MED)) evaporate the water and then re-condense it. At peak performance these distillation processes produce a freshwater output of about 30-40 per cent of the seawater taken in. The residue has to be discharged as brine. Membrane-based processes (such as reverse osmosis (RO), electro-de-ionization (EDI) and electro-dialysis (ED)) force feed-water through a semi-permeable membrane that blocks various particulates and dissolved ions, leaving the feed-water behind as an enhanced brine, with or without further refinements. (Details of these processes can be found in WHO, 2007 and in GCC, 2014). The energy needed for all forms of desalinization is usually obtained from fossil fuels. However, combined plants for nuclear power generation and water desalinization have been developed in a number of places (for example, Argentina, India, Japan and Pakistan), and the International Atomic Energy Agency has conducted studies on how far this might be developed (IAEA, 2007). At present, very little desalinization is powered by solar energy.

One estimate puts it as low as 1 per cent (Kalogirou, 2009). Projects are emerging, however, to develop this form of desalinization. For example, in Abu Dhabi, United Arab Emirates, the Environment Agency completed 22 small (25 m^3/day) solar desalinization plants for brackish groundwater in 2012 (The National, 2012). In Chile, Fundación Chile started a small pilot project partly powered by solar energy in Arica in 2013 (Arica, 2013).



Figures 2. Proportion of thermal and membrane technologies installed 1980 – 2014. Source: GWI, 2015.

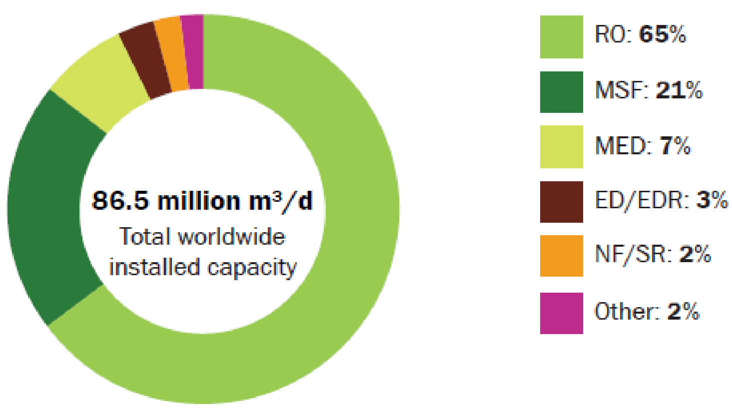


Figure 3. Proportion of different technologies in use 2014. RO: Reverse Osmosis; MSF: Multi-stage flash; MED: Multi-effect distillation; ED/EDR: Electrodialysis/Electrodialysis Reversal; NF/SR: Nanofiltration/Sulfate Removal. Source: GWI, 2015.

Many countries have installed major amounts of desalinization capacity over the past 70 years: the largest amounts of capacity have been installed in Saudi Arabia (capable of producing over 10 million m^3 per day), the United States of America (over 8 million m^3 per day (but see below), the United Arab Emirates (about 7 million m^3 per day) and Spain (about 5 million m^3 per day). . More recently, Algeria, Australia, India and Israel also substantially increased their capacities (GWI, 2014).

2.1 The Persian Gulf area

The Persian Gulf area has the biggest concentration of installed desalinization capacity in the world. In total, the desalinization capacity of the area is around 9.2 million megalitres a year. Ninety-six per cent of this capacity is located in the six countries that form the Gulf Cooperation Council (GCC - Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates).

2.2 The GCC States

These six States have a common approach to desalinization. They are located in an arid, hot desert region, characterized by an average rainfall ranging between 75 and 140 mm a year and by limited, non-renewable groundwater resources. Surface freshwater resources comprise only 0.6 per cent of their total area. Natural freshwater resources range from 60 to 370 cubic meters a year per head across the GCC countries (World Bank, 2005). The resources *per capita* are expected to decrease in the future by up to 20 per cent, due largely to population growth. The total GCC population in 2012 was 44,643,654, of which Saudi Arabia constituted 62 per cent. This population is increasing at an average rate of 14 per cent annually. The discovery of oil and gas resulted in the GCC countries being the world's top fossil-fuel exporters with the highest *per capita* incomes and the fastest-growing economies in the world, which underlies the population growth. From 1998 to 2008, real GDP for GCC countries grew at an average rate of 5.2 per cent annually.

Bridging the gap between demand for, and supply of, freshwater has remained a major issue. To meet the need for freshwater, desalinization of seawater has been one of the main water-supply alternatives that the GCC countries have adopted. Desalinization has become the backbone of many GCC States. For example, Qatar draws as much as 99 per cent of its drinking water from this source. In Saudi Arabia, 50 per cent of municipal water supplies are obtained from desalinization: in 2012 this represented deliveries of 955,000 megalitres per year (SWCC, 2014). The total desalinization capacity installed in the GCC States in 2012 for water production was 8.9 million megalitres a year. This production capacity was divided: Saudi Arabia (KSA) 39 per cent, United Arab Emirates (UAE) 18 per cent, Kuwait 18 per cent, Qatar 15 per cent, Bahrain 6 per cent, and Oman 4 per cent (GCC, 2012). This is shown in Figure 4.

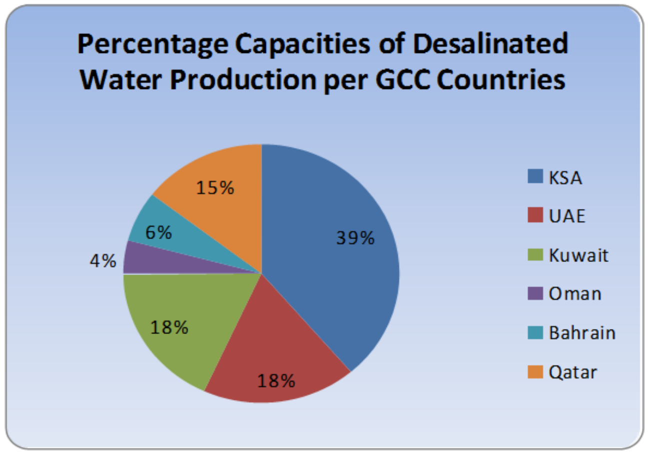


Figure 4. Desalinization capacity in the GCC States, 2012. Source GCC, 2012.

The practice of desalinization in the GCC States is heavily influenced by the high local level of electricity consumption, which is largely due to the demand for air-conditioning and cooling, necessary in the hot desert climate, and to the energy-intensive petro-chemical industries. The demand for electricity and water is also influenced by the pricing policy. Water and electricity subsidies are a commonplace practice among the GCC countries. The shared rationale behind energy and water subsidization includes: cultural considerations, expanding access to energy and water, protecting the poor, consumption smoothing, fostering industrial development, avoiding inflationary pressures, and political considerations. The result of the lower prices is to increase demand for both electricity and water. However, there is widespread recognition of the harmful effects caused by the current water and electricity tariff rates (Saif, 2012).

The high level of use of thermal technologies for desalinization in the GCC States is mainly due to the predominant method of electricity generation, which is through gas-fired power plants. A by-product of the electricity generation process is steam, which can be utilized by MSF and MED thermal desalinization plants for their energy needs. The two plants need to be co-located in order for the desalinization plant to capitalize on the power stations' by-product of steam. This co-location of power and plants is referred to as co-generation. Roughly 60 per cent of the MSF plants in the United Arab Emirates are co-generation, while that percentage stands at 70 per cent in Qatar. The quality of the water available for desalinization also plays a role. It has the 4 Hs: high salinity, high turbidity, high temperature and high marine life. These factors have in the past made it less suitable for membrane technology (Al Hashemi et al. 2014).

The thermal technology most used in the GCC States is the MSF, which is characterized by a high consumption of energy. Reverse osmosis (RO) is the next most used, and the least used is MED: see figure 5. The GCC States constitute around 88 per cent of the world's use of desalinization by thermal processes.

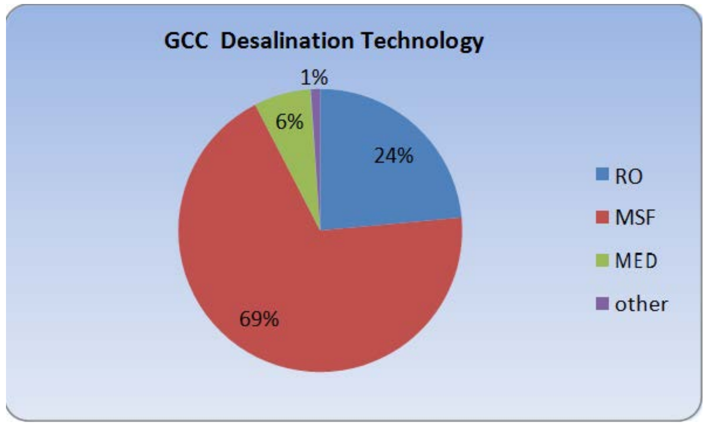


Figure 5. Use of the different Desalinization Technologies in GCC States. Source: GCC, 2012.

Although this was the balance between thermal and membrane technologies in the GCC States in 2012, the situation is changing quickly, because the GCC States will in future be adopting more RO projects, as a step towards minimizing energy consumption and decreasing environmental impacts. Most of the desalinization plants under construction in 2012 were RO or combined RO/MSF, and the balance is expected to change even more in the future (GCC, 2012).

The GCC States are continuing to invest heavily in their water and energy sectors as shown by many independent water and power plant (IWPP) projects. For example, in 2009, Qatar initiated a 30-year water and electricity master plan that will see major investments in desalinization, water infrastructure and wastewater treatment (GWI, 2015). Between 2010 and 2015, Qatar plans to invest approximately 5,470 million United States dollars in desalinization projects, with an additional 1,100 million dollars investment in IWPP production facilities between 2013 and 2017. Likewise, the UAE plans to invest 13,890 million dollars in new desalinization plants and distribution networks between 2012 and 2016.

Generally, this investment in further desalinization is counterbalanced by a new interest in adopting an integrated water policy that uses wastewater and drainage water as a valuable source of water and to augment the water supply by enforcing recycling and re-use in agricultural and industrial activities. To this are added an interest in increasing water storage, particularly through groundwater recharge, and attempts to educate the public on the need for water conservation (Darwish and Mohtara, 2013; Al Hashemi et al. 2014). For example, Qatar has also created a National Food Security Program (QNFSP), with a mandate to manage water resources efficiently in agriculture and food production through the use of technologies to minimize water consumption. As well as supplying the agricultural sector with freshwater, a core objective of the QNFSP is to use the solar desalinization of water to replenish the country's aquifers (QNFSP, 2012). Similarly, Abu Dhabi, United Arab Emirates, has already invested to increase water storage capacity (EAD, 2009).

2.3 Other States in the Persian Gulf area

The other States in the Persian Gulf area (the Islamic Republic of Iran and Iraq) make significantly less use of desalinization than the GCC States, although it still plays a part in their water supply arrangements.

It is assumed that the Islamic Republic of Iran has a desalinization capacity of about 400 megalitres per day (this is about 4.5 per cent of that installed in the GCC States). In terms of technology, the Islamic Republic of Iran's existing desalinization plants use a mix of thermal processes and RO. MSF is the most widely used thermal technology, although MED and vapour compression (VC) also feature (GWI, 2014).

Although Iraq is believed to have about the same amount of installed desalinization capacity as the Islamic Republic of Iran (Iraq is reported to have a capacity of 430 megalitres per day), it is used in a quite different way. Much of the water of the Euphrates and Tigris Rivers has a salinity above 1,000 parts per million. The Iraqi authorities therefore use desalinization mainly to improve the poor quality of the river water, and only undertake a modest amount of seawater desalinization (ESCWA, 2009).

2.4 United States of America

Outside the Persian Gulf area, the United States has the largest installed desalinization capacity in the world. This is concentrated in California, Florida and Texas. However, desalinization of seawater is only a small part of the desalinization carried out in the United States. In 2010, seawater desalinization represented only 10 per cent of the desalinization capacity – 82 per cent was for brackish-water desalinization (largely from brackish groundwater, but also from rivers) and 8 per cent for waste-water re-use (Shea, 2010).

In California, however, the situation is changing. In November 2002, California voters adopted by the initiative procedure (by-passing the State legislature) Proposition 50, the “Water Security, Clean Drinking Water, Coastal and Beach Protection Act, 2002”. This legislation allocated the sum of 50 million dollars for grants for brackish-water and ocean-water desalinization projects. This grant programme - administered by the State Department of Water Resources - aimed to assist local public agencies to develop new local water supplies through the construction of brackish water and ocean water desalinization projects and help advance water desalinization technology. Two rounds of funding were conducted in 2004 – 2006. A third funding round announced eight further grants in August 2014, totalling nearly 9 million dollars for a mix of plant construction, pilot projects and research (DWR, 2014).

Statistics on desalinization in California show that there are 10 seawater desalinization plants in California, with a daily capacity of about 23 megalitres. Not all these plants are in regular operation, but are used only when other water supplies need to be supplemented. Currently, there are proposals for a further 15 seawater desalinization plants. If all these plants were built, they would have capacity to provide some 946 – 1,400 megalitres per day

– about 5 - 7 per cent of California's water demand in the early 2000s. One of these projects (Carlsbad) is expected to become operational in 2016 and will then be the largest seawater-desalinization plant in the United States, capable of delivering 190 megalitres per day of drinkable water (SWRCB, 2015).

3. Other countries with large desalinization capacities

A review of the countries other than those in the ROPME/RECOFI area[1] and the United States that have recently installed major desalinization capacitiesshows the following picture.

3.1 Algeria

Algeria is invested heavily in seawater desalinization capacity during the 2000s. By 2013, ten major plants had been put into service, with a capacity of 1,410 megalitres per day. In addition, 21 smaller plants with an aggregate capacity of 60 megalitres per day have been created. Further plants, with a further aggregate capacity of 850 megalitres per day, are expected to come into service in the near future, including that at Al Mactaa (500 megalitres per day), which will be one of the largest in the world (ADE, 2014)

3.2 Australia

At the start of the 2000s, the only operational seawater desalinization plants in Australia were on small islands. A prolonged drought in the middle of the 2000s, affecting most of the most heavily populated areas, led in 2007 to the creation of a National Urban Water and Desalination Plan, estimated to cost 840 million dollars, together with a National Centre of Excellence in Desalination, based in Perth, Western Australia. Desalinization is one of the options to be regularly considered under this plan. A major desalinization plant, with a capacity of 144 megalitres per day, has been in operation near Perth since 2006. Another major desalinization plant was built, partly financed by this plan, at a cost of 1,500 million dollars, for the city of Adelaide, South Australia, with a capacity of 280 megalitres per day. This is said to give the city a climate-independent source of water. In the light of the operating costs and the recovery of the local river system, the plant has, however, been placed on stand-by (ANAO, 2013). Similarly, major desalinization plants have been built to service Brisbane, Melbourne and Sydney, but have been placed in stand-by because of the recovery of other sources of supply (BT, 2010; ABC, 2012; SDP, 2015).

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[1] Regional Organization for the Protection of the Marine Environment (ROPME) Members: Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Regional Commission for Fisheries (RECOFI) Members: Bahrain, Iran (Islamic Rep. of), Iraq, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates.

3.3 China

In 2012, the Chinese National Development and Reform Commission (NDRC) said that, under a first plan covering 2011-2015, China aims by 2015 to produce 2,200 megalitres per day of freshwater from desalinization. This compares with 660 megalitres per day in 2011. The NDRC said it will encourage innovation and upgrade desalinization facilities, as well as cultivate a number of desalinization facility manufacturers with international competitiveness. The NRDC will also encourage the use of desalinated seawater. More than half of freshwater provided in the islands of China, and more than 15 per cent of water delivered to coastal factories, is to come from the sea by 2015, according to the plan (PD (E), 2012).

3.4 Israel

Israel relies substantially on desalinization of seawater for its water supply. In 2008, desalinization represented 17 per cent (383 megalitres per day) of its water supply. By 2013, this was expected to rise to 32 per cent (4,950 megalitres per day) of the supply (Tenne, 2011).

3.5 Japan

Although Japan has relatively limited natural freshwater resources (it has about half the world average of natural freshwater resources per head), desalinization has not so far played a major role in meeting general demand for water: a 2006 World Bank review of water management in Japan does not mention desalinization (World Bank, 2006). The main focus in Japan on desalinization has been in providing suitable cooling water for nuclear power plants – at least 10 such plants have associated desalinization plants (IAEA, 2002). Nevertheless, desalinization is used locally to supplement natural freshwater supplies for domestic and industrial use. For example, the authorities on Okinawa, the main island of the Ryukyu archipelago, installed in 1997 a desalinization plant with a capacity of 40 megalitres per day (about 10 per cent of the island's daily demand for water) (Yamazato, 2006), and the city of Fukuoka on the southern Japanese island of Kyushu, after some major water shortages, installed in 2005 a desalinization plant capable of supplying 50 megalitres per day (Shimokawa, 2008).

3.6 Spain

Spain has long had difficulties in providing adequate water supplies in some parts of the country. This is particularly the case along the Mediterranean coast, which has undergone massive development for tourism. In 2001, the Spanish authorities adopted legislation for a National Hydrological Plan. Among other things, this legislation declared a substantial number of desalinization plants as projects being in the public interest (Spain, 2001). In 2005, this National Hydrological Plan was amended, and a new list of projects along the Mediterranean coastline was added, which the Ministry of the Environment and its associated bodies were to implement as a matter of urgency. This list included about 20 desalinization projects (Spain, 2005). The desalinization component of the Plan is reported to have had an estimated cost of about 3,000 million dollars. By 2013, 27 of the 51 approved plants had been built at a cost of about 2,200 million dollars. However, the economic recession starting in 2008 is reported to have reduced the demand for water to such an extent that many of the plants are standing idle or working at well below their planned capacity (Cala, 2013).

3.7 Other States

Many small islands have very limited natural freshwater resources, and have decided to supplement these with desalinization. In the Caribbean, the following use desalinization: Antigua and Barbuda, Aruba (the Netherlands), the Cayman Islands (United Kingdom of Great Britain and Northern Ireland), Curaçao (the Netherlands), Cuba and Trinidad and Tobago (Scalley, 2012; CWCL, 2015). Elsewhere, Malta (46 megalitres per day, 57 per cent of supply; (NSO, 2014)) and Singapore (capacity of 455 megalitres per day, 25 per cent of supply; (PUB, 2014)) are examples of island States which derive high proportions of their public water supplies from desalinization.

In temperate zones, where natural freshwater supplies are usually adequate, authorities in some places are creating desalinization plants as an insurance against long droughts and other disruptions of supply. For example, Thames Water in the United Kingdom has built a plant on the Thames estuary with a capacity of 150 megalitres per day (WTN, 2014).

In Chile, the northern provinces are some of the most arid areas in the world, yet it is here that the main minerals deposits are found that enabled mining to contribute 12.1 per cent of Chilean GDP in 2013 (BdeC, 2014). Since the extraction of metals from ore requires substantial quantities of water, there is a growing pressure in these northern provinces on freshwater resources. Many mines rely on freshwater from local rivers, but such abstractions (also called withdrawals) compete with growing demand from the local population. Some mines use seawater, but this imposes extra costs of safeguards against the corrosion that seawater causes. More recently, some mines have installed desalinization plants to provide them with freshwater. There has been debate in the Chilean Chamber of Deputies about making the use of desalinized water compulsory if freshwater is to be used (Moreno et al., 2011; CdD, 2013). It seems likely that further desalinization plants will be constructed.

4. Social and economic aspects of desalinization

Freshwater is essential to all life on land. Yet 97 per cent of all the water on earth is in the ocean (USGS, 2014). According to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014), about 80 per cent of the world's population already suffers serious threats to its water security, as measured by indicators including water availability, water demand,

and pollution.

As the description of the nature, location and magnitude of desalinization shows, there are parts of the world where desalinization is essential to human populations at present, or greater, levels. The largest area of this kind is the six GCC States, but island States, such as Malta and Singapore, are also in this category. Such States are likely to continue to generate significant growth in population over the coming years, together with the associated economic development. The only source of additional freshwater for such growing populations is likely to remain desalinization.

Climate change is likely to add to the number of States that will wish to explore the use of desalinization. The IPCC Fifth Report (IPCC, 2014) concludes that:

(a) The spatial distribution of the impacts of climate change on freshwater resource availability varies considerably between climate models, and depends strongly on the projected pattern of rainfall change. There is strong consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projections for south and East Asia;

(b) Some water-stressed areas are likely to see increased runoff in the future, and therefore less exposure to water resources stress;

(c) Over the next few decades, and for increases in global mean temperature of less than around 2°C above preindustrial levels, changes in population will generally have a greater effect on changes in the freshwater available per head than will climate change. Climate change would, however, regionally exacerbate or offset the effects of population pressures;

(d) Estimates of future water availability are sensitive not only to climate and population projections and assumptions on usage per head, but also to the choice of hydrological impact model and to the measure of stress or scarcity that is adopted.

As an indication of the potential magnitude of the impact of climate change, one estimate quoted by the IPCC forecasts that

(a) A 1°C rise in global mean temperature (compared to the 1990s) will meant that about 8 per cent of the global population will see a severe reduction in water resources (that is, a reduction in runoff either greater than 20 per cent or more than the standard deviation of current annual runoff);

(b) A 2°C rise (on the same basis) will increase that proportion to 14 per cent; and

(c) A 3°C rise (on the same basis) will increase that proportion to 17 per cent.

The spread across climate and hydrological models was, however, large. The IPCC report includes desalinization as one of the range of adaptive measures that may prove particularly effective but notes that desalinization will increase green-house gas emissions to the extent that it relies on fossil fuel for its energy requirements.

It therefore seems likely that desalinization will increasingly be considered as a future adaptation measure for communities suffering increased water stress. Given that;

(a) Desalinization is, at least at present, significantly more expensive than most other forms of water supply when other options are available, and

(b) Most current forms of desalinization are using fossil fuels as an energy source, it is more likely that, outside areas where adequate alternative sources of water are simply not available, desalinization plants will be built as a fall-back provision, rather than as a primary source of freshwater.

5. Environmental impacts of desalinization

A major environmental impact of the majority of the present desalinization plants is the emission of greenhouse gases to generate the required energy. In some cases, especially in the GCC States, this is to some extent reduced through co-generation, by which the waste heat from electricity generation is used to desalinate water, without further major demands for energy. In those States, some 60 – 70 per cent of desalinization is done in this way. Where solar or nuclear energy can be used to power the desalinization, this impact is reduced or eliminated.

The other main forms of environmental impact arise from the intake of feedwater and the discharge of brine. The discharges are discussed in Chapter 20. Intake pipes create a risk to marine biota. The risk is highly variable, and is dependent on the technology employed for the seawater intake. In particular, it depends on how far the intake pipe is from the shore, as well as how the intake pipes are located with reference to the water column or the seabed. Biota living in the vicinity of a desalination plant's intake pipe can collide with, or be held against, the intake screens (impingement), or be sucked in with the feedwater into the plant (entrainment). Careful planning of the intake arrangements for each desalinization plant is needed to minimize this form of impact. For example, the intake arrangement Fukuoka in Japan has the intake pipes buried in a sandy seabed, which acts as a form of sand-filter to prevent non-microscopic biota entering the pipes (Shimokawa, 2008). However, such an arrangement can require substantial disruption of the seabed during construction and also lead to maintenance problems.

6. Significant environmental, social and economic aspects, knowledge gaps and capacity-building gaps

Desalinization has become essential to the functioning of many communities around the world. This is most evident in the GCC States and a number of small island States and territories. The impacts of climate change on freshwater supply are likely to increase the usefulness of desalinization as one of the effective forms of adaptation to these impacts, at least as a fall-back provision for periods when natural freshwater supplies are deficient.

There are many commercial firms specializing in the design and construction of desalinization plants. The technology is therefore available on the market. States and communities, however, need to have the capacities to negotiate in this market and to obtain the technologies that they need at a fair price.

In several cases, desalinization plants have been built which have proved to be inefficient or too large for the eventual requirement. There is therefore a case for more efficient sharing of knowledge on the planning, construction and operation of these plants.

Given their continuing importance, the need exists for better knowledge of how to operate desalinization plants with the lowest possible inputs of energy. Considerable progress seems to be possible in this direction: Malta, for example, reports having reduced the energy demand for its desalinization by 33 per cent in a decade (NSO, 2014).

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