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„Desalination: the Effect of Different Factors on the Water Price“

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List of Abbreviations

RO	Reverse Osmosis
UF	Ultrafiltration
NF	Nanofiltration
MF	Microfiltration
TDS	Total Dissolved Solids
MED	Multiple-Effect Distillation
MSF	Multi-Stage Flash
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
TWC	Total Water Cost
O&M	Operating and Maintenance
NPV	Net Present Value
IRR	Internal Rate of Return
PBP	Payback Period
LCOE	Levelized Cost of Electricity
LCOW	Levelized Cost of Electricity

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Introduction and Overview

Earth's water is highly difficult to precisely estimate. A possible distribution can be seen in Table 1:

	Volume ($\times 10^3$ km^3)	*Percentage of total*
Oceans and seas	1,338,000	96.54
Ice caps and glaciers	24,064	1.74
Groundwater	23,400	1.69
Permafrost	300	0.022
Lakes	176	0.013
Soil	16.5	0.001
Atmosphere	12.9	0.0009
Marsh/wetlands	11.5	0.0008
Rivers	2.12	0.00015
Biota	1.12	0.00008
Total	1,385,984	100.00

Table 1 Estimate of Earth's Water Distribution Source: (Davie, 2008)

Roughly 1.4 billion (US) km^3 (equal to 1.4 * 10^9 km^3 or 1.4 * 10^{18} m^3) is the total amount of earth's water. The immense majority, or 96.5 per cent, of this water is saline ocean water. Assuming that groundwater, which is less than one km deep in the ground is accessible, adding other fresh water sources to that amount and subtracting fresh water in form of snow and ice, then the total amount of fresh water accessible for human consumption is 0.27 per cent. This amount may sound little, however, Davie claims that for a population of 7 billion people that would equal to 146 million liters (146,000 m^3) of water per person per day. (Davie, 2008) No further explanation can be found about the numbers regarding the total amount available. A possible explanation is that the author already took into account the hydrological cycle (explained in the following pages) and natural recharge rate of the groundwater.

Within the earth's climate range, water appears in all three stages, i.e. gas (in form of water vapor), liquid and solid. Water acts as an "climate ameliorator" through the energy that is absorbed and released during the transformation between the different states. These three states make the earth habitable for life forms. Water lowers climate extremes, e.g. by transporting energy (heat)

from equatorial regions to the poles. In addition to the mentioned physical properties, the low viscosity makes water transport efficient. Also, the chemical properties of water are essential for life. Water is one of the best naturally occurring solvents and we therefore use it for washing and disposal of pollutants. Moreover, it solves the nutrients from the soil, which makes it for plants possible to absorb those nutrients. Furthermore, the ability to dissolve gases like oxygen makes life in oceans, rivers and lakes possible. Even the human body consists of 60 per cent water and is able to survive without food for many weeks, but only a couple of days without water. (Davie, 2008)

Many countries produce large portions of their electrical energy, through water and the principles of gravity, in a sustainable way. Even in spirituality water has an important role. In Christianity baptism is a symbol of cleansing, in Islam washing with water before prayer is an essential ritual and in Hinduism bathing in the river Ganges offers spiritual cleansing. (Davie, 2008)

The way water moves around earth and its atmosphere is called the hydrological cycle. Figure 1 shows the schematics of the hydrological cycle from a global perspective. The numbers represent the total amount of water in thousands of km^3. Through evaporation (E) of liquid water, it moves around the atmosphere in form of water vapor. The water vapor then condenses into liquid or solid state and falls down to the earth's surface as precipitation (P). More water evaporates from the oceans than goes back through precipitation, and the opposite is true for the land. To close the hydrological cycle, the ocean

receives the difference in form of runoff (Q), e.g. rivers as surface runoff. A fraction of the runoff is subsurface runoff (Q_G). (Davie, 2008)

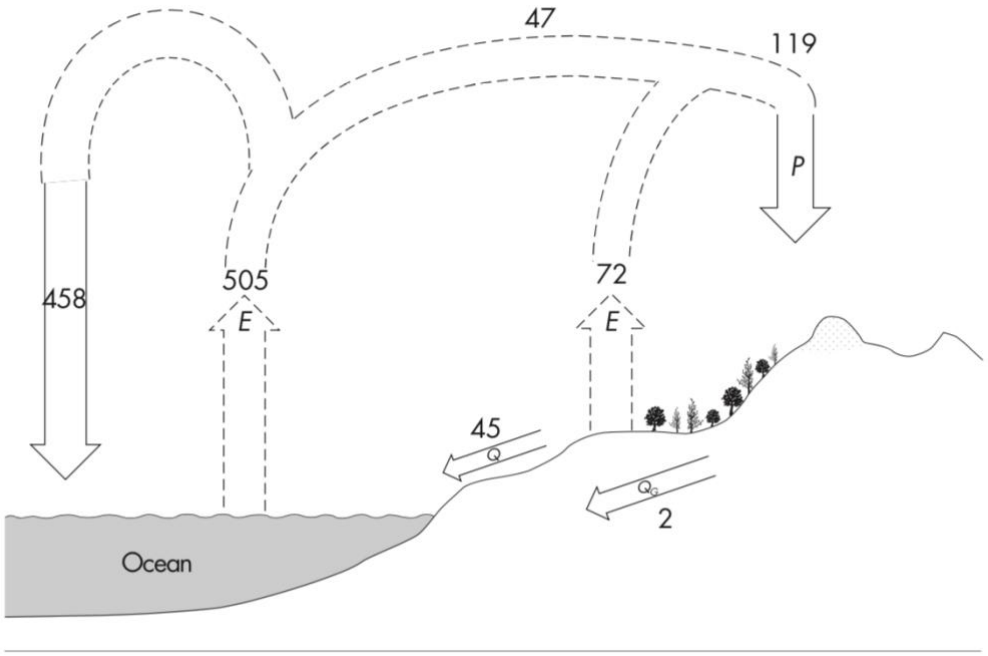

Figure 1 Global Hydrological Cycle Source: (Davie, 2008)

The global hydrological cycle adds up to the previously mentioned numbers, however, the distribution varies significantly around the globe.

Even if the planet's capacity of fresh water remains constant, human utilization of water is expected to rise further. The shift to more meat-based diets, population growth, climate change and other factors reinforce water usage. In addition, water quality is degrading, which is alarming for human health and the ecosystem. For regions where they can afford water treatment, the cost will rise, and other regions will suffer from decreasing water quality. Furthermore, the physical availability of fresh water does not guarantee safe and affordable supply for everyone. At least 780 million people lack access to clean drinking water, 2.5 billion people have no access to a proper sanitation system and two to five million people, primarily children, die of water-related diseases every year. (Gleick, 2014) It is expected, that by the year 2025, 2.8

billion people will face water scarcity and by 2050 the number is likely to increase to 4 billion people worldwide. (Kucera, 2014)

Comparing the current water use to the available and renewable supply, determines the water stress level. The higher the percentage, the higher the water stress in a given region. Figure 2 shows the water stress level for the year 2013. Especially the Middle Eastern region is extremely stressed. As a result of higher water stress, many regions are condemned to face water scarcity in the future, including the Southwestern United States, Northern, Southern and Eastern Africa, the Middle East and the majority of the rest of Asia. The water stress is amplified in regions with unstable and rapid population growth and industrialization. The forecast does not take into account any new policies regarding water management, such as re-use or desalination. (Kucera, 2014)

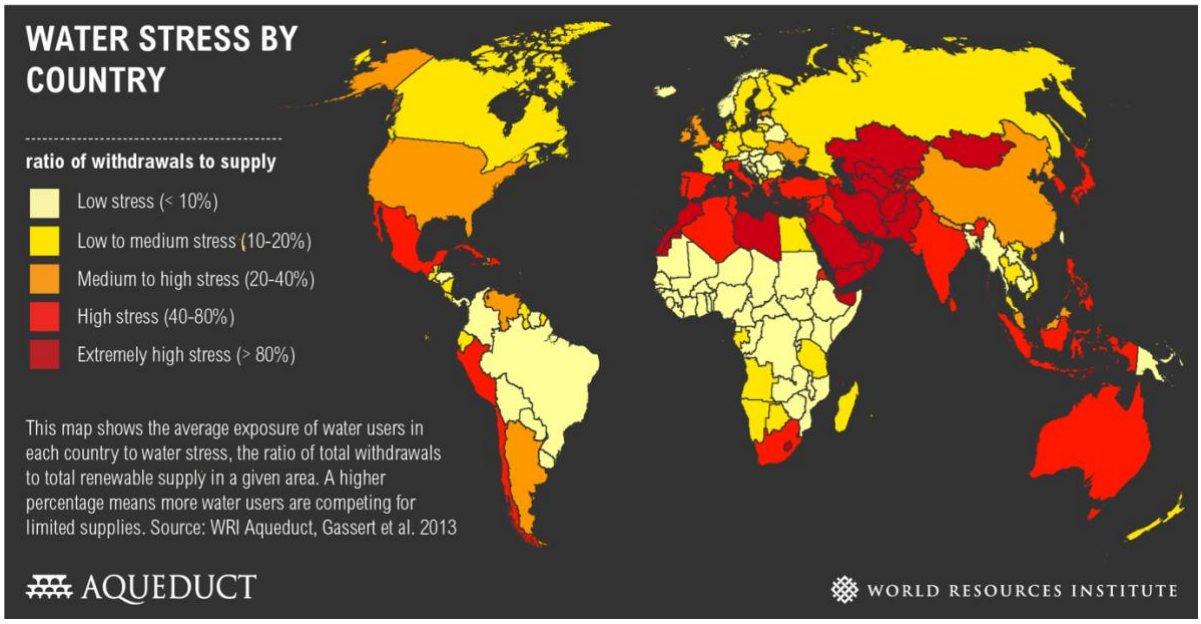

Figure 2 Water Stress by Country Source: (Maddocks, 2013)

Not only population growth increases water stress, but also the fact that the per capita demand is increasing. Estimates suggest that the per capita demand increases faster than the population growth by a factor of 2. In the United States the water demand is almost 400 liters per person and day. Other western countries use 150 liters per person and day. In Africa, the average per capita use is only 20 liters, due to shortages of water, limited availability and access to water. According to the WHO, 15 to 20 liters are necessary for

survival and 50 liters for operation of basic infrastructure, like schools and hospitals. The WHO warns that by 2025 the demand for fresh water will exceed the current supply by 56 per cent. (Kucera, 2014)

Climate change is a considerable factor in water scarcity. It increases the likelihood of droughts. In addition to the stress on water by population growth, growth in per capita demand and industrialization, those factors accelerate climate change, and extreme climate events are more likely to happen. In most of Latin America, Mediterranean regions, Australia, Southeast and Southwest of Asia droughts are very likely to occur in the coming years. In addition, many of those regions are forecasted to have population, industrialization and urbanization growth, which increases the per capita water demand. The UN estimates that by 2020 there will be 27 cities with a population greater than 10 million. All of those cities, except New York City, Paris and Moscow, are in danger of experiencing droughts. (Kucera, 2014)

Water issues are becoming more and more complex and can't be addressed exclusively on national or regional scale. According to UNESCO "water has long ceased to be solely a local issue". (UNESCO, 2012) If the problem of water scarcity is not solved, it threatens socioeconomic development and even national security. In many regions water is shared through hydrological units, like rivers and underground aquifers across borders, and global trade. Throughout history, many conflicts have been evolved around water. Even in ancient times people were aware of the importance of water, e.g. when in 51 BC Caesar cut off the water supply of Uxellodunum from the local spring and defended the other nearby spring during a siege. Consequently, the Gauls surrendered due to water shortage. Or more recently, in 1999 Puerto Rican protesters blocked a water intake of Blanco River, used by the US Navy, because it caused chronic water shortages in neighboring towns. Climate change and the presence of multinational corporations in the water sector lead to the globalization of water issues. The former vice president of the World Bank, Ismail Serageldin, once said during a speech in 1995: "The wars of this

century have been for oil, but the wars of the next century shall be for water" (Gleick, 2014)

Can the water problem be solved by desalination? For this purpose, this work will address the economic perspective of desalination. Several papers and case studies will be searched for information on the price of desalination. That information will be collected and a cost database will be prepared. The information will be used to calculate the Total Water Cost (TWC) per m^3 of desalinated water. Factors that could influence the price, e.g. plant size, location or feed water quality, will be investigated with regression analysis.

History of Desalination

The oldest mention of desalination is estimated to be around 1500 BC. In Exodus, in the Old Testament it is written:

“22 So Moyses brought the sons of Israel from the Red Sea and they went to the desert of Sour. And they marched three days in the wildness and they found no water to drink. And then they arrived to Merra and they could not drink from the
23 water of Merra, because they were bitter, therefore he
24 gave to the place the name Bitterness. And the people murmured against Moyses. Saying: What shall we drink?
25 and Moyses cried onto the Lord. And the Lord showed him a wood and he put it into the water and the water became sweet.”

A possible explanation is that the wood has ion-exchange properties. (Delyannis, 2003) Another explanation is that the water was not salty but foul tasting because of algae, therefore, the wood could have brought up better quality water to the surface through stirring. (Hillel, 2007)
The Greeks had first philosophical ideas about water and energy in the antiques. The first of the seven wise men of antiquity, Thales of Militus (640-546 BC), said that the sea that surrounds earth, is the mother of all life and water is fertile and molded. Embedokles (495-435 BC) established the theory of the elements and defined one of the four elements to be water (Fire, Air, Water and Earth). In modern times those four elements can be interpreted as: Energy, Atmosphere, Water and Soil. (Delyannis, 2003)

Aristotle (384-322 BC) described the hydrological cycle of water, in an exceptionally accurate way, as follows:

“Now the sun moving, as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest water is every day carried out and is dissolved into vapor and rises to the upper regions, where it is

condensed again by the cold and so returns to the earth. This, as we have said before, is the regular cycle of nature."

Furthermore, he understood the concept of desalination by evaporation. He wrote that the vapor from seawater becomes sweet and the condensate does not form salt. (Delyannis, 2003) After Aristotle no significant improvements regarding seawater desalination have been made up to the 300's AD, only secondary and tertiary references can be found with no new experiments. (Birkett, 1984)

In the mid forth century St. Basil reported that sea-men boiled seawater in a vessel on board of ships by fire. A sponge was placed at the opening of the vessel and the evaporated water was condensed inside of the sponge. The sponge then could be squeezed out and fresh drinking water was available on

board of the ship. An illustration of the process can be seen in Figure 3. (Birkett, 1984)

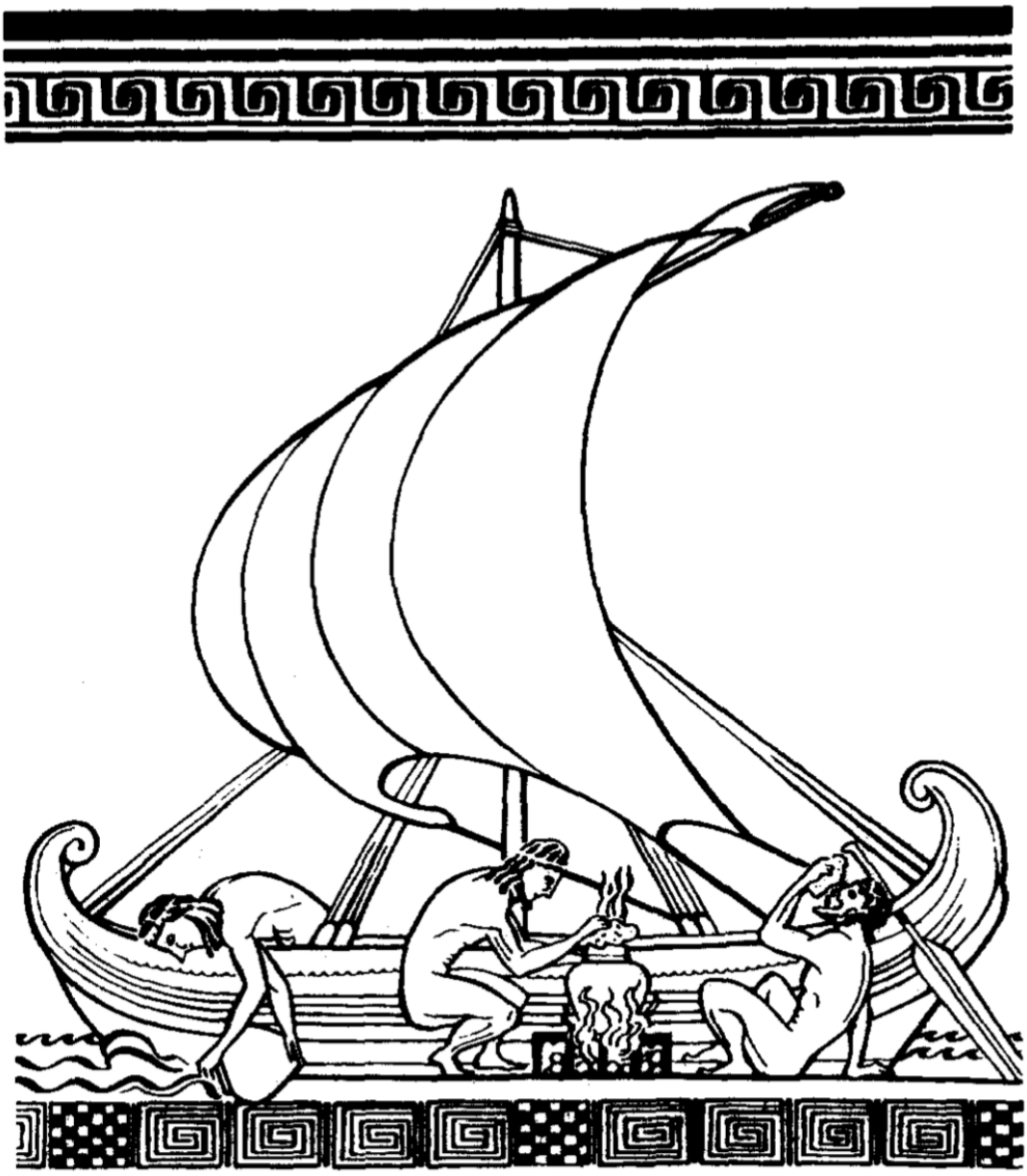

Figure 3 Desalination on Board of a Ship in the 4th century Source: (Birkett, 1984)

In the late 700's, Jabir Ibn Hayyan published a work about distillation. His work, among others by Greek, Persian and Egyptian scholars went to Europe through the Moorish conquest of the Iberian Peninsula. Centers of learning were established, e.g. the University in the city of Toledo. Also the multi-

talented Leonardo da Vinci had designs for distillation, including a still on a kitchen stove to produce fresh water from seawater. (Birkett, 1984)

In 1560 a garrison of 700 Spanish soldiers were trapped on an island near the coast of Tunisia by a siege of the Turks. It is speculated that during that time the first major land-based desalination plant was built. Out of necessity, the Spanish captain ordered a distillery to be built. It was capable of producing forty barrels of fresh water from seawater per day. Unfortunately, no further information about the plant design can be found. Later during the century, Sir Richard Hawkins reported during his travels to the South Sea that he was able to provide his men with fresh water with onboard desalination. He was the first to investigate the importance of fuel efficiency for desalination: “for with fore billet (of wood) I stilled a hog’s head of water”. Francis Bacon, in the same period, reviewed works on water purification and Robert Boyle published works on chemistry, including the behavior of gases under pressure and vacuum. In the early 1600’s Sir Walter Raleigh conducted experiments on seawater distillation during his prison time in the Tower of London. Later in the century, the first disputes over patents regarding desalination were fought. Specifically, the English patents NO. 184 and No. 226 in 1675 and 1683 by William Walcot and Robert Fitzgerald, respectively. Although Walcot was the first to register his patent, Fitzgerald managed to put his patent to commercial use, thanks to his influential business partners. In fact, they promoted the distillation device so heavily, published brochures to demonstrate the advantages and economies of the device, that one such device was put on the ship of his Majesty Charles II for demonstration purposes. Fitzgerald also got the backing of Samuel Pebys, the Secretary of the Admiralty of Charles II, who wrote a letter to the Admiral of the Majesty’s ship to participate in the desalination experiment. Interestingly both patents did not go into detail about the functional design of their devices, but both specified the necessary ingredients (chemical additives). The success of Fitzgerald’s model was due to his political and influential backing rather than the superiority of his model. Even land-based distilleries were built in 1692 and 1693 based on his model. Walcot’s and

Fitzgerald's design both suffered from scaling issues and made them mostly unsuitable for long term use. (Birkett, 1984)

In the following years no significant advancements in desalination were recorded until 1739, where Stephen Hales pointed out the importance of fuel efficiency onboard of ships. He mentioned that a good still should be able to produce three times the amount (or weight) of water as there is coal used. More importantly, he sought the optimal recovery ratio of the feed water. During the desalination process he removed water from the process and noted that the first batch was of excellent quality and the quality of the following samples decreased when the brine became more and more concentrated, up to the point where the water became harsh and undrinkable. He defined the optimal recovery ratio as one third of the feed water for optimal water quality. Today's optimal recovery ratios aim to reduce scaling rather than improving water quality. Most of the other works on desalination of the 18th century focused on improving the water quality, which was acidic due to the use of additives and fuel economy was a major research topic, especially for inboard desalination. Thomas Jefferson, during his time as Secretary of State of the United States, published a paper titled "Report on the Method for Obtaining Fresh Water from Salt", where he summed up the work of a dozen previous researchers, detailing the results of experiments regarding fuel efficiency. He wanted to make information about onboard desalination available to all captains and shipping firms and proposed to print a description on the back of clearance papers for each ship that departs the ports of the United States. During the late 18th century a new approach was discussed by Anton Maria Lorgna. He published a paper, where he described that he desalinated seawater by freezing it during cold winter nights. Freezing the water resulted in fresh product water after melting. However, all in all, it can be said that during the period from 1650 – 1800 many works have been published with no significant change to the basic model of distillation but with progress on sharing information and execution of the models. (Birkett, 1984)

The improvements of James Watt on the steam engine in the late 1700's and the resulting advent of the steam engine and age of steam had positive effects on desalination in the beginning of the 19th century. Especially the

advancements on the surface condenser had a positive effect on the distilling apparatus. There are three reasons for the positive effect of the steam engine on desalination:

1. The development of steam power resulted in improvements in the knowledge of thermodynamics of the steam process. This in turn resulted in an increasing development of an engineering database and publication of steam tables
2. Boilers on ships needed pure water to operate the steam engine. Also, locomotives had the need to rely on desalinated water to use in areas with no access to fresh water sources.
3. Steam technology led to European colonialism. This led to the necessity to supply fresh water in remote areas of the world, where only seawater and/or brackish water were available, due to the establishment of communication lines and coaling stations for steamers on their ways to the colonies. Also, for garrisoning of soldiers in areas with no access to fresh water.

There was an increase in the production of pure white sugar in tropical areas, due to an increase in demand, probably indirectly related to European colonialism. The process consisted of evaporating sugar syrup to achieve crystallization of the sugar. A simple open boiling pan was used but due to the higher demand, it was not efficient. Because for low outputs, it was possible to burn the plant remains, but higher outputs needed additional energy sources, which affected the price of sugar. Thus, the need for less energy intense processes arose to maintain low sugar prices. In 1812 or 1813 Howard introduced the concept of vacuum pan evaporation and in 1834 the surface condenser was invented by Hall. Rillieux of New Orleans registered a patent on multi-effect evaporation in 1843. The design was a two-effect system with false bottom vessels. In the same year, the first triple effect unit with horizontal evaporator tubes was installed in a sugar refinery in Louisiana (more on the role of sugar production on desalination technologies and the functionality of multiple effects in the chapter about Multi-Effect Distillation). (Birkett, 1984; Kucera, 2014) Rillieux's fellow countryman Degrand introduced a single effect

evaporator in 1833, where the latent heat was used to preheat the feedwater. This design lead to substantial efficiency improvements and shortly after in 1836 he improved his design with a double effect evaporator. It was used in the French Antilles. Although not designed for desalination purposes, these models showed the potential of such evaporator devices. A vertical tube seawater distilling unit was introduced in 1852 by Normandy and gained a British patent. Thanks to the simplicity of Normandy's design, it became quickly popular for onboard desalination purposes. The design became so popular that in 1885 the British Board of Trade would allow ships to be off to the sea with half the previously specified amount of water, if they had installed a distiller on board. In 1886 Yaryan developed the first long tube vertical rising films evaporator and shortly after the company Mirrlees-Watson of Glasgow produced a variation, Yaryan's horizontal tube model. Lillie in 1888 introduced the horizontal spray film evaporator, which had, compared to Yaryan's model, the feed water on the outside rather than on the inside and was a commercially successful for many years. In 1899 and 1903 Kestner improved the rising film long tube vertical evaporator and also the falling film long tube vertical design. At the end of the 19th century England was involved in lengthy military action in Egypt and Sudan. The British troops were stationed in Suakim, Sudan and fresh water was not available. To supply the troops with drinking water, the boilers of steam ships, which were placed at the port of Suakim for that purpose, were used. Later the steam ships were replaced and two six-effect distillers were installed by the Mirrlees-Watson Company with a capacity of 350m^3/day (no information can be found that specifies if the capacity is for each unit respectively or for both combined). The Mirrlees-Watson Company also installed units in Kossier and Camran at the Red Sea, for the Uganda Railway at Mombasa, for the Cape of Good Hope Government Railways, in Argentina, Australia and Russia. (Birkett, 1984)

In the beginning of the next century, namely 1900, Waterhouse patented the concept of multi-stage flash distillation (MSF). However, his model was never built in real life. He neglected to do the engineering calculations for MSF, because the number of stages is more a matter of investment cost rather than thermal efficiency. Therefore, it took more than half a century until the first

large scale MSF unit was built and Waterhouse is not recognized as the true inventor of MSF (more on MSF history and concept can be found in the next chapter). In 1900 a triple-effect system by the design of Lillie was installed in Dry Tortugas, Florida, with a capacity of 60000 U.S. gallons/day, equivalent to approximately 230 m^3/day. The fuel efficiency of the system was as follows: for each pound of coal it was capable of producing 21.6 pounds of water. A model of the system can be seen in Figure 4. In 1907 two distillers were installed by the Ottoman Empire in Jeddah, Saudi Arabia. They were simply called “Kindasa”, the Arabic word for condenser. They were later replaced by King Abdul-Aziz in 1928 with newer tube units with a capacity of 135m^3/day each by the Weir Company. These units are no longer in operation but interesting sculptures are formed from the boilers and presented on the road in Jeddah (see Figure 5). (Birkett, 1984)

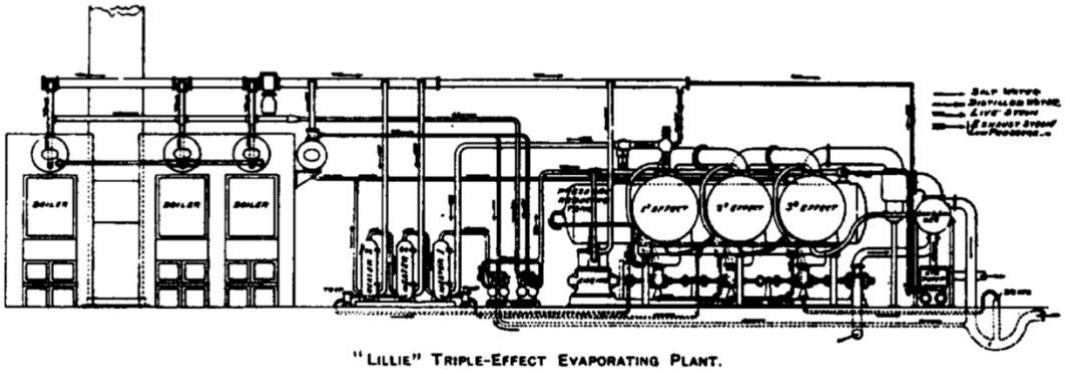

Figure 4 Triple Effect Evaporator by Lillie in Dry Tortugas, Florida Source: (Birkett, 1984)

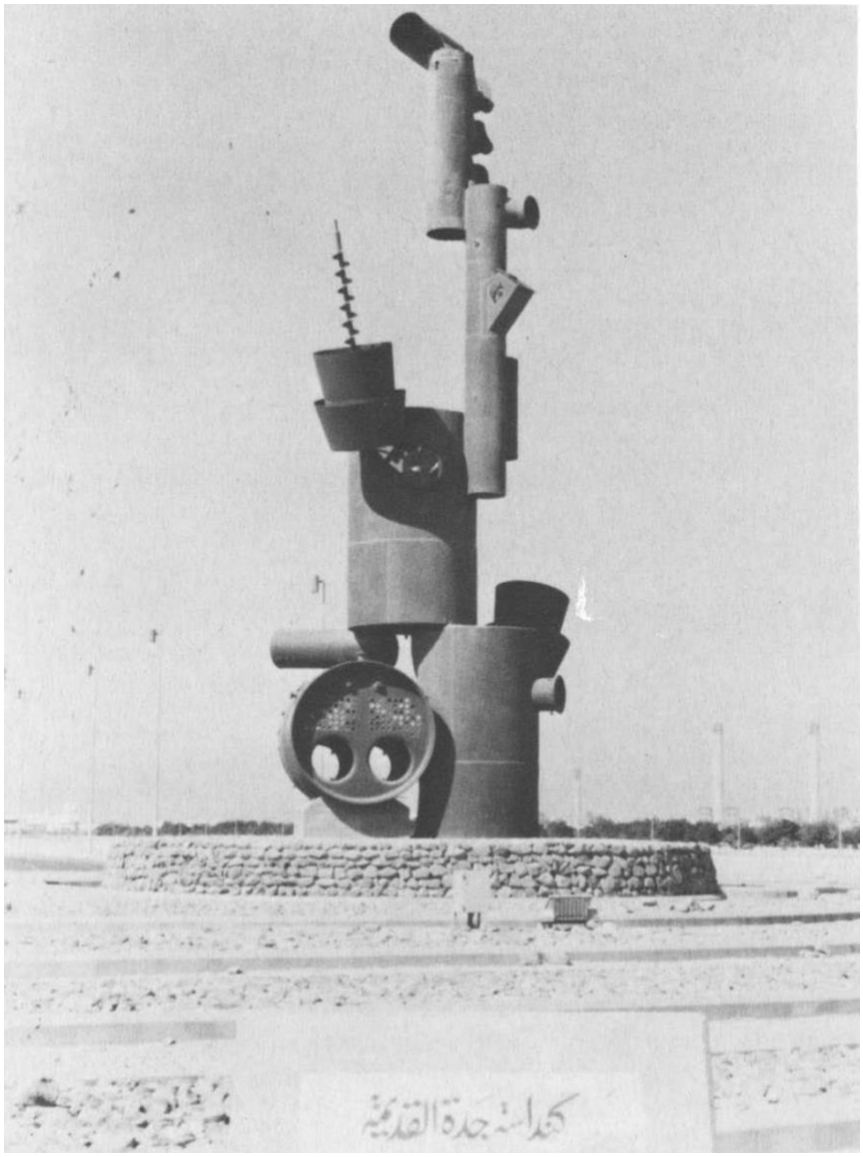

Figure 5 Monument built from parts of old distillery in Jeddah Source: (Birkett, 1984)

Weir of Glasgow installed in 1910 a submerged tube distiller near Safaga in Egypt, which was in service up to at least 1970. Later, in 1933, an updated version, a six-effects distiller, was installed in Qusair by the Weir company. 50 years later, in 1983, Birkett, the author of the source, visited the facility and the distiller was still working and producing 30m^3/day. In the 1920's and 1930's desalination became popular in the Caribbean and the hotspots of such activity were Curaçao and Aruba. In 1928 Aiton Ltd. Installed a thermo-compression evaporator unit with a capacity of 50-60 m^3/day. Later the Weir Company installed 9 or 10 submerged tube units in the Caribbean. Desalination through freezing was practiced for a long time in Russia by natural freezing due to

subzero temperatures but the first model through artificial refrigeration was introduced in 1936 by Messr, Wolff and Marr and was called the Rocket Ice Making and Cold Distilling. During the era of the Second World War, multiple-effect distillation plants of increasing size have been built due to improvements and refinements throughout history. (Birkett, 1984)

Membrane desalination was investigated by Zsigmondy in 1918 and McBain in 1931. However, according to Crittenden et al. the first person to observe separation by osmosis was Jean Antoine Nollet in 1749. Only during the 1950's reverse osmosis was investigated further and put into practice (see next chapter for details). (Birkett, 1984; Crittenden et al., 2012)

Another method made appearance in the 1930's, namely electrodialysis. It's intended purpose was to purify casein, grape juice and sugar by simple cells using parchment or cellophane membranes. During the next decade improvements were made including a multi compartment cell by Meyer and Straus in 1940. However, electrodialysis for desalination purposes was practiced later in the 1950's after Juda and McRae developed long lasting ion exchange membranes suitable for desalination. (Birkett, 1984)

During the 1980's water became scarce in some regions and it was no longer seen as a commodity but a product that can be sold for a profit. Hence, there were investments from the private sector in research and development of desalination. As a result, the cost of desalinated water dropped. The price for membrane units in the Reverse Osmosis technology dropped by 80 per cent from the 1980's during a period of 20 years. Other techniques have been developed over the years, but none were as commercially successful as the thermal and membrane technologies. (Kucera, 2014)

Desalination Methods

There are many desalination methods, but only a couple are commercially used. The following methods exist:

- Distillation/thermal process
    - Multi-stage flash distillation (MSF)
    - Multiple-effect distillation (MED)
    - Vapor-compression (VC)
- Ion exchange
- Membrane processes
    - Electrodialysis reversal (EDR)
    - Reverse osmosis (RO)
    - Nanofiltration (NF)
    - Membrane distillation (MD)
    - Forward osmosis (FO)
- Freezing desalination
- Geothermal desalination
- Solar desalination
    - Solar humidification – dehumidification (HDH)
    - Multiple-effect humidification (MEH)
    - Seawater greenhouse
- Methane hydrate crystallization
- Wave-powered desalination (Greenlee et al., 2009; Khawaji et al., 2008; Kucera, 2014; Van der Bruggen & Vandecasteele, 2002)

Commercial desalination consists mainly of membrane processes and distillation. Worldwide, 40 per cent of desalinated water are produced with the MSF technology and 44 per cent with RO. However, 80 per cent of all desalination plants are RO plants, which indicates that MSF plants are larger in capacity. In the Middle East 87 per cent of desalinated water is produced by MSF and in the United States 85 per cent of desalinated water is produced by

membrane technologies, with RO having a market share of 69 per cent of the total desalinated water. (Greenlee et al., 2009)

To give the reader a better understanding of how the costs of desalination are composed, the commercially most successful methods will be described in detail in the following part:

Reverse Osmosis

Reverse Osmosis (RO) is a separation technology, which uses semipermeable membranes to remove impurities, including salinity, from the feed water. The semipermeability of the membrane means that some components are highly permeable, and others are impermeable. The membrane itself is typically made from a synthetic material, with a thickness of around 1 mm. The feed water stream is pushed into the membrane and the part that is pushed through is the product stream and the impermeable components remain on the feed side and are pushed out as the waste stream. (Crittenden et al., 2012)

There are 4 main types of membranes currently used: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis, in ascending order of fineness or decreasing size, as seen in Figure 6. RO has different uses, e.g. softening, specific containment removal, water reuse, high-purity process

water. Relevant for this work is the use for desalination of seawater, ocean water and brackish water. (Crittenden et al., 2012; Greenlee et al., 2009)

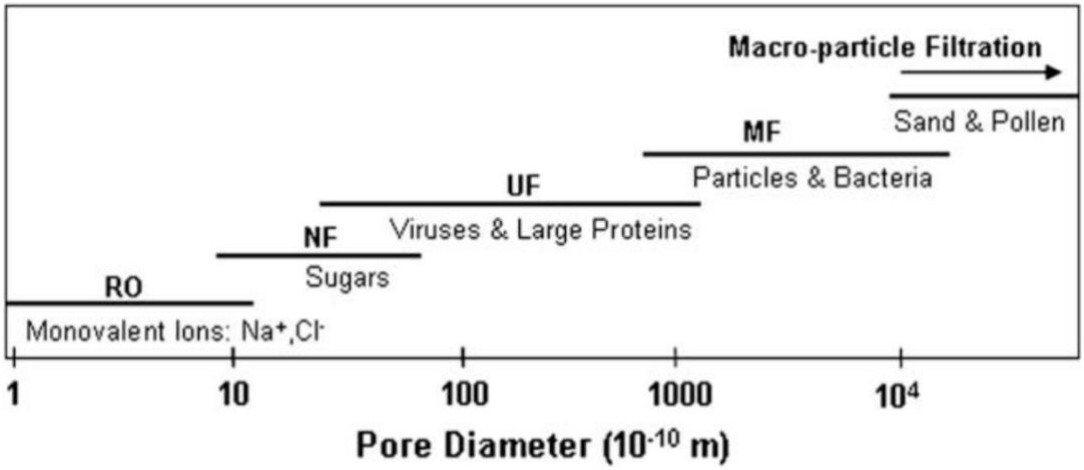

Figure 6 Range of nominal pore diameters for commercially available membranes (Greenlee et al., 2009)

History of RO

In 1749 Jean Antoine Nollet observed as the first person the semipermeability of membranes through osmosis. However, the first serious inspections into that matter were performed in 1949 by the University of California at Los Angeles (UCLA) and in 1955 at the University of Florida. The latter was funded by the newly founded U.S. Department of Interior Office of Saline Water. In the mid 1960s scientists at both Universities succeeded in producing fresh water from seawater, however the fresh water flux was too weak for commercial application. An asymmetric RO system was developed in 1959 by Loeb and Sourirajan with the aim to reduce the thickness of the membrane. The asymmetry of the membrane means that it consists of an active layer and a support layer. Both layers are made from the same material, meaning that they are chemically homogenous but differ physically (heterogenous). The active layer is very thin and provides the ability for separation. At the same time, which the thin-film membranes were developed, the spiral wound element was

developed to increase the packing density. These advancements made the commercial use of membrane desalination attractive. (Crittenden et al., 2012)

In June of 1965 the first membrane desalination plant began operation in the City of Coalinga, California. The plant provided 19 m^3/d of potable water. The feed water contained 2500 mg/L of Total Dissolved Solids (TDS) and operated at a pressure of 41 bar (600 psi). The construction of other plants followed shortly after. The creation of Water Plant 21 in California lead to the designation of industry standards, e.g. the 8-inch spiral wound element. In 1977 in Pelican Bay, Florida the first RO plant was built for softening applications. Many ground water sources in Florida are colored and hard and the membranes are able to get rid of both issues simultaneously. By 2008, the total worldwide installed capacity of membrane desalination amounted to 42,000,000 m^3/d. In the US alone, the capacity is 5,700,000 m^3/d produced by 1100 plants, which is 3 percent of the total water provided by public water systems. There are membrane desalination plants in every US state. (Crittenden et al., 2012)

RO Process description

The solutes in the water and the water are different in chemical and physical properties. Due to this fact RO is possible. The feed stream is pushed with high pressure across the surface of the semipermeable membrane. The output of the non-permeable side of the membrane is a more concentrated feed stream, whereas on the permeable side the solutes have been rejected. This process is continuous and there is no periodic backwash cycle. (Crittenden et al., 2012)

The smallest element of the production capacity is the membrane element, which is enclosed by the pressure vessel. The pressure vessels are mounted on skids. Each skid is having pipes for the feed, concentrate and permeate stream. A stage consists of pressure vessels that are operated in parallel. Multistage systems are also possible, which can have two different characteristics, as seen on Figure 7. Firstly, it is possible to run the concentrate through an additional stage to improve water recovery (Figure 7 (a)). Secondly,

the permeate can be run through an additional stage to increase the solute removal (Figure 7 (b)). In each additional stage of the multistage system the number of vessels is reduced to compensate for the loss in stream velocity of the feed channel. An array is a unit of production capacity consisting of one or more stages. The inside of a typical RO facility can be seen in Figure 8. Several factors influence the permeate to feed-water flow (recovery) ratio, such as the osmotic pressure, concentration polarization and solubility of sparingly soluble salts. The ratios range from 50 to 90 percent. (Crittenden et al., 2012)

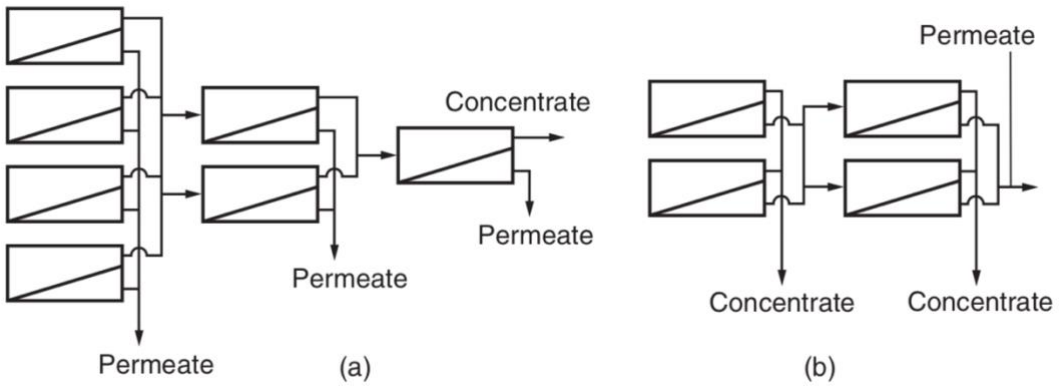

Figure 7 Array configurations of RO facilities Source: (Crittenden et al., 2012)

Figure 8 Inside of a typical RO facility Source: (Lowell, 2015)

Pretreatment

As water is removed during the RO process, the feed becomes more concentrated and some salts become insoluble during the process. The salts can cause scaling in the membrane and even damage it beyond repair. To control scaling, it is possible to adjust the pH-value with the aid of acid during the pretreatment process to change the solubility of the salts. Another common method, which can be used in addition or instead of pH control, is the addition of an antiscalant. (Crittenden et al., 2012)

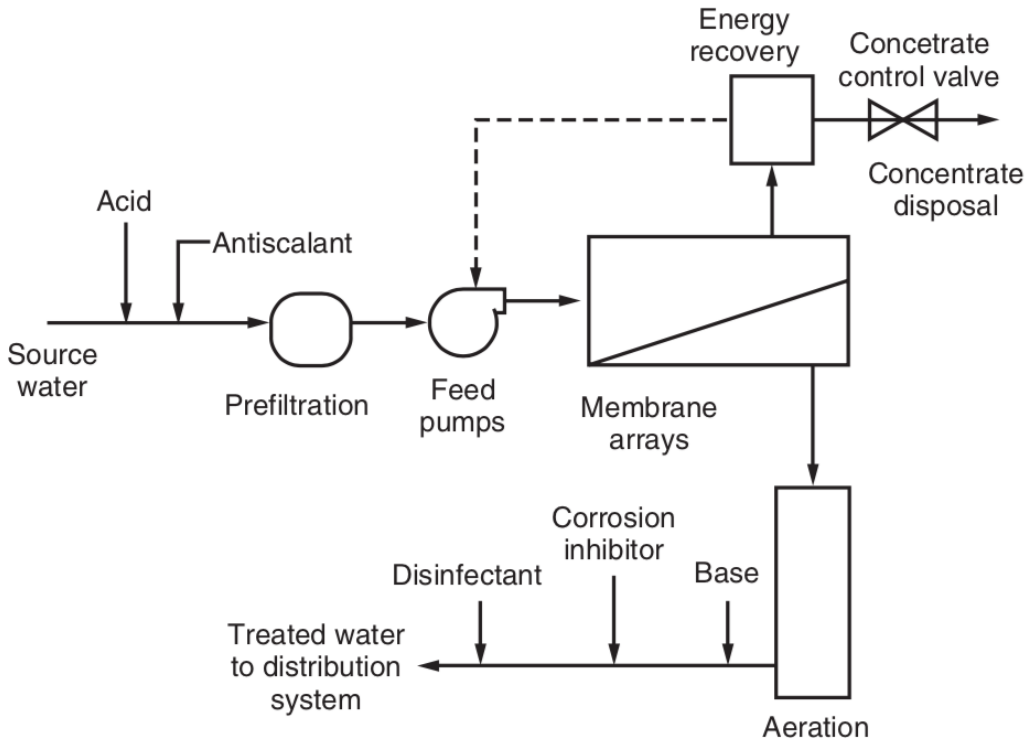

Figure 9 Schematics of a RO facility Source: (Crittenden et al., 2012)

The second pretreatment process is filtration, which can be cartridge filtration, granulate filtration or membrane filtration. The aim is to remove particles that can clog the feed channel or gather on the membrane surface. Cartridge filtration is the lower bound of the pretreatment process and strainers with a maximum opening of 5μm are used. It is more common to use granulate or membrane filtration at this step for surface water. The addition of a disinfectant is necessary to prevent biofouling, but it should be bore in mind that the

disinfectant must be compatible with the membrane material. After pretreatment, the feed pumps pressurize the water from 55 to 86 bar (800 to 1200 psi) for seawater RO. (Crittenden et al., 2012)

Posttreatment

The purpose of posttreatment is to remove dissolved gases and alkalinity and to adjust the pH value. Membranes lack the ability to remove gases and hydrogen sulfide efficiently, therefore these substances must be removed before distribution to the consumer. If sulfides are removed, additional measures must be taken to prevent odor and corrosion problems. If CO_2 is removed, it raises the pH value of the water and therefore less base is needed to neutralize the acidity, which was added to the water in pretreatment, to avoid scaling. The added acidity can also cause corrosion problems to the equipment and piping and should be addressed by adding corrosion inhibitors. (Crittenden et al., 2012)

Concentrate Stream

After the concentrate stream passes through the final membrane, there is still high pressure on the stream. The energy in form of pressure would be wasted through the concentrate control valve, therefore it is possible and applied by many RO facilities, to install energy recovery equipment on the concentrate line. The concentrate itself must be discarded and some treatment may be necessary before disposal. Some disposal methods are: ocean, brackish river,

sewer, deep-well injection, evaporation ponds, infiltration basins and irrigation. (Crittenden et al., 2012)

Membrane Element Configuration

There are two types of configuration for RO membranes, spiral-wound and hollow-fine-fiber. This work focuses on the more commonly used spiral-wound configuration:

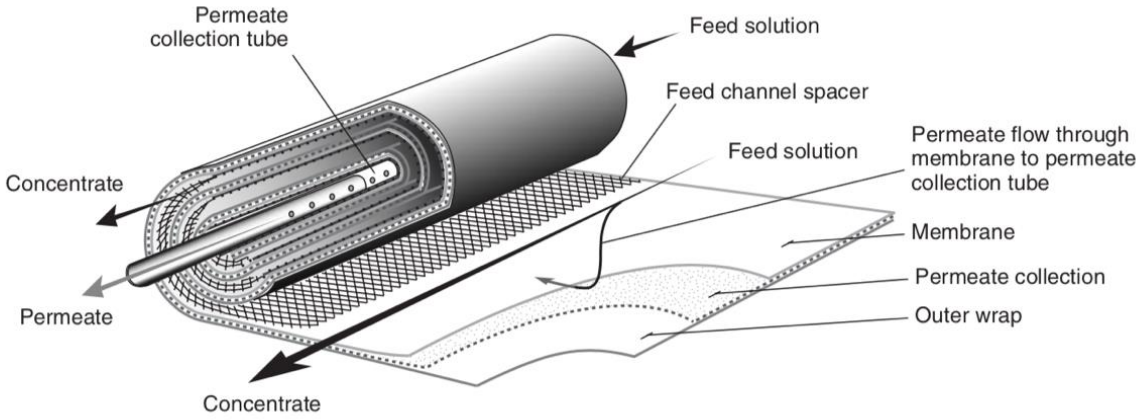

Figure 10 Construction of a spiral-wound membrane element Source: (Crittenden et al., 2012)

The spiral-wound-module consists of several elements in series. Two sheets of flat-sheet membrane material are sealed along 3 sides to form an envelope, with an active membrane layer facing out. To avoid the surfaces touching each other a permeate carrier spacer material is placed inside the envelope, which provides a flow-path for the permeate. Multiple envelopes are connected to a perforated central tube, the permeate collection tube. Mesh spacers are placed on the feed side to create a flow path for the feed water. Due to rolling the envelopes around the permeate collection tube, a spirally shaped feed channel is formed by the exterior spacer. One side of this channel is supplied with the feed water and the concentrate flows from the other end, therefore it is known as the feed-concentrate channel. The water that flows through this channel is exposed to the membrane surface. (Crittenden et al., 2012)

The elements are usually from 1m to 1.5m in length and the diameter is from 0.1m to 0.46m, although 0.2m is the most common. Four to seven elements

are connected together is series in a pressure vessel. They are connected together by their permeate collection tubes. (Crittenden et al., 2012)

In the process of operation, feed-water is pressurized and pumped into the pressure vessel from which it enters the first membrane element. The water follows the path and flows tangentially across the membrane surface, from which some of the water passes through the membrane surface and enters the membrane envelope and finally reaches the permeate collection tube. The rest of the feed water, which is now the concentrate, enters the next membrane element in series. The process is repeated until all elements in the series have been passed and the concentrate exits the pressure vessel. Each spiral-wound element provides a permeate recovery rate of 5 to 15 percent. (Crittenden et al., 2012)

Multi-Stage Flash (MSF)

The multi-stage flash is a distillation (or thermal) process, which uses the principle of flash evaporation. (Khawaji et al., 2008) That means that the feed water is heated in the heating section of the system and enters a lower pressure chamber. Due to the difference in pressure, the water “flashes” into steam. The steam is turned into distillate by the condensers. The feed water runs through multiple low pressure chambers, known as stages, to increase the water recovery. (Voutchkov, 2012)

History

In 1965, the Scottish Professor Robert Silver registered the patent for the Multi-Stage-Flash process – MSF (although other sources claim that the concept was invented in the 1950s (Shatat & Riffat, 2014) which implies that the patent was registered much later than the invention, since the design was presented in 1959 (Al-Wazzan & Al-Modaf, 2001)). It built the groundwork for today’s MSF desalination plants. The most remarkable part of his work is the simplicity by which he implemented the technical aspect of the flash process. He avoided the immersion heater principle, where the heating element is submerged into the water, by physically separating the heat input from the actual evaporation,

which otherwise would cause extreme scaling on the heat exchanger surface and was the main difficulty in evaporation of saline water. (Kucera, 2014)

In 1957 the Westinghouse Company built the first commercial MSF plant in Shuwaik near Kuwait's harbor. It was a simple four-stages system based on an older model of a multi-effect system, the once-through system, and had a capacity of 2270 m^3/day. In 1959 a 19-stage system based on the design of Professor Silver was presented. The Weir Westgate Company built 5 plants based on that design from 1965 to 1966 with a capacity of 4540 m^3/day each. (Al-Wazzan & Al-Modaf, 2001)

The new design ignited a new era for seawater desalination. New MSF plants were built constantly, reaching a total capacity of 40 million m^3/day in 2014. Some of the largest plants operating today use the MSF technology. It is common to build such a plant next to a power plant to heat up the water through the excess heat of the power plant. (Kucera, 2014)

Nowadays, modern plants have around 20 stages. MSF desalination is not the most energy efficient method and also not the cheapest in relation to the investment, but, the robust construction, long operating life of 20 to 30 years and the possibility to use excess energy from a power plant explain the high market share of MSF. (Kucera, 2014) Roughly half of the worlds desalinated water is achieved by distillation processes, of which 84 percent are accounted

to MSF. Most MSF plants are located in the Middle East due to low energy prices. (Shatat & Riffat, 2014)

MSF Process Description

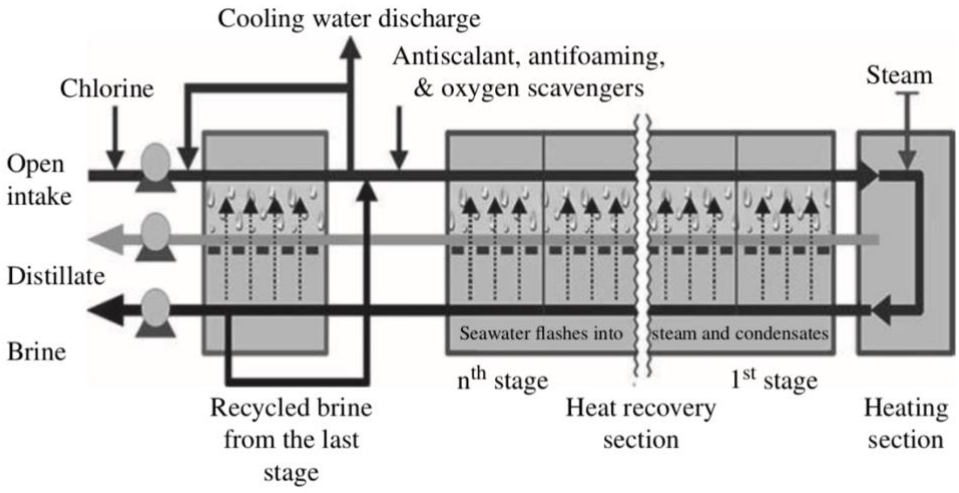

Figure 11 Schematic of an MSF plant Source: (Voutchkov, 2012)

Figure 11 shows the schematic of an MSF plant. The feed water (saline water or seawater), is heated in a vessel, called the brine heater. It is heated up to a point where the temperature reaches a point slightly lower than the saturation boiling temperature, usually 90°C to 115°C. The heated feed water flows into a series of vessels in sequence with a decreasing ambient pressure. The low pressure causes the water to boil instantly and "flash" into steam. Consequently, a minor percentage of the water is transformed into vapor until the water cools down and boiling comes to a halt. The flashing process produces fresh water in form of a distillate by collecting the condensate on the condenser, where heat exchanger tubes are installed, which runs through all stages. But, before the steam reaches the condenser, entrainment separators remove the high salinity mist from the low salinity rising steam. The distillate, now pure water, is collected in distillate trays from where it runs from stage to stage. In the last stage the distillate is collected and transferred to the product water tank. The seawater runs as a feed through the inner tube of the condenser. The cool water allows for the steam inside the stages to condensate. At the same time the steam warms up the feed water and by the time it reaches the brine heater, less energy is needed to increase the

temperature to the desired level. Recent MSF plants recycle some of the brine, which means it is collected at the last stage and added to the source water. The benefits of brine recycling are on the one hand, the reduction of the amount of source water collected by the intake and on the other hand, the brine is still warm and increases the temperature of the feed water in addition to the steam at the condensation process. According to El-Dessouky et al. (1998) it also reduces the use of additives to the feed-water like anti-scalants, because the brine already contains those additives that were added at the beginning of the cycle and also reduces the size of the pretreatment facilities. (El-Dessouky et al., 1998) The result is a feed water temperature that almost reaches the desired operating temperature, and therefor reduces the operating costs of the MSF system. When the heated water leaves the heating section and enters the first stage, the pressure, at each consecutive stage is continuously reduced below atmospheric pressure. This causes the water to boil at each stage, although the temperature is reduced at each stage. In other words, boiling is achieved by reducing pressure instead of increasing temperature. (Shatat & Riffat, 2014; Voutchkov, 2012)

At each stage roughly 1 per cent of the total volume of the feed water is recovered. That means a plant with 20 stages, where at each stage 1 percent is recovered, has a total water recovery of 20 percent. In comparison, RO systems have a recovery of 40 to 45 percent. Latest MSF technology allows to implement 45 stages, and therefor 45 percent recovery, which can compete with RO in terms of recovery. (Voutchkov, 2012)

Pretreatment

The main goal of the pretreatment process is, among other things, the reduction or prevention of scale formation. To achieve this goal, different methods can be applied, including additives and nanofiltration. (Ghani & Al-Deffeeri, 2010) Before the water enters the desalination plant and becomes the feed water, a simple screening or filtration can be applied. Pretreatment of

the feed water is in contrast more thorough and can consist of the addition of an anti-scalant and foaming inhibitor. (El-Dessouky et al., 1998)

Untreated feed water should reach a top brine temperature (TBT) in MSF desalination of 110-112°C to avoid excessive scale deposits. Scale deposits have influence on pumping power, fouling factor and overall heat transfer and can cause surface friction losses and pressure drop. (Al-Rawajfeh, 2011)

In the group of additive treatments, acid treatment is a possibility for scale prevention. Acid, usually H_2SO_4, is added to the feed water and reacts with the carbonate of the seawater. The reaction produces H_2O and CO_2 and hence, prevents the formation of calcium carbonate $CaCO_3$, which causes scale. The dosing should be precise to achieve the desired pH value, otherwise corrosion problems may arise. Another additive treatment possibility is chemical additive treatment, which is the use of scaling inhibitors or anti-scalants, with the goal to suppress or delay scale formation. A positive side effect of chemical treatment is the prevention of adhesion of percipitated particles to the inner tube surfaces. However, chemical treatment requires the need for mechanical cleaning of the internal tubes by a sponge ball. A hybrid treatment of the two previously mentioned methods is also possible. Adding less scale inhibitors than when using chemical treatment alone and using acid for partial depletion of carbonate. (Ghani & Al-Deffeeri, 2010)

Nanofiltration (NF) is a membrane filtration method that is suitable for pretreatment because it can be configured at a loose membrane structure, which allows to be operated at lower pressures than RO and consequently lower cost. NF also achieves a higher flux than RO and the MSF process can be supplied with sufficient filtered feed water. The pores are larger than in the RO process (Figure 6), however they are still able to filter scale forming divalent ions such as calcium and magnesium. By preventing those ions from entering the thermal process, a higher TBT can be applied, and the MSF plant can operate more efficiently. Anti-scalants cannot allow the TBT to increase effectively because their effectiveness reduces with increasing temperature and higher temperatures increase scale formation that cannot be prevented by

current anti-scalants. Table 2 shows the effectiveness of NF pretreatment. For example, the process was able to reject calcium and magnesium ions by 71 and 82 percent, respectively and a total TDS reduction of 38 percent. Consequently a TBT of 175°C was suitable. (Al-Rawajfeh, 2011 & 2016)

Ions	NF Feed [ppm]	NF permeate [ppm]	Rejection rate (%)
Ca^{2+}	600	176.7	71
Mg^{2+}	1550	272.4	82
Na^{+}	14840	10523.0	29
K^{+}	500	483.0	3
Ba^{2+}	0.07	0.017	76
Sr^{2+}	18	4.3	76
SO_4^{2-}	3440	423.2	88
HCO_3^{-}	128	48.0	62
CO_3^{2-}	38	3.2	92
Cl^{-}	26253	17425.5	34
TDS	47367	29360.0	38
pH	8.2	7.8	–

Table 2 Water composition before and after NF treatment Source: (Al-Rawajfeh, 2016)

Posttreatment

Caused by some pretreatment methods, the product water is aggressive and must therefore be treated before pumped into main water pipes. The untreated water can attack the iron pipes and cause corrosion and dissolve the protective layer of the pipes, namely calcium and other salts. Also, to make the water safe and suitable for human consumption. Hence, post-treatment is necessary and contains the following steps:

1. Increase pH level and add alkalinity as HCO_3^-
2. Addition of calcium as $CaCO_3$ (Semiat, 2000)
3. Aeration (Nada et al., 1987)

Because in the stages of the MSF process there is a lack of oxygen, due to operation under vacuum, the addition of compressed air helps to enrich the water with oxygen and increase the taste. Passing the water through

limestone, causes the calcium in the limestone to dissolve and enrich the water with $CaCO_3$. (Nada et al., 1987)

If post-treated water is mixed with other water supply sources, then it should match the existing water source within reasonable limits to avoid problems like excess gases. (Gacem et al., 2012)

Multiple-Effect Distillation (MED)

The Multiple-Effect Distillation is based on the oldest desalination method. It is a thermodynamically efficient method. In a series of evaporator vessels called effects, the ambient pressure is reduced in the various effects. This method allows for multiple boilings without adding additional heat. The preheated seawater is sprayed on the surface of the evaporator tubes to allow rapid evaporation. (Khawaji et al., 2008)

History

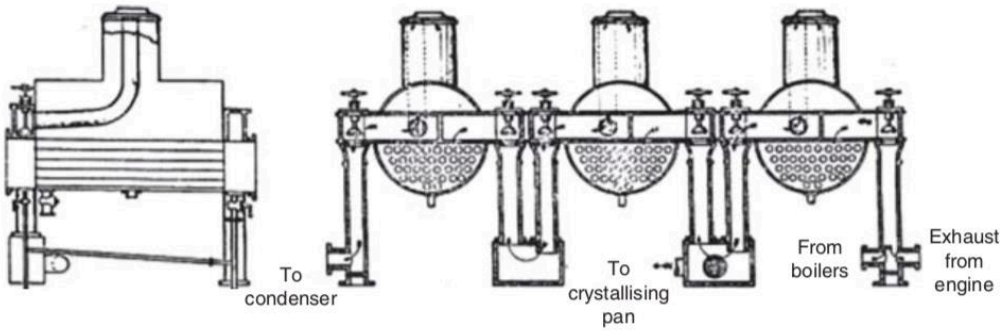

Figure 12 Rillieux's multiple-effect evaporator patent 1846 Source: (Kucera, 2014)

Progress in the world of evaporators began in the 19th century, but for a different reason than seawater desalination. The world-wide demand for pure, white refined sugar expanded rapidly. To understand the relevance, a very brief description of the sugar process is given. Sugar beets or canes are cut into small pieces and with the addition of heat, the water in the sugar canes or beets evaporates. This process is carried out as long as the sugar starts to crystalize. This process required enormous amounts of energy, which led the rising of sugar prices. As a first solution, manufacturers began to burn the

begasse (plant remains) and use them as an energy source. While the solution was clever, it was not good enough, meaning that more energy was needed than the plant remains could deliver. Consequently, additional energy had to be bought, which impacted the sugar prices again. In 1846 (according to Birkett it was in 1843), Norbert Rillieux registered the patent for multiple-effect evaporator, which can be seen in Figure 12. He explained that for every pound of steam, as many pounds of water can be evaporated as there are bodies in the system. The energy provided by the begasse was now efficient enough for the process. Evaporators in today's sugar industry vary only slightly from the original model. The concepts on energy saving learned from this model can be applied to seawater desalination. (Kucera, 2014)

The difference from concentrating sugar and producing drinkable water from seawater, is that in the first case the steam is used to produce sugar and in the latter case the steam is the product. In sugar production, crystallization produces the product, while in water production crystallization leads to scale and must be avoided. In the 1960s the produced fresh water was expensive and only used in regions where it was absolutely necessary, or costs were not important, like strategically important military sites. The high price was due to the risk of scaling, the high danger of corrosion because of the salt water and the immense energy consumption, due to the lack of a large number of stages. The largest plant at that time produced 7500 m^3/d of water and had a submerged evaporator (the heater is submerged in water). The biggest problem with this kind of heating is that the heater is in constant contact with the saltwater and scaling on the exchanger tubes is inevitable. The solution to this was the thin film method (and will be explained in the following section). MED plants with film evaporators are popular among plants with a capacity of 5000 to 25000 m^3/d, and therefore have a high market share in this capacity segment. (Kucera, 2014) MSF replaced MED until the 1980s where new

designs were introduced. Those were able to operate on lower temperature and therefore minimize corrosion and scaling. (Buros, 2000)

Process Description

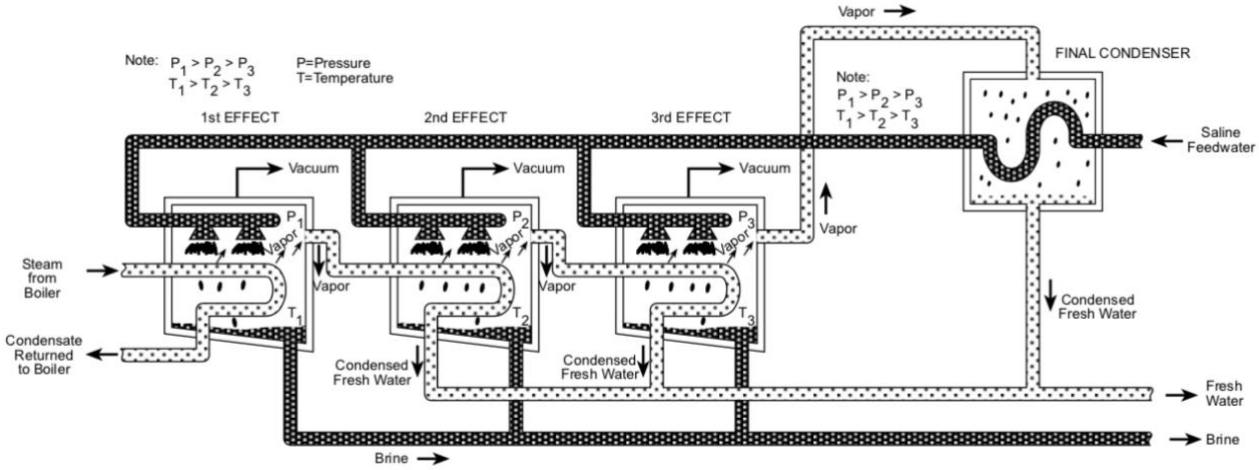

Figure 13 Schematics of a multi-effect distillation plant with horizontal tubes Source: (Buros, 2000)

Like MSF, MED is based on the principles of evaporation and condensation, uses multiple effects and reduced ambient pressure. After the first effect, no additional heat is added to the following effects and boiling is achieved by reducing pressure. Each effect consists of: a vessel, heat exchanger area and devices for transporting different fluids between effects. Different models and designs exist for the heat exchanger area, including vertical tubes with falling brine film or rising liquids and horizontal tubes with falling film. The most common by far are horizontal tubes with falling film. The schematics of such a system can be seen on Figure 13. (Buros, 2000)

The evaporator tube of the first effect is heated by steam, typically but not necessarily, provided by a nearby power plant. Heating by a boiler is also possible. The seawater is then applied to the evaporator tubes, usually in equal amounts to all effects. There are several methods to apply the water to the tube, in case of the thin film method, water is sprayed on the tubes to form a thin film, which leads to fast boiling and evaporation. After the evaporator tube of the first effect is heated by the external heat source, the cooler feed water causes the steam inside of the tube to condensate. The condensate of the

steam flows back to the boiler of the heat source. In exchange, a portion of the seawater that is sprayed onto the tube, evaporates. The vapor from the condensation heats the evaporator tube of the second effect. The second effect has a lower atmospheric pressure than the first effect and compensates for the heat loss and causes the water in the second stage to boil and evaporate. The vapor that was fed into the second effect from the first effect condensates and is collected as distillate. The process repeats as the vapor from the evaporation of the second stage is fed into the third stage. The process continues for all following stages. In the last step of the process, the vapor enters the so-called final condenser, where it condensates on the feed water tube and flows into the product water tube. At the same time the seawater is preheated by the vapor. The portion of the feed water that doesn't evaporate, is collected as brine and discharged. Some plant designs transfer the brine to the next effect, where some of it flashes into steam due to the lower atmospheric pressure and is then processed with the vapor from the regular evaporation process in each effect. The total efficiency of a MED plant is dependent on the temperature range available and the temperature difference allowed between the effects. Plant's effects vary from 4-21 effects. Recent plants operate at a top temperature in the first effect of around 70°C to reduce the amount of scale. (Buros, 2000; Shatat & Riffat, 2014)

Pretreatment and Posttreatment

The feed water quality in a MED plant is not as important as in a RO plant. Therefore, pretreatment costs are lower. (Shatat & Riffat, 2014) Since the market share of MED is around 3 percent worldwide (Greenlee et al., 2009), there isn't enough literature on the Pre- and Posttreatment. MED is a distillation method similar to MSF and therefor it is assumed that Pre- and Posttreatment are similar to MSF.

Cost of Freshwater from Desalination

Literature Review

When reading about costs of desalination, typically three types of costs are discussed in the literature. Those costs are capital cost or capital expenditure (CAPEX), operating cost (OPEX) and Total Water Cost (TWC). (Huehmer, 2016)

Capital Cost

The capital cost includes expenses related to the implementation of a desalination project and include both direct and indirect costs. The costs range from the conception to design, permitting, financing, construction,

commissioning and acceptance testing for normal operation. These points include the following costs:

- Installed process equipment (e.g. membrane racks, pumps, etc.)
- Auxiliary equipment
- Piping
- Raw water transfer
- Site civil works
- Intake construction
- Brine discharge infrastructure
- Buildings
- Roads
- Laboratories
- Procurement of land
- Interest payment
- Working capital
- Freight and insurance
- Contingencies
- Import duties
- Project management
- Architectural and engineering fees
- Water storage
- Permitting
- Taxes (Ghaffour et al., 2013; Huehmer, 2016)

Operating Cost

The operating cost, operating expenditure (OPEX) or operation and maintenance cost (O&M) consists of the ongoing costs for operating the desalination plant. It contains the following components:

- Replacement parts (membranes for RO, broken parts, etc.)
- Chemicals for pre- and post-treatment
- Energy costs to run the plant
- Environmental monitoring
- Labor costs

- Management costs
- Laboratory analysis and monitoring
- Disposal cost
- Institutional charges (compliance and regulatory costs, access charges) (Huehmer, 2016; Kucera, 2014; Ziolkowska, 2015)

Some of the costs, like labor costs, are fixed costs, i.e. they are independent from the amount of water produced. Others, are dependent on the output, like energy costs and costs for chemicals. (Kucera, 2014)

Plant Lifetime

To assign the CAPEX to each unit of product water, it is necessary to amortize the capital expenditure over the lifetime of the plant. To do this, first a plant lifetime has to be determined. In the literature there is different data on the

matter. Most authors assume a lifetime between 20 to 30 years. The following table sums up the different statements:

Lifetime in years	Source
10	(Eslamimanesh & Hatamipour, 2010; Kumar et al., 2015)
15	(Suárez et al., 2015)
20	(Choi et al., 2015; Hossam-Eldin et al., 2012; Kalogirou, 2001; Karagiannis & Soldatos, 2007; Mabrouk & Fath, 2015; Mokhtari et al., 2016; Palenzuela et al., 2015; Shahabi et al., 2015; Szacsvay et al., 1999)
25	(Al-Hamahmy et al., 2016; Aparicio et al., 2017; Ashour & Ghurbal, 2004; Bilton et al., 2011; Moser et al., 2013; Wade, 2001)
30	(Abo Zaid, 2015; Ettouney et al., 2002; Fiorenza et al., 2003; Rahimi et al., 2015)

As can be seen in the table above, 20 years and 25 years are the most commonly used values, with 9 and 6 mentions in the sample, respectively. 30 years is used relatively often with 4 mentions. 10 and 15 years are rarely used. If the mode value of the sample is taken, then 20 years should be used for the calculations. However, most papers, where the data is coming from, used 25 years for their calculation (e.g. Cooley & Ajami and Lapuente), hence, the data for this work will be normalized for a plant lifetime of 25 years.

Data

In the literature, often, the capital cost is stated as a one-time fixed cost. The OPEX is reported as an annual cost. Because they are stated in different ways, it is necessary to convert the CAPEX to an annual cost over the lifetime of the plant, typically a lifetime between 20 and 30 years is assumed. After both costs are annualized, it is possible to calculate the total annual cost of a plant.

(Kucera, 2014) From the annual cost, the Total Water Cost (TWC) per unit of product water can be calculated.

To evaluate an investment, most commonly, the Net Present Value (NPV), the Internal Rate of Return (IRR) or the (Discounted) Payback Period (PBP) are used. For the calculation of the NPV, it is required to know the initial capital investment (I_0), the revenues (R_t) and costs (C_t) in year t, for all years up to the last year (n), as well as an discount rate (i). The formula for the NPV is as follows:

$$NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+i)^t} - I_0$$

Often in scientific literature, the choice of an appropriate discount rate can be difficult or random, because it varies from countries, industries and over time. The selection can be difficult because it is also affected by non-technological aspects and expresses the return of the investor. To calculate without the need of a discount rate, the IRR is an appropriate method, as it calculates the break-even point of the NPV (NPV = 0). It calculates the discount rate that is required to achieve the break-even point at the end of the technical or accounting lifetime. In this case the discount rate can be seen as the return on investment of the project. (Papapetrou et al., 2017)

For desalination projects, the revenue represents the amount of water sold. To calculate, the knowledge of the water produced and the price at which it can be sold is required. In practice, for example, the water is sold to a municipality at the predetermined price and amount. For theoretical calculations it is difficult to determine a water price over a period of 20 to 30 years (lifetime of a desalination plant) due to the volatility of the market. Electricity producers face a similar problem, where they are uncertain of the electricity price. In the case of electricity, the Levelized Cost of Electricity (LCOE) is used to tackle this problem. The LCOE evaluates the price at which the electricity would have to be sold to break even for the project. To calculate the LCOE, the discounted cost over the lifetime of the project is calculated and divided by the discounted

energy produced over the lifetime. The same concept can be adapted for water desalination and is called Levelized Cost of Water (LCOW). The annual cost of operation in time t ($O\&M_t$) and the amount of water produced in year t ($M_{w,t}$) are introduced and result in the following equation: (Papapetrou et al., 2017)

$$LCOW = \frac{I_0 + \sum_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{w,t}}{(1+i)^t}}$$

While the NPV, IRR and LCOW have their reasons to exist, there is a more appropriate and commonly used method to determine desalination costs. Many expressions are used for the method, e.g. amortization factor, simplified cost of water, annualized life cycle cost, or simply annualized cost (AC). The latter will be used in this work. The equation is:

$$AC = \frac{(I_o * \alpha) + O\&M}{M_w}$$

The amortization factor is expressed with α and calculated as follows:

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1}$$

(Papapetrou et al., 2017)

or rewritten as:

$$\alpha = \frac{i}{1 - (1+i)^{-n}}$$

(“energycommunity.org,” n.d.)

Having a closer look at the AC equation, one can see that I_0 represents the CAPEX and M_w is the capacity of the desalination plant per year. The capacity per year is the theoretical maximum capacity multiplied by the plant availability. Or in other words, the capacity per day multiplied by the number of days that the plant is in operation (e.g. if the plant has an availability of 95 percent it

means that the availability is 346 days a year). Making these changes in the denomination, it becomes apparent that the AC is the Total Water Cost (TWC):

$$TWC = \frac{(CAPEX * \alpha) + O\&M}{Capacity * Plant\ Availability}$$

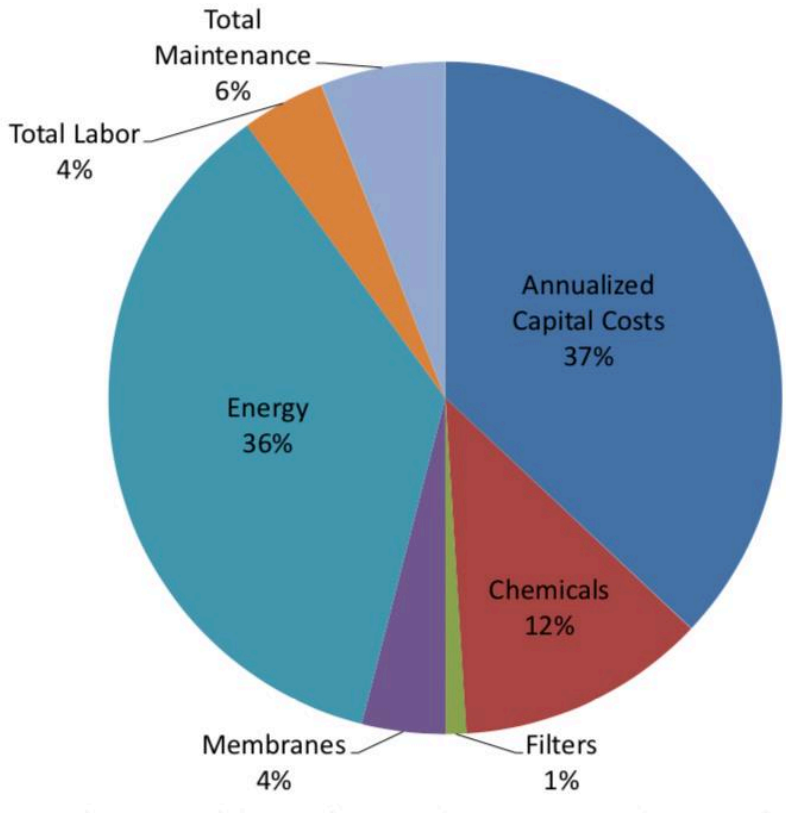

Figure 14 Annual Cost Breakdown of a Typical Seawater Desalination Plant Source: (Gleick, 2014)

Figure 14 shows the cost break down of a seawater desalination plant. In this case, a reverse osmosis plant with a capacity if 190000 m^3/day, energy costs of $0.07/kWh, membrane life of five years, nominal interest rate of 5 per cent and a depreciation period of 25 years. Naturally, these costs vary from project to project, however, this is a rough representation of other desalination plants. The annualized capital costs represent about one third of the total annual costs. As can be seen in the graphic, the energy costs are the largest O&M cost and also represent one third of the total annual cost. The remaining costs

depend on the location and feed water quality, but in general chemicals are responsible for about 10 per cent of the total cost. (Gleick, 2014)

Abo Zaid claims different values. She assumes, for reverse osmosis, investment costs of 22 - 27%, and O&M costs of 73 – 78%. For MSF distillation she assumes 25 – 30% investment costs and 70 – 75% O&M costs. (Abo Zaid, 2015)

Lapuente calculated the portion of costs for the Segura River Basin area in a case study of eight desalination plants that produce water for that region. The results are similar to those of Cooley and Ajami, as can be seen in Figure 15. Capital costs are around 39% and O&M costs are 61%. The biggest O&M cost is again the energy cost, with 38% of the total cost. (Lapuente, 2012)

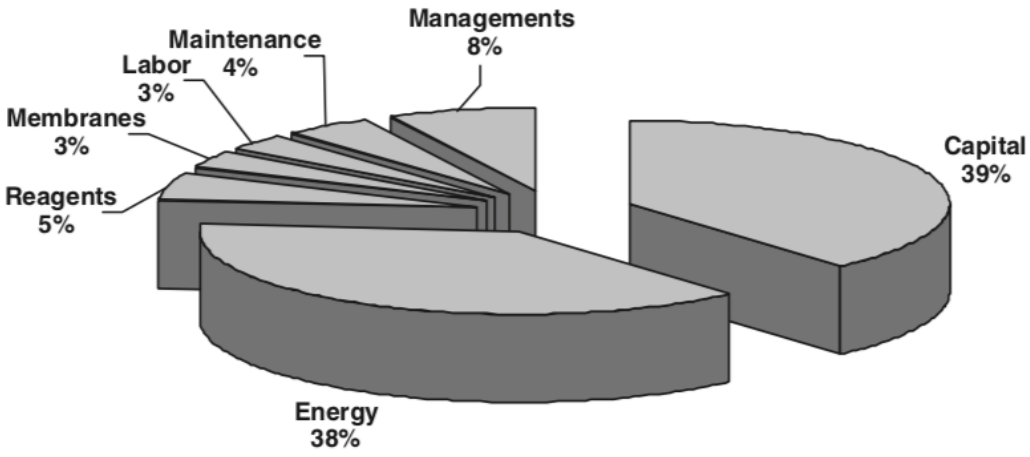

Figure 15 Cost Breakdown for Desalinated Water in the Segura River Basin Source: (Lapuente, 2012)

Many sources for the data have not included the O&M costs, but only the CAPEX. Therefore, it is necessary to estimate the O&M costs for the missing

data points. Summing up the previous information, the following table is obtained:

	CAPEX in %	**O&M in % (including energy costs)**
(Gleick, 2014)	37	63
(Abo Zaid, 2015)	24.5*)	75.5*)
(Lapuente, 2012)	39	61
Mean value	33.5	66.5
*) mean value of the range		

The papers, where the data for the following analysis is coming from, are from different years, so the prices will be adjusted for August 2018 using the U.S. Bureau of Labor Statistics' inflation calculator (https://data.bls.gov/cgi-bin/cpicalc.pl). The vast majority of the data is in US Dollars. The fraction that is in other currencies will be converted to US Dollars using the average exchange rate of that year. The collected data will be normalized according to the previously mentioned points and the result is the total water cost adjusted for 2018 prices.

Regression Analysis

In this chapter the collected data will be analyzed to identify which factors influence the water price for desalination, i.e. size, location, total dissolved solids (TDS) in the feed water or year of construction. The Database will be split into seawater reverse osmosis desalination (SWRO) and brackish water reverse osmosis desalination (BWRO) and analyzed separately, to rule out the influence of the different source water types on the price. Also, the SWRO plants will be split into OECD and Non-OECD countries in a separate analysis to investigate the influence of location.

Simple Regression by Feed Water Type

Plant size

In the first analysis, the influence of the plant size on the TWC will be investigated. In the scatter plot in Figure 16, the x-axis represents the independent variable, in this case the plant size in terms of capacity per day (m^3/day) and on the y-axis the values for the dependent variable, the TWC, are represented. The red line is the logarithmic trendline of the data. It suggests that for smaller desalination plants the size has a bigger impact on the price than desalination plants with a capacity larger than 100,000 m^3/day. The trendline is steep from 0 – 100,000 and levels off once it passes the 100,000 m^3/day barrier. However, smaller plants are able to produce water

across a large range of prices, even as low as plants with a capacity of 500,000 m^3/day.

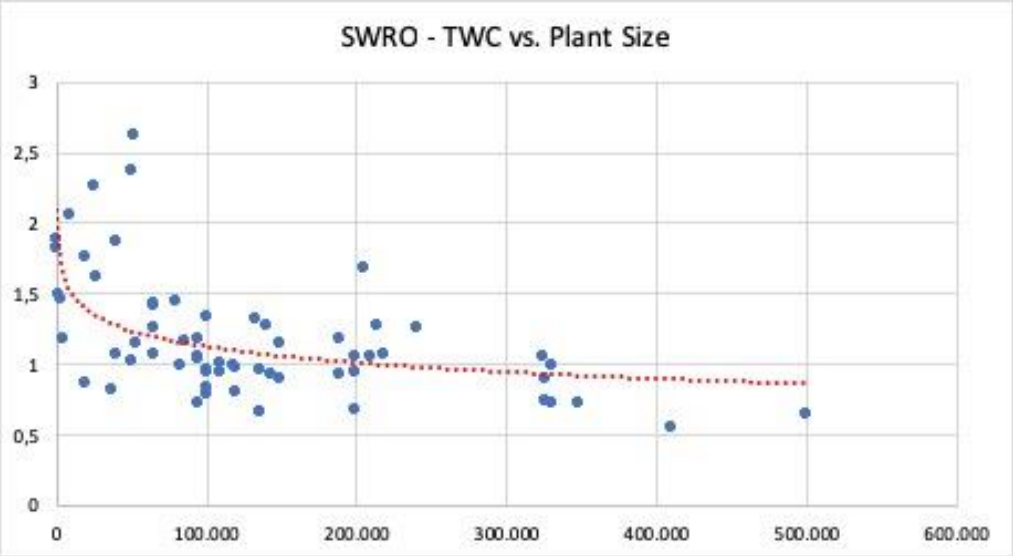

Figure 16 SWRO – TWC vs. Plant SIze

After conducting the regression analysis, the following data is received (excerpt, full output in Appendix 1):

Nr. Of observations	64	
R^2	0.269	
Standard Error	0.373	
Significance F	0.000	
	Coefficient	**P-value**
Intercept	1.445	0.000
Capacity in 100,000 m^3/day	-0.206	0.000

Overall, as it should be expected due to the principle of economies of scale, the coefficient of capacity is negative. This means that there is a negative correlation between TWC and capacity. Also, the significance F and the p-value are very low, which indicates that the results are statistically reliable. However, the overall regression accuracy R^2 is only 26.9 per cent, which says

that the regression line does not fit the data very well. The expected TWC can be calculated according to this formula:

$$TWC\ in\ \$ = \$1.445 - 0.206 * Capacity\ in\ 100{,}000\ m^3/day$$

The following scatter plot shows the accuracy of the prediction compared to the actual data (i.e. the deviation of the prediction from the actual data):

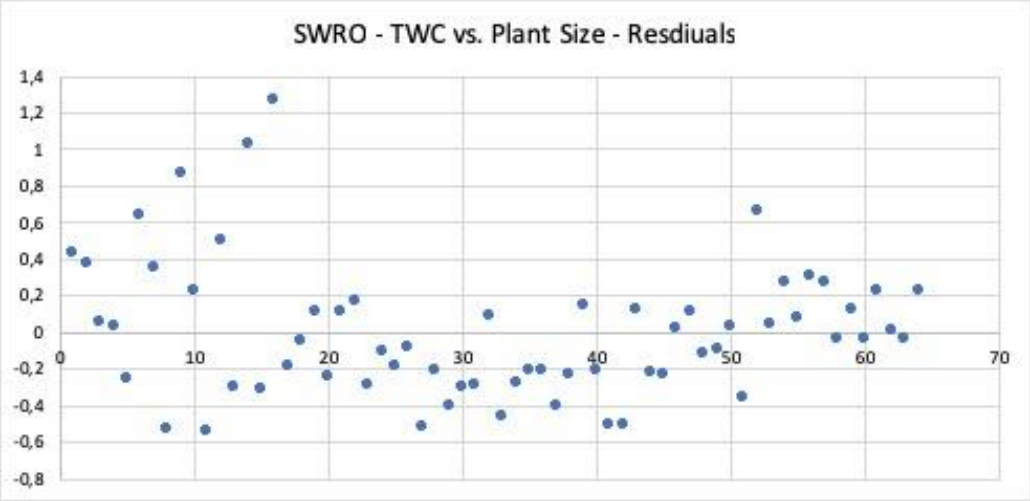

Figure 17 SWRO - TWC vs. Capacity – Residuals

It is interesting to note that in Figure 17 the predicted TWC gets more accurate from observation number 20 (compare Appendix 2) and is within the range of -0.4 to 0.4 (with a few exceptions).

Figure 18 shows the available data for BWRO desalination plants. There are two data points in the rough range of 60,000 m^3/day and 100,000 m^3/day that does not fit the principle of economies of scale as their prices increase with

increasing plant size. The logarithmic trendline doesn't show any considerable variation.

Figure 18 BWRO - TWC vs. Capacity

The result of the regression analysis is as follows (excerpt, full output in Appendix 3):

Nr. Of observations	26	
R^2	0.015	
Standard Error	0.205	
Significance F	0.557	
	Coefficient	**P-value**
Intercept	0.400	0.000
Capacity in 100,000 m^3/day	0.109	0.557

Surprisingly, the coefficient of capacity is positive which would mean that the larger the plant size the higher the TWC. As could be expected with the result, the R^2 is only 1.45 per cent. Also, the significance F is rather high, over 50 per cent. It could have been possible that the unexpected result is due to the fact that brackish water desalination can be split into two different types of feed water, i.e. groundwater and surface water. But, after checking the data, all of

the data points for brackish water in the database consist of groundwater desalination plants.

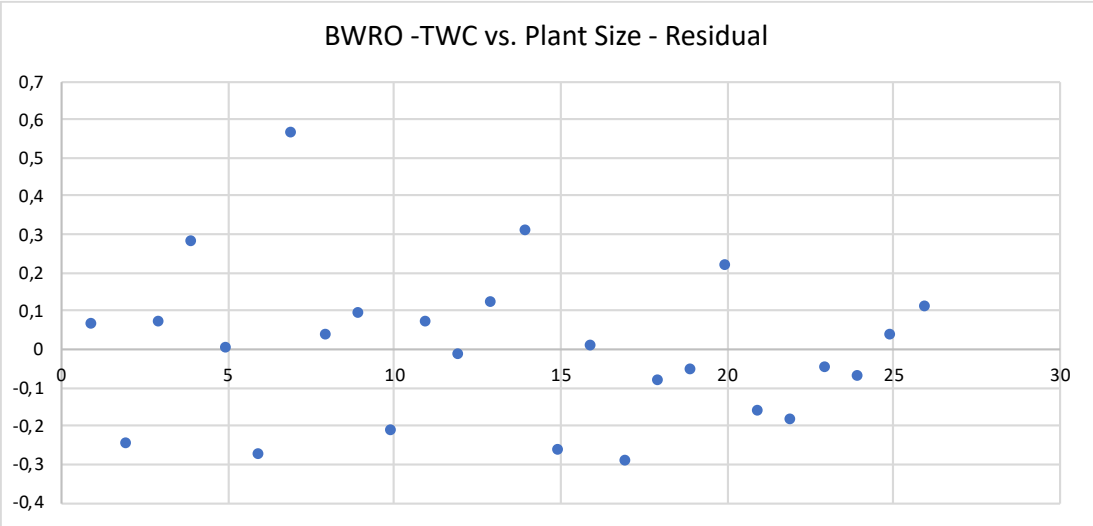

Figure 19 BWRO - TWC vs. Capacity – Residuals

Figure 19 shows the scatter plot of the residuals (compare Appendix 4).

Total Dissolved Solids (TDS)

In this chapter it will be analyzed, whether the TDS of the feed water influences the price of the water. TDS concentration can vary significantly across

locations and different source waters. Table 3 shows the typical concentration of seawater.

Salt	Concentration, mg/L
Cations	
Sodium, Na^+	10,800
Magnesium, Mg^{2+}	1,290
Calcium, Ca^{2+}	412
Potassium, K^+	399
Strontium, Sr^{2+}	7.9
Barium, Ba^{2+}	0.02
Anions	
Chloride, Cl^-	19,400
Sulfate, SO_4^{2-}	2,700
Total carbonate, CO_3^{2-}	142
Bromide, Br^-	67
Fluoride, F^-	1.3
Phosphate, HPO_4^{2-}	0.5
Total	35,200

Table 3 Concentration of TDS in Seawater Source:(Crittenden et al., 2012)

On average the TDS in sweater is 35,000 mg/L and the majority of that concentration is Sodium Na^+ and Chloride Cl^-. However, the average TDS varies across oceans:

Seawater Source	TDS (mg/L)
Atlantic Ocean	33,500
Pacific Ocean	33,500
Caribbean	36,000
Mediterranean	38,000
Gulf of Oman	40,000
Indian Ocean	40,000
Red Sea	41,000
Persian Gulf	45,000
Source: (Moonkhum et al., 2012)	

First, the analysis will be done for SWRO and then for BWRO. Some data points have been excluded in this part, due to the lack of information, regarding the TDS of the source water.

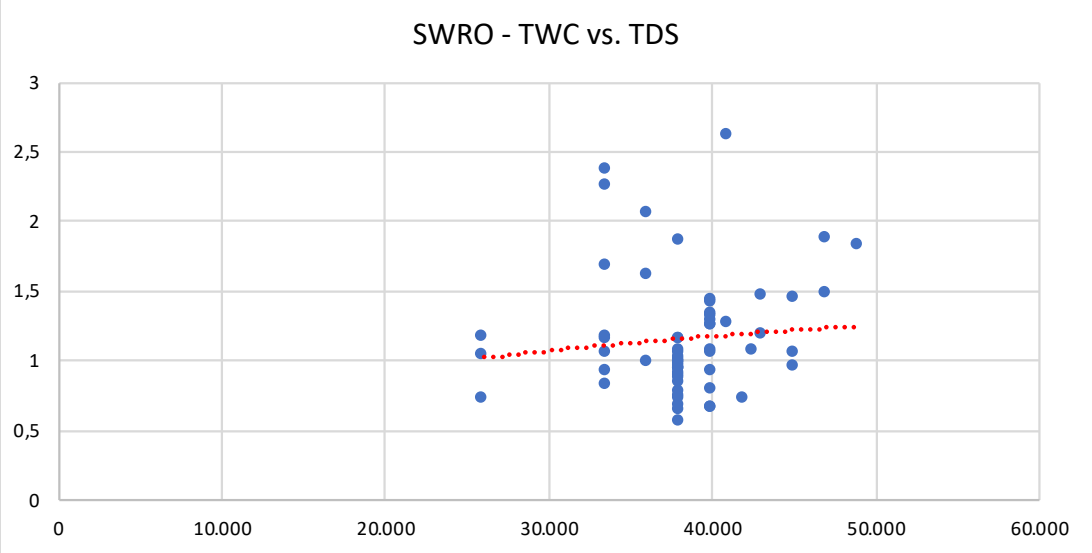

Figure 20 SWRO - TWC vs. TDS

Having a look at Figure 20, the red trendline reveals a slight increase in cost, although not by much. There are even some plants that produce cheaper water

at 42,500 mg/L than plants at 33,000 mg/L. Executing the regression analysis, we get the following results (excerpt, full output in Appendix 5):

Nr. Of observations	63	
R^2	0.014	
Standard Error	0.430	
Significance F	0.354	
	Coefficient	**P-value**
Intercept	0.714	0.144
TDS in 1000mg/L	0.012	0.354

Forming an equation from the regression analysis, would result in the following:

$$TWC\ in\ \$ = \$0.714 + 0.012 * TDS\ in\ 1000mg/L$$

However, the results of the regression analysis reveal that the TDS does not have a strong relationship to the TWC. The overall regression accuracy R^2 is a meager 1.4 per cent. Moreover, the F- and p – values are too high to indicate statistical significance of the results. Consequently, it can be said, that the source water TDS has no significant influence on the price of the water for the given data. Having a look at the residuals (Figure 21), confirms the

insignificance of the results, although it is not much worse than the residuals from the analysis of the pant size.

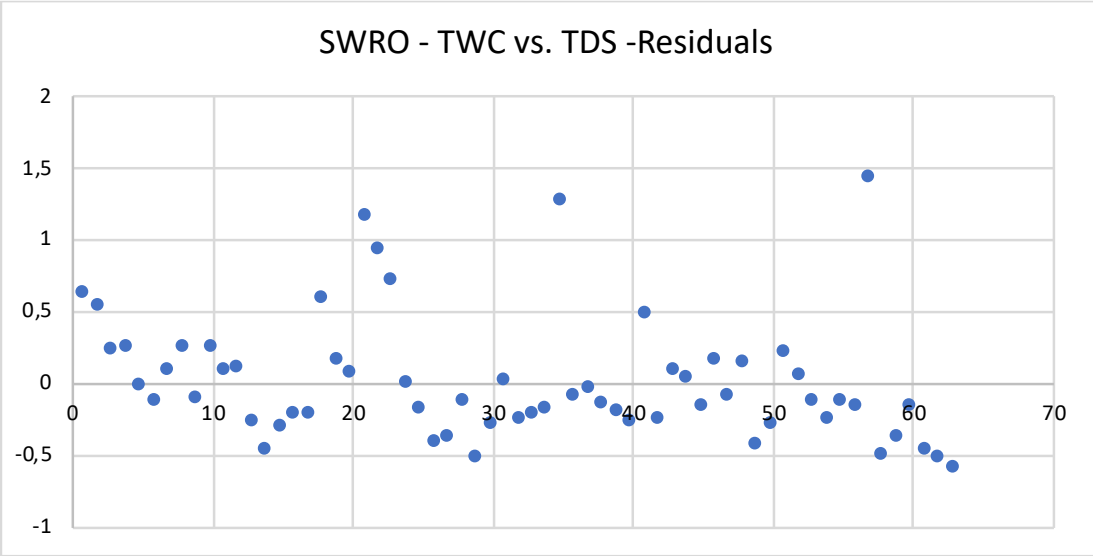

Figure 21 SWRO -TWC vs. TDS – Residuals

The trendline in case of BWRO (Figure 22) is contrary to common sense, as it indicates lower costs for higher salinity.

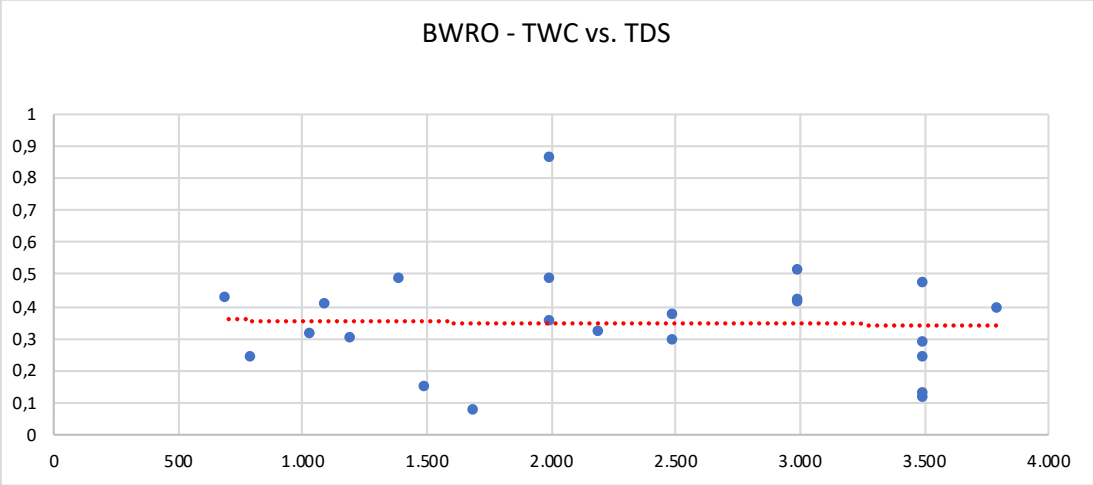

Figure 22 BWRO - TWC vs. TDS

The excerpt of the regression analysis returned following results (full results in Appendix 7):

Nr. Of observations	23	
R^2	0.005	
Standard Error	0.170	
Significance F	0.757	
	Coefficient	**P-value**
Intercept	0.375	0.000
TDS in 1000mg/L	-0.011	0.757

Interestingly, the coefficient of the TDS is negative, which indicates, as the trendline suggested, a negative correlation between TWC and TDS. However, the R^2 value is so low and the significance F is so high, that statistical significance can be ruled out. The predicted value for the TWC would be:

$$TWC\ in\ \$ = \$0.375 - 0.011 * TDS\ in\ 1000mg/L$$

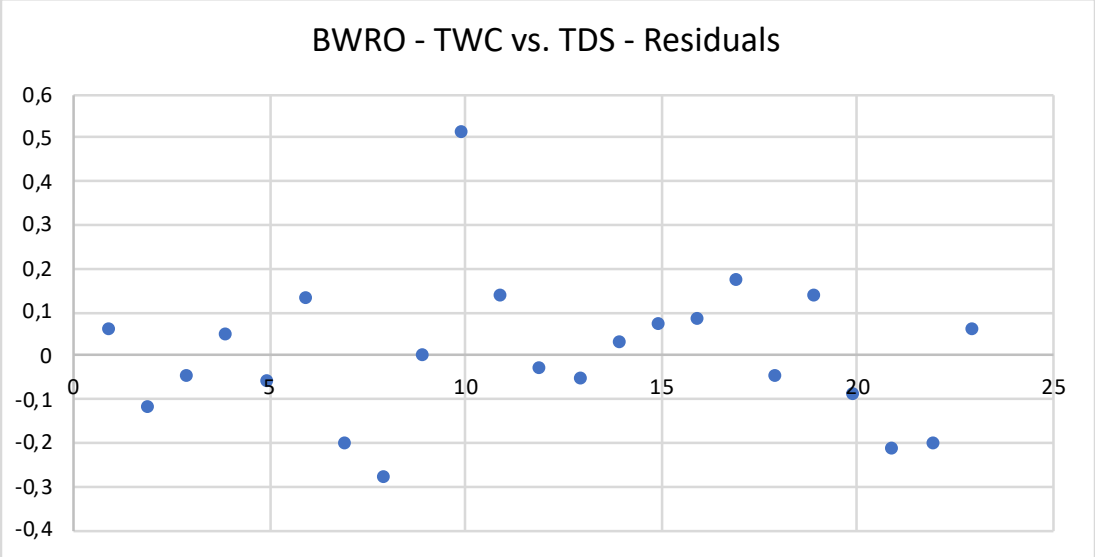

Figure 23 BWRO - TWC vs. TDS – Residuals

Year of Construction

It is possible that the year of construction plays an effect on the TWC, because of advancements in technology and the learning curve. For that purpose, the year that the plant started operation has been determined for both categories, SWRO and BWRO, and data points with missing information have been removed.

For SWRO the trendline suggests that the year of construction has indeed an effect on the price. The line is steeper than on the previous results. The data-points suggest that after the year 2000 the results are mixed.

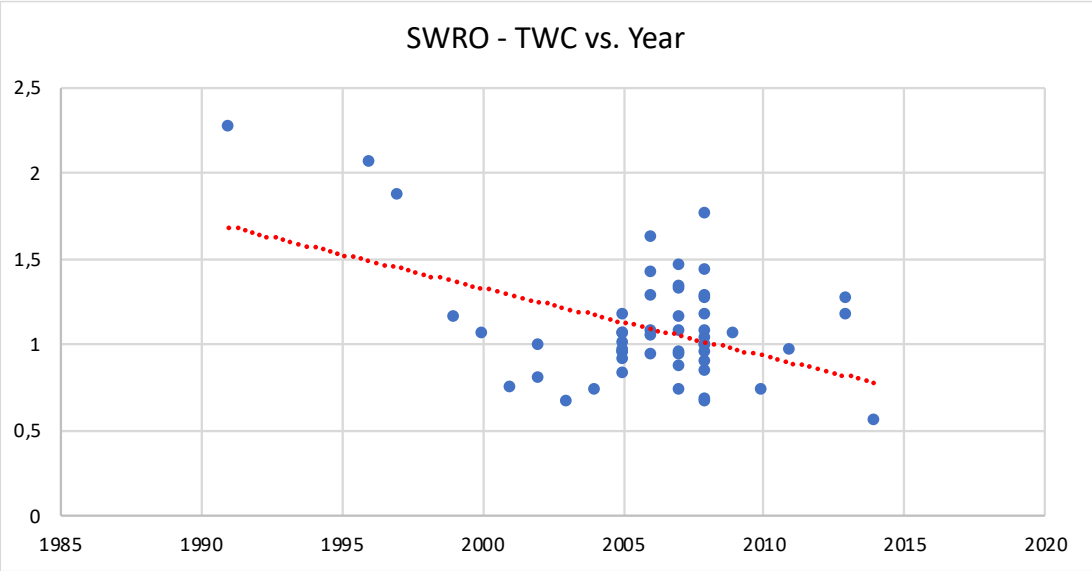

Figure 24 SWRO - TWC vs. Year

The results of the regression are as follows (full results in Appendix 9):

Nr. Of observations	54	
R^2	0.215	
Standard Error	0.430	
Significance F	0.000	
	Coefficient	**P-value**
Intercept	80.271	0.000
Year	-0.040	0.000

The R^2 value is similar to the value from the regression regarding the plant size, namely approximately 21.5 per cent. The F- and p-values suggest statistical significance. The coefficient indicates that each year the cost of desalinated water reduces by approximately 4 cents/m^3. Of course, the result does not take into account that at some point the technological limits will be reached and improvements are not as significant as at the beginning. The formula for the predicted water price according to the results of the regression is therefore:

$$TWC\ in\ \$ = \$80.271 - 0.040 * Year$$

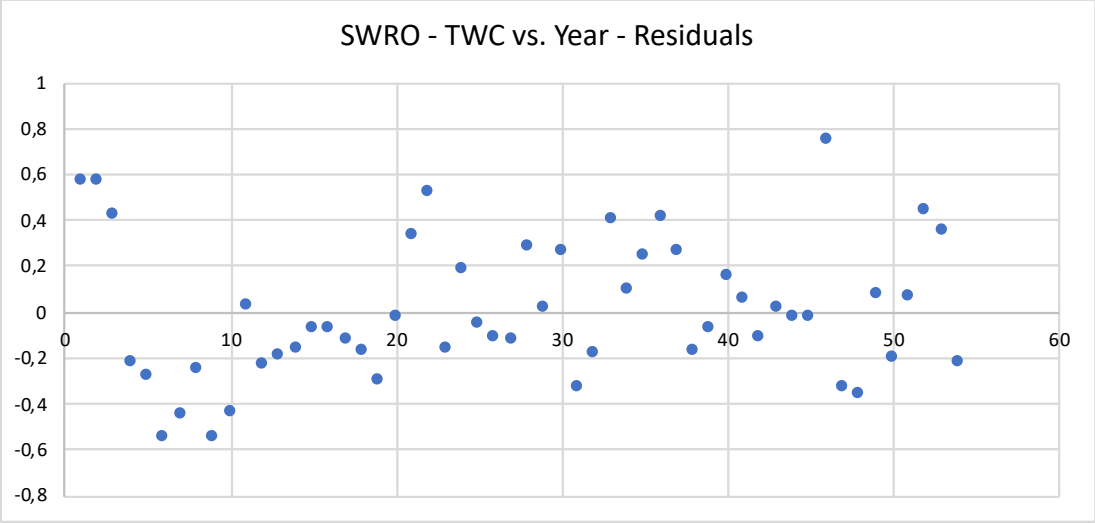

Figure 25 SWRO - TWC vs. Year - Residuals

The quality of the predicted values can be seen in Figure 25, and is somewhat similar to the results from SWRO regarding plant size.

In case of BWRO the trendline returned again conflicting results when comparing to SWRO. The ascending trendline suggests that each year the average TWC increases.

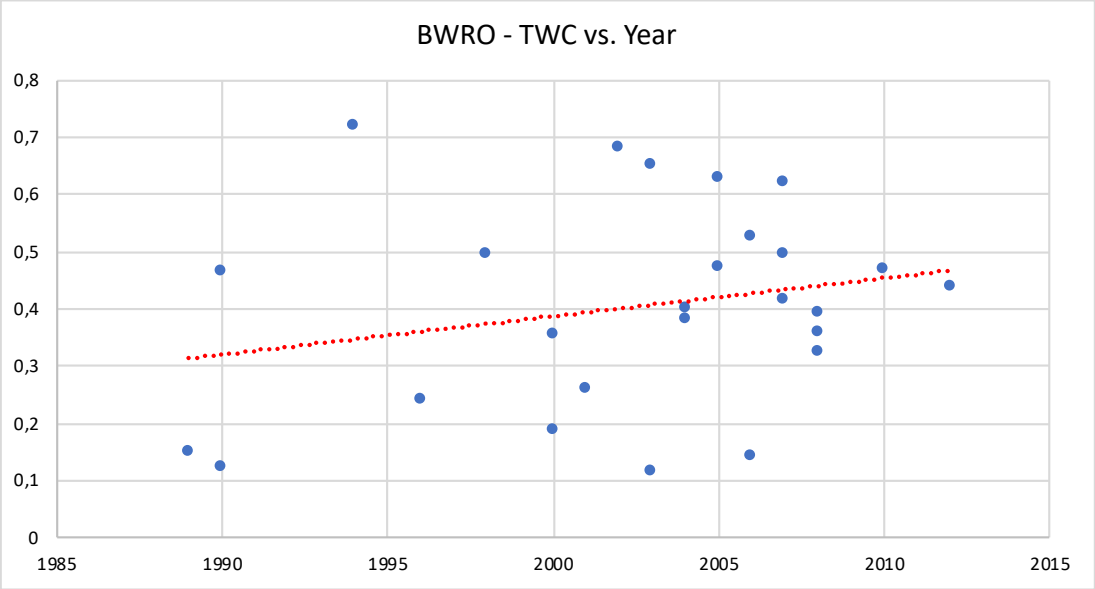

Figure 26 BWRO - TWC vs. Year

The results of the regression analysis confirm what the trendline suggested:

Nr. Of observations	26	
R^2	0.057	
Standard Error	0.174	
Significance F	0.241	
	Coefficient	**P-value**
Intercept	-12.957	0.256
Year	0.007	0.242

The coefficient of year is positive, and it would mean that each year, the water price increases by 0.7 cents. However, the low R^2 value and high p-values

indicate statistical insignificance of the results. Furthermore, the residuals confirm the inaccuracy of the predicted values:

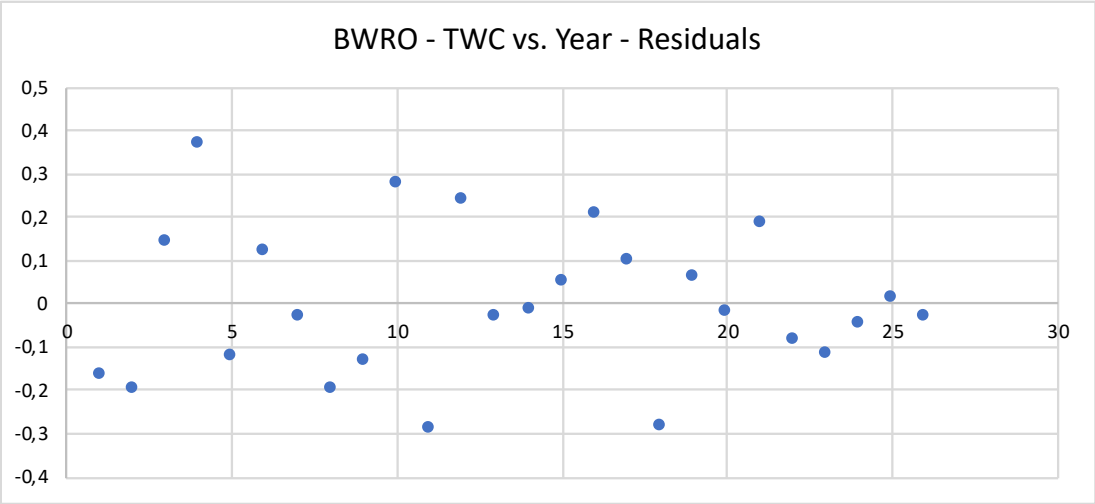

Figure 27 BWRO - TWC vs. Year – Residuals

Simple Regression by Region

Each region and country is different in terms of water quality, wage level, land prices, energy prices and many other factors. Therefore, it can be rational to perform the analysis for the different regions. Sorting the data by country is for the database of this work not feasible, since there is not enough data for each country. A broader categorization is necessary. Therefore, in this part, the SWRO plants will be split into OECD and Non-OECD countries. BWRO will not be analyzed in this part, since all the desalination plants in the database are from the same region (Texas) and the results would be identical as in the previous part. Full results of the regression analysis and residuals can be found in the Appendix.

Plant Size

The downward slope of the trendline (Figure 28) in the analysis for OECD countries comparing TWC with plant size, suggests that economies of scale

are to be achieved. For capacities of up to 100,000 m^3/day, the trendline is steeper, however still considerable for larger plants.

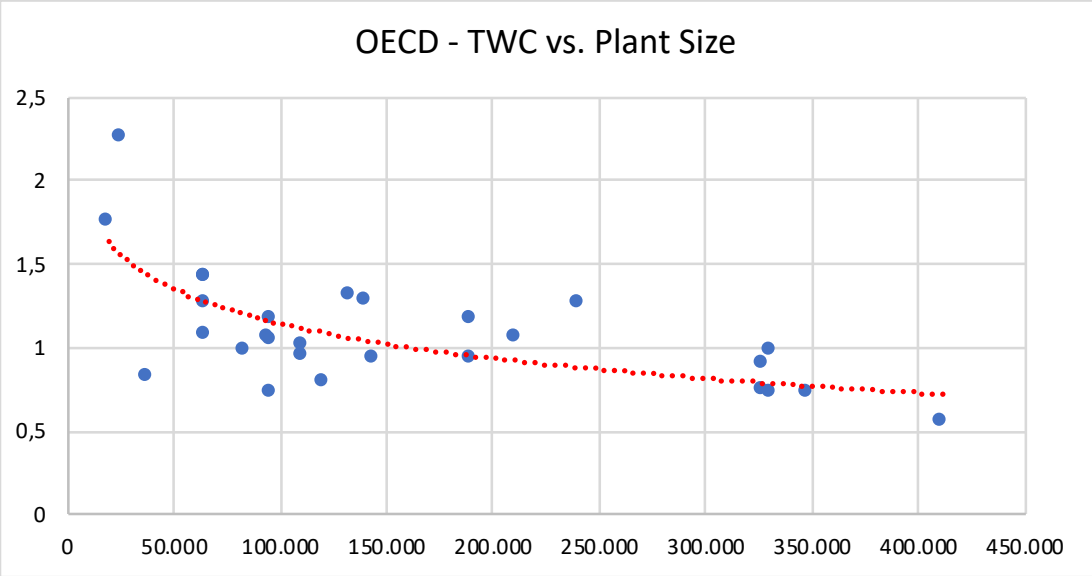

Figure 28 OECD - TWC vs. Plant Size

Nr. Of observations	28	
R^2	0.333	
Standard Error	0.290	
Significance F	0.001	
	Coefficient	**P-value**
Intercept	1.369	0.000
Capacity in 100,000 m^3/day	-0.179	0.001

The regression analysis returned the best R^2 value so far at 33.3 per cent. The result is statistically significant, as the F- and p- values are fractionally small. The predicted values are calculated according to the following formula:

$$TWC\ in\ \$ = \$1.369 - 0.179 * Capacity\ in\ 100{,}000 m^3/day$$

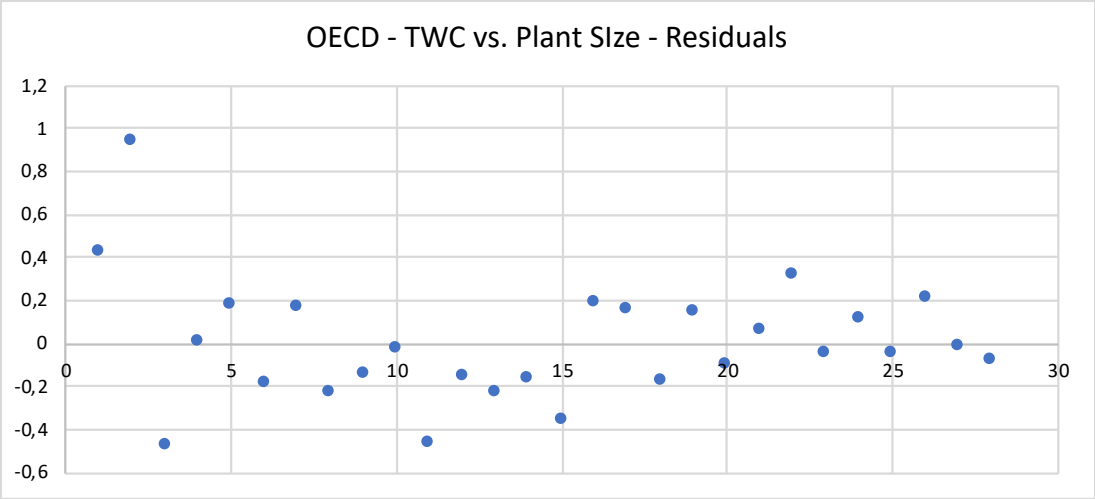

Figure 29 OECD - TWC vs. Plant Size – Residuals

The residuals (Figure 30) show that the quality of the predicted values is better than the previous predictions. The majority of the values is correct within the interval of -0.2 to 0.2 $.

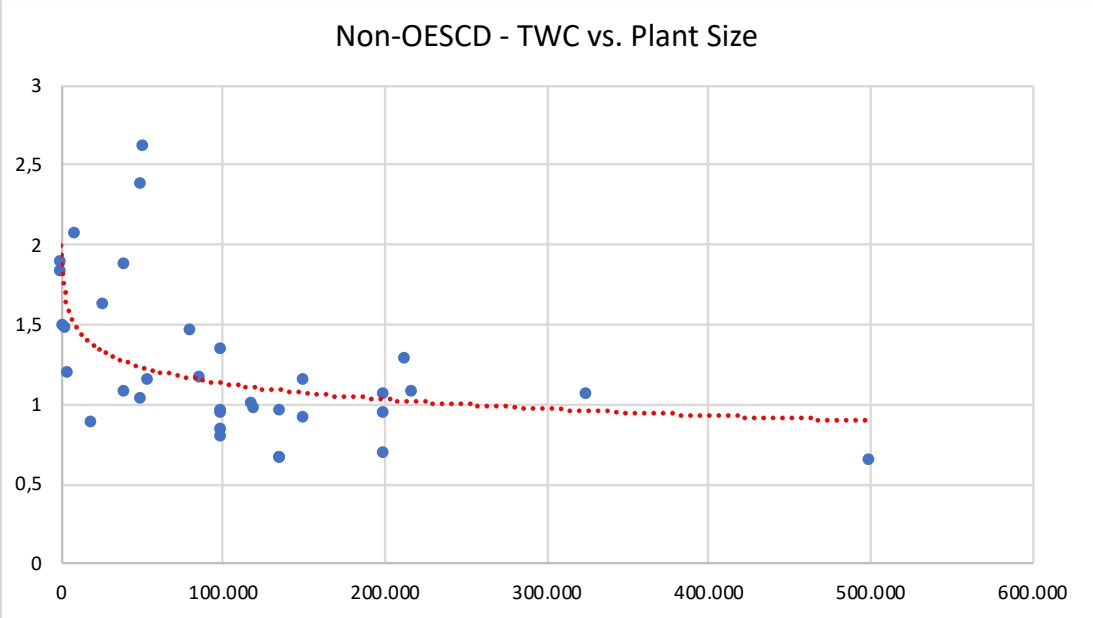

Figure 30 Non-OECD - TWC vs. Plant Size

Compared to OECD countries, the trendline (Figure 30) seems to be less steep, hence, indicating that the plant size has a lower influence on the price

in Non-OECD countries. However, the regression analysis returned similar results than for OECD countries:

Nr. Of observations	35	
R^2	0.256	
Standard Error	0.423	
Significance F	0.002	
	Coefficient	**P-value**
Intercept	1.487	0.000
Capacity in 100,000 m^3/day	-0.238	0.002

The R^2 value is slightly lower at 26 per cent and statistical significance is present. The predicted values are calculated as follows:

$$TWC\ in\ \$ = \$1.487 - 0.238 * Capacity\ in\ 100{,}000 m^3/day$$

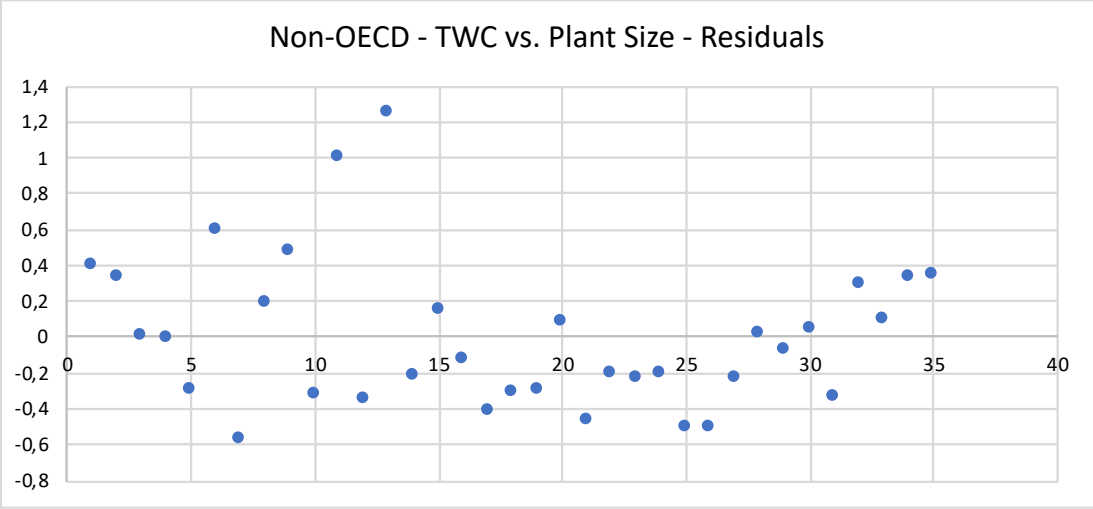

Figure 31 Non-OECD - TWC vs. Plant Size – Residuals

The result for the residuals is considerably worse than for OECD countries, with the majority of the prediction being off at an interval of -0.4 to 0.4 $.

TDS

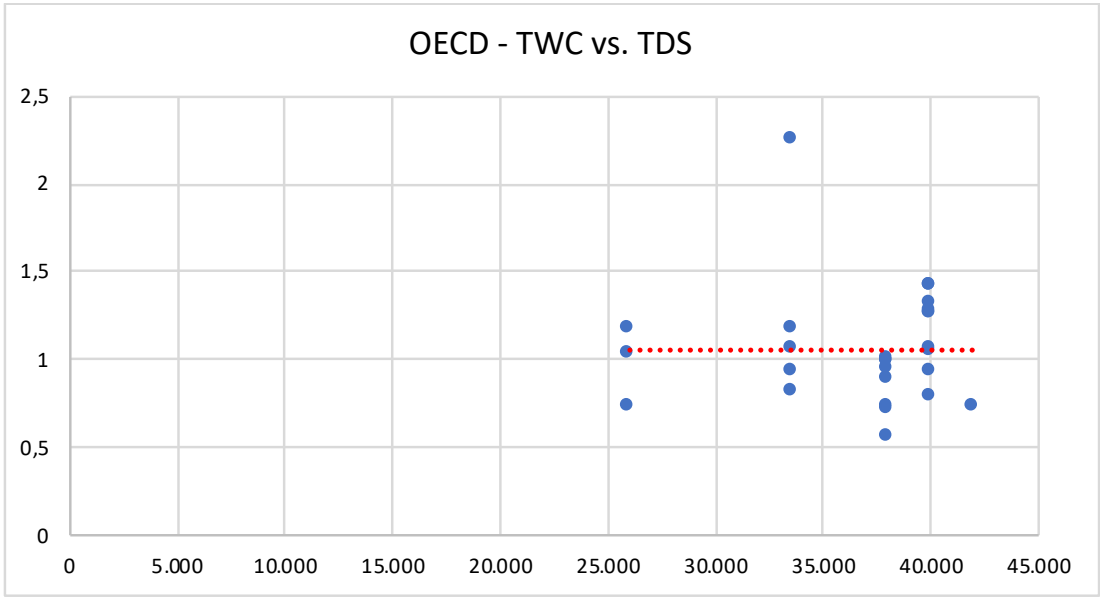

Figure 32 OECD - TWC vs. TDS

The TDS in OECD countries has almost no effect on the water price according to the trendline (Figure 32). The regression confirms what the trendline indicated:

Nr. Of observations	27	
R^2	0.000	
Standard Error	0.335	
Significance F	0.964	
	Coefficient	**P-value**
Intercept	1.083	0.052
TDS in 1000 mg/L	-0.001	0.963

The R^2 value is virtually zero and the significance F is almost 100 per cent, which is statistically valueless.

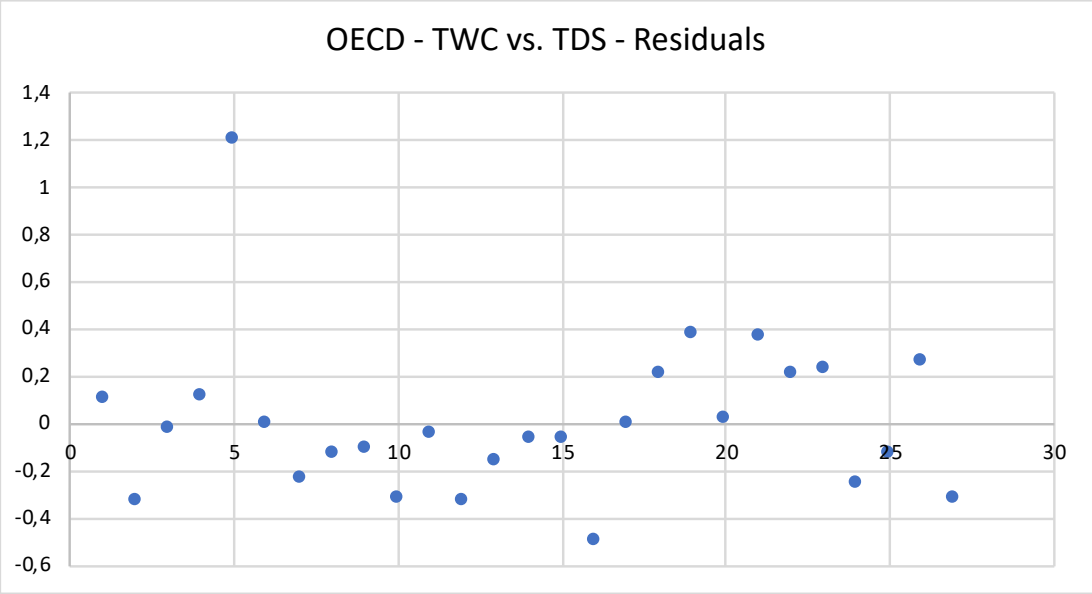

Figure 33 OECD - TWC vs. TDS – Residuals

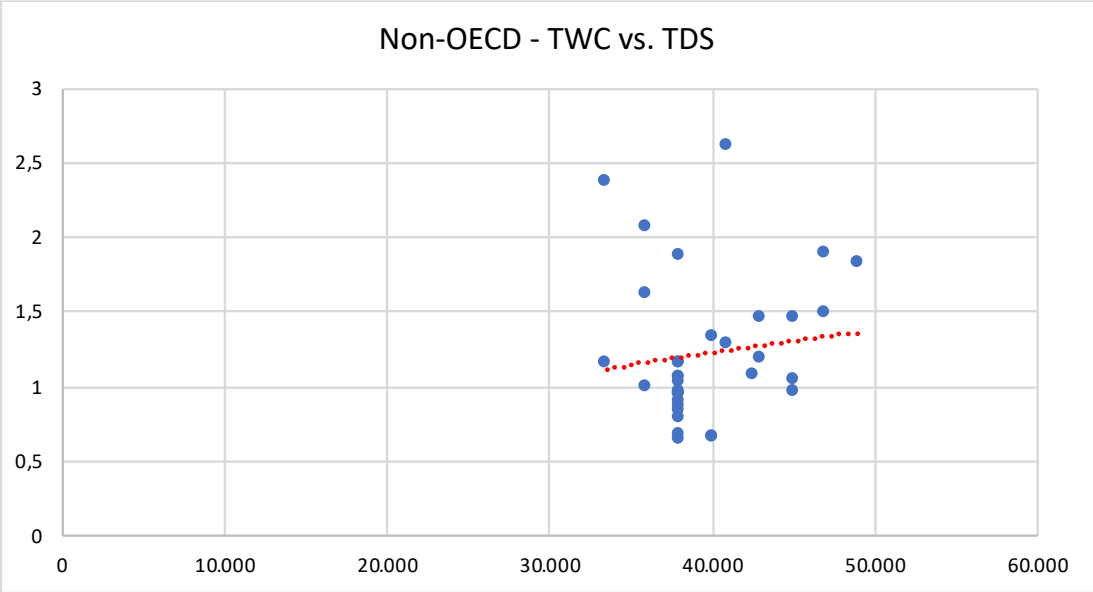

Figure 34 Non-OECD - TWC vs. TDS

For Non-OECD countries the trendline indicates that higher salinity has a positive correlation with the price. However, the regression analysis, although better than the OECD counterpart, returned statistically insignificant results:

Nr. Of observations	35	
R^2	0.021	
Standard Error	0.485	
Significance F	0.402	
	Coefficient	**P-value**
Intercept	0.475	0.597
TDS in 1000mg/L	0.019	0.402

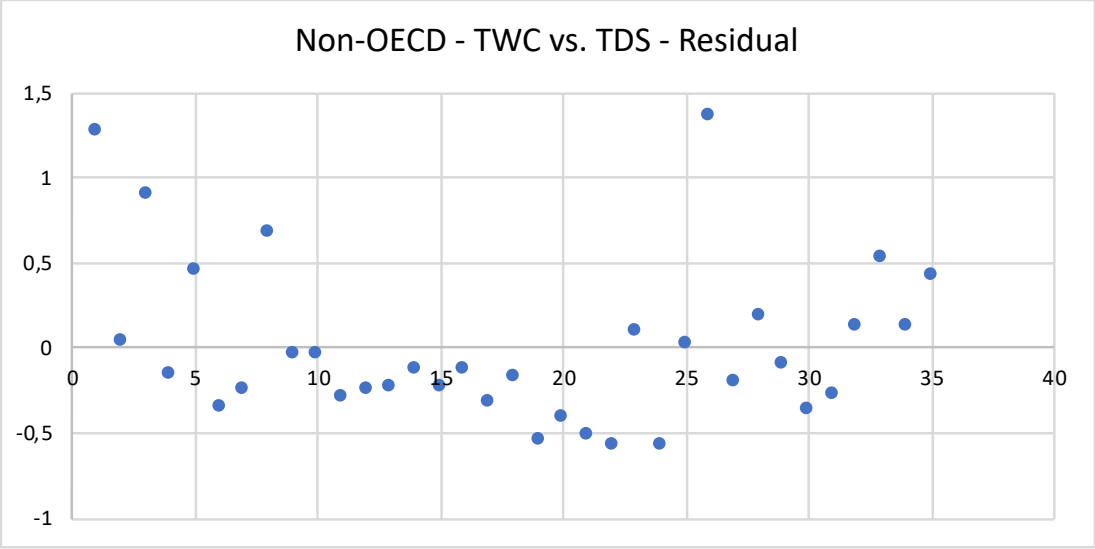

Figure 35 Non-OECD - TWC vs. TDS – Residuals

Year

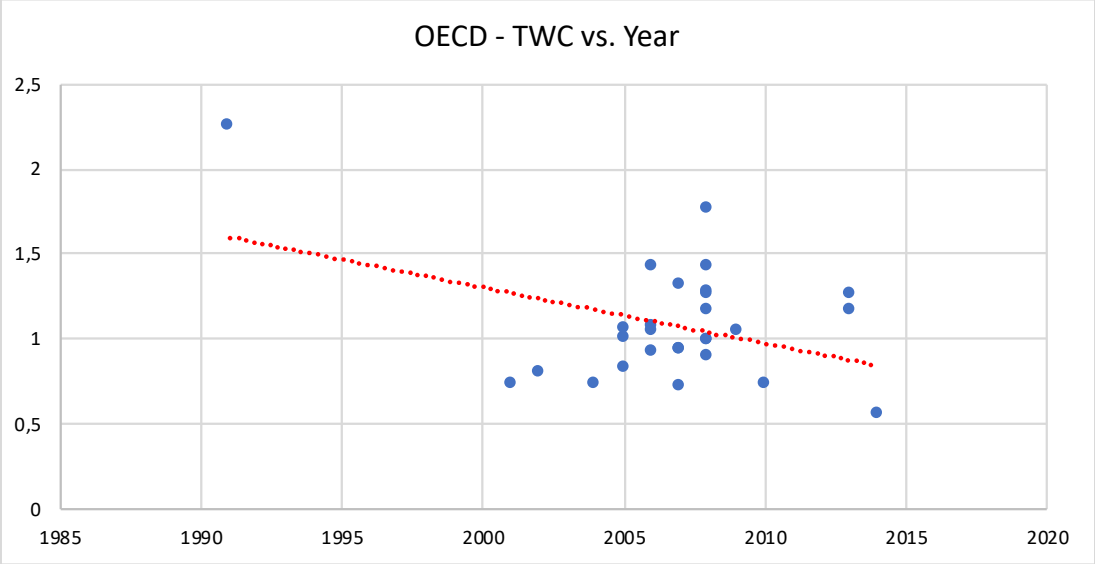

Figure 36 OECD - TWC vs. Year

The year in which the desalination plant started operation apparently has an effect in OECD countries, according to the trendline (Figure 36). The regression analysis provides the following result:

Nr. Of observations	28	
R^2	0.1568	
Standard Error	0.3263	
Significance F	0.037	
	Coefficient	**P-value**
Intercept	66.7058	0.0342
Year	-0.0327	0.037

The R^2 value is at 16 per cent lower than for the plant size, however, the results are statistically significant. The regression indicates that each year the TWC is

reduced by approximately 3 cents. The equation for the predicted values is as follows:

$$TWC\ in\ \$ = \$66.7058 - 0.0327 * Year$$

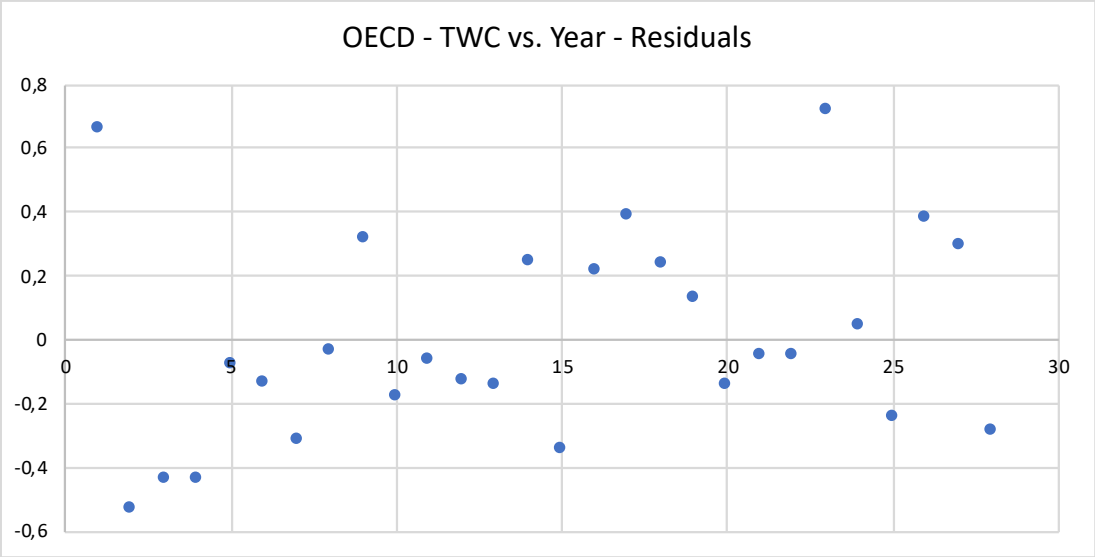

Figure 37 OECD - TWC vs. Year – Residuals

Nevertheless, the quality of the predicted values is questionable according to the residuals (Figure 37). The majority of the is within an interval of -0.4 to 0.4 $, with some values considerably worse.

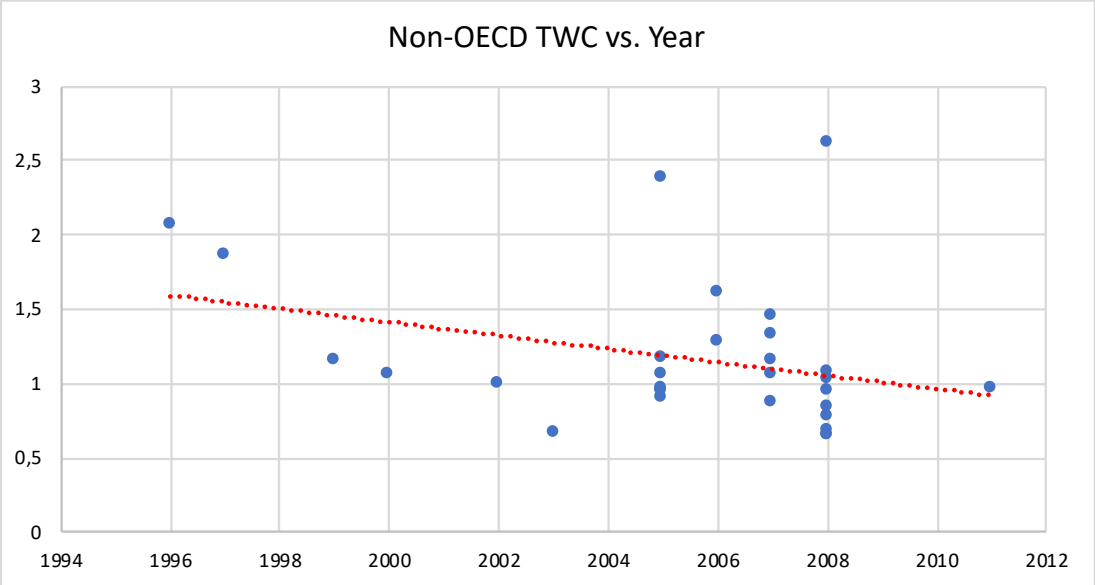

Figure 38 Non-OECD - TWC vs. Year

Also, Non-OECD countries get more economical as years pass by (Figure 38).

Nr. Of observations	30	
R^2	0.1029	
Standard Error	0.4709	
Significance F	0.0839	
	Coefficient	**P-value**
Intercept	91.2281	0.0801
Year	-0.0449	0.0839

However, the significance F is slightly above of 0.05, and therefore not statistically significant. Otherwise, the results would suggest a 4.5 cents reduction in water price each year.

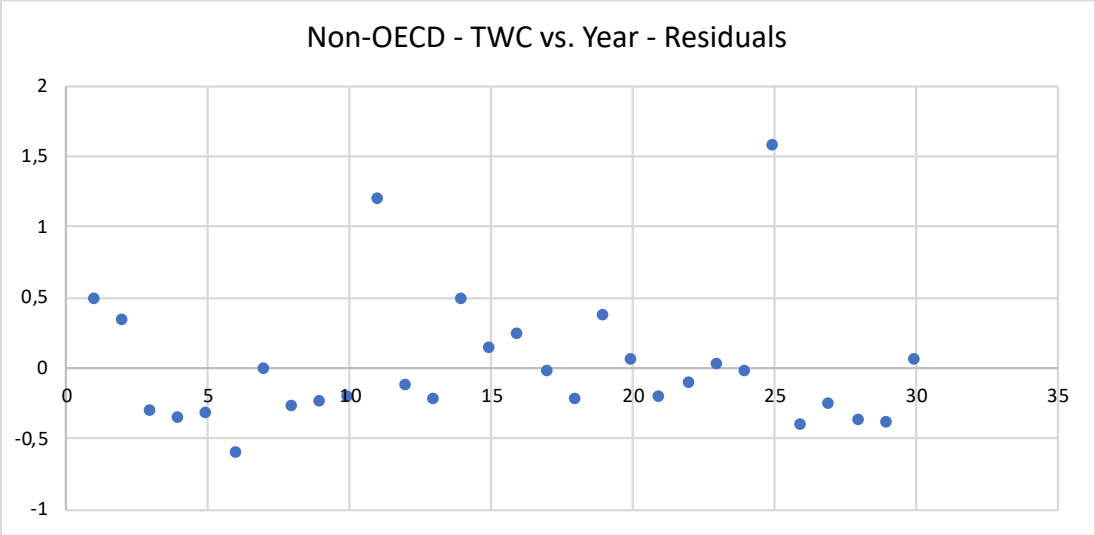

Figure 39 Non-OECD - TWC vs. Year - Residuals

In each of the tests, the R^2 value for OECD countries was better than for Non-OECD countries. A possible explanation could be that some Non-OECD countries have significant subsidies on energy prices compared to others. As explained in previous chapters, the energy costs represent around one third of the total water price. According to the Internation Energy Agency (IEA), energy

subsidies (oil, electricity and natural gas) in Saudi Arabia amounted to almost 30 billion US$ in 2016. (IEA.org, n.d.)

Multiple Regression by Feed Water Type

In this section a Multiple Linear Regression will be performed to see if the model is improved by combining multiple independent variables to a single regression analysis. First, all independent variables, i.e. plant size, TDS and year, will be combined in a single multiple regression model. The results will be interpreted and insignificant variables will be removed and the analysis will be repeated with only the significant variables.

As can be seen in the following table, the R^2 value of the regression improved to almost 35 per cent. The p-values for the independent variables capacity

(plant size) and year are significant, but for TDS it would be considered not significant.

Nr. Of observations	62	
R^2	0.347	
Standard Error	0.355	
Significance F	0.000	
	Coefficient	**P-value**
Intercept	53.26	0.039
Capacity in 100,000 m^3	-0.166	0.001
TDS in 1,000 mg/L	0.012	0.244
Year	-0.026	0.043

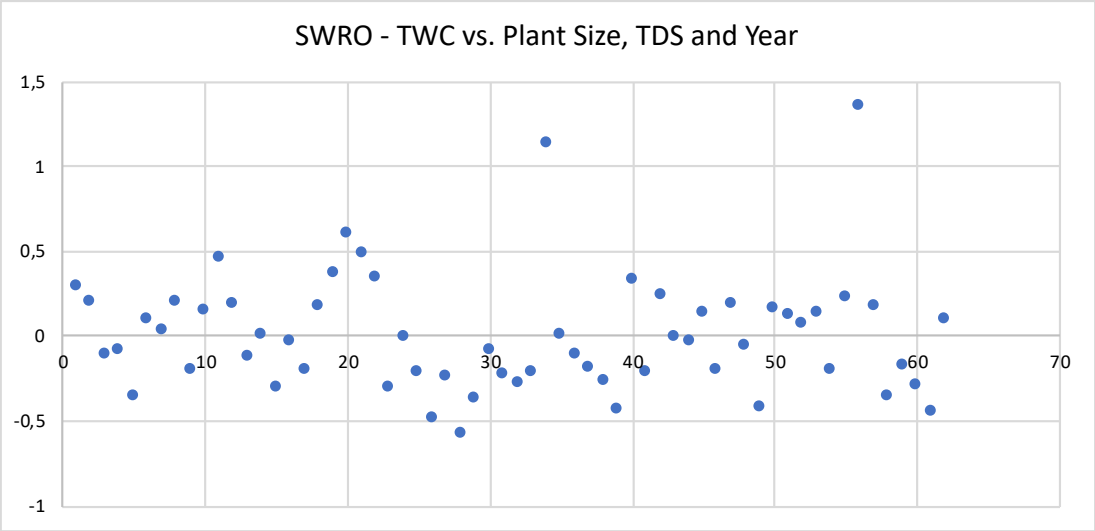

Figure 40 SWRO - TWC vs. Plant Size, TDS and Year

The residuals show no unusual pattern compared to the previous results and are within a similar interval.

Removing TDS from the sample, because of the high p-value, and running the regression with the remaining variables, yields the following results:

Nr. Of observations	62	
R^2	0.331	
Standard Error	0.356	
Significance F	0.000	
	Coefficient	**P-value**
Intercept	53.360	0.033
Capacity in 100,000 m^3	-0.165	0.001
Year	-0.027	0.037

The R^2 value is approximately the same as before, however in this model, i.e. plant size and year as independent variables, all the p-values are significant. So, the predicted TWC can be calculated according to this formula:

$$TWC\ in\ \$ = \$53.36 - 0.165 * Plant\ Size\ in\ 100{,}000m^3/day - 0.027 * Year$$

The residuals show the same pattern as before and the standard error is also about the same.

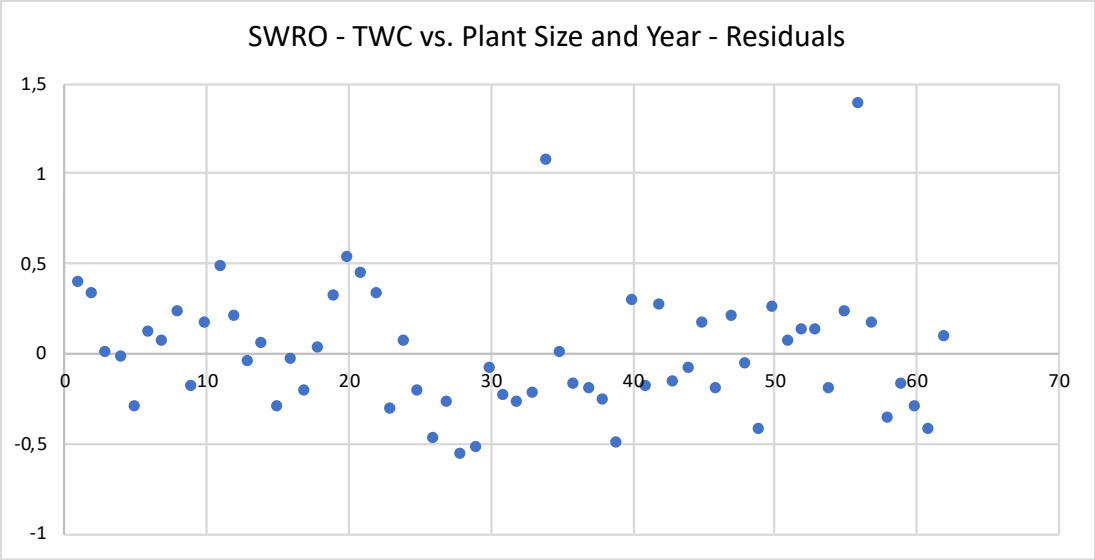

Figure 41 SWRO - TWC vs. Plant Size and Year

For BWRO the regression analysis including all variable, returned the following results:

Nr. Of observations	23	
R^2	0.126	
Standard Error	0.192	
Significance F	0.455	
	Coefficient	**P-value**
Intercept	-17.091	0.210
Capacity in 100,000 m^3	0.066	0.716
TDS in 1,000 mg/L	-0.043	0.315
Year	-0.009	0.197

The p-value of all variables is insignificant. The data for the analysis does not fit the model for BWRO very well. A complete list of the results for BWRO,

including a model with Plant Size and TDS as independent variables, can be found in Appendix 29 - Appendix 32.

Multiple Regression by Region

In this section, the multiple regression analysis will be performed for SWRO plants classified by region, i.e. OECD and Non-OECD countries.

Conducting the regression analysis for all independent variables at the same time for OECD countries, yields the following results:

Nr. Of observations	27	
R^2	0.380	
Standard Error	0.275	
Significance F	0.011	
	Coefficient	**P-value**
Intercept	45.098	0.121
Capacity in 100,000 m^3	-0.138	0.020
TDS in 1,000 mg/L	0.013	0.302
Year	-0.022	0.129

As can be seen in the table above, the p-value for the variables TDS and Year is higher than statistical significance. Adding TDS and Year to capacity in the multiple regression naturally improves the R^2 value slightly, however the results for those two variables are not significant.

Similarly, the results for Non-OECD countries, for the variables TDS and Year, are insignificant. Again, the model returned a slightly higher R^2 value than the

model of the simple regression but with insignificant results for the other two variables. The excerpt of the results can be seen in the following table:

Nr. Of observations	35	
R^2	0.315	
Standard Error	0.419	
Significance F	0.008	
	Coefficient	**P-value**
Intercept	67.176	0.131
Capacity in 100,000 m^3	-0.195	0.014
TDS in 1,000 mg/L	0.007	0.713
Year	-0.033	0.137

Alternative Fresh Water Source

Water transfer

A possibility to provide water scarce regions with water is by water transfer. This transfer can happen from water rich regions, fresh water sources or even desalinated water from coastal areas to non-coastal areas. The transfer can happen by canal, tunnel or pipeline, in order of increasing cost of transfer. The type of soil is also a significant factor in water transport costs. (Zhou & Tol, 2005)

According to Zhou & Tol, 2005 and my personal experience, not much has been published regarding the costs of water transport. Zhou explains it by the lack of willingness of engineering companies to share cost information due to the commercial sensitivity of the data. Furthermore, most of the available data dates back to or refers to Kally, 1993. (Zhou & Tol, 2005) More recent studies include the works of Berkoff and Alghariani. (Alghariani, 2003; Berkoff, 2003)

Kally claims that it costs 21.4 US cents per m^3 to transfer water from the Nile river to the West Bank by canal. Included in that cost is a fee of 4 cents for the water extracted from the Nile. The cost would fall from 21.4 cents to 19.8 cents if the yearly capacity would be increased from 100 million m^3/year to 500

million m^3/year. The cost breakdown can be seen in the following table, calculated with a 5 per cent interest rate in 1988 US Dollar cents:

	100 mil m^3/year	**500 mil m^3/year**
Payment of investment	8.7	7.6
Energy for pumping	5.2	5.2
O&M	3.5	3.0
Cost of water at source	4.0	4.0
Total	21.4	19.8
(Kally & Fishelson, 1993)		

To calculate just the cost of water transfer, the cost of the water at the source is deducted and the cost of 17.4 cents and 15.8 cents remains, respectively, for the two different capacities. As can be seen, the cost for the water and energy to transfer 1 m^3 of water are not affected by economies of scale of the larger capacity.

The costs are for a length of 200 km. In other words, it costs 8.7 cents and 7.9 cents to transport 1 m^3 of water across a distance of 100km in 1988. Adjusted for inflation, the price for 2018 is 19 cents and 17.2 cents, respectively. According to Zhou, the soil for the canal for the transfer is soft but stable. Kally, furthermore, has listed the costs for other type of soil and transfer for a different project in the Red Sea. It would cost 13 per cent more if the soil was rocky, 175 per cent for sandy soil and 138 per cent more for a tunnel. A pipeline would cost 271 per cent more. (Kally & Fishelson, 1993; Zhou & Tol, 2005) Thus, the

following inflation corrected prices (in cents) for water transfer per m^3 every 100km (according to Kally), result in the following table:

	100 mil m^3/year	**500 mil m^3/year**
Canal in stable soft soil	19	17.2
Canal in rocky soil	21.4	19.4
Canal in Sandy Soil	52.3	47.3
Tunnel	45.1	40.85
Pipeline	70.5	63.8

Gruen (2000) reports about a pipeline project in Turkey to transfer water from the Dragon River on Turkey's Mediterranean Border to Güzelyurt in Northern Cyprus. The pipeline, with a capacity of 75 million m^3/year, is supposed to transfer water over a distance of 78km. The estimated cost for 1999 amounts to 25 to 34 cents. (Gruen, 2000) Adjusted for inflation, the cost is 38 to 52 cents, and converted to 100 km it is 48.7 to 66.7 cents.

In Spain, the National Hydrologic Plan consists of two pipelines from the river Ebro. The first one is a 200km long pipeline that is supposed to supply Barcelona. The second pipeline 700 km long and is built from the Cherta dam (at the mouth of the river Ebro) to Almería. Combined, the project had an estimated cost of 4.2 billion euros and a capacity of 1050 mill m^3/year. The cost of the transferred water was estimated in 2001 at 0.312 €. Converted to US Dollar cents and adjusted for inflation, the cost is 38.1 cents/m^3. (Uche et al., 2001) However, the author doesn't mention the distance. The pipelines are of different length and it is not clear if the price is an average price or total price.

Alghariani estimates the cost with 83 cents for 1991 in North Africa. Although the distance is not clear. The adjusted price is 1.55 US Dollars. (Alghariani, 2003) Berkoff quotes a WWF report (which could not be found during my research) estimating the costs of delivered water in China for different regions

between 1 and 15.8 Yuan. The distances are not specified in his work. (Berkoff, 2003)

Water Storage

In some water scarce regions water is available, but the spatial, sporadic and temporal distribution of rainfall doesn't match the water demand of the region. Consequently, vast amounts of water flood out to the sea from water scarce regions. A solution to this problem can be water storage, to time the supply with demand. There are four primary ways to store water:

- In the soil profile
- In underground aquifers
- In small reservoirs and
- In large reservoirs behind large dams.

Storing water in the soil profile, although important for crop production, is a short-term solution, i.e. water can sometimes only be stored for a couple of days. Therefore, it will not be further investigated in this work. Small, reservoirs can store water for many months and large reservoirs and underground storage store water for years. In fact, underground aquifers store water without any significant evaporation loss. Furthermore dams can use the water flow for hydropower to generate electricity. (Keller et al., 2000)

To qualify as a small reservoir or small dam, the maximum height must not exceed 15 meters with a total volume of less than 0.75 million m^3. Usually small reservoirs are built close to the point of use and are therefore highly flexible. The water travels on average only a couple of hours to the destination and water flow can easily be adjusted according to rainfall, e.g. for irrigation. Usually there are fewer administrational parties involved and therefore it is easier to manage. However, the high surface area compare to the total

volume, makes small dams prone to evaporation. In reality, up to 50% in arid areas. (Keller et al., 2000)

Large reservoirs or large dams are more complex to operate than small reservoirs due to the larger area that they supply, and inevitably higher number of parties involved, which makes management more challenging. This is aggravated by the fact that most large dams are multipurpose, e.g. hydropower generation and irrigation. Because of the larger supply area, the flexibility of the water supply is lower than for smaller reservoirs. With a travelling speed of the water of around 3 km per hour it can take weeks for the water to reach its destination. For example, the water from the High Aswan Dam on the Nile, Egypt takes 10 days to travel to the Nile Delta. If unexpected rainfall occurs, the dam is not able to adapt timely and the unused water will flow into the Mediterranean Sea unused. Furthermore, social and environmental issues can arise. Dams that are built on-stream can restrict fish passage and flood habitats (fauna, flora and also human habitat of indigenous cultures). Hence, many newer projects are built for off-stream storage. However, the relatively low cost for a unit of water makes large dams an attractive option. Due to the higher depth, less evaporation occurs on larger projects and they can save water for up to many years. (Keller et al., 2000)

Underground aquifers can store water for many years with little to no evaporation loss and can be used to aid in water supply in years of drought. Another advantage is that underground storage usually is under the point of use and therefore almost instantly available on demand. It just needs to be pumped to the surface. The quality of the water is excellent for drinking in many regions as the water is naturally filtered from biological pollutants as it reaches the aquifer. This a good source of drinking water for many developing countries as they lack proper treatment facilities. Currently many regions suffer from insufficient natural recharge rates of the groundwater as water withdrawal exceeds the recharge rate. In many regions the groundwater level declines 2 meters every year. This leads to the possibility that the remaining water is polluted. Possibly because the falling water levels enable oxidation of natural deposits like arsenic. The cost of pumping should also be taken into account.

The best practice would be to extract as much water as the natural recharge rate is able to reproduce. But in many regions this is not affordable, as they rely on water to produce valuable resources. Therefore, artificially recharging aquifers with excess water whenever possible is a solution to sinking groundwater levels without the need to cut back on consumption. (Keller et al., 2000)

Keller has estimated the costs for micro-storage projects, small and medium storage projects, large storage projects and artificial aquifer recharge. The costs can be seen in the following table, adjusted to 2018 prices:

	Lifetime delivery costs (cents/m^3)		
	Low	**Median**	**High**
Large storage project	0.3	0.8	5
Medium and small storage projects	1.1	2.7	17.2
Micro-storage projects	1.1	2.7	17.2
Artificial groundwater recharge	29.7	32.8	35.9
(Keller et al., 2000)			

It is not clear if the author used discount rates, annualized rates for investment capital or simply the cost for storing and transferring water for the storage projects. Therefor only the prices for groundwater recharge will be used in the analysis. For water cost of dams the following data of Kally will be used.

Kally reports the costs of two possible dams in Jordan with its neighbors for 1983. The author also takes into account the revenue from generating

electricity. The data can be seen in the following table, with prices adjusted for 2018:

	Dam in Israeli-Jordanian Territory	**Dam in Jordanian-Syrian Territory**
Investment (millions of dollars)	1031	2062
Repayment on investment (5% interest rate)	17.3	40
Production of electricity (cent/m^3)	-5.2	-7.7
Other expenditure (cent/m^3)	5.2	10.3
Cost of water (cent/m^3)	17.3	42.6
(Kally & Fishelson, 1993)		

Conclusion

In many parts of the world, desalination is used to compensate for water shortages. A big obstacle is the cost of fresh water produce by desalination. This work analyzed the different factors that could influence the price of the produced water, namely the plant size, the total dissolved solids in the feed water and the year of construction. Furthermore, the plants have been split into two regions, OECD and Non-OECD countries, in a separate analysis, to reduce the effect of the region on the water price. The results of the analysis of the divided regions returned statistically superior results. Overall, the plant size as an independent variable delivered the statistically best results, which means that bigger plants are able to produce fresh water more efficiently, probably due to economies of scale. Furthermore, the year of construction influences the water price. Newer plants produce water at a lower cost than older plants. This effect can be explained by the learning curve and technological improvements.

Alternative sources of water, including dams, pipelines and artificial groundwater recharge are an option. However, there is a lack of sufficient scientific literature on costs regarding those alternatives, due to the reluctance of companies to share cost information about those projects. Furthermore, water transfer across borders is a non-desirable option for countries, mainly due to political reasons.

Based on the results in this work it is expected that the price of desalinated water will become more and more competitive. On the one hand, due to technological improvements and on the other hand, water shortages, caused by population growth and climate change, will increase the need for bigger desalination plants, which are able to produce water more efficiently.

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Appendix

The appendix contains results of the regression analysis, which has been done with Microsoft Excel.

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,518823579							
R Square	0,269177906							
Adjusted R Square	0,257390453							
Standard Error	0,372954018							
Observations	64							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	3,17636216	3,17636216	22,83596834	1,1228E-05			
Residual	62	8,62387139	0,1390947					
Total	63	11,8002335						
	Coefficients	*tandard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	1,445225496	0,07388677	19,5600033	3,25681E-28	1,297527945	1,59292305	1,29752794	1,59292305
Capacity	-0,206477737	0,04320794	-4,7786994	1,1228E-05	-0,29284917	-0,1201063	-0,2928492	-0,1201063

Appendix 1 SWRO - TWC vs. Capacity – Regression

Capacity	*Observation*	*redicted TWC*	*Residuals*
250	1	1,4447093	0,43804363
500	2	1,44419311	0,37684447
2.000	3	1,44109594	0,04876487
3.500	4	1,43799878	0,02665436
4.800	5	1,43531456	-0,250626
9.840	6	1,42490809	0,63589191
18.925	7	1,40614958	0,35335042
20.000	8	1,40392995	-0,5327299
25.360	9	1,39286274	0,86413726
27.250	10	1,38896031	0,22303969
37.850	11	1,36707367	-0,5414737
40.000	12	1,3626344	0,5056656
40.000	13	1,3626344	-0,2978344
50.000	14	1,34198663	1,03161337
50.000	15	1,34198663	-0,3184866
52.000	16	1,33785707	1,27264293
54.000	17	1,33372752	-0,1861275
65.000	18	1,31101497	-0,052625
65.000	19	1,31101497	0,11638948
65.000	20	1,31101497	-0,241614
65.000	21	1,31101497	0,108707
80.200	22	1,27963035	0,17236965
83.270	23	1,27329148	-0,2842915
86.000	24	1,26765464	-0,1066546
94.625	25	1,24984594	-0,1920459
95.000	26	1,24907165	-0,0782847
95.000	27	1,24907165	-0,5175716
95.000	28	1,24907165	-0,2074716
100.000	29	1,23874776	-0,3992478
100.000	30	1,23874776	-0,2970478
100.000	31	1,23874776	-0,2841478
100.000	32	1,23874776	0,09225224
100.000	33	1,23874776	-0,4567478
110.000	34	1,21809999	-0,2743
110.000	35	1,21809999	-0,2119
119.000	36	1,19951699	-0,205517
120.000	37	1,19745221	-0,3994522
120.000	38	1,19745221	-0,2299522
133.000	39	1,17061011	0,14828989
136.000	40	1,16441577	-0,206606
136.360	41	1,16367245	-0,5060725
136.360	42	1,16367245	-0,5081725
140.000	43	1,15615666	0,12292108
143.700	44	1,14851699	-0,218517
150.000	45	1,13550889	-0,2325089
150.000	46	1,13550889	0,01399111
189.000	47	1,05498257	0,11681689
189.250	48	1,05446638	-0,1227664
200.000	49	1,03227002	-0,08927
200.000	50	1,03227002	0,02552998
200.000	51	1,03227002	-0,35377
205.000	52	1,02194613	0,66172109
210.000	53	1,01162225	0,04084068
213.475	54	1,00444715	0,27275285
218.000	55	0,99510403	0,07439597
240.000	56	0,94967893	0,30912713
325.000	57	0,77417285	0,27702715
326.144	58	0,77181074	-0,0334107
326.144	59	0,77181074	0,12518926
330.000	60	0,76384896	-0,037849
330.000	61	0,76384896	0,22515104
347.900	62	0,72688945	0,00391055
411.000	63	0,596602	-0,040102
500.000	64	0,41283681	0,23116319

Appendix 2 SWRO - TWC vs. Capacity – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,120542252							
R Square	0,014530434							
Adjusted R Square	-0,026530797							
Standard Error	0,204977215							
Observations	26							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,01486818	0,01486818	0,353872346	0,557496741			
Residual	24	1,008375807	0,04201566					
Total	25	1,023243987						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,400076962	0,047788761	8,37177934	1,39926E-08	0,301445807	0,498708118	0,30144581	0,49870812
Capacity	0,109475664	0,184032394	0,59487171	0,557496741	-0,270348529	0,489299856	-0,2703485	0,48929986

Appendix 3 BWRO - TWC vs. Capacity - Regression

Capacity	*Observation*	*Predicted TWC*	*Residuals*
87	1	0,400172277	0,063211545
216	2	0,400313176	-0,250576588
379	3	0,400491373	0,068463876
568	4	0,400698578	0,27847799
818	5	0,400972089	-0,002689534
954	6	0,401121277	-0,277272942
1.500	7	0,401719097	0,561480903
1.600	8	0,401828573	0,034971427
2.309	9	0,402604866	0,090474141
3.785	10	0,404221067	-0,215345298
3.800	11	0,404237038	0,066162962
5.700	12	0,406317075	-0,014317075
7.600	13	0,408397113	0,118002887
8.706	14	0,409608403	0,307534557
9.464	15	0,410437224	-0,267375004
9.500	16	0,410477151	0,003922849
10.902	17	0,412011984	-0,296626084
11.000	18	0,412119285	-0,087319285
11.356	19	0,412509277	-0,058367209
11.356	20	0,412509277	0,213303418
22.712	21	0,424941591	-0,164698379
24.605	22	0,427013643	-0,186689627
28.000	23	0,430730148	-0,050120502
28.400	24	0,431168051	-0,074668051
55.670	25	0,461022065	0,035077935
104.099	26	0,514039842	0,104981087

Appendix 4 BWRO - TWC vs. Capacity – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,118843901							
R Square	0,014123873							
Adjusted R Square	-0,002038031							
Standard Error	0,430155488							
Observations	63							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,161700819	0,16170082	0,87389908	0,353564147			
Residual	61	11,2870584	0,18503374					
Total	62	11,44875922						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,713744788	0,482517741	1,47920942	0,14423028	-0,251109068	1,678598643	-0,251109068	1,67859864
TDS	0,011685329	0,012500009	0,9348257	0,35356415	-0,013309983	0,036680642	-0,013309983	0,03668064

Appendix 5 SWRO - TWC vs. TDS – Regression

TWC	*Observation*	*Predicted TWC*	*Residuals*
1,88275293	1	1,262955273	0,619797655
1,82103757	2	1,286325932	0,534711642
1,48986081	3	1,262955273	0,226905539
1,46465313	4	1,216213956	0,248439177
1,18468853	5	1,216213956	-0,03152543
1,05246293	6	1,181157967	-0,128695042
1,25838992	7	1,181157967	0,077231956
1,42740444	8	1,181157967	0,246246476
1,06940096	9	1,181157967	-0,111757007
1,41972196	10	1,181157967	0,238563997
1,25880606	11	1,181157967	0,07764809
1,27907774	12	1,181157967	0,097919772
0,95780974	13	1,239584615	-0,281774872
0,7308	14	1,204528626	-0,473728626
0,8395	15	1,157787308	-0,318287308
0,943	16	1,157787308	-0,214787308
0,9438	17	1,157787308	-0,213987308
1,68366723	18	1,105203325	0,578463904
1,17078691	19	1,017563354	0,153223553
1,17179946	20	1,105203325	0,066596134
2,257	21	1,105203325	1,151796675
2,0608	22	1,134416649	0,926383351
1,8683	23	1,157787308	0,710512692
1,1476	24	1,157787308	-0,010187308
1,0512	25	1,239584615	-0,188384615
0,7384	26	1,157787308	-0,419387308
0,798	27	1,181157967	-0,383157967
0,994	28	1,134416649	-0,140416649
0,6576	29	1,181157967	-0,523557967
0,7315	30	1,017563354	-0,286063354
1,161	31	1,157787308	0,003212692
0,903	32	1,157787308	-0,254787308
0,9417	33	1,157787308	-0,216087308
0,9675	34	1,157787308	-0,190287308
2,3736	35	1,105203325	1,268396675
1,0578	36	1,157787308	-0,099987308
1,0578	37	1,105203325	-0,047403325
1,0062	38	1,157787308	-0,151587308
0,9546	39	1,157787308	-0,203187308
0,8256	40	1,105203325	-0,279603325
1,612	41	1,134416649	0,477583351
0,93	42	1,181157967	-0,251157967
1,2772	43	1,192843297	0,084356703
1,0416	44	1,017563354	0,024036646
0,9317	45	1,105203325	-0,173503325
1,331	46	1,181157967	0,149842033
1,0648	47	1,157787308	-0,092987308
1,3189	48	1,181157967	0,137742033
0,726	49	1,157787308	-0,431787308
0,8712	50	1,157787308	-0,286587308
1,452	51	1,239584615	0,212415385
1,1495	52	1,105203325	0,044296675
1,0695	53	1,210371291	-0,140871291
0,897	54	1,157787308	-0,260787308
1,0235	55	1,157787308	-0,134287308
0,989	56	1,157787308	-0,168787308
2,6105	57	1,192843297	1,417656703
0,644	58	1,157787308	-0,513787308
0,782	59	1,157787308	-0,375787308
0,989	60	1,157787308	-0,168787308
0,6785	61	1,157787308	-0,479287308
0,6555	62	1,181157967	-0,525657967
0,5565	63	1,157787308	-0,601287308

Appendix 6 SWRO - TWC vs. TDS - Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,068276804							
R Square	0,004661722							
Adjusted R Square	-0,042735339							
Standard Error	0,170386495							
Observations	23							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,002855389	0,002855389	0,098354662	0,756906989			
Residual	21	0,60966271	0,029031558					
Total	22	0,612518099						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,375353322	0,09057693	4,144027864	0,000460461	0,186988284	0,563718359	0,186988284	0,56371836
TDS	-0,011353961	0,036203446	-0,313615468	0,756906989	-0,086643149	0,063935228	-0,086643149	0,06393523

Appendix 7 BWRO - TWC vs. TDS – Regression

TWC	*Observation*	*Predicted TWC*	*Residuals*
0,4218488	1	0,367405549	0,054443251
0,24256306	2	0,366270153	-0,123707093
0,31	3	0,36356791	-0,05356791
0,40427177	4	0,362863965	0,041407802
0,29946057	5	0,361728569	-0,062268001
0,48512612	6	0,359457776	0,125668343
0,14926958	7	0,35832238	-0,209052805
0,07376187	8	0,356119712	-0,282357846
0,35	9	0,3526454	-0,0026454
0,86	10	0,3526454	0,5073546
0,48512612	11	0,3526454	0,13248072
0,31811549	12	0,350374608	-0,032259119
0,29	13	0,34696842	-0,05696842
0,37	14	0,34696842	0,02303158
0,41	15	0,341291439	0,068708561
0,42	16	0,341291439	0,078708561
0,51158754	17	0,341291439	0,170296105
0,28617267	18	0,335614459	-0,049441792
0,47	19	0,335614459	0,134385541
0,24009524	20	0,335614459	-0,095519214
0,11537276	21	0,335614459	-0,2202417
0,12936697	22	0,335614459	-0,206247493
0,39	23	0,332208271	0,057791729

Appendix 8 BWRO - TWC vs. TDS – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,46336881							
R Square	0,214710655							
Adjusted R Square	0,199608936							
Standard Error	0,3046273							
Observations	54							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	1,319364746	1,31936475	14,21763086	0,00041783			
Residual	52	4,825485164	0,09279779					
Total	53	6,14484991						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	80,27068488	20,99856396	3,82267497	0,000354619	38,1339836	122,407386	38,1339836	122,407386
Year	-0,039471485	0,010468148	-3,7706274	0,00041783	-0,06047736	-0,0184656	-0,0604774	-0,0184656

Appendix 9 SWRO - TWC vs. Year – Regression

Year	*Observation*	*Predicted TWC*	*Residuals*
1991	1	1,682958305	0,574041695
1996	2	1,485600881	0,575199119
1997	3	1,446129396	0,422170604
1999	4	1,367186426	-0,219586426
2000	5	1,327714941	-0,276514941
2001	6	1,288243456	-0,549843456
2002	7	1,248771971	-0,450771971
2002	8	1,248771971	-0,254771971
2003	9	1,209300486	-0,551700486
2004	10	1,169829001	-0,438329001
2005	11	1,130357516	0,030642484
2005	12	1,130357516	-0,227357516
2005	13	1,130357516	-0,188657516
2005	14	1,130357516	-0,162857516
2005	15	1,130357516	-0,072557516
2005	16	1,130357516	-0,072557516
2005	17	1,130357516	-0,124157516
2005	18	1,130357516	-0,175757516
2005	19	1,130357516	-0,304757516
2006	20	1,090886031	-0,021485071
2006	21	1,090886031	0,328835934
2006	22	1,090886031	0,521113969
2006	23	1,090886031	-0,160886031
2006	24	1,090886031	0,186313969
2006	25	1,090886031	-0,049286031
2007	26	1,051414546	-0,107614546
2007	27	1,051414546	-0,119714546
2007	28	1,051414546	0,279585454
2007	29	1,051414546	0,013385454
2007	30	1,051414546	0,267485454
2007	31	1,051414546	-0,325414546
2007	32	1,051414546	-0,180214546
2007	33	1,051414546	0,400585454
2007	34	1,051414546	0,098085454
2008	35	1,011943061	0,246446862
2008	36	1,011943061	0,415461382
2008	37	1,011943061	0,267134678
2008	38	1,011943061	-0,172443061
2008	39	1,011943061	-0,068943061
2008	40	1,011943061	0,158843846
2008	41	1,011943061	0,057556939
2008	42	1,011943061	-0,114943061
2008	43	1,011943061	0,011556939
2008	44	1,011943061	-0,022943061
2008	45	1,011943061	-0,022943061
2008	46	1,011943061	0,747556939
2008	47	1,011943061	-0,333443061
2008	48	1,011943061	-0,356443061
2009	49	0,972471576	0,079991349
2010	50	0,933000091	-0,202200091
2011	51	0,893528606	0,064281137
2013	52	0,814585636	0,444220421
2013	53	0,814585636	0,357213824
2014	54	0,775114151	-0,218614151

Appendix 10 SWRO - TWC vs. Year – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,23796265							
R Square	0,05662622							
Adjusted R S	0,01731898							
Standard Err	0,17440178							
Observations	26							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,04381743	0,04381743	1,44060544	0,24175523			
Residual	24	0,72998355	0,03041598					
Total	25	0,77380098						
	Coefficients	*Standard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-12,956614	11,131018	-1,1640098	0,25586154	-35,929906	10,0166779	-35,929906	10,0166779
Year	0,0066719	0,00555875	1,20025224	0,24175523	-0,0048008	0,01814459	-0,0048008	0,01814459

Appendix 11 BWRO - TWC vs. Year – Regression

Year	*Observation*	*Predicted TWC*	*Residuals*
1989	1	0,31379463	-0,164058
1990	2	0,32046653	-0,1966182
1990	3	0,32046653	0,14291729
1994	4	0,34715413	0,36998883
1996	5	0,36049793	-0,1201739
1998	6	0,37384173	0,11923728
2000	7	0,38718553	-0,0330435
2000	8	0,38718553	-0,1983098
2001	9	0,39385743	-0,1336142
2002	10	0,40052933	0,27864724
2003	11	0,40720123	-0,2918153
2003	12	0,40720123	0,24147061
2004	13	0,41387313	-0,0332635
2004	14	0,41387313	-0,0155906
2005	15	0,42054503	0,04985497
2005	16	0,42054503	0,20526767
2006	17	0,42721693	0,09918307
2006	18	0,42721693	-0,2841547
2007	19	0,43388883	0,06221117
2007	20	0,43388883	-0,0194888
2007	21	0,43388883	0,1851321
2008	22	0,44056073	-0,0840607
2008	23	0,44056073	-0,1157607
2008	24	0,44056073	-0,0485607
2010	25	0,45390452	0,01505072
2012	26	0,46724832	-0,0304483

Appendix 12 BWRO - TWC vs. Year – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,577104651							
R Square	0,333049778							
Adjusted R Square	0,307397846							
Standard Error	0,290289872							
Observations	28							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	1,094089478	1,094089478	12,9834191	0,00130367			
Residual	26	2,190973448	0,08426821					
Total	27	3,285062926						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	1,368498465	0,096272884	14,21478624	9,0074E-14	1,17060672	1,56639021	1,17060672	1,56639021
Capacity	-0,178917419	0,04965444	-3,60325118	0,00130367	-0,2809836	-0,0768513	-0,2809836	-0,0768513

Appendix 13 OECD - TWC vs. Plant Size – Regression

Capacity	*Observation*	*Predicted TWC*	*Residuals*
18.925	1	1,334638343	0,424861657
25.360	2	1,323125008	0,933874992
37.850	3	1,300778222	-0,475178222
65.000	4	1,252202143	0,00618778
65.000	5	1,252202143	0,1752023
65.000	6	1,252202143	-0,182801182
65.000	7	1,252202143	0,167519822
83.270	8	1,21951393	-0,23051393
94.625	9	1,199197857	-0,141397857
95.000	10	1,198526917	-0,02774001
95.000	11	1,198526917	-0,467026917
95.000	12	1,198526917	-0,156926917
110.000	13	1,171689304	-0,227889304
110.000	14	1,171689304	-0,165489304
120.000	15	1,153797562	-0,355797562
133.000	16	1,130538298	0,188361702
140.000	17	1,118014078	0,161063661
143.700	18	1,111394134	-0,181394134
189.000	19	1,030344543	0,141454917
189.250	20	1,02989725	-0,09819725
210.000	21	0,992771885	0,05969104
240.000	22	0,93909666	0,319709398
326.144	23	0,784970038	-0,046570038
326.144	24	0,784970038	0,112029962
330.000	25	0,778070982	-0,052070982
330.000	26	0,778070982	0,210929018
347.900	27	0,746044764	-0,015244764
411.000	28	0,633147873	-0,076647873

Appendix 14 OECD - TWC vs. Plant Size – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,505483211							
R Square	0,255513277							
Adjusted R Square	0,232953073							
Standard Error	0,422917661							
Observations	35							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	2,025732508	2,025732508	11,32584085	0,00195191			
Residual	33	5,902358477	0,178859348					
Total	34	7,928090984						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	1,486527107	0,10516454	14,13525046	1,48135E-15	1,27256824	1,70048597	1,27256824	1,70048597
Capacity	-0,237551651	0,070586691	-3,365388663	0,001951914	-0,3811614	-0,0939419	-0,3811614	-0,0939419

Appendix 15 Non-OECD - TWC vs. Plant Capacity – Regression

Capacity	*Observation*	*Predicted TWC*	*Residuals*
250	1	1,485933228	0,396819701
500	2	1,485339349	0,335698225
2.000	3	1,481776074	0,008084739
3.500	4	1,478212799	-0,013559667
4.800	5	1,475124628	-0,290436102
9.840	6	1,463152024	0,597647976
20.000	7	1,439016777	-0,567816777
27.250	8	1,421794282	0,190205718
40.000	9	1,391506447	0,476793553
40.000	10	1,391506447	-0,326706447
50.000	11	1,367751282	1,005848718
50.000	12	1,367751282	-0,344251282
52.000	13	1,363000249	1,247499751
54.000	14	1,358249216	-0,210649216
80.200	15	1,296010683	0,155989317
86.000	16	1,282232687	-0,121232687
100.000	17	1,248975456	-0,409475456
100.000	18	1,248975456	-0,307275456
100.000	19	1,248975456	-0,294375456
100.000	20	1,248975456	0,082024544
100.000	21	1,248975456	-0,466975456
119.000	22	1,203840643	-0,209840643
120.000	23	1,201465126	-0,233965126
136.000	24	1,163456862	-0,205647119
136.360	25	1,162601676	-0,505001676
136.360	26	1,162601676	-0,507101676
150.000	27	1,130199631	-0,227199631
150.000	28	1,130199631	0,019300369
200.000	29	1,011423805	-0,068423805
200.000	30	1,011423805	0,046376195
200.000	31	1,011423805	-0,332923805
213.475	32	0,97941372	0,29778628
218.000	33	0,968664508	0,100835492
325.000	34	0,714484242	0,336715758
500.000	35	0,298768853	0,345231147

Appendix 16 Non-OECD - TWC vs. Plant Size – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,009248525							
R Square	8,55352E-05							
Adjusted R Square	-0,039911043							
Standard Error	0,335310532							
Observations	27							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,000240445	0,00024045	0,002138563	0,96348273			
Residual	25	2,810828821	0,11243315					
Total	26	2,811069266						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	1,082782254	0,531298681	2,03799161	0,052263315	-0,0114479	2,17701237	-0,0114479	2,17701237
TDS	-0,000664115	0,014360929	-0,0462446	0,963482725	-0,030241	0,02891277	-0,030241	0,02891277

Appendix 17 OECD - TWC vs. TDS – Regression

TDS	*Observation*	*Predicted TWC*	*Residuals*
26.000	1	1,065515252	0,105271655
26.000	2	1,065515252	-0,334015252
26.000	3	1,065515252	-0,023915252
33.500	4	1,060534386	0,111265074
33.500	5	1,060534386	1,196465614
33.500	6	1,060534386	-0,002734386
33.500	7	1,060534386	-0,234934386
33.500	8	1,060534386	-0,128834386
38.000	9	1,057545867	-0,113745867
38.000	10	1,057545867	-0,319145867
38.000	11	1,057545867	-0,051345867
38.000	12	1,057545867	-0,331545867
38.000	13	1,057545867	-0,160545867
38.000	14	1,057545867	-0,068545867
38.000	15	1,057545867	-0,068545867
38.000	16	1,057545867	-0,501045867
40.000	17	1,056217636	-0,00375471
40.000	18	1,056217636	0,202172288
40.000	19	1,056217636	0,371186807
40.000	20	1,056217636	0,013183325
40.000	21	1,056217636	0,363504329
40.000	22	1,056217636	0,202588422
40.000	23	1,056217636	0,222860104
40.000	24	1,056217636	-0,258217636
40.000	25	1,056217636	-0,126217636
40.000	26	1,056217636	0,262682364
42.000	27	1,054889405	-0,324089405

Appendix 18 OECD - TWC vs. TDS – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,146347731							
R Square	0,021417658							
Adjusted R Square	-0,008236352							
Standard Error	0,484870799							
Observations	35							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,169801145	0,169801145	0,722251668	0,4015302			
Residual	33	7,758289839	0,235099692					
Total	34	7,928090984						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,475010026	0,888573544	0,534575927	0,596526807	-1,3328064	2,2828265	-1,3328064	2,2828265
TDS	0,018913296	0,022254762	0,84985391	0,401530195	-0,0263644	0,06419095	-0,0263644	0,06419095

Appendix 19 Non-OECD - TWC vs. TDS – Regression

TDS	*Observation*	*Predicted TWC*	*Residuals*
33.500	1	1,108605452	1,264994548
33.500	2	1,108605452	0,040894548
36.000	3	1,155888693	0,904911307
36.000	4	1,155888693	-0,161888693
36.000	5	1,155888693	0,456111307
38.000	6	1,193715286	-0,354215286
38.000	7	1,193715286	-0,250715286
38.000	8	1,193715286	0,674584714
38.000	9	1,193715286	-0,046115286
38.000	10	1,193715286	-0,032715286
38.000	11	1,193715286	-0,290715286
38.000	12	1,193715286	-0,252015286
38.000	13	1,193715286	-0,226215286
38.000	14	1,193715286	-0,135915286
38.000	15	1,193715286	-0,239115286
38.000	16	1,193715286	-0,128915286
38.000	17	1,193715286	-0,322515286
38.000	18	1,193715286	-0,170215286
38.000	19	1,193715286	-0,549715286
38.000	20	1,193715286	-0,411715286
38.000	21	1,193715286	-0,515215286
40.000	22	1,231541878	-0,573941878
40.000	23	1,231541878	0,099458122
40.000	24	1,231541878	-0,576041878
41.000	25	1,250455174	0,026744826
41.000	26	1,250455174	1,360044826
42.500	27	1,278825119	-0,209325119
43.000	28	1,288281767	0,176371365
43.000	29	1,288281767	-0,103593242
45.000	30	1,32610836	-0,368298617
45.000	31	1,32610836	-0,27490836
45.000	32	1,32610836	0,12589164
47.000	33	1,363934952	0,518817977
47.000	34	1,363934952	0,12592586
49.000	35	1,401761545	0,419276029

Appendix 20 Non-OECD - TWC vs. TDS – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,395994646							
R Square	0,15681176							
Adjusted R Square	0,124381443							
Standard Error	0,326397965							
Observations	28							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,515136498	0,5151365	4,835344657	0,03697735			
Residual	26	2,769926428	0,10653563					
Total	27	3,285062926						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	66,70580831	29,84277126	2,23524175	0,034207163	5,36311346	128,048503	5,36311346	128,048503
Year	-0,032701404	0,014871428	-2,1989417	0,036977348	-0,0632701	-0,0021327	-0,0632701	-0,0021327

Appendix 21 OECD - TWC vs. Year – Regression

Year	*Observation*	*Predicted TWC*	*Residuals*
1991	1	1,597313146	0,659686854
2001	2	1,270299107	-0,531899107
2002	3	1,237597703	-0,439597703
2004	4	1,172194896	-0,440694896
2005	5	1,139493492	-0,081693492
2005	6	1,139493492	-0,133293492
2005	7	1,139493492	-0,313893492
2006	8	1,106792088	-0,037391127
2006	9	1,106792088	0,312929877
2006	10	1,106792088	-0,176792088
2006	11	1,106792088	-0,065192088
2007	12	1,074090684	-0,130290684
2007	13	1,074090684	-0,142390684
2007	14	1,074090684	0,244809316
2007	15	1,074090684	-0,348090684
2008	16	1,04138928	0,217000643
2008	17	1,04138928	0,386015163
2008	18	1,04138928	0,237688459
2008	19	1,04138928	0,129397627
2008	20	1,04138928	-0,14438928
2008	21	1,04138928	-0,05238928
2008	22	1,04138928	-0,05238928
2008	23	1,04138928	0,71811072
2009	24	1,008687876	0,043775049
2010	25	0,975986472	-0,245186472
2013	26	0,87788226	0,380923797
2013	27	0,87788226	0,293917199
2014	28	0,845180857	-0,288680857

Appendix 22 OECD - TWC vs. Year – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,320823863							
R Square	0,102927951							
Adjusted R Square	0,070889664							
Standard Error	0,470868729							
Observations	30							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0,712301294	0,712301294	3,212654593	0,08388321			
Residual	28	6,20808607	0,22171736					
Total	29	6,920387364						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	91,22805506	50,24480301	1,815671464	0,080144802	-11,69375827	194,149868	-11,693758	194,149868
Year	-0,044907773	0,025054717	-1,792387958	0,08388321	-0,096230034	0,00641449	-0,09623	0,00641449

Appendix 23 Non-OECD - TWC vs. Year – Regression

Year	*Observation*	*Predicted TWC*	*Residuals*
1996	1	1,592140058	0,468659942
1997	2	1,547232285	0,321067715
1999	3	1,457416739	-0,309816739
2000	4	1,412508966	-0,361308966
2002	5	1,32269342	-0,32869342
2003	6	1,277785647	-0,620185647
2005	7	1,187970101	-0,026970101
2005	8	1,187970101	-0,284970101
2005	9	1,187970101	-0,246270101
2005	10	1,187970101	-0,220470101
2005	11	1,187970101	1,185629899
2005	12	1,187970101	-0,130170101
2005	13	1,187970101	-0,233370101
2006	14	1,143062328	0,468937672
2006	15	1,143062328	0,134137672
2007	16	1,098154555	0,232845445
2007	17	1,098154555	-0,033354555
2007	18	1,098154555	-0,226954555
2007	19	1,098154555	0,353845445
2007	20	1,098154555	0,051345445
2008	21	1,053246782	-0,213746782
2008	22	1,053246782	-0,110246782
2008	23	1,053246782	0,016253218
2008	24	1,053246782	-0,029746782
2008	25	1,053246782	1,557253218
2008	26	1,053246782	-0,409246782
2008	27	1,053246782	-0,271246782
2008	28	1,053246782	-0,374746782
2008	29	1,053246782	-0,397746782
2011	30	0,918523462	0,039286281

Appendix 24 Non-OECD - TWC vs. Year – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,58911808							
R Square	0,347060113							
Adjusted R Square	0,31328736							
Standard Error	0,354643324							
Observations	62							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	3,877422036	1,29247401	10,2763347	1,59871E-05			
Residual	58	7,294769453	0,12577189					
Total	61	11,17219149						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	53,25514219	25,28111777	2,1065185	0,0394964	2,649486719	103,860798	2,64948672	103,860798
Capacity	-0,16605818	0,046005712	-3,6095122	0,00064068	-0,258148617	-0,0739677	-0,2581486	-0,0739677
TDS	0,012281913	0,010428213	1,17775818	0,24370311	-0,008592423	0,03315625	-0,0085924	0,03315625
Year	-0,026103075	0,01260574	-2,0707292	0,04284455	-0,051336206	-0,0008699	-0,0513362	-0,0008699

Appendix 25 SWRO - TWC vs. Plant Size, TDS and Year

Capacity	TDS	Year	*Observation*	*Predicted TWC*	*Residuals*
0,0025	47	2001	1	1,599723345	0,283029584
0,005	49	2001	2	1,623872025	0,197165549
0,02	47	2001	3	1,596817327	-0,106956514
0,035	43	2001	4	1,545198802	-0,08054567
0,048	43	2001	5	1,543040046	-0,35835152
2,1	40	2009	6	0,95661832	0,095844605
0,65	40	2008	7	1,223505756	0,034884167
0,65	40	2008	8	1,223505756	0,203898687
0,65	40	2006	9	1,275711906	-0,206310946
0,65	40	2006	10	1,275711906	0,144010058
2,4	40	2013	11	0,802388565	0,456417492
1,4	40	2008	12	1,098962121	0,180115618
1,36	45	2011	13	1,088704787	-0,130895044
3,479	42	2010	14	0,726084841	0,004715159
1	38	2008	15	1,140821567	-0,301321567
2	38	2008	16	0,974763387	-0,031763387
1,1	38	2007	17	1,150318824	-0,206518824
0,95	26	2008	18	1,00174152	0,169045387
1,89	34	2013	19	0,807245802	0,364553657
0,2536	34	1991	20	1,653251063	0,603748937
0,0984	36	1996	21	1,579212699	0,481587301
0,4	38	1997	22	1,527590303	0,340709697
0,54	38	1999	23	1,452136007	-0,304536007
3,25	45	2000	24	1,061988656	-0,010788656
3,26144	38	2001	25	0,948012484	-0,209612484
1,2	40	2002	26	1,288792209	-0,490792209
1,19	36	2002	27	1,241325138	-0,247325138
1,3636	40	2003	28	1,235522015	-0,577922015
0,95	26	2004	29	1,106153821	-0,374653821
0,86	38	2005	30	1,242378938	-0,081378938
1,5	38	2005	31	1,136101703	-0,233101703
1	38	2005	32	1,219130793	-0,277430793
1,2	38	2005	33	1,185919157	-0,218419157
0,5	34	2005	34	1,246891274	1,126708726
2	38	2005	35	1,053072613	0,004727387
0,94625	34	2005	36	1,172787812	-0,114987812
1,1	38	2005	37	1,202524975	-0,196324975
1	38	2005	38	1,219130793	-0,264530793
0,3785	34	2005	39	1,267067343	-0,441467343
0,2725	36	2006	40	1,289271217	0,322728783
1,437	40	2006	41	1,145024119	-0,215024119
2,13475	41	2006	42	1,041438937	0,235761063
0,95	26	2006	43	1,053947671	-0,012347671
1,8925	34	2007	44	0,963449109	-0,031749109
1	40	2007	45	1,191488468	0,139511532
0,4	38	2007	46	1,26655955	-0,20175955
1,33	40	2007	47	1,136689269	0,182210731
3,3	38	2007	48	0,784990829	-0,058990829
0,2	38	2007	49	1,299771186	-0,428571186
0,802	45	2007	50	1,285777553	0,166222447
1,5	34	2007	51	1,028626944	0,120873056
2,18	43	2008	52	1,000141524	0,069358476
3,26144	38	2008	53	0,765290958	0,131709042
0,5	38	2008	54	1,223850657	-0,200350657
3,3	38	2008	55	0,758887754	0,230112246
0,52	41	2008	56	1,257375232	1,353124768
5	38	2008	57	0,476588849	0,167411151
1	38	2008	58	1,140821567	-0,358821567
0,8327	38	2008	59	1,1686031	-0,1796031
2	38	2008	60	0,974763387	-0,296263387
1,3636	40	2008	61	1,105006639	-0,449506639
4,11	38	2014	62	0,467762177	0,088737823

Appendix 26 SWRO - TWC vs. Plant Size, TDS and Year – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,575712216							
R Square	0,331444556							
Adjusted R Square	0,30878166							
Standard Error	0,355804875							
Observations	62							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	3,70296205	1,851481025	14,6249866	6,94311E-06			
Residual	59	7,469229439	0,126597109					
Total	61	11,17219149						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	55,36046169	25,30043658	2,188122783	0,03263304	4,734405034	105,986518	4,73440503	105,986518
Capacity	-0,16543056	0,046153296	-3,584371498	0,00068585	-0,257783093	-0,073078	-0,2577831	-0,073078
Year	-0,026917843	0,012627968	-2,131605175	0,03721458	-0,052186349	-0,0016493	-0,0521863	-0,0016493

Appendix 27 SWRO - TWC vs. Plant Size and Year

Capacity	Year	*Observation*	*Predicted TWC*	*Residuals*
0,0025	2001	1	1,497444737	0,385308192
0,005	2001	2	1,497031161	0,324006414
0,02	2001	3	1,494549702	-0,00468889
0,035	2001	4	1,492068244	-0,027415111
0,048	2001	5	1,489917646	-0,305229121
2,1	2009	6	0,935111395	0,11735153
0,65	2008	7	1,20190355	0,056486373
0,65	2008	8	1,20190355	0,225500893
0,65	2006	9	1,255739235	-0,186338275
0,65	2006	10	1,255739235	0,163982729
2,4	2013	11	0,777810856	0,480995201
1,4	2008	12	1,07783063	0,201247109
1,36	2011	13	1,003694324	-0,045884581
3,479	2010	14	0,68006481	0,05073519
1	2008	15	1,144002854	-0,304502854
2	2008	16	0,978572294	-0,035572294
1,1	2007	17	1,154377641	-0,210577641
0,95	2008	18	1,152274382	0,018512525
1,89	2013	19	0,862180442	0,309619018
0,2536	1991	20	1,725083551	0,531916449
0,0984	1996	21	1,61616916	0,44463084
0,4	1997	22	1,53935746	0,32894254
0,54	1999	23	1,462361496	-0,314761496
3,25	2000	24	0,987126836	0,064073164
3,26144	2001	25	0,958316468	-0,219916468
1,2	2002	26	1,272423799	-0,474423799
1,19	2002	27	1,274078104	-0,280078104
1,3636	2003	28	1,218441516	-0,560841516
0,95	2004	29	1,259945753	-0,528445753
0,86	2005	30	1,247916661	-0,086916661
1,5	2005	31	1,142041102	-0,239041102
1	2005	32	1,224756382	-0,283056382
1,2	2005	33	1,19167027	-0,22417027
0,5	2005	34	1,307471662	1,066128338
2	2005	35	1,059325822	-0,001525822
0,94625	2005	36	1,233648275	-0,175848275
1,1	2005	37	1,208213326	-0,202013326
1	2005	38	1,224756382	-0,270156382
0,3785	2005	39	1,327571475	-0,501971475
0,2725	2006	40	1,318189272	0,293810728
1,437	2006	41	1,125545385	-0,195545385
2,13475	2006	42	1,010116211	0,267083789
0,95	2006	43	1,206110067	-0,164510067
1,8925	2007	44	1,023273922	-0,091573922
1	2007	45	1,170920697	0,160079303
0,4	2007	46	1,270179033	-0,205379033
1,33	2007	47	1,116328612	0,202571388
3,3	2007	48	0,790430409	-0,064430409
0,2	2007	49	1,303265145	-0,432065145
0,802	2007	50	1,203675948	0,248324052
1,5	2007	51	1,088205417	0,061294583
2,18	2008	52	0,948794793	0,120705207
3,26144	2008	53	0,769891568	0,127108432
0,5	2008	54	1,226718134	-0,203218134
3,3	2008	55	0,763512566	0,225487434
0,52	2008	56	1,223409523	1,387090477
5	2008	57	0,482280614	0,161719386
1	2008	58	1,144002854	-0,362002854
0,8327	2008	59	1,171679387	-0,182679387
2	2008	60	0,978572294	-0,300072294
1,3636	2008	61	1,083852302	-0,428352302
4,11	2014	62	0,468006756	0,088493244

Appendix 28 SWRO - TWC vs. Plant Size and Year – Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,354412894							
R Square	0,1256085							
Adjusted R Square	-0,012453316							
Standard Error	0,1918562							
Observations	23							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	0,10046583	0,03348861	0,90979898	0,45482324			
Residual	19	0,69936723	0,0368088					
Total	22	0,79983306						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-17,09103505	13,1664175	-1,2980779	0,20979785	-44,648664	10,4665935	-44,648664	10,4665935
Capacity	0,065874506	0,17843894	0,36917113	0,71608225	-0,3076025	0,4393515	-0,3076025	0,4393515
TDS	-0,042982005	0,04166755	-1,0315462	0,31523767	-0,1301932	0,04422918	-0,1301932	0,04422918
Year	0,008799284	0,00658076	1,33712182	0,1969723	-0,0049744	0,02257298	-0,0049744	0,02257298

Appendix 29 BWRO - TWC vs. Plant Size, TDS and Year

Capacity	TDS	Year	*Observation*	*Predicted TWC*	*Residuals*
0,284	1,038	2008	1	0,5520202	-0,1955202
0,5567	3	2007	2	0,4768542	0,0192458
0,28	3,5	2004	3	0,41073787	-0,0301282
0,038	3	2005	4	0,425086526	0,04531347
0,11	2,5	2008	5	0,477718345	-0,1529183
0,057	2	2008	6	0,495717998	-0,103718
0,076	3,5	2006	7	0,414898038	0,11150196
0,015	2	2012	8	0,528148405	0,43505159
0,016	3,8	2012	9	0,45084667	-0,0140467
0,095	2,5	2007	10	0,467930943	-0,0535309
0,00215768	1,694	1989	11	0,338071386	-0,1883348
0,00817649	1,2	2004	12	0,491690242	-0,0934077
0,00378541	1,1	2010	13	0,548494886	-0,0795396
0,24605177	1,5	1996	14	0,424071285	-0,1837473
0,02309101	2,2	1998	15	0,39689502	0,09618399
0,11356235	0,8	2000	16	0,48062815	-0,1264861
0,00567812	2	2002	17	0,439541491	0,23963508
1,04098825	3	2007	18	0,508756449	0,11026448
0,00087064	3,5	1990	19	0,269160386	0,19422344
0,0946353	3,5	2006	20	0,416125629	-0,2730634
0,03785412	3,5	2000	21	0,359589494	-0,1707137
0,11356235	1,4	2005	22	0,498835367	0,12697733
0,08706447	0,7	1994	23	0,430385112	0,28675785

Appendix 30 BWRO - TWC vs. Plant Size, TDS and Year - Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,208154991							
R Square	0,0433285							
Adjusted R Square	-0,05233865							
Standard Error	0,195598759							
Observations	23							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	0,03465557	0,01732778	0,45290887	0,642137984			
Residual	20	0,76517749	0,03825887					
Total	22	0,79983306						
	Coefficients	*tandard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,513534837	0,10457643	4,91061752	8,4432E-05	0,295392232	0,73167744	0,29539223	0,73167744
Capacity	0,104328263	0,17954154	0,58108148	0,56767692	-0,27018882	0,47884535	-0,2701888	0,47884535
TDS	-0,035024572	0,04204485	-0,8330287	0,41466628	-0,122728601	0,05267946	-0,1227286	0,05267946

Appendix 31 BWRO - TWC vs. Plant Size and TDS

Capacity	TDS	*Observation*	*Predicted TWC*	*Residuals*
0,284	1,038	1	0,506808558	-0,1503086
0,5567	3	2	0,466540666	0,02955933
0,28	3,5	3	0,42016075	-0,0395511
0,038	3	4	0,412425596	0,0579744
0,11	2,5	5	0,437449517	-0,1126495
0,057	2	6	0,449432404	-0,0574324
0,076	3,5	7	0,398877784	0,12752222
0,015	2	8	0,445050617	0,51814938
0,016	3,8	9	0,382110717	0,05468928
0,095	2,5	10	0,435884593	-0,0214846
0,00215768	1,694	11	0,45442832	-0,3046917
0,00817649	1,2	12	0,47235839	-0,0740758
0,00378541	1,1	13	0,475402733	-0,0064475
0,24605177	1,5	14	0,486668133	-0,2463441
0,02309101	2,2	15	0,438889824	0,05418918
0,11356235	0,8	16	0,497362942	-0,1432209
0,00567812	2	17	0,444078082	0,23509849
1,04098825	3	18	0,517065617	0,10195531
0,00087064	3,5	19	0,391039669	0,07234415
0,0946353	3,5	20	0,400821972	-0,2577598
0,03785412	3,5	21	0,39489809	-0,2060223
0,11356235	1,4	22	0,476348199	0,1494645
0,08706447	0,7	23	0,498100922	0,21904204

Appendix 32 BWRO - TWC vs. Plant Size and TDS - Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,616776079							
R Square	0,380412732							
Adjusted R Square	0,299597001							
Standard Error	0,275183949							
Observations	27							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	1,069366539	0,35645551	4,70716194	0,010517117			
Residual	23	1,741702728	0,07572621					
Total	26	2,811069266						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	45,09756701	28,04241964	1,608191	0,12143546	-12,91259779	103,107732	-12,912598	103,107732
Capacity	-0,137699709	0,055231799	-2,4931238	0,02029952	-0,251955389	-0,023444	-0,2519554	-0,023444
TDS	0,013025561	0,012341454	1,05543166	0,302189	-0,012504682	0,0385558	-0,0125047	0,0385558
Year	-0,0220719	0,014012981	-1,5751038	0,12888883	-0,051059961	0,00691616	-0,05106	0,00691616

Appendix 33 OECD - TWC vs. Plant Size, TDS and Year

Capacity	TDS	Year	*Observation*	*Predicted TWC*	*Residuals*
2,1	40	2009	1	0,986972779	0,065490146
0,65	40	2008	2	1,208709257	0,049680666
0,65	40	2008	3	1,208709257	0,218695186
0,65	40	2006	4	1,252853057	-0,183452097
0,65	40	2006	5	1,252853057	0,166868907
2,4	40	2013	6	0,857375266	0,401430791
1,4	40	2008	7	1,105434475	0,173643264
3,479	42	2010	8	0,801064103	-0,070264103
1,1	38	2007	9	1,142765166	-0,198965166
0,95	26	2008	10	0,985041486	0,185745421
1,89	33,5	2013	11	0,842935969	0,328863491
0,2536	33,5	1991	12	1,553849575	0,703150425
3,26144	38	2001	13	0,977566907	-0,239166907
1,2	40	2002	14	1,265405818	-0,467405818
0,95	26	2004	15	1,073329086	-0,341829086
0,94625	33,5	2005	16	1,14946527	-0,09166527
1,1	38	2005	17	1,186908966	-0,180708966
0,3785	33,5	2005	18	1,22764428	-0,40204428
1,437	40	2006	19	1,144483386	-0,214483386
0,95	26	2006	20	1,029185286	0,012414714
1,8925	33,5	2007	21	0,97502312	-0,04332312
1,33	40	2007	22	1,137145355	0,181754645
3,3	38	2007	23	0,839825806	-0,113825806
3,26144	38	2008	24	0,823063607	0,073936393
3,3	38	2008	25	0,817753906	0,171246094
0,8327	38	2008	26	1,157500398	-0,168500398
4,11	38	2014	27	0,573785741	-0,017285741

Appendix 34 OECD - TWC vs. Plant Size, TDS and Year - Residuals

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,560838074							
R Square	0,314539345							
Adjusted R Square	0,248204443							
Standard Error	0,418692066							
Observations	35							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	2,493696545	0,831232182	4,74168703	0,007776856			
Residual	31	5,43439444	0,175303046					
Total	34	7,928090984						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	67,17593629	43,35074876	1,549591142	0,13138966	-21,23849872	155,590371	-21,238499	155,590371
Capacity	-0,194518586	0,074688333	-2,604403899	0,01400532	-0,346846446	-0,0421907	-0,3468464	-0,0421907
TDS	0,007241993	0,019536439	0,370691555	0,71338836	-0,032602837	0,04708682	-0,0326028	0,04708682
Year	-0,032933607	0,021581164	-1,526034778	0,1371403	-0,07694868	0,01108147	-0,0769487	0,01108147

Appendix 35 Non-OECD - TWC vs. Plant Size, TDS and Year

Capacity	TDS	Year	*Observation*	*Predicted TWC*	*Residuals*
0,0025	47	2001	1	1,615677001	0,267075928
0,005	49	2001	2	1,62967469	0,191362884
0,02	47	2001	3	1,612272926	-0,122412113
0,035	43	2001	4	1,580387175	-0,115734042
0,048	43	2001	5	1,577858433	-0,393169908
1,36	45	2011	6	1,007797969	-0,049988226
1	38	2008	7	1,125931529	-0,286431529
2	38	2008	8	0,931412943	0,011587057
0,0984	36	1996	9	1,682028778	0,378771222
0,4	38	1997	10	1,604912352	0,263387648
0,54	38	1999	11	1,511812537	-0,364212537
3,25	45	2000	12	1,002427514	0,048772486
1,19	36	2002	13	1,27209065	-0,27809065
1,3636	40	2003	14	1,234356589	-0,576756589
0,86	38	2005	15	1,25196495	-0,09096495
1,5	38	2005	16	1,127473055	-0,224473055
1	38	2005	17	1,224732348	-0,283032348
1,2	38	2005	18	1,185828631	-0,218328631
0,5	33,5	2005	19	1,289402673	1,084197327
2	38	2005	20	1,030213762	0,027586238
1	38	2005	21	1,224732348	-0,270132348
0,2725	36	2006	22	1,318827027	0,293172973
2,13475	41	2006	23	0,992794755	0,284405245
1	40	2007	24	1,173349121	0,157650879
0,4	38	2007	25	1,275576287	-0,210776287
0,2	38	2007	26	1,314480004	-0,443280004
0,802	45	2007	27	1,248073766	0,203926234
1,5	33,5	2007	28	1,029016874	0,120483126
2,18	42,5	2008	29	0,928988566	0,140511434
0,5	38	2008	30	1,223190822	-0,199690822
0,52	41	2008	31	1,241026429	1,369473571
5	38	2008	32	0,347857185	0,296142815
1	38	2008	33	1,125931529	-0,343931529
2	38	2008	34	0,931412943	-0,252912943
1,3636	40	2008	35	1,069688557	-0,414188557

Appendix 36 Non-OECD - TWC vs. Plant Size, TDS and Year – Residuals

Abstract

Water shortage is becoming a big challenge in the 21st century. A possible solution to the problem can be desalination. This Master Thesis analyzes different factors that influence the price of desalinated water. Those factors are the size of the desalination plant, the total dissolved solids (TDS) in the feed water and the year of construction. Furthermore, the analysis will be split into OECD and Non-OECD countries in a separate analysis to reduce the effect of region on the price. Alternative sources of freshwater, like dams, pipelines and artificial groundwater recharge are reviewed, to compare the prices with desalination.

A technical description of the most popular desalination methods (Reverse Osmosis, Multi-Stage Flash and Multiple-Effect Distillation) will be provided to enable the reader to comprehend the factors that influence the price of desalination.

Zusammenfassung

Wasserknappheit stellt ein immer größer werdendes Problem im 21. Jahrhundert dar. Eine Möglichkeit dieses Problem anzugehen bietet Meerwasserentsalzung an. Diese Masterarbeit untersucht die verschiedenen Faktoren, welche den Preis für entsalztes Wasser beeinflussen können. Diese Faktoren sind die Größe der Entsalzungsanlage, die Menge an schwerlöslichen Stoffen im zu entsalzenden Wasser und das Baujahr der Anlage. Des Weiteren werden im zweiten Teil der Analyse die Daten in OECD und Nicht-OECD Länder aufgeteilt um den Effekt der Region auf den Preis zu reduzieren. Alternative Möglichkeiten um an Süßwasser zu gelangen, wie etwa Dämme, Pipelines und künstliche Grundwasseraufstockung werden ebenfalls untersucht um die Preise mit Meerwasserentsalzung zu vergleichen. Eine technische Beschreibung der am häufigsten genutzten Entsalzungsmethoden (Umkehrosmose, mehrstufige Entspannungsverdampfung und Multieffekt-Destillation) wird ebenfalls erwähnt um der/dem LeserIn ein besseres Verständnis darüber zu geben, wie der Wasserpreis bei Meerwasserentsalzung zustande kommt.