Ecole Normale Supérieure

CERES-ERTI Centre d'Enseignement et de Recherches sur l'Environnement et la Société
Environmental Research and Teaching Institute

ATELIER *L'EAU Qualité vs Quantité*

1er semestre - Année 2012-2013

Seawater desalination : technical, environmental and social aspects

Alexandre PELUFFO, Yulia NEGER

24 rue Lhomond 75005 Paris
www.environnement.ens.fr

Contents

1

Why desalinate water ?

1.1 Freshwater resources and availability

Water is the keystone to life as we know it. Every single living cell requires water in order for all the chemical reactions that characterizes the cell's living state to take place(Berg, Tymoczko, and Stryer 2012). For this reason the presence of water is considered to be the main condition for the presence of life[1]. Because of the critical role water plays in life processes and more generally in our way of life, water is a primary resource and the key to the building and functioning of any human society. However its availability on the globe is extremely heterogenous in space and time (WHO/UNICEF 2003) and very little of the very abundant ingredient of our blue planet is in a consumable form (Cf. figure 1.1).

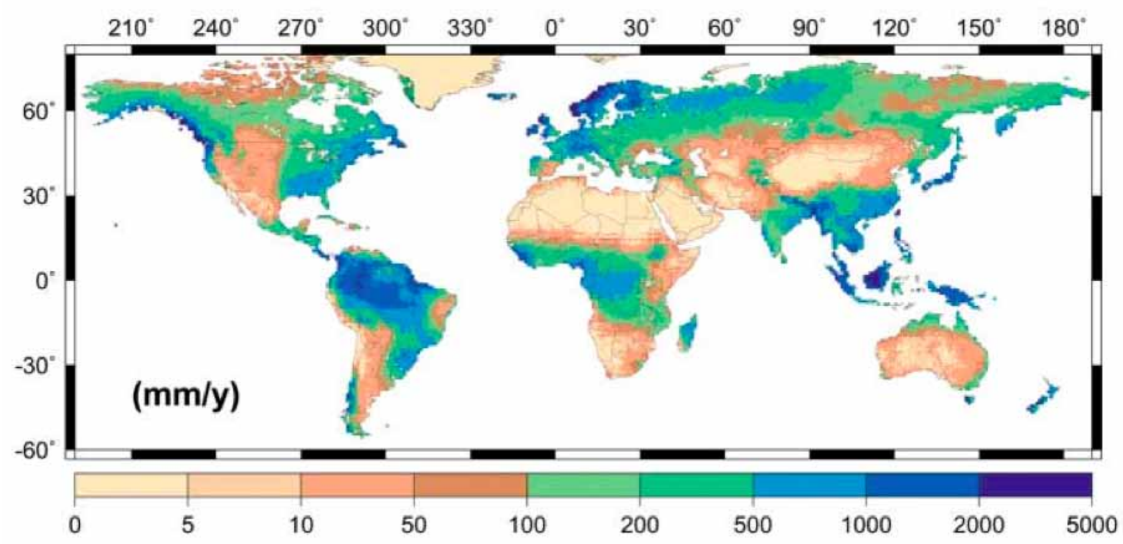


Figure 1.1: **Annual water runoff in mm/year** | from Oki and Kanae (2006)

Water's distribution is as heterogenous as human population distribution, however these two distribution do not overlap(Kummu et al. 2010; Oki and Kanae 2006). As a result many populations experience physical water scarcity[2]. Today it is a fact that 1.2 billion people lack access to safe drinking water (Montgomery and Elimelech 2007) and many of these people are included in the 2.4 billion people which live in costal areas (Schiffler 2004)[3].

A physical lack of water may be the result of natural process that have started before the colonization by man such as the lack of rainfall in a particular region or soil dynamics (Oki and Kanae 2006; Kummu et al. 2010). However, physical water scarcity in a particular region may be caused by demand driven factors,

---

[1] Who hasn't heard of the Mars mission looking for water as an indicator to the presence of life

[2] Defined as a situation where water availability in a country or in a region is below 1000 m^3 per person per year (Pereira, Cordery, and Iacovides 2009)

[3] Costal areas are defined by the World Resources Institute as areas up to 100 km from the sea

that is when the demand exceeds the water flow available in that particular region (Kummu et al. 2010). Man made water scarcity may be the result of desertification (caused by man's impact on vegetation) and/or inappropriate water management methods (Pereira, Cordery, and Iacovides 2009). It is important to point out that water demand concerns mainly water flows and not water stocks and that lack of physical water in a particular region should be centered on the available water flow rather than the stock (Oki and Kanae 2006), for this reason water management decision that do not take into consideration such aspects may lead a region to water scarcity. Demand driven water scarcity may be caused by many factors. Figure 1.2 shows the contribution of human activities to the global water footprint[4]. We can see that the main activities impacting water resources are agriculture and industrial use (Kummu et al. 2010; Hoekstra and Chapagain 2006; Pereira, Cordery, and Iacovides 2009).

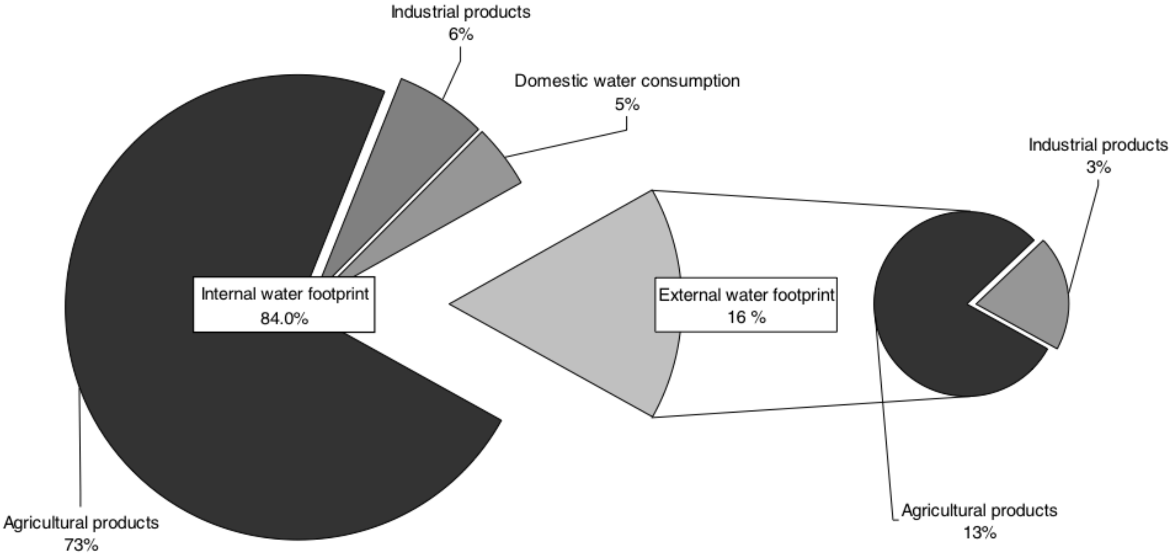


Figure 1.2: **Contribution of the different human activities to the global water footprint** | Internal water footprint is the water footprint that result from the freshwater use inside a country and external water footprint the water that is used outside to produce the goods utilized by that country (from Hoekstra and Chapagain (2006))

Beyond the physical lack of water, another type of water scarcity which is termed social water scarcity may impact human societies. In contrast with the notion of physical water scarcity which embraces the quantitative aspects, social water scarcity includes the idea that water may be lacking not because it is not available, but because it is in a form that is not usable (particularly because of pollution and contamination by pathogens) and the population living close to that source of water does not have the necessary financial, technical and geopolitical resources to mobilize it and/or to cope with a water shortage situation (Ohlsson and Turton 1999). An example of social water scarcity is Bangladesh, which receives an important amount of freshwater annually and has underground water resources. However the spatial and temporal distribution of freshwater is very heterogenous and the country lacks the financial and technical resources that are needed to have access to this water (Rahman 2005). Moreover many of the country's groundwater and river are polluted and their drainage basin are under the control of other surrounding countries, which demonstrates the role that geopolitical relationships can play in social water scarcity (Rahman 2005). In contrast, countries such as Saudi Arabia and Qatar experience severe physical water scarcity. However due to their high income resulting from oil transactions, these countries can afford the technology to desalinate and distribute water, therefore avoiding water scarcity (Dawoud 2005).

Besides the lack of water to drink, the problems caused by water scarcity can be very important and very broad (Pereira, Cordery, and Iacovides 2009). As mentioned previously, agriculture is the primary caused of water scarcity and therefore may be the primary activity to suffer from it. Industrial and tourism development are also primary consumer of water and therefore can be the cause and the victim of water scarcity (Pereira, Cordery, and Iacovides 2009). Countries experiencing water scarcity may also be affected by many

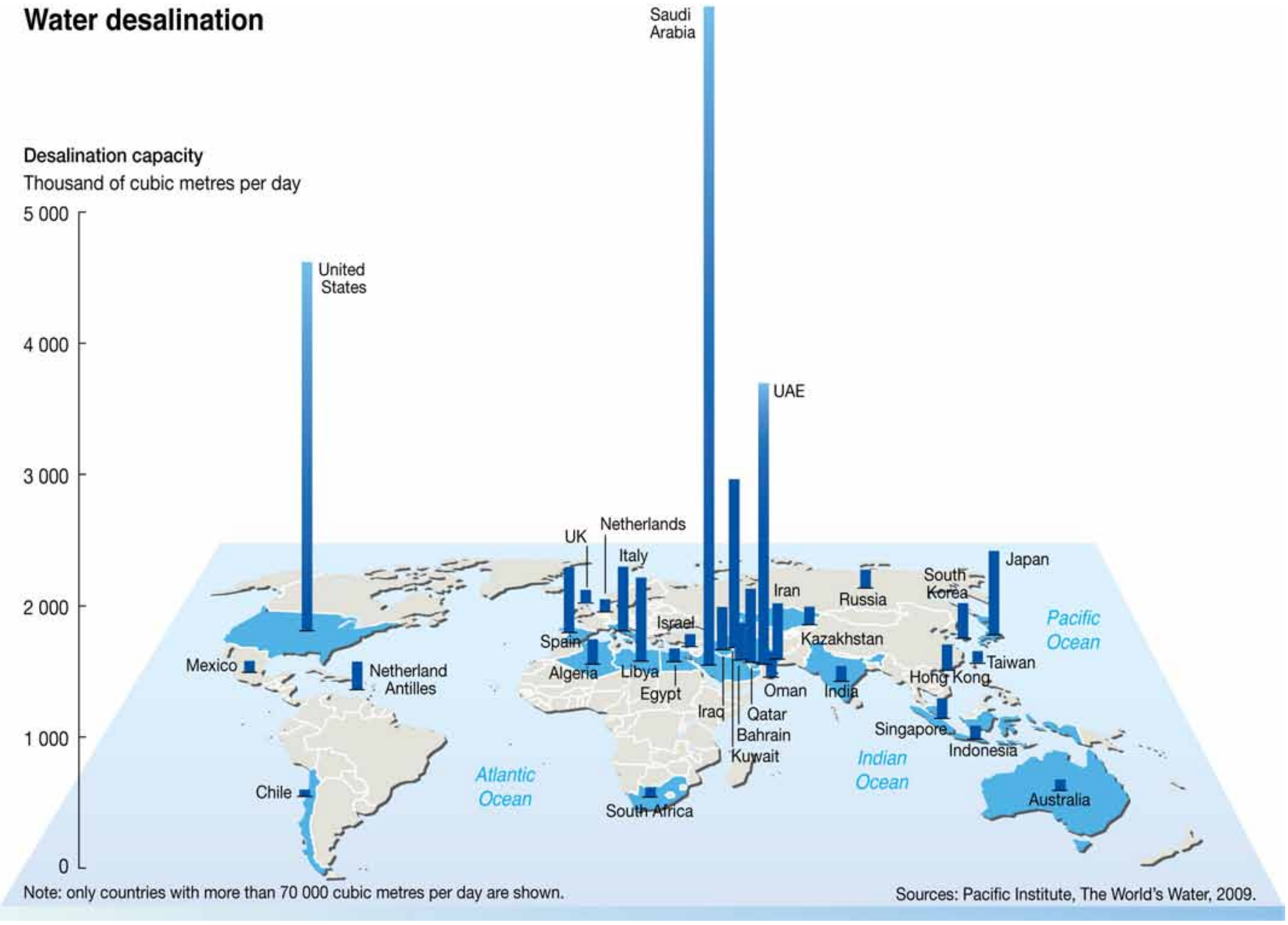
---

[4] Water footprint of a country is defined as the total volume of freshwater that is used to produce the goods and services consumed by the people of the country from(Hoekstra and Chapagain 2006)

health problems that can be the direct result of scarcity, such as water contamination (Ohlsson and Turton 1999). But health problems may also be the result of malnutrition and hunger that are due to lack of water to produce food (Pereira, Cordery, and Iacovides 2009; Ohlsson and Turton 1999). Finally ecosystems services may also be impacted and are generally the last priority on the list of water managers (Pereira, Cordery, and Iacovides 2009).

1.2 Desalination to face water scarcity

As mentioned previously, water utilization depends on water cycles (Oki and Kanae 2006). To cope with water scarcity many approaches have been used to limit the stress on water cycles and flows. As pointed out by Schiffler (2004) the World Bank emphasized that easy and cheap options to cope with water scarcity have already been exploited (Pereira, Cordery, and Iacovides 2009; Boutkan and Stikker 2004). For countries that have access to seawater (which represents 97% of the globe's water (Oki and Kanae 2006)), desalination, that is the removal of salt (mainly NaCl) from water, allows for access to an almost unlimited supply of water (Elimelech and Phillip 2011) and has been widely used by many countries (Figure 1.3). However, other aspects may limit this approach, such as the direct impact on ecosystems caused by desalination plant and the indirect impact, through the high use of energy, of desalination on social and ecological systems (Elimelech and Phillip 2011). To better understand the components of this global issue we present here a brief review of the technical, environmental and social aspects of desalination and propose new solutions from biology.



Note: only countries with more than 70 000 cubic metres per day are shown.

Sources: Pacific Institute, The World's Water, 2009.

Figure 1.3: **Desalination capacity around the world** | In 10^3 m^3/day. Shown for the countries that have a desalination capacity above 70 000 m^3/day. From Corcoran et al. (2010)

2

Desalination Methods - Principles and Limits

According to the Global Water Intelligence database, approximately 130 countries around the world use various desalination techniques to extract fresh water from salty water (most commonly brackish or sea water) (Cooley, Gleick, and Wolff 2006). We will review the most common methods in this chapter.

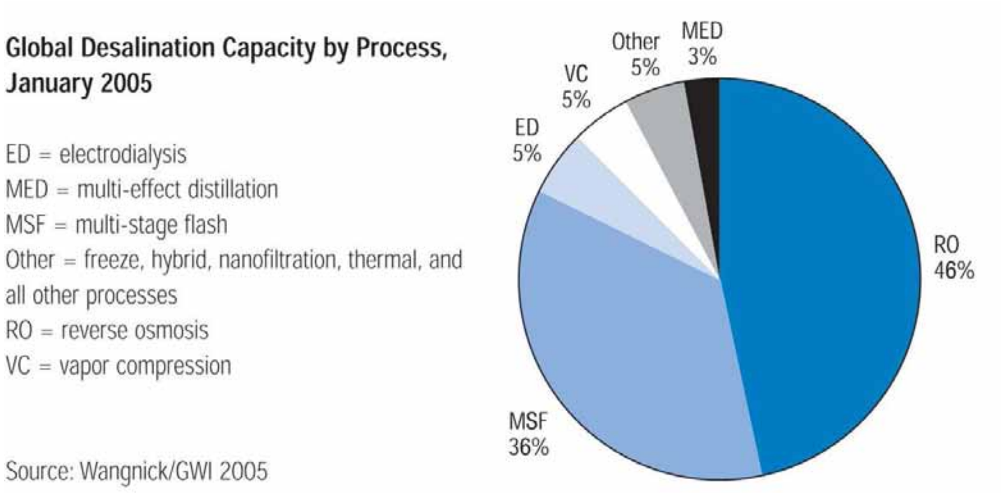


Figure 2.1: Global desalination capacity by process, from Cooley, Gleick, and Wolff (2006).

2.1 Thermal processes

The first desalination method – and still one of the most common (Fig.2.1) – is based on thermal distillation of salty water. In this process, heat is used to produce a phase change of water, physically separating water vapour from the original salt solution and condensing it to produce freshwater.

In **Multi-Stage Flash (MSF)**(Fig.2.2), which accounts for the greatest installed thermal distillation capacity, water is heated in evaporation chambers, each with successively lower pressures and temperatures that cause flash evaporation of hot brine, followed by condensation on cooling tubes. The steam generated by "flashing" is condensed in heat exchangers that are cooled by the incoming feed water. This warms up the feed water, reducing the total amount of thermal energy needed (Miller 2003; Cooley, Gleick, and Wolff 2006).

2.2 Membrane and filtration processes

The second approach to desalination is to physically separate the components using a membrane that mimics the natural process of osmosis and can selectively permit or prohibit the passage of certain ions. The two major membrane technologies currently employed are **Electrodialysis (ED)** and **Reverse Osmosis (RO)**.

Electrodialysis, which accounts for 5% of global desalination capacity (Fig.2.1), is an electrochemical separation process that uses electrical currents to move salt ions selectively through a series of membranes,

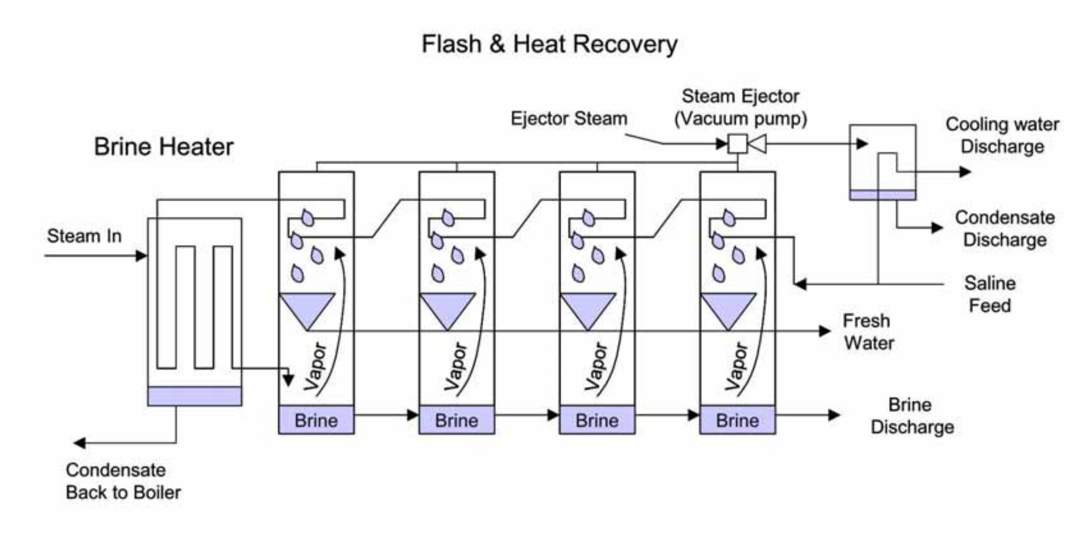


Figure 2.2: Schematic diagram of Multi-Stage Flash (MSF) desalination process, from Miller (2003).

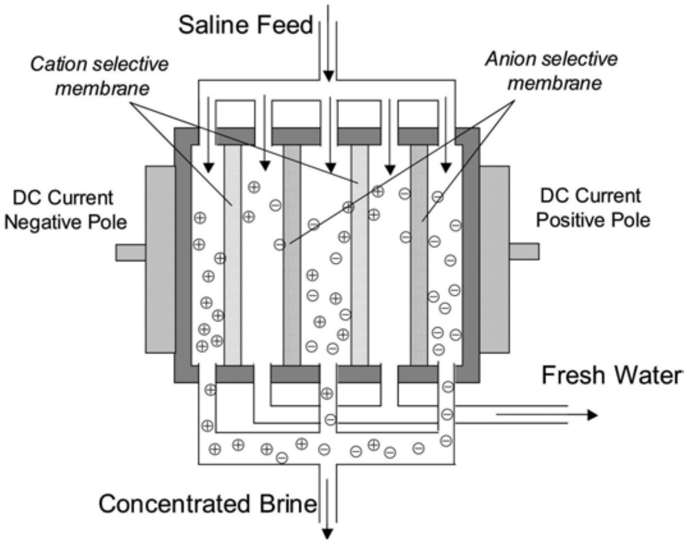


Figure 2.3: Schematic diagram of Electodialysis desalination process, from Miller (2003).

leaving fresh water behind (as illustrated in Fig.2.3). In this process, water is fed to flow channels which have an anion-selective membrane on one side and a cation-selective membrane on the other. The electric field, which flows across the channels, diverts the anions towards the positive electrode, making them pass through the anion-selective membrane and trapping them in the concentrate channel as they cannot pass through the cation-selective membrane. The cations are subject to the same process, but in the opposite direction. Finally, the water feed is separated into brine, in the concentrate channels, and product water in the diluted channels (Cooley, Gleick, and Wolff 2006).

In **Reverse Osmosis**, which accounts for 46% of global desalination capacity (Fig.2.1), saltwater is pressurized against a semi-permeable membrane that lets water pass through but retains salt (Elimelech and Phillip 2011). The RO process usually begins with pre-treatment of the feed water in order to remove contaminants and prevent biofouling (i.e. growth of microbes on the membrane surface). After the pretreatment stage, a high-pressure pump pushes the treated water through the membrane which retains salt. Finally, the post-treatment stage prepares the final product for distribution, removes dissolved gases (CO2) and adjusts pH via the addition of Ca or Na salts (see Fig.2.4) (Miller 2003; Cooley, Gleick, and Wolff 2006).

The energy required by membrane technologies increases with the salt content of treated water. Such techniques are therefore more commonly used to desalinate brackish water, even though seawater desalination is also possible (but more expensive). RO and ED generally have lower capital costs and require less energy than thermal systems: the energy demand of MSF desalination is at least 30 times the theoretical minimum

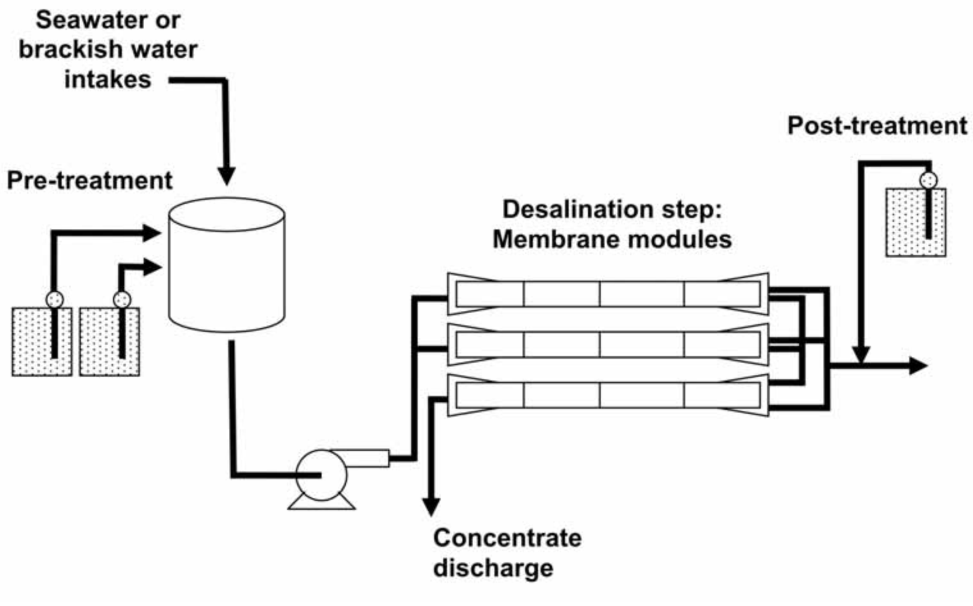


Figure 2.4: Schematic diagram of Reverse Osmosis desalination process, from Zander et al. (2008).

energy for desalination (Miller 2003) while RO plants require only 3-10 times the theoretical minimum energy (Miller 2003; Elimelech and Phillip 2011). However, membrane technologies require energy in the form of electricity and are prone to biofouling.

An interesting perspective may be to integrate both thermal and membrane technologies to create hybrid facilities. The right combination of thermal and membrane processes could improve desalination efficiency and/or reduce energy costs.

2.3 Chemical desalination

Finally, there are also chemical approaches to desalination, including ion exchange, liquid-liquid extraction and gas hydrate. Given the maturity and relative efficiency of the major commercial techniques it is somewhat unlikely that the future of desalination will be based on such processes, even though some are rather promising. For instance, liquid-liquid extraction utilizing polyglycol polymers could be employed to separate a polymer phase containing dissolved water from a salt-containing aqueous phase using less thermal energy than processes described above (Zander et al. 2008; Miller 2003).

3

Case study: Desalination in Israel

3.1 Water scarcity in Israel

With less than 250 m^3 per capita per year (Tal 2006), Israel is considered among the most water stressed countries in the world (Miller 2003). Due to its arid nature, variable precipitation quantities and recurring droughts, Israel suffers from a rather unreliable water supply. Recurring dry years combined with overpumping of natural reservoirs and the steady growth of the population have led to the elaboration of an ambitious cutting-edge water management strategy.

Figure 3.1: **Major water resources in Israel** | From Tal (2006).

3.2 Water Availability and Distribution

Israel's sole source of natural water is rainfall. Rainwater is stocked in three main reservoirs: the Kinneret(also called Sea of Galilee),which holds about 33% of the country's renewable water supply, the Coastal

Aquifer (35-40% of groundwater supply), and the Mountain Aquifer which is still subject to international dispute (Fig. 3.1) (Tal 2006; Kislev 2011). These sources provide around 1800 MCM (million cubic meters) of extremely hard water[1] per year (Water Commission 2002). However, these are endangered due to contamination, overpumping and decrease in precipitation.

Historically, the main use of water was in agriculture (up to 400 MCM a year in the 1980s) especially following mass immigration and settling. As Israel's population grew and urban water consumption increased, freshwater was diverted from agriculture to households and industry. In addition to its own consumption, Israel provides water to the Palestinian Authority (28.6 MCM/year according to the Interim Agreement of 1995) and to the Kingdom of Jordan (as decided in the Peace Treaty of 1994)(Kislev 2011).

To supply demand, Israel has elaborated water transport, collection and treatment infrastructures. Rainwater collection reservoirs provide 125 MCM/year (7% of total water) and 91% of municipal sewage is treated. 73% of the treated sewage water is recycled and used for irrigation (1/5 of total supply) and the rest is returned to regional aquifers(Tal 2006). Nevertheless, these measure were not sufficient to sustain growing demand. The Israeli government therefore decided to undertake a large-scale Desalination Master Plan in 1997.

3.3 The Desalination Master Plan - Is It Really Necessary?

According to the Desalination Master Plan, which was finally approved in 2002, five large-scale RO facilities were to be installed along the Mediterranean coast by 2014 and supply 600 MCM/year of desalinated water (c.f Table 3.1) (Kislev 2011; Tenne, Hoffman, and Levi 2012). This plan is expected to provide a reliable and continuous supply of freshwater, improve water quality, reduce withdrawals from natural reservoirs and prevent their further degradation. And indeed, water quality and realisability have increased. Nowadays, water supplied in Israel is much "softer" (75-120 ppm as CaCo3) and contains lower boron and chloride concentrations (Tenne, Hoffman, and Levi 2012). In addition, Israel's desalination facilities are among the most cost efficient in the world (Tenne 2010). Lastly, some hope that some day desalinated water will be shared with the Palestinian Authority.

RO Desalination Plant	Year opened	Production capacity (MCM/year)
Ashkelon	2005	119
Palmachim	2007	45
Hadera	2009	120
Sorek	2013	150*
Ashdod	2013	100*

** Sorek and Ashdod: predicted production capacity*

Table 3.1: Israel's Desalination Master Plan:

The addition of 50% to natural resources via seawater desalination is without doubt an attractive solution to scarcity problems in this arid country. However, many specialists believe that Israel has not exhausted all the other more cost-effective and potentially less environmentally damaging alternatives (Becker 2010). For instance, supporting agriculture in arid areas is considered unsustainable and some believe it is actually one of the reasons for Israel's water problems (Dickie 2007). On top of that, Israel may have exposed itself to several sources of vulnerability by choosing to go down the road of desalination:

First of all, RO desalination may have a substantial impact on the integrity of marine ecosystems. Seawater intake, for example, can cause entrainment and death of fish and planktonic organisms. In addition, discharge of highly saline brine and pretreatment chemicals back to the sea may have long-term consequences on the marine environment. Moreover, as RO plants consume energy in the form of electricity they may also have a substantial carbon footprint(Elimelech and Phillip 2011).

Secondly, by opting for desalination, Israel may face an even bigger problem than water scarcity. As global energy sources are dwindling, this tiny country will have to deal with price variability and ultimately

---

[1] Water is classified as "very hard" when its hardness is above 181 ppm as CaCO3. The average hardness of natural water in Israel is 250-350 ppm as CaCO3. Even after softenning through ion exchangers, water causes scaling of pipes and water heaters and considerably diminishes their life expectancy. (Tenne, Hoffman, and Levi 2012)

with the quest for alternative energy sources to fuel its desalination plants. And this is quite a big bet to take, on the long run (Garb 2008). Lastly, Israel will also become dependent on water quality in the Mediterranean.

Why did Israel opt for desalination? According to A. Kartin (2001), the answer lies in the way the Israeli Jewish society perceives the Israeli-Arab conflict. In fact, agricultural activity – which uses roughly 60% of the annual water consumption (1996-2011) (Water Commission 2011) – and rural settlement are two of the factors responsible for creating the national identity.

The process of establishing Jews as a nation has always been tightly linked to land transformation and rural settlement. And a Jewish presence in the region, based on agricultural activity, is still one of the major national objectives of the Israeli government. The country's water resources are therefore used to promote agriculture and establish control over territory, thereby contributing national security.

Given the social and ideological importance of agriculture in Israeli society, it seems unrealistic, in the short term, to cut-off its water supply. However, Israel will certainly have to face many new challenges, both environmental and technological, in order to secure its freshwater supply, its electricity and its natural resources.

4

Biological approaches, the future of desalination ?

Desalination can be the key to overcome water scarcity in many countries that have access to seawater. However as shown for Israel, modern desalination plants are still very costly in terms of technological and energy costs and may have a strong environmental impact (Lattemann and Höpner 2008).This high energy cost can only be paid by rich countries, leaving the developing ones without a proper access to usable water and in a situation of social water scarcity, that is in a social and economical context that does not allow these countries to use seawater as a water resource. Developing new desalination methods has been pointed out as one of the main engineering challenge for the twenty-first century by the American National Academy of Engineering (Riley, Gerba, and Elimelech 2011; Yoon and Riley 2009). The Academy emphasize the fact that we need to develop cheaper techniques that will also have a lower impact on the environment(Riley, Gerba, and Elimelech 2011). The answer to this may lie in Biology.

4.1 Biologically inspired design

Although much progress have been made in desalination methods, energy costs and environmental impacts are still to high. Based on thermodynamical calculations and knowledge of technical constrains, engineers estimate that 2 kWh/m^3 is the lower limit to energy consumption for desalination. The most utilized and energy efficient process for desalination is reverse osmosis (Elimelech and Phillip 2011). Most of the research to reduce the energy use in reverse osmosis desalination has focused on creating high permeability (flux) membranes and low fouling membranes (Riley, Gerba, and Elimelech 2011).

A first manner of using biology to improve desalination methods is to use organisms as an inspiration. Every living cells require water to function and for this reason, these cells contain membranes and proteins that have been shaped by evolution and that have allowed them to transfer water from the extracelluar environment (Fu and Lu 2007; Berg, Tymoczko, and Stryer 2012). Aquaporin are proteins that are found in cell's membrane (which encloses the cell's intracellular environment) and that allow only water molecules to pass through. Inspired design from biological membranes and aquaporin proteins can be use to increase the specificity and efficiency of the water transfer across reverse osmosis membranes. Bowen (2006) was the first to propose that we inspire the design of engineered membranes from biological membranes.

Biomimetic membranes utilize bacterias (*Escherichia coli*[1]) to produce aquaporins that may be latter modified by adding chemical components(Tang et al. 2013). These proteins are then added to a synthesized lipid bilayer (Figure 4.1) to which different type of synthetic polymers may be added (Tang et al. 2013) .

Because they can be more efficient in filtering water and may be constructed through synthetic biology methods, the biomimetic membranes may lower the cost of production and the energy consumption used by desalination process (Tang et al. 2013; Riley, Gerba, and Elimelech 2011). However, how efficient these membranes may be, they still require an energy input.

---

[1] Which are greatly modified by biochemists to produce usable proteins

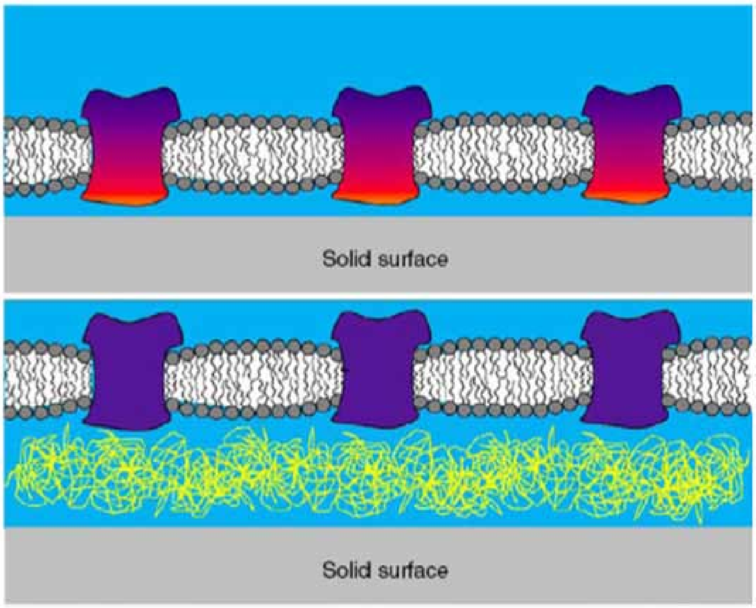


Figure 4.1: **Bioengineered membrane |** Synthetic lipid bilayer containing aquaporins and polymers. Only water can go through the aquaporin, the ions that are present in the solution are blocked by the membrane. From Tang et al. (2013)

4.2 Microbial communities as a device to desalinate water

Thermodynamics dictate a minimum energy of desalination, where the minimum energy needed to desalt water is independent of the technology or mechanism used for desalination (Riley, Gerba, and Elimelech 2011). But regardless of how far we will be able to go towards that limit, conventional desalination methods will always require an energy input, whether it is renewable or not (Shannon et al. 2008). The solution to this problem is the coupling of an energy producing process to desalination.

Bacterias used for waste management may be used to produce energy (Lovley 2008; Rabaey et al. 2007) , which in turn may be used to power desalination process. But recent work has shown that it is possible to go even further, by using the bacterias both as a purification device, a desalination unit and a power plant. The first development in the field is Microbial Fuel Cells (MFC) which can produce electricity. In this system, bacterias use an anode to allow extracellular electron transfer, which is essential to their physiology and other bacteria in an other compartment use the produced electrons for other biochemical reactions (Figure 4.3). The transport of the electrons from the anode to the cathode generates a potential difference therefore producing electricity.

The MFC may be modified to be used as a MDC (Microbial Desalination Cells)(Cao et al. 2009). In this fuel cell two membranes separate the anode (colonized by *Geobacter species*) and the cathode (which may be colonized by bacterias residing in the streamflow). The first membrane is an AEM (Anion Exchange Membrane) and the second a CEM (Cation Exchange Membrane). During the desalination process the AEM will only let the Cl^- ions (which is attracted to the anode) pass and the CEM will only be permeable to $Na+$ ions. As a result the water is treated from waste that serves as a food source for bacterias. The metabolism of the bacteria will generate extracellular electron transfer which will generate electricity. This will physically alter the solution's property leading to the separation of the sodium and the chloride and their evacuation out of the water (Cao et al. 2009; Mehanna et al. 2010). Moreover the ecological and populational process driving the bacterial community seems to lead to a greater optimization of the electron transferring, which both increases the bacteria's capacity to feed and indirectly the voltage production (Rabaey et al. 2007).

Using microbial communities as a device to desalinate water may allow to lower significantly the cost of water desalination as it will be coupled with water treatment and require no direct energy input. Moreover, the energy produced by the process may be used to power the facility hosting these microbial devices. Additionally, the bacterial community may be modified to filtered molecules such as nitrates and toxic compounds (Lovley 2008; Betts 2009). The current limitation to the development of this approach is the ability to control the bacterial community which may change during the water treatment as the water to be treated is

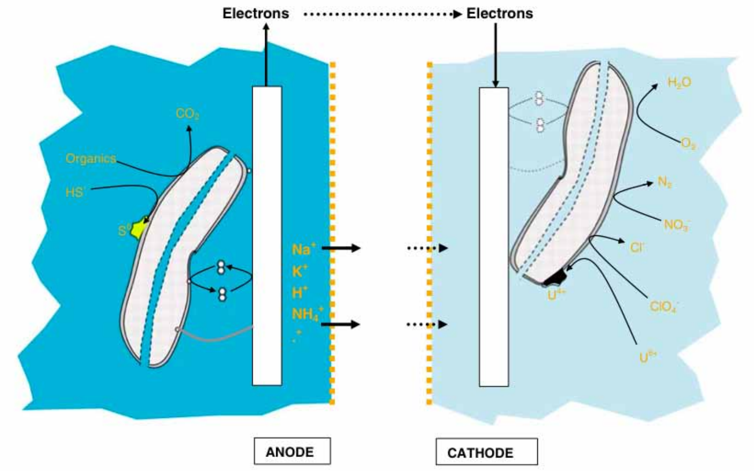


Figure 4.2: **Schematic representation of a microbial fuel cell** | Bacterias that live in aerobic condition furnish electrons to the anode via oxydation of organic matter present in the water stream. Bacterias that live in anaerobic condition use the electrons to reduce oxygen to water and for the process of denitrification. Generally the bacterias present in the aerobic condition are the controlled ones and usaly come from the *Geobacter* group. However the bacterias that develop in anaerobic conditions are less studied and may come from the stream flow to be filtered. From Rabaey et al. (2007)

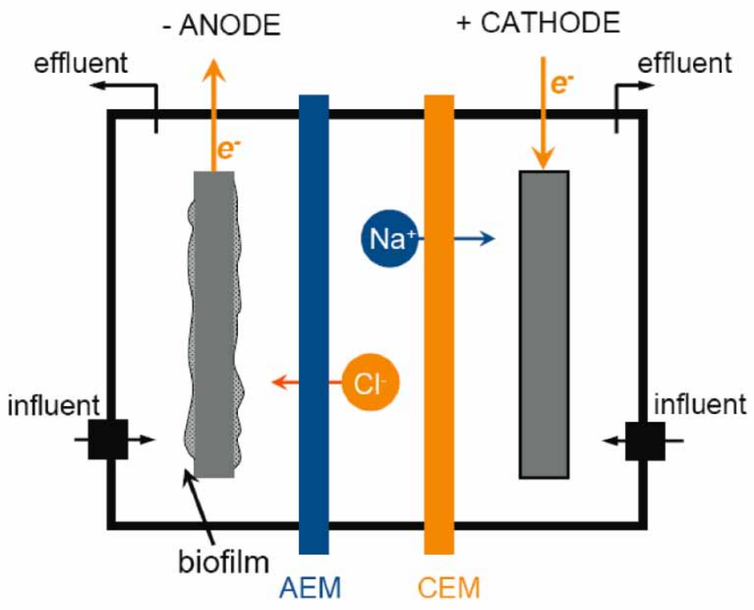


Figure 4.3: **Schematic representation of a microbial desalination cell** | From Cao et al. (2009)

a source of other bacterias which may alter the community's functioning (Cao et al. 2009; Rabaey et al. 2007).

Biological approaches to desalination are only starting to be developed and need more applied research to be used at a very wide scale. But microbial communities can change significantly the way we look at water management. The small size of the devices hosting these communities, the fact that they require no energy input and may also treat water from waste, make it a very promising tool to face water scarcity for countries that cannot afford the high costs of reverse osmosis and distillation technology. For hundreds of year we have developed new technologies to have access to freshwater, however we are now realizing that the energy consumption of these technologies may impact our planet's climate and ecosystems at a global scale, while only benefiting local regions that have the resources to afford these technologies. But a new solution is now possible by using our knowledge and the process of life itself.

Bibliography

Becker, N. (2010). "Desalination and Alternative Water-Shortage Mitigation Options in Israel: A Comparative Cost Analysis". In: *Journal of Water Resource and Protection* 02.12, pp. 1042–1056. ISSN: 1945-3094. DOI: `10.4236/jwarp.2010.212124`. URL: `http://www.scirp.org/journal/PaperDownload.aspx?DOI=10.4236/jwarp.2010.212124`.

Berg, J., J.L. Tymoczko, and L. Stryer (2012). *Biochemistry*. W.H Freeman.

Betts, K. (2009). "Using microbes and wastewater to desalinate water". In: *Environmental Science & Technology* 43.18, pp. 6895–6895. ISSN: 1520-5851.

Boutkan, E. and A. Stikker (2004). "Enhanced water resource base for sustainable integrated water resource management". In: *Natural Resources Forum*. Vol. 28. 2. Wiley Online Library, pp. 150–154.

Bowen, W. R. (Nov. 2006). "Biomimetic separations learning from the early development of biological membranes". In: *Desalination* 199.1-3, pp. 225–227. ISSN: 00119164. DOI: `10.1016/j.desal.2006.03.053`.

Cao, X. et al. (Sept. 2009). "A New Method for Water Desalination Using Microbial Desalination Cells". In: *Environmental Science & Technology* 43.18, pp. 7148–7152. ISSN: 0013-936X. DOI: `10.1021/es901950j`.

Cooley, H., PH Gleick, and G. Wolff (2006). "Desalination: with a Grain of Salt". In: *Pacific Institute. June* June. URL: `http://mx1.wecalc.org/reports/desalination/desalination\_report.pdf`.

Corcoran, E. et al., eds. (2010). *Sick Water? The central role of waste- water management in sustainable development. A Rapid Response Assessment.* Norway: United Nations Environment Pro- gramme.

Dawoud, Mohamed A. (Dec. 2005). "The role of desalination in augmentation of water supply in GCC countries". In: *Desalination* 186.1-3, pp. 187–198. ISSN: 00119164. DOI: `10.1016/j.desal.2005.03.094`.

Dickie, P. (2007). "Desalination: option or distraction for a thirsty world?" In: *World Wildlife Fund Global Freshwater Programme* June. URL: `http://scholar.google.com/scholar?hl=en\&btnG=Search\&q=intitle:Desalination+:+option+or+distraction+for+a+thirsty+world+?\#1`.

Elimelech, M. and W. A. Phillip (Aug. 2011). "The future of seawater desalination: energy, technology, and the environment." In: *Science (New York, N.Y.)* 333.6043, pp. 712–7. ISSN: 1095-9203. DOI: `10.1126/science.1200488`. URL: `http://www.ncbi.nlm.nih.gov/pubmed/21817042`.

Fu, D. and M. Lu (2007). "The structural basis of water permeation and proton exclusion in aquaporins (Review)". In: *Molecular membrane biology* 24.5-6, pp. 366–374.

Garb, Y. (2008). "Desalination in Israel: Status, Prospects, and Contexts". In: *Water Wisdom. Amman* April 2008. URL: `http://www.ygarb.com/publications/garb(2008)desalination--status,prospects,contexts--talk.pdf`.

Hoekstra, A. Y. and A. K. Chapagain (Dec. 2006). "Water footprints of nations: Water use by people as a function of their consumption pattern". In: *Water Resources Management* 21.1, pp. 35–48. ISSN: 0920-4741. DOI: `10.1007/s11269-006-9039-x`.

Kislev, Y. (2011). *The Water Economy in Israel.* Tech. rep. Taub Center for Social Policy Studies in Israel.

Kummu, M. et al. (July 2010). "Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia". In: *Environmental Research Letters* 5.3, p. 034006. ISSN: 1748-9326. DOI: `10.1088/1748-9326/5/3/034006`.

Lattemann, S. and T. Höpner (2008). "Environmental impact and impact assessment of seawater desalination". In: *Desalination* 220.1, pp. 1–15.

Lovley, D. R. (Dec. 2008). “The microbe electric: conversion of organic matter to electricity.” In: *Curr Opin Biotechnol* 19.6, pp. 564–71. ISSN: 1879-0429. DOI: `10.1016/j.copbio.2008.10.005`.

Mehanna, M. et al. (Dec. 2010). “Microbial electrodialysis cell for simultaneous water desalination and hydrogen gas production.” In: *Environ Sci Technol* 44.24, pp. 9578–83. ISSN: 1520-5851. DOI: `10.1021/es1025646`.

Miller, JE (2003). “Review of water resources and desalination technologies”. In: *Sandia National Laboratories Report, SAND2003-0800* March, pp. 3–54. URL: `http://mit.ittelkom.ac.id/courses/mechanical-engineering/2-500-desalination-and-water-purification-spring-2009/readings/MIT2\_500s09\_read19.pdf`.

Montgomery, M. A. and M. Elimelech (Jan. 2007). “Water And Sanitation in Developing Countries: Including Health in the Equation”. In: *Environmental Science & Technology* 41.1, pp. 17–24. ISSN: 0013-936X. DOI: `10.1021/es072435t`.

Ohlsson, L. and A. R. Turton (1999). “The turning of a screw: Social resource scarcity as a bottleneck in adaptation to water scarcity”. In: *Occasional Paper Series, School of Oriental and African Studies Water Study Group, University of London*.

Oki, T. and S. Kanae (Aug. 2006). “Global hydrological cycles and world water resources.” In: *Science* 313.5790, pp. 1068–72. ISSN: 1095-9203. DOI: `10.1126/science.1128845`.

Pereira, L. S., I. Cordery, and I. Iacovides (2009). *Coping with water scarcity: Addressing the challenges*. Springer.

Rabaey, K. et al. (May 2007). “Microbial ecology meets electrochemistry: electricity-driven and driving communities.” In: *ISME J* 1.1, pp. 9–18. ISSN: 1751-7362. DOI: `10.1038/ismej.2007.4`.

Rahman, M. M. (2005). “Bangladesh–from a country of flood to a country of water scarcity–sustainable perspective for solution”. In: *Seminar on Environment and Development, Hamburg, Germany*, pp. 9–10.

Riley, M. R., C. P. Gerba, and M. Elimelech (2011). “Biological approaches for addressing the grand challenge of providing access to clean drinking water.” In: *J Biol Eng* 5.1, p. 2. ISSN: 1754-1611. DOI: `10.1186/1754-1611-5-2`.

Schiffler, M. (2004). “Perspectives and challenges for desalination in the 21st century”. In: *Desalination* 165, pp. 1–9.

Shannon, M. A. et al. (2008). “Science and technology for water purification in the coming decades”. In: *Nature* 452.7185, pp. 301–310. ISSN: 1476-4687.

Tal, A. (Aug. 2006). “Seeking sustainability: Israel’s evolving water management strategy.” In: *Science (New York, N.Y.)* 313.5790, pp. 1081–4. ISSN: 1095-9203. DOI: `10.1126/science.1126011`. URL: `http://www.sciencemag.org/content/313/5790/1081.shorthttp://www.ncbi.nlm.nih.gov/pubmed/16931752`.

Tang, CY Y. et al. (Jan. 2013). “Desalination by biomimetic aquaporin membranes: Review of status and prospects”. In: *Desalination* 308, pp. 34–40. ISSN: 00119164. DOI: `10.1016/j.desal.2012.07.007`.

Tenne, A. (2010). “Sea Water Desalination in Israel: Planning, coping with difficulties, and economic aspects of long-term risks”. In: *Israel Water authority, Ministry of Infrastructure ...* October, pp. 1–13. URL: `http://water.gov.il/Hebrew/Planning-and-Development/Desalination/Documents/Desalination-in-Israel.pdf`.

Tenne, A., D. Hoffman, and E. Levi (2012). “Quantifying the actual benefits of large-scale seawater desalination in Israel”. In: URL: `http://www.tandfonline.com/doi/abs/10.1080/19443994.2012.695047`.

Water Commission (2002). *State of Israel Water in Israel: consumption and production 2001*. Tech. rep. State of Israel, Ministry of National Infrastructures.

— (2011). *Water consumption in Israel 1996-2011(in Hebrew)*. Tech. rep. State of Israel, Ministry of National Infrastructures.

WHO/UNICEF (2003). *Global water supply and sanitation assessment: 2000 report*. Tech. rep.

Yoon, J. Y. and M. R. Riley (2009). “Grand challenges for biological engineering.” In: *J Biol Eng* 3, p. 16. ISSN: 1754-1611. DOI: `10.1186/1754-1611-3-16`.

Zander, A. K. et al. (2008). *Desalination: A National Perspective*. Ed. by Committee on Advancing Desalination Technology. The National Academies Press. ISBN: 0309119243.