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Seawater desalination using wind energy.
Case study: Johnny Cay-Colômbia

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Abstract

Water scarcity is a current problem in certain parts of the world and several studies indicate that every day it is spreading to other regions of the globe, mainly due to population growth, the desire to improve life's quality and climate changes.

To minimize this growing problem seawater desalination techniques have been applied. However, conventional systems are very expensive and require a lot of energy, usually from fossil fuels.

On islands and remote areas, where electrical installations are economically unviable and the wind resource is abundant, desalination of seawater using the kinetic energy of wind comes up as a possible solution to the shortage of drinking water.

This work aims to study the technical and economic feasibility of a seawater desalination microsystem by reverse osmosis, using wind power and with a practical application in the small Colombian island, Johnny Cay, which has no drinking water nor electricity.

Keywords: Drinking water, reverse osmosis, desalination, wind energy.

Resumo

A escassez de água potável é um problema atual em certas regiões do planeta e vários estudos indicam que todos os dias se está a alastrar a outras regiões do globo.

Na literatura há uma enorme quantidade de indicadores e de índices relacionados com a água. Cada um deles tem sido definido sob diferentes premissas e condições, por isso, a sua aplicabilidade pode ou não ser adequada em todas as áreas de estudo. Um dos indicadores mais utilizados é o "índice de *stress* hídrico" que afirma que quando as reservas anuais de água estão abaixo dos 1 000 m^3 por pessoa, a população enfrenta escassez de água. No entanto a água é um recurso muito complexo. Ao contrário do que acontece com um recurso estático, como terra, a água ocorre num ciclo muito dinâmico de chuva, escoamento e evaporação, com enormes variações temporais e espaciais, bem como variações na qualidade. A água pode ser um incómodo (em cheias), bem como um recurso de salvação (em secas) sendo que ambas as condições podem ocorrer num local dentro de um único ano. Por esta razão, a disponibilidade anual de água num determinado local tem pouco significado quando estamos a avaliar a sua escassez.

Existem três fatores que são a principal causa da falta de água no globo: a variabilidade climática; o rácio *supply/demand* e os acessos. O primeiro destes fatores é um fenómeno natural causado principalmente pela variação da quantidade de precipitação. No entanto, há estudos que indicam que, devido às alterações climáticas, há cada vez fenómenos mais extremos de precipitação, causando cheias e/ou secas mais ou menos intensas e prolongadas. O segundo fator tem diversas origens, entres elas, o desenvolvimento económico de uma região, que potencia o uso de água nas indústrias e noutros setores, por outro lado a sobrepopulação, a poluição, o aumento da qualidade de vida e o ineficiente uso do recurso disponível. O terceiro fator é o principal no que toca aos números de pessoas afetadas (663 milhões), neste caso o recurso existe mas por razões económicas não está disponível.

Para travar este problema sugeriram-se algumas soluções, entre elas a dessalinização da água do mar. Atualmente há mais do que 17 000 centrais de dessalinização no mundo que, combinadas, produzem um total de 80 milhões m^3 de água potável em mais de 150 países, abastecendo mais de 300 milhões de pessoas.

Todas estas centrais funcionam com base em dois principais processos de dessalinização: os processos térmicos (ou de mudança de fase), que usam um método equivalente ao ciclo da água, ou seja, a água salgada aquece, evapora, condensa e precipita sob a forma de água potável e os processos de membranas, onde, como o nome indica, o processo de separação dos sais minerais da água é feito com recurso a uma membrana. Dentro das tecnologias com base em processos de membranas destacam-se os sistemas de osmose inversa (*reverse osmosis* em inglês, ou RO) que representam 65% da capacidade total instalada em dessalinização. Nesta tecnologia a água do mar é bombeada (com recurso a uma bomba de alta pressão) contra uma membrana semipermeável, na qual ficam retidos a maioria dos sais contidos na água, produzindo assim água potável.

O custo dos sistemas RO decresceram bastante desde a sua comercialização em 1970 até hoje, devido a melhorias das tecnologias das membranas, bombagem e sistemas de recuperação de energia. No entanto, os seus custos continuam a ser bastantes elevados, principalmente devido à grande quantidade de energia necessária para abastecer a bomba de alta pressão. Energia essa que vem com impactos ambientais associados, mais especificamente a emissão de gazes de efeito de estufa, devido aos combustíveis fósseis utilizados pelos sistemas convencionais na produção de eletricidade. Este facto motivou o desenvolvimento de tecnologias de dessalinização integradas com fontes de energia limpa e grátis, as energias renováveis.

Em ilhas e regiões remotas, onde as instalações elétricas são economicamente inviáveis e o recurso eólico é abundante, a dessalinização da água do mar através da energia disponível no vento surge como uma possível solução à escassez de água potável.

O presente trabalho tem como objetivo o estudo da viabilidade técnico-económica de um microssistema de dessalinização da água do mar por osmose inversa, utilizando energia eólica e tendo como caso de aplicação na ilha Johnny Cay, que não possui água potável nem eletricidade.

Johnny Cay é uma pequena ilha Colombiana localizada no mar das Caraíbas. Esta é principalmente visitada por turistas que aproveitam o sol e as águas cristalinas para beber uma bebida fresca ou comer peixe acabado de pescar num dos diversos restaurantes e bares espalhados pela ilha. No entanto, como não existe água potável nem gelo estes bens têm de ser importados para fazer face a uma demanda média anual de 120 450 L e 369 380 kg, respetivamente. Isto dificulta as contas dos comerciantes ao mesmo tempo que traz prejuízos ambientais devido ao combustível gasto para transportar os bens, e à grande quantidade de plástico necessário.

Tendo em conta as necessidades previstas da ilha, bem como o recurso de energia renovável disponível, é proposta a implementação de um microssistema híbrido composto por uma turbina eólica ligada a um sistema de dessalinização da água do mar por osmose inversa (*seawater reverse osmosis* em inglês, ou SWRO) e a um gerador de reserva, de maneira a produzir água potável e fornecer eletricidade para a comunidade local. Um sistema de energia solar fotovoltaica será também utilizado para suportar as necessidades elétricas.

Em ilhas pequenas, onde a mão-de-obra qualificada é escassa e o orçamento é limitado, o custo de investimento juntamente com a simplicidade pode ser um fator preponderante na escolha de um sistema de dessalinização. Tendo isto em conta, como grande parte da energia necessária numa unidade SWRO é consumida pela bomba de alta pressão (*high pressure pump* em inglês, ou HPP), a ideia de uma ligação mecânica entre a turbina e a HPP parece à primeira vista mais simples e económica do que a utilização de um aerogerador, visto que deste modo vão existir menos formas de conversão de energia envolvidas (com o uso de um aerogerador normal seria necessária a conversão de energia mecânica em elétrica que teria de ser novamente convertida em energia mecânica antes de chegar ao RO).

No sistema estudado a energia disponível do vento é transferida para as pás do rotor que está acoplado a uma bomba de cilindrada fixa, esta, por sua vez, está ligada a um sistema hidráulico que ocupa toda a extensão interior da torre da turbina, desde a altura da *nacelle* até ao solo. A velocidade de rotação do rotor é proporcional ao fluxo bombeado pela bomba. Através de um conjunto de válvulas no sistema hidráulico o fluxo do óleo que chega ao RO e ao gerador é mantido praticamente constante enquanto o excesso é desviado de volta para o cimo da torre. A energia contida no óleo é então transferida à água salgada através de um motor acoplado à bomba de alta pressão do RO fazendo movimentar 1,43 m^3/h de água salgada através de dois módulos de membranas do tipo *spiral-wound*. Deste fluxo 0,5 m^3/h sai sob forma de água potável.

Palavras-chave: Água potável, osmose inversa, dessalinização, energia eólica.

“The cure for anything is salt water: sweat, tears, or the sea.”

— *Karen Blixen*

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Symbols and Notations

ΔP_{loss}	Pressure drop per membrane element (bar)
$\Delta\pi$	Osmotic pressure difference (bar)
γ	Recovery ratio
η	Efficiency
$\eta_{aerodynamic}$	Aerodynamic efficiency
$\eta_{generator}$	Generator efficiency
$\eta_{hydraulic}$	Hydraulic efficiency
$\eta_{RO_{HPP}}$	Efficiency of the high pressure pump
η_{total}	Global efficiency
θ	Phase angle (°)
π	Osmotic pressure (bar)
π_f	Feed osmotic pressure (bar)
π_c	Concentrate osmotic pressure (bar)
π_p	Permeate osmotic pressure (bar)
ρ	Air density (kg/m^3)
ω	Rotation (rad/s)
ω_{motor}	Motor shaft rotation (rad/s)

A	Rotor swept area (m^2)
C_P	Power coefficient
cc	Displacement (cm^3/rev)
c_c	Brine concentration (g/m3)
c_f	Feed concentration (g/m3)
c_i	Ion concentration (g/m3)
c_p	Permeate concentration (g/m3)
f	Frequency (Hz)
I_{ph}	Phase current (A)
J_w	Membrane water flux ($L/h/m^2$)
L_p	Membrane permeance ($L/m^2/h/bar$)
Mi	Molecular ion mass (g/mol)
p_c	Concentrate pressure (bar)

P_e	Electric power generated (kW)
p_f	Feed pressure (bar)
$P_{gen_{in}}$	Power available in generator's shaft (W)
P_{in}	Wind power (kW)
P_{motor}	Power required by the engine (kW)
P_{out}	Useful power (kW)
p_p	Permeate pressure (bar)
P_{RO}	Hydraulic power provided by the RO_{HPP} (kW)
P_{rotor}	Power available in rotor's level (W)
q_c	Concentrate flow (m^3/h)
q_f	Feed flow (m^3/h)
q_p	Permeate flow (m^3/h)
Re	Rejection
RO_{HPP}	High pressure pump of the reverse osmosis system
SEC	Specific energy consumption
T_{motor}	Torque provided by the motor (Nm)
u	Wind velocity (m/s)
V_{ph}	Phase voltage (V)
z	Height (m)
z_i	Valence of the Ion
z_0	Characteristic length of the ground roughness (m)
z_R	Reference height (m)

BWRO	Brackish Water Reverse Osmosis
EC	Electrical Conductivity ($\mu S/cm$)
ED	Electrodialysis
FAO	Food and Agriculture Organization
GAC	Activated Carbon Filter
GHG	Greenhouse Gases
MED	Multi-Effect Distillation
MF	Microfiltration
MMF	Multimedia Filter
MSF	Multi-Stage Flash Distillation

MVC	Mechanical Vapor Compression
NF	Nanofiltration
PMSG	Permanent Magnet Synchronous Generator
RO	Reverse Osmosis
SD	Solar Distillation
SWRO	Seawater Reverse Osmosis
TBT	Top Brine Temperature (ºC)
TDS	Total Dissolved Solids (ppm)
TMP	Transmembrane Pressure (bar)
TVC	Thermal Vapor Compression
UF	Ultrafiltration
UN	United Nations
WBG	World Bank Group

Chapter 1 – Introduction

1.1. Motivation and Methodology

The present work was first developed in *Delft University of Technology,* where an initial bibliographic review was carried out on desalination technologies by reverse osmosis, as well as the calibration and installation of the necessary equipment for data colection related to the operation of the studied system.

Later, in Leeuwarden, together with *SolteQ Energy B.V.* (company holding the system patent), several tests were performed and the collected data were analyzed, allowing us to draw some conclusions that led to the development of this work.

Since the main motivation is the creation of a desalination system that can be installed in remote areas without drinking water, a review of the water resource and its scarcity in the world was also made.

1.2. Water Supply

1.2.1. Hydrological cycle

As far as a reasonable time scale is considered, the amount of water in planet Earth is huge and constant, simply because it is not lost to space. It can be found in three basic states: solid, liquid and gaseous, and in every moment the sum of the amounts of water in each state is constant over time. Water is in constant motion, circulating among the ocean, atmosphere and land in an endless cycle, called the hydrologic cycle (Figure 1).

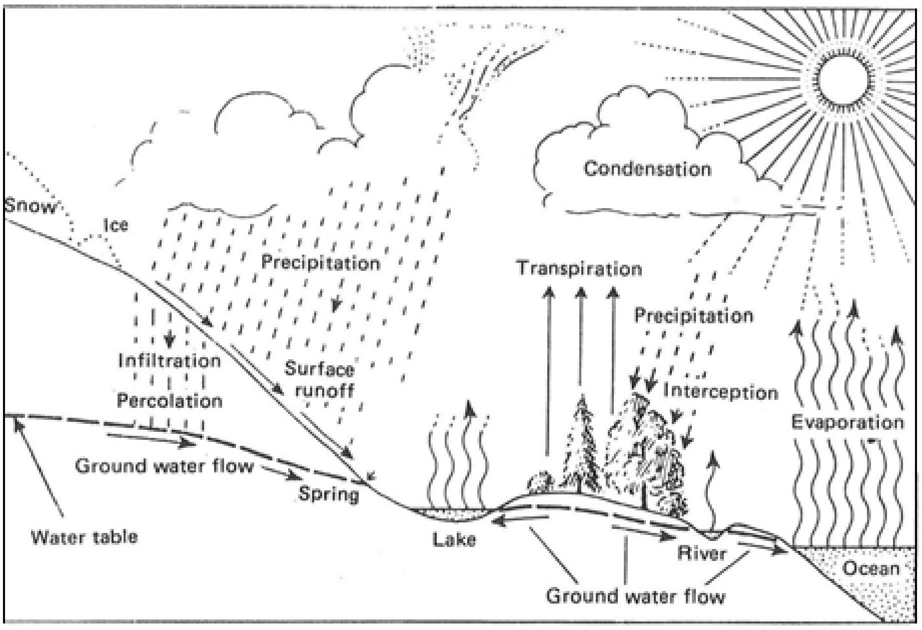


Figure 1 – Water cycle. [1]

The solar radiation is the main driving force of the water cycle: it warms the surface causing the evaporation of water contained in the oceans, lakes, rivers, plant leaves, etc. In the atmosphere, water vapor condenses to form clouds, which, with favorable weather conditions, precipitate as rain, snow or hail.

The precipitation can occur directly on the sea or on the land surface. When it reaches the land, rain can be intercepted by vegetation and part of it is returns to the atmosphere by evapo-transpiration. When it reaches the ground, the water can slip, or seep into the ground until it reaches the phreatic surface (saturated soil). During its infiltration, it can be absorbed by plant roots and consequently leaked back into the atmosphere again and again.

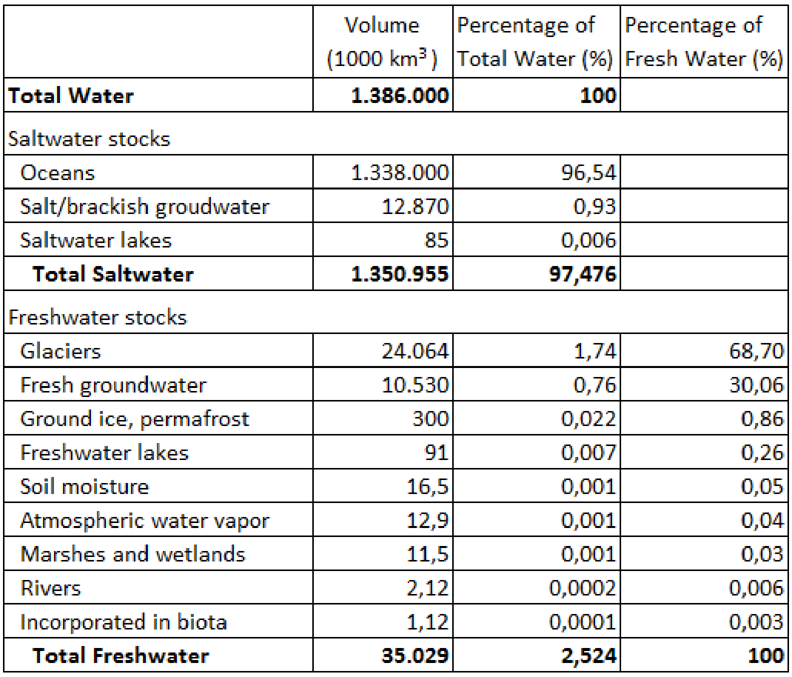
The surface runoff follows the course of less resistance and finds the ground water flow in lakes and rivers where they can be stored for a while but eventually return to the ocean.

The hydrologic cycle has an additional importance to life on earth, since evaporation is a cleansing process; the salty seawater is transformed into clean water precipitation. Therefore, the water reserves in the continents consist mainly on drinking water reserves, with the exception of ground water with dissolved salts (brackish water) and water polluted by humans. [1]

1.2.2. Water reservoir

Water reserves available amount nearly to 1 386 million cubic kilometers. Nevertheless, not all of it is available for human consumption since it is estimated that of the total existing water only about 2.5% is drinkable and it is deposited into four major natural reservoirs: The glaciers, the atmosphere, groundwater and surface water. (Table 1)

Table 1 – Water reservoirs. Adapted from: [2]



	Volume (1000 km^3)	Percentage of Total Water (%)	Percentage of Fresh Water (%)
Total Water	**1.386.000**	**100**	
Saltwater stocks			
Oceans	1.338.000	96,54	
Salt/brackish groudwater	12.870	0,93	
Saltwater lakes	85	0,006	
Total Saltwater	**1.350.955**	**97,476**	
Freshwater stocks			
Glaciers	24.064	1,74	68,70
Fresh groundwater	10.530	0,76	30,06
Ground ice, permafrost	300	0,022	0,86
Freshwater lakes	91	0,007	0,26
Soil moisture	16,5	0,001	0,05
Atmospheric water vapor	12,9	0,001	0,04
Marshes and wetlands	11,5	0,001	0,03
Rivers	2,12	0,0002	0,006
Incorporated in biota	1,12	0,0001	0,003
Total Freshwater	**35.029**	**2,524**	**100**

Glaciers

While glaciers account for only 1.7% of the total water on Earth, they represent 68.7% of the reserves of drinking water. The polar ice has no major influence on the hydrological cycle, since its volume keeps nearly constant overtime, however the seasonal ice in the high mountains (corresponding to 1% of the total drinking water [3]) can have a major impact since its rapid melting could lead to situations of flooding and contamination of other water resources. [3]

Atmosphere

The water primarily exists in the atmosphere as a gas (water vapor) but also in its liquid and solid state, in small water droplets and ice crystals (forming the clouds).

Despite its huge volume, water in the atmosphere represents only 0.04% of the drinking water reservoirs, however it has great importance as a transport factor, since approximately 40 000 km^3 of water per year are transported from oceans to continents. [4]

The presence of water in the atmosphere also affects the weather and climate, because 19% of the incident solar radiation (short waves) is reflected in clouds and 17% is absorbed by water molecules in the troposphere. Water vapor is also responsible for much of the absorption of infrared radiation emitted by the earth, thus being the main cause of the natural greenhouse effect (without it, the average temperature of the earth would be about -23 $^{\circ}C$ instead of 15 $^{\circ}C$). [5] [6]

Groundwater

When it infiltrates into the soil, rainwater passes through a portion of the ground called unsaturated zone, where the pores are partly filled by water and air. Part of the infiltrated water is absorbed by the roots of plants and other living forms or evaporates back into the atmosphere. The remainder continues its downward movement due to the force of gravity.

On its way, the excess water builds up in deeper areas, completely filling the pores and forming a saturated zone. The water circulating in a saturated zone is called groundwater. The amount of water stored in rock depends on the porosity (the void volume of pores relative to the total volume of the rock) and the groundwater flow depends on the permeability (the ease with which the water flows through the rock) which is related to the size and the volume of interconnected pores, and also the shape, distribution and variation of the grain size. [7]

These two characteristics are very important to form an aquifer (underground water reservoir). For example, the argillite and siltstone have high porosity (35 – 60%) but low permeability. Thus, despite the large storage capacity, it is not possible to form an aquifer because with this type of rock structure it is not possible to extract water in sufficient volume for use.

In addition to its geological composition, aquifers are mainly classified according to their hydraulic characteristics, in phreatic or artesian, depending on the pressure they are submitted to.

The phreatic aquifer is closer to the surface, where the saturated zone has direct contact with the non-saturated zone (phreatic level), being submitted to atmospheric pressure. In this type of aquifer, the water that infiltrates into the soil goes through the unsaturated zone and recharges the aquifer directly. (Figure 2, top)

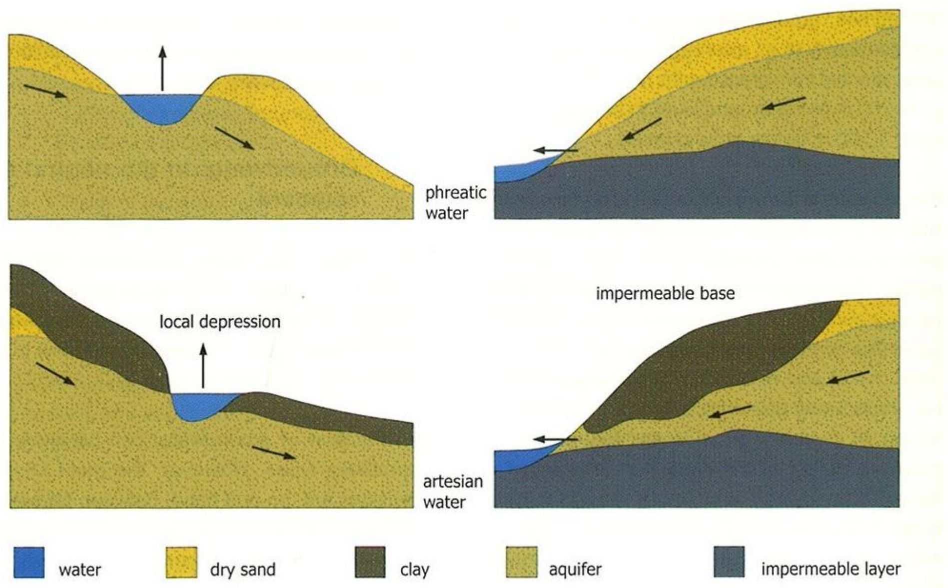


Figure 2 – Pheratic water (top) and artesian water (bottom). [8]

The artesian aquifer is bounded on the top and bottom for low permeability rock layers (such as clay, shale thin, massive igneous rocks, etc.). There is no unsaturated zone, and in this case, the groundwater is subjected to a pressure greater than atmospheric, due to a confining layer above it, which is also saturated with water. (Figure 2, bottom) Thus, the water level has enough pressure to reach a height above the top of the aquifer, but is prevented by the neighboring layer. In artesian aquifer, the water level is called potentiometric surface (or piezometric surface). When drilling a well it is possible to check that the potentiometric surface reaches a height above the top of the artesian aquifer and it may even exit to the surface if there is enough pressure. (Figure 3) The water that recharges the aquifer needs to cross the less permeable layer above it, in a very slow process, or seep where the aquifer is free. [8] [9]

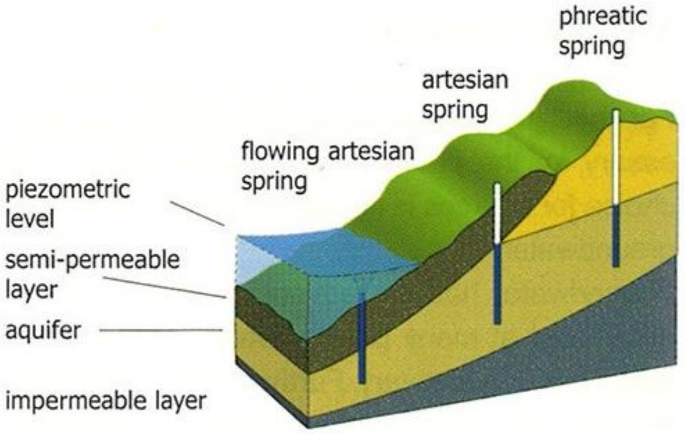


Figure 3 – Artesian aquifer. [14]

Groundwater is the main source of drinking water for humans, since it represents 30% of total reserves of drinking water (or 96% excluding the glaciers). This resource is available almost everywhere and, in addition, its chemical composition is generally constant and reliable and it can sometimes be consumed without pretreatment. However, its use should be controlled according to the natural replacement time of the aquifer, which, as it was seen, depends strongly on its geological characteristics (it may take only some weeks or many decades) and caution must be taken, in order not to contaminate it, because this may affect the entire aquifer during a long period of time.

Surface water

Surface water includes rivers, lakes, soil moisture, wetlands and biological water (present in animals and plants). It represents only 0.35% of the total reserves of drinking water, however it is very important for human activities, whether for use in irrigation canals, dams, transportation, tourism and many other applications. One of the main characteristics of surface water is its constant movement and exchange with other surface reservoirs and with atmospheric and groundwater. This exchange allows the transit of nutrients, favoring the formation of a huge amount of ecosystems. Contrary to groundwater, surface water varies widely in terms of quantity (depending mainly on the seasonal climate variability) and quality (especially depending on the influence of man) and therefore it should be taken special attention to its treatment.

1.2.3 Water quality

The natural flow of water passing through the rocks present in the environment leads to their slow dissolution. Such process leads to an accumulation of substances dissolved in the liquid medium.

The chemical quality of water is usually expressed as total dissolved solids, TDS and it is usually expressed in parts per million (ppm) or its equivalent, milligrams per liter (mg/L). [2]

Water is considered to be drinking water when the concentration of TDS is less than 1 000 ppm, brackish water when TDS lies in the range 1 000 ppm to 10 000 ppm, and salty water when TDS is higher than 10 000 ppm. The seawater has a TDS between 30 000 - 40 000 ppm. [8]

Apart from being generally a good measure of the concentration of ionic substances in the water, TDS is a somewhat a rough classification of chemical water quality since it only gives us the concentration of dissolved ions but not its nature.

When compounds are dissolved in water, most dissociates into ions. Most of the present ions are:

- Cations: Na^+, K^+, Ca^{2+}, Mg^{2+} and Fe^{2+}, Mn^{2+}, NH_4^+ in smaller amounts.

- Anions: Cl^-, HCO_3^-, SO_4^{2-}

Table 2 – Ion concentration in river water and seawater. [8]

Ions	Average river (mg/L)	Seawater (mg/L)
HCO_3^-	58	142
Ca^{2+}	15	400
SO_4^{2-}	11	2 560
Cl^-	8	18 980
Na^+	4	10 560
Mg^{2+}	4	1 272
K^+	2	380

Calcium, magnesium and iron are necessary nutrients and water can even be a source of these minerals. The iron and manganese sulfate can give a bad taste to the water, although they are not toxic. High levels of sodium in combination with chlorine give the water a salty taste. Calcium and magnesium in excess originates the commonly called "hard water", interfering with certain water uses. Fluor, nitrate and sodium in excess can have negative effects on human health. [12]

There are other physical and chemical parameters also important to consider regarding the water quality: such as pH, dissolved oxygen, the microbiological composition, transparency, taste and odor. These parameters should not be forgotten, however, measuring only the TDS, it is possible to reach important conclusions regarding the desalination of sea water, the theme on which this work is focused.

The total concentration of dissolved solids may be measured by evaporating the water and weighing the remain solids, however this method is not the best solution when the goal is to continue with liquid water. Instead of it, it is preferable to take advantage of the fact that ions are electrically charged species.

A water solution with ions acts as an electrical current conductor. For a given applied voltage, the amount of current that can flow through solution is proportional to the concentration of ionic species in the solution. In other words, pure water has a high resistance to the passage of electric current since it has small amounts of ions, unlike seawater which conducts electricity much more easily, because it has a higher conductance.

Therefore, it is possible to have an idea of the concentration of ions in a solution by measuring its electrical conductivity, EC, which is the equivalent to the conductance per distance unit between two points.

The S.I. unit of electrical conductivity is S/m, however when talking about water quality it is more common to use the µS/cm due to the low magnitude of values.

Very pure and deionized water typically has an electrical conductivity of the order about 1 µS/cm, rain water conductivity can be in the range between 20-40 µS/cm, surface water is usually around 30-400 µS/cm. At the outlet of a water treatment, station water will normally have high conductivity (300-1000 µS/cm) due to the ionic substances used in the treatment. This water is unsuitable to drink but can be used for irrigation of farmland or be deposited into rivers, lakes or in the ocean. [12]

The ratio between EC and TDS depends on the specific ions present in the solution. However, it is common to use the factor $K = 0.7$ in equation (1), and this factor can range between 0.5 and 0.9 depending on the TDS level. [13] [14]

$$TDS\ [mg/L] \approx K\ x\ EC\ [\mu S/cm] \tag{1}$$

1.3. Water Demand

1.3.1. Water uses

There are several types of water use, usually divided into three major groups: domestic and municipal uses, industrial uses and agricultural uses. [15]

- Domestic and municipal uses include: water for drinking, cooking, personal hygiene, schools, hospitals, firefighters, gardens, street cleaning, among others.

- Industrial uses: chemical industry, steel, iron, paper, cooling in thermal power plants, hydroelectric production, among others.
- Agricultural uses: mainly irrigation.

On a global scale a total amount of about 3 907 km^3 of water is withdrawn from water reservoirs every year. Agriculture is responsible for 71% of this water use, industry 18% and lastly domestic uses 11% (Figure 6). It should be stressed that this amount do not correspond to the global consumption, which has a lower value, since part of the water withdrawn from rivers and aquifers is returned to the origin before use, but with a delay in time and changed quality.

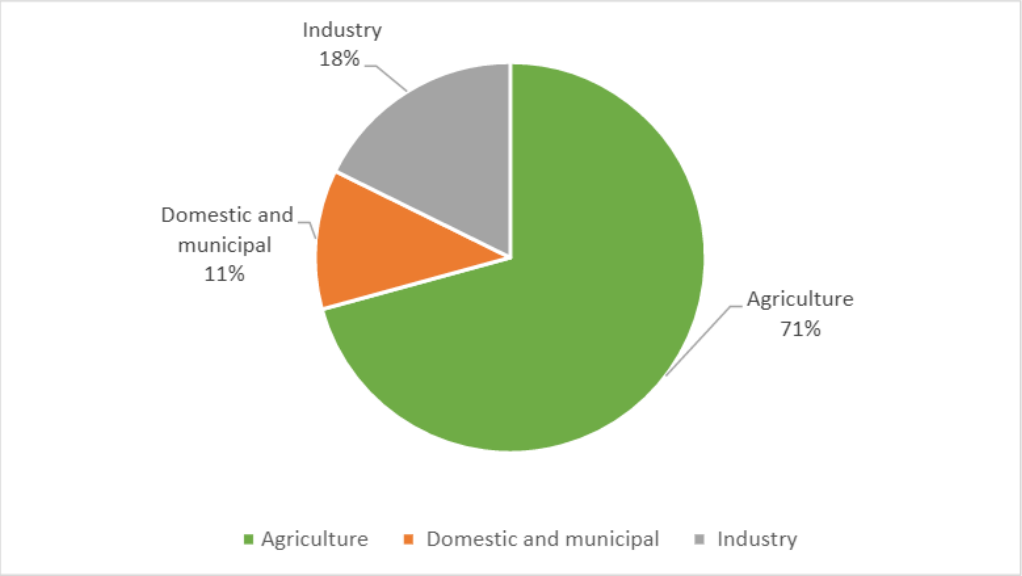


Figure 4 – Global water demand distribution by sector. Data from: [16]

However, according to the WBG data [16], water use distribution among these groups is different from country to country, and is strongly influenced by local economy (Figure 7). This is easily explained, since countries with higher GNI (gross national income) per capita have more industry, and thus a higher share of water for this sector, and also higher share of water use for the domestic sector mainly due to the higher family life quality (pools, watering private garden systems; immersion baths, etc.), and thus, a correspondent decrease in the share of agriculture, also due to the use of more efficient farming techniques. [17]

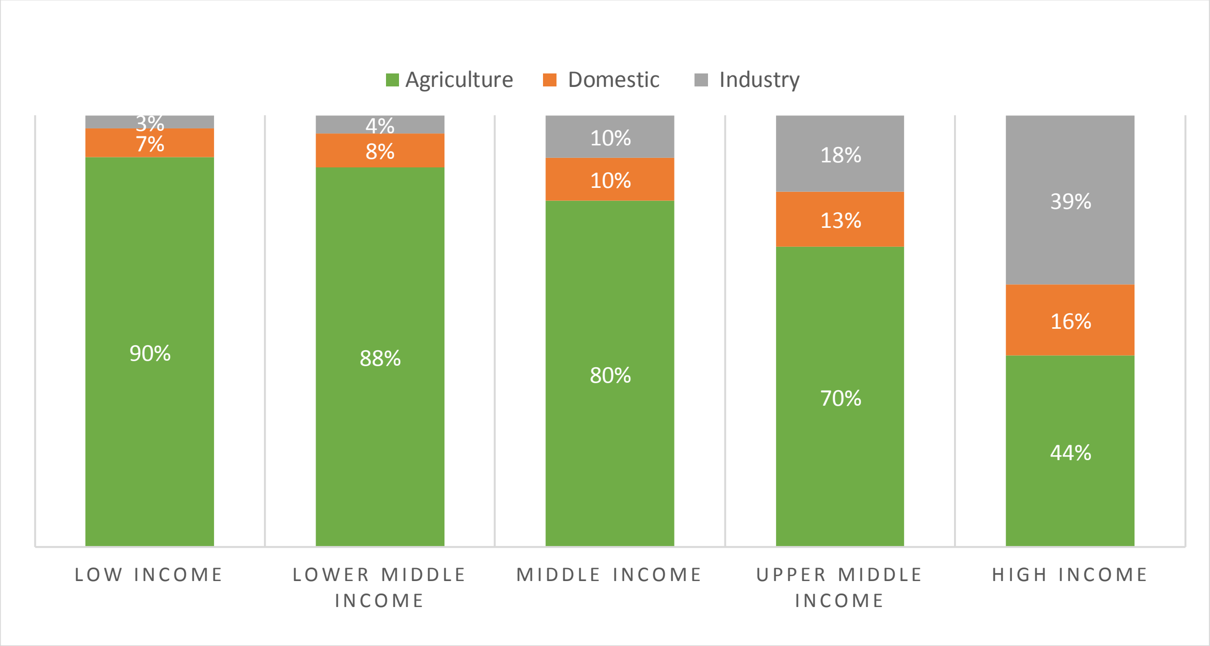


Figure 5 – Global water demand distribution by sector and economy. Data from: [16]

Agriculture

As seen, most of the extracted volume of water for this sector is used for irrigation allowing to ensure higher crop yields and to produce during seasons with insufficient precipitation.

Specialized agencies like FAO consider that the only hope of feeding a world population in continuous expansion is to increase the irrigated crop. On the other hand, agriculture, particularly irrigated agriculture, is a major source of diffuse pollution, and thus a cause for concern. [18]

More than half of the irrigated area in the world is concentrated in four countries: China, India, Pakistan and Bangladesh. United States and Russia also have large areas of irrigation.

Industry

Industrial consumption accounts for about a quarter of total world consumption. There are huge variations in regional and local character in industrial consumption, determined by the levels of technological development and industry type.

The unitary consumption tends to be higher in heavy industry, in older technological processes and warmer climates. This means that the current trend of industrialization of the least developed countries account for high rates of consumption while in developed countries, with modern technology, industrial water consumption has remained steady in recent decades, despite the increase in industrial production.

The electric production is a special case of water consumption for industrial purposes, including both consumption for cooling thermal power plants and for hydroelectric production. In the use of water in thermal power plants, the consumption corresponds to the fraction of the used volume that is lost to the atmosphere by evaporation in the cooling process. Taking as an example the Netherlands, 63 % of the total water consumption is for this purpose. [8] In the case of hydropower production there are almost no water losses in the production process, since the used water is returned to the river after passing through the turbines. However, there is a consumption corresponding to the difference between the evaporated water in the reservoir and the evaporation that would exist if the same amount of water in the corresponding river.

Domestic and municipal

In domestic and municipal uses, are included: water for drinking, cooking, personal hygiene, schools, hospitals, firefighters, gardens, street cleaning and municipal swimming pools, among others.

This group appears with high priority both in developed countries and in developing countries, where, unlike the other groups, the water required here must be of very high quality being necessary the existence of specialized water treatment companies. This means that this water must have an embedded energy content that is much higher than for the other applications.

1.3.2. Changes in demand

Demand growth slowed in developed countries but is still increasing rapidly in developing countries. [19] The pressures that lead to the continued growth in demand are linked to three fundamental aspects:

- Increased population and urbanization
- Increased agriculture and industry
- Waste and water pollution

Population increase represents an increase in domestic consumption, but the increasing urbanization represents a further increase in demand. Even in developing countries, while consumption in rural area is typically of the order 10-30 L/person/day, the unit consumption easily reaches 150 L/person/day in urban areas. [20]

With growing population and urbanization, the needs for agricultural and industrial production also increase, leading to an exponential rising in water consumption. These trends pose two serious problems: first, domestic and municipal consumption requires good water quality, which is being, day-by-day, more difficult to find; also, the result of water consumption growth results in higher waste and increasing waste volumes of water polluted by organic and inorganic substances.

In African continent, for instance (Figure 8), it is estimated that already in 2020 a large part will have an increase in demand exceeding 1.7 times the current use. By 2040 it is expected that this demand increase will spread to the entire continent simply because other regions are expected to have high population growth and/or improving the quality of life in the coming decades.

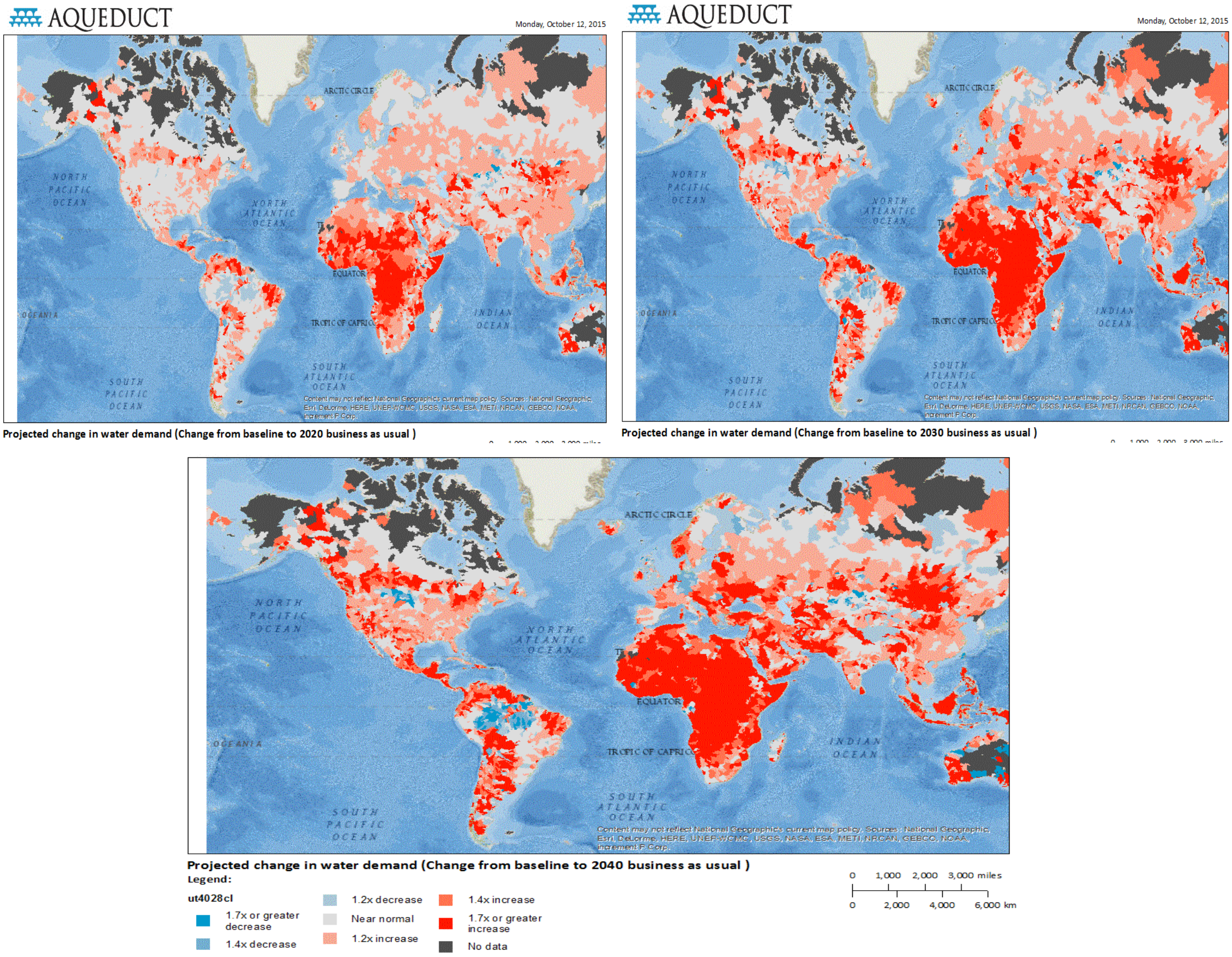


Figure 6 – Projected changes in water demand for 2020 and 2030 (top) and 2040 (bottom). [21]

1.4. Water scarcity

1.4.1. Factors

“What is water scarcity? When an individual does not have access to safe and affordable water to satisfy her or his needs for drinking, washing or their livelihoods we call that person water insecure. When a large number of people in an area are water insecure for a significant period of time, then we can call that area water scarce. It is important to note, however, that there is no commonly accepted definition of water scarcity.” [22]

In the literature there is a huge amount of indicators and indexes related to water. Each of them has been defined under different assumptions or conditions, so, its applicability may be adequate or not in all areas of study. [23]

One of the most used indicators is the "water stress index" that says that one area is experiencing water stress when the annual water supplies drop below 1 700 m^3 per person. When annual water supplies drop below 1 000 m^3 per person, the population faces water scarcity, and below 500 cubic meters "absolute scarcity" (Figure 9). [24]

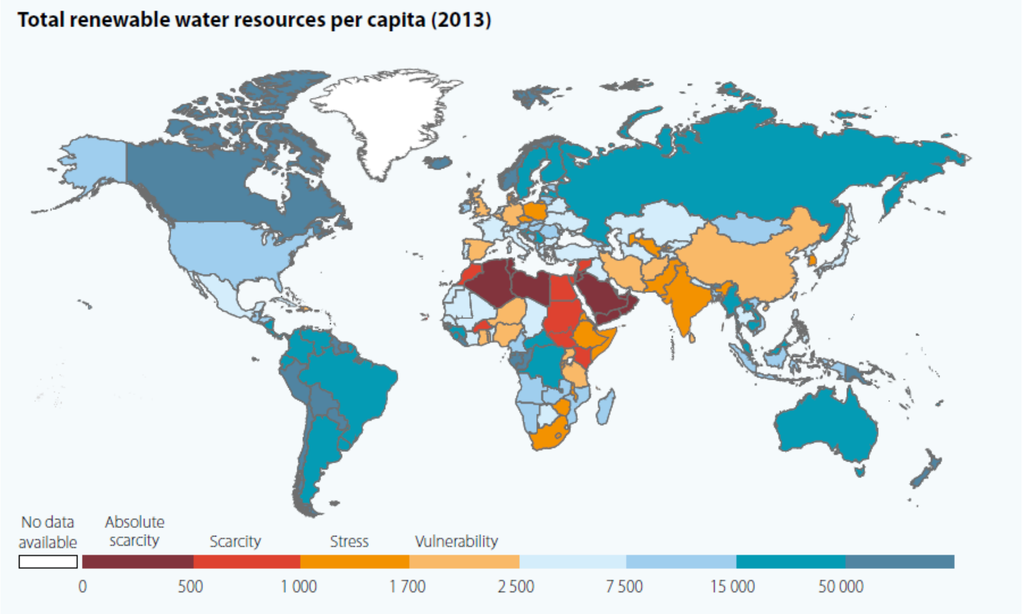


Figure 7 – Total renewable resources *per capita* (2013). [24]

However, water is a very complex resource. In opposition to what happens with a static resource such as land, water occurs in a very dynamic cycle of rain, runoff and evaporation, with enormous temporal and spatial variations as well as variations in quality that completely govern its value to people and ecosystems. Water can be a nuisance (in floods) as well as a lifesaving resource (in droughts) and both those conditions can occur in a location within a single year. For this reason, annual average water availability in such a situation has little meaning to measure water scarcity.

So, rather than showing all the existing indicators, it was decided to show the influence of the main factors in the absence of water, these factors being: the climate variability, the supply/demand ratio and the accesses.

Climatic variability

Climate variability is a normal weather and climate characteristic. It has daily, seasonal and annual cycles that depend on many factors and had always influenced societies throughout the world. The changes in precipitation, both in quantity and duration, over a period are one of the factors where it is possible to verify the presence of climate variability and, as it was seen, it is probably the most important factor in fresh water distribution on the planet.

Taking as an example the Portuguese case, from 2000 to 2011 (Figure 10) it can be seen that there is a seasonal variation in rainfall, with an average of 118 mm in December and only 9 mm in July. These variations can lead to flood situations in the winter months and drought in the summer months. On the demand side, water use is also increased in summer months, mainly because high temperature makes the water demand increase, with an increase of irrigation, hygiene needs, tourism, etc.

In addition to the seasonal precipitation variations, it is also common to have interanual variations. In Portugal the average precipitation in 2000 was about 1 449 mm while in 2004 was 398 mm, a reduction of 72.5% (Figure 11).

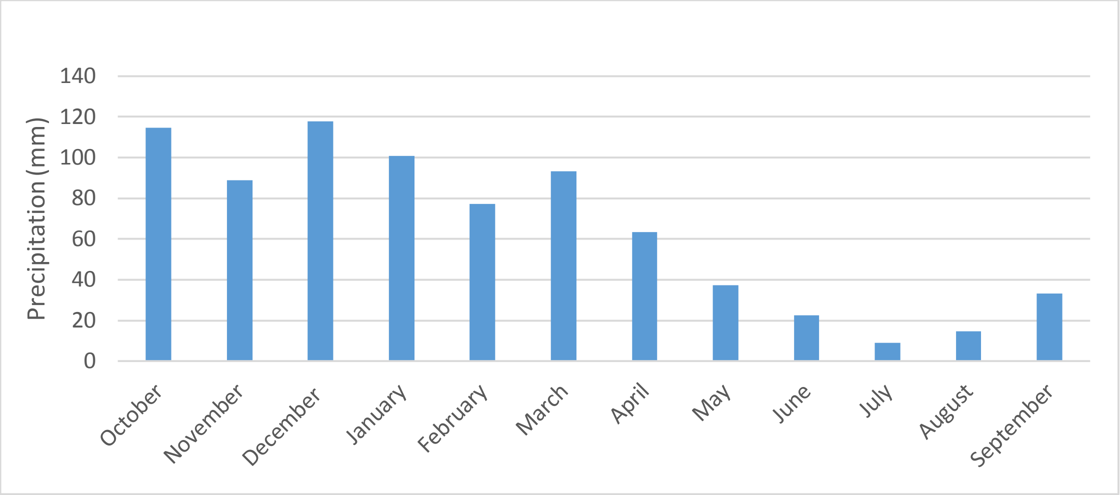


Figure 8 – Average seasonal precipitation in Portugal (2000-2011). Data from: [25]

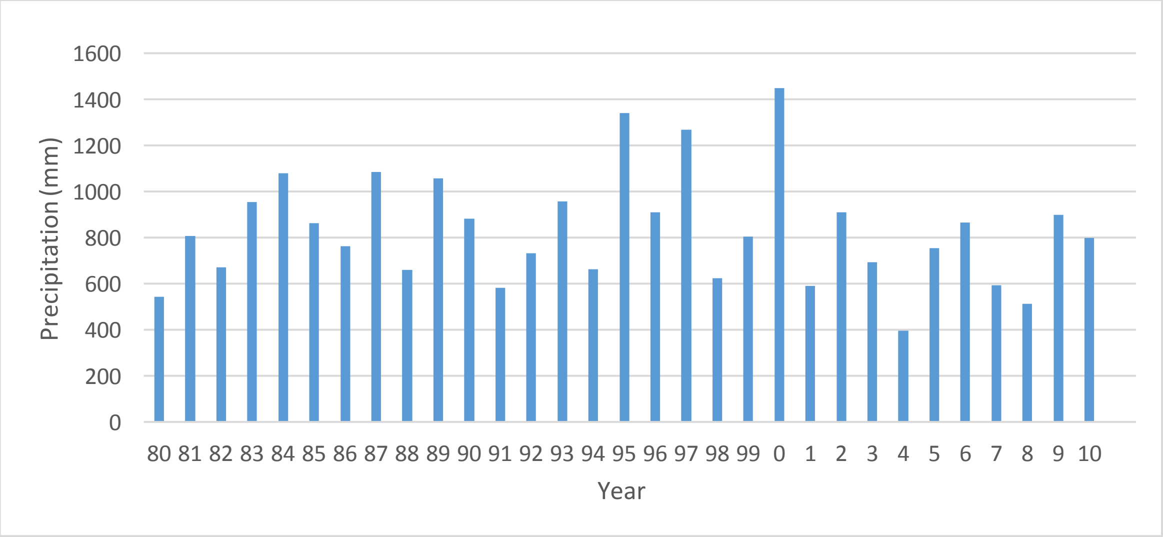


Figure 9 – Average interanual precipitation in Portugal (1980-2010). Data from: [25]

For those living in arid and semi-arid areas, climatic variability is even more extreme, with rainfall periods that are short and floods that can be particularly destructive. In this scenario, the use of dams is an important solution for these countries to store water from the periods with excess to periods with shortage. However, these periods may be longer than desirable, or the country may not be able to afford such infrastructure.

West Africa witnessed a wet period during 1930-1960, followed by droughts in the period 1970-1980 and better rainfalls in the years 1990 and 2000. These years have shown the vulnerability of population to climate variability, with droughts leading to massive famine events in the Sahel areas. [26]

Figure 12 shows parts of the world where the seasonal variability of water resource is larger (in dark red) and lower (white).

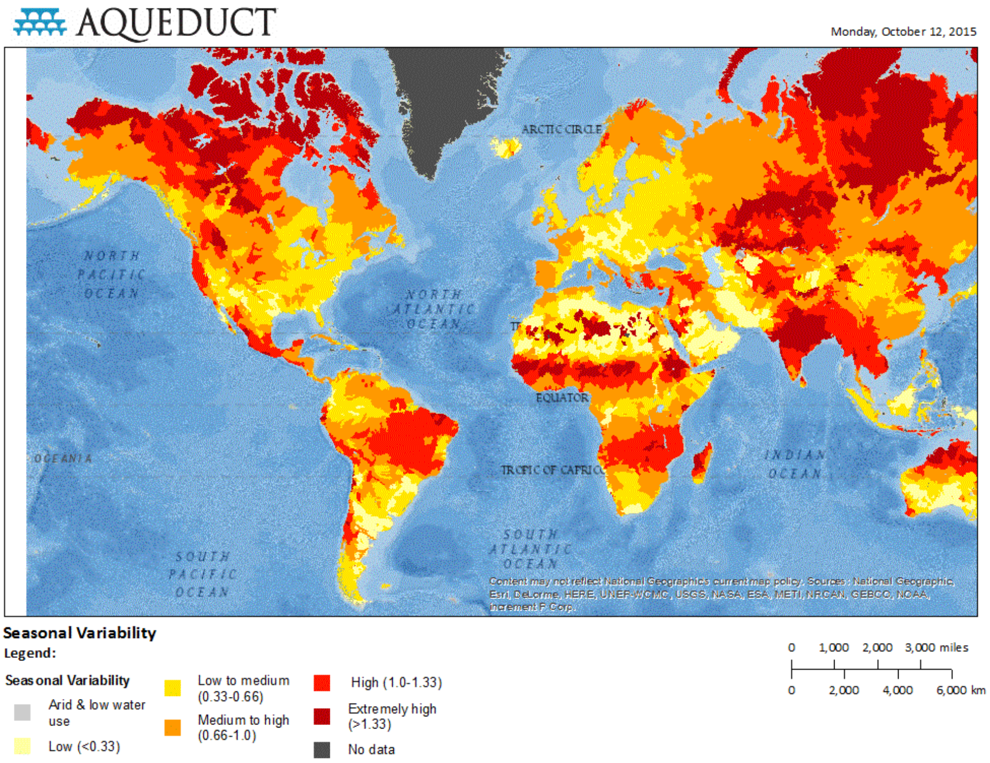


Figure 10 – Global season variability of the water resource. [21]

Climate change add a new dimension to these problems, with an increase of greenhouse gases in the atmosphere, leading to an overall increase in the atmospheric temperature, and thus to a defrost of some glaciers reserves and increasingly intense and frequent events of extreme precipitation. [27]

Supply *vs* demand

Figure 13 shows the ratio of the water consumption in one year to the annually renewable water resource available, or *water stress*. It is perceived that in part of Europe, USA, Mexico, Middle East, India and China exists high water stress (red), unlike much of the African continent, South and Central America (lighter colors) where large water resources exist when compared with the extractions.

To summarize we conclude that the areas with greater water stress in the figure are mainly due to excessive consumption, due to either overpopulation (as is the case of China and India) or strong industrialization and urbanization (as in Europe and the United States). However, it can also be due to the extreme lack of resources (in the case of the Middle East). On the other hand, areas with less water stress are mainly due to the high presence of available renewable resource (such as Russia, Canada and Brazil) or the weak economic development (taking as an example the African continent).

However, high water stress zones shown in the figure have no immediate problems of water shortages. This is mainly due to the existence of large water reserves underground, however they can have serious problems in the future, since groundwater withdrawals already exceed natural recharge rates leading to the level of these reserves to decrease substantially from year to year. [28]

A recent study by *Wada et al., 2010* showed that groundwater depletion rates have more than doubled between 1960 and 2000 in sub-humid and arid areas, particularly in parts of China, India and the United States of America. [29]

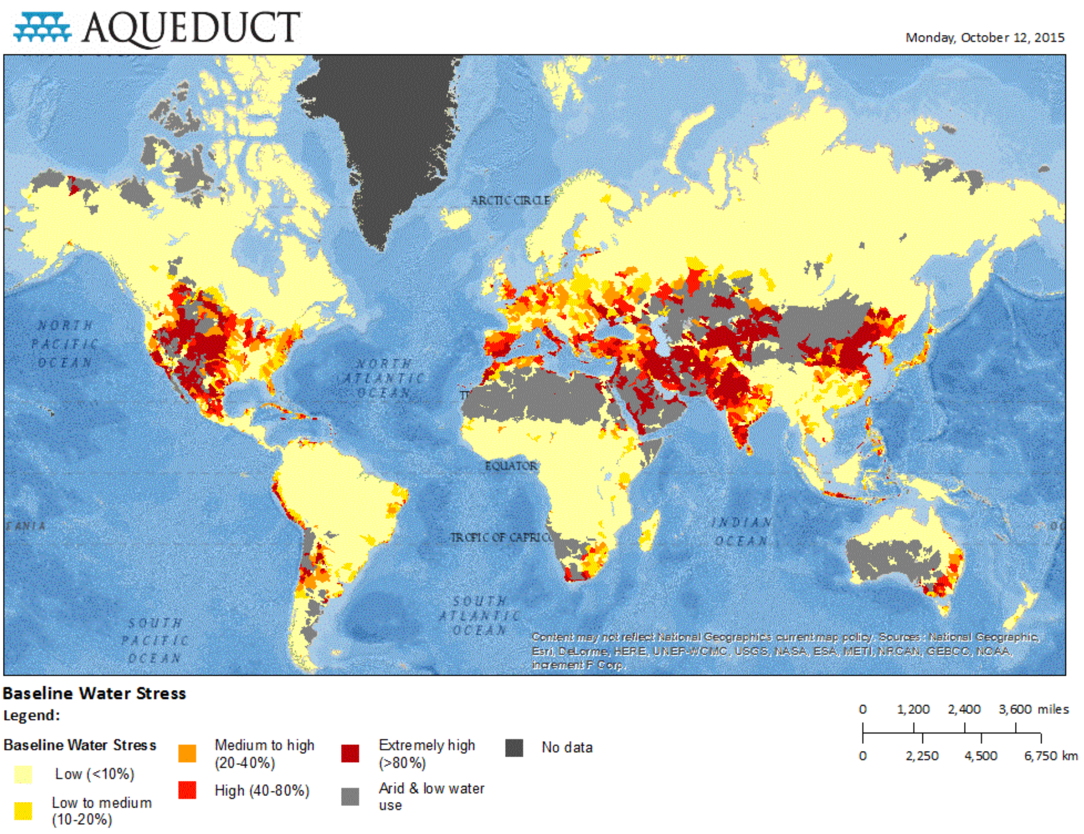


Figure 11 – Global water stress. [21]

Access

Despite global concerns about water scarcity and, all the measures already taken to reduce this problem, currently there are still about 663 million people who do not have access to safe drinking water, and half of them are in the Sub-Saharan Africa. [30] But the maps presented above show that, in fact, sub-Saharan Africa has even a higher amount of water per capita (Figure 9), a lower ratio of water consumption per annual renewable water resource (Figure 13) and in certain areas equal seasonal climatic variability (Figure 12) when comparing, for example, with the European average, where 99% of the population are able to use water without any problem. [30]

Putting all these factors together, we may conclude that the problem main source is not the lack of resources or excessive demand but local economics. This includes lack of economic resources for the construction of dams, water transport facilities, or sanitation and wastewater treatment infrastructure.

In Figure 14, "Access to water" measures the percentage of people without access to drinking water sources. Higher values indicate areas where populations have less access to safe drinking water sources, and thus high risks to those using water.

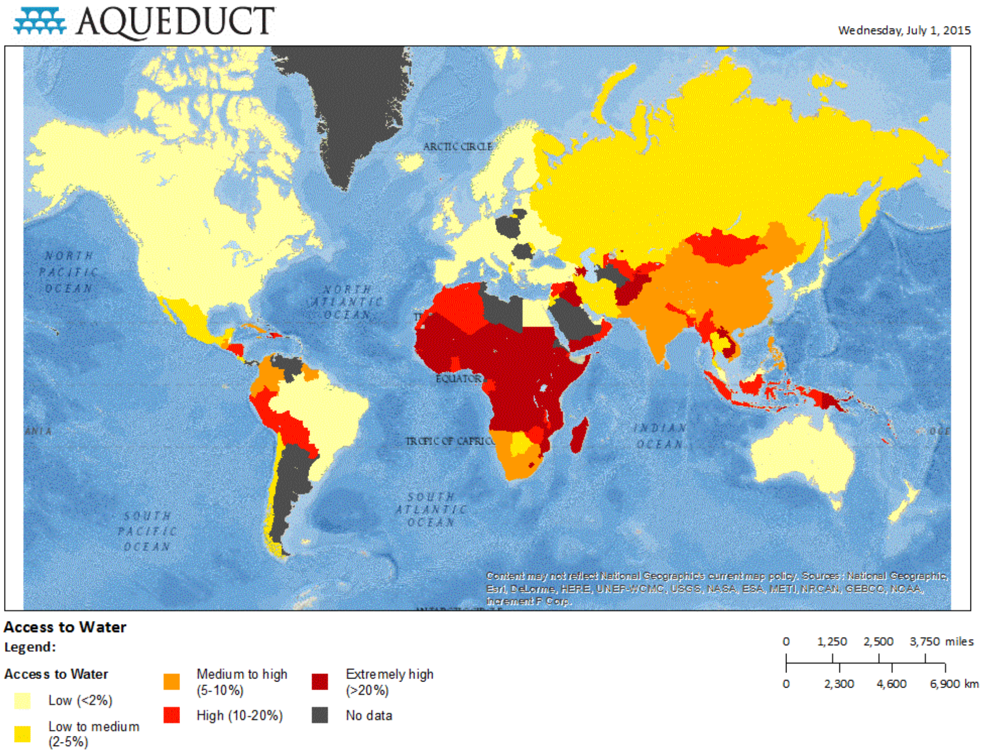


Figure 12 – Access to water (percentage of population without access to drinking water). [21]

Comparing this figure with the above mentioned (Figures 9, 12 and 13) it can be seen that in certain regions (particularly in equatorial Africa, and central/south America) it is not the lack of water in their physical appearance the problem but actually the accesses. It can be said that in this case it is witnessed economic scarcity, because the drinking water exists but because of human, institutional or financial issues, access to it is limited, making the people to travel long distances in search of this good, or use it in a wrong way.

1.4.2. Solutions

"If I had only one hour to save the world, I would spend fifty-five minutes defining the problem, and only five minutes finding the solution."- Einstein

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As explained in the phrase attributed to Einstein, to understand the causes of a problem is the first step toward finding its solution. Taking into account the main factors involved in the shortage of water around the world it can be said that for this problem there are several possible solutions, more or less expensive and with different degrees of complexity. This include:

- ✓ Methods to decrease waste: the investment in more efficient irrigation techniques, development of modern sanitation systems, as more economic discharges, water distribution system monitoring, alerting people to the problem.

- ✓ Rainwater: the captured rainwater is and can be used for domestic and industrial purposes such as watering gardens, washing cars and driveways, use in irrigation and cooling industry.

- ✓ Water recycling: recycling is one of the pillars for sustainability and this could reduce the amount of water taken from rivers, lakes and aquifers. For example, water from sewage from homes and industries can be taken to treatment plants, where it is treated (wastewater) and reused in industry or irrigation, where is not necessary to have high quality water. Even so, this can only be made locally, since it implies the use of two distribution grids (drinking water and wastewater).

- ✓ Dams’ construction: with the use of dams it is possible to store water from flood periods to be consumed in times of drought.

- ✓ Decontamination of rivers and lakes: with population growth in cities, sewers, industry and agriculture undue wastewater is thrown in many rivers and lakes around the world leading to their pollution. One possible solution involves for environmental restoration of these rivers identifying the main sources of pollution.

- ✓ Financial support for the poorest countries: support from the richest countries for the construction of dams, transport infrastructures and water sanitation.

- ✓ Seawater desalination: a number of countries in the world who suffer or may suffer with the lack of drinking water are located by the sea (as many islands and countries in the Middle East). The solution seems obvious: to get water from the sea, take the salt off and make it ready for consumption. This is seen as one of the most important solutions to the shortage of drinking water in the near future and it will be analyzed with more detail in the next chapter.

1.5. Thesis structure

This document is structured in four chapters: in Chapter 1 the importance of drinking water production, the main factors acting on water resource and water scarcity around the globe is presented; in Chapter 2 a review about the state of the art of the main desalination technologies, with special attention to seawater reverse osmosis (SWRO) will be provided; in Chapter 3 the case study will be presented, including the corresponding energy and financial analysis; in Chapter 4 the main conclusions of the performed study will be discussed.

Chapter 2 – Desalination: State of Art

2.1. Introduction

The process of desalination is a group of methods that aims to remove most of the mineral salts from seawater, brackish water and wastewater in order to make it drinkable. The first major development of this process began in the 40's because of the Second World War, when various military establishments in arid regions needed drinking water to supply the troops. [31] Currently, several countries use desalination to produce drinking water. Saudi Arabia, for instance, produces about 70% of all consumed freshwater by desalination. Other countries, like Qatar and Kuwait, rely 100% on desalinated water for domestic and industrial use. [32]

Due to the great advances in desalination technologies (which led to a sharp reduction in price of the cubic meter of treated water), but also due to the growing needs of drinking water (due to strong population, urban and industrial growth, combined with climate change and pollution of freshwater reserves) an exponential increase in these technologies has been recently occurring (Figure 15). [32]

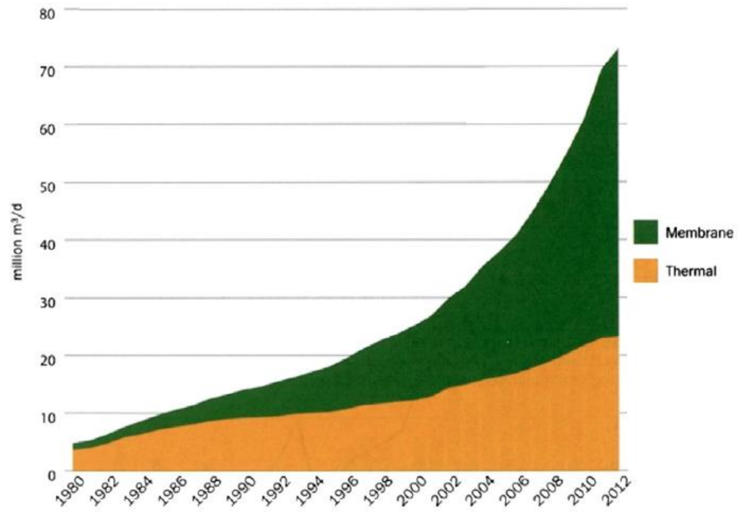


Figure 13 – Installed membrane and thermal water desalination capacity. [32]

There are currently more than 17 000 desalination plants in the world that, combined, produce a total amount of about 80 million m^3 of drinking water in more than 150 countries, supplying more than 300 million people. [33]

Those plants operate using two major desalination techniques: the thermal processes (or phase change), that use a method similar to the water cycle, i.e., salt water heats up, evaporates, condenses and precipitates in the form of potable water; and membrane processes in which the process for separation of minerals from the water is done using a membrane.

Thermal processes include:

- ✓ *Solar distillation* (SD);
- ✓ *Multi effect evaporation/distillation* (MEE or MED);
- ✓ *Multi-stage flash distillation* (MSF);
- ✓ *Thermal vapor compression* (TVC);

- ✓ *Mechanical vapor compression* (MVC).

Membrane processes include:

- ✓ *Microfiltration* (MF);
- ✓ *Ultrafiltration* (UF);
- ✓ *Nanofiltration* (NF);
- ✓ *Electrodialysis* (ED);
- ✓ *Reverse osmosis* (RO).

Another technique, also used but not falling into any of these two groups is the Ion Exchange, IE, which uses a resin with acid or basic radicals in its molecular structure that are exchanged for ions present in the water. [34] [35]

An important technology among these is RO, with a market share about 65% of the total installed capacity, followed by MSF with 22% and MED with 8%, and so those will be explained in detail, with special importance to the reverse osmosis, technology that will be used in the case study. The remaining 7% of the applications belong to other technologies. (Figure 16) [36]

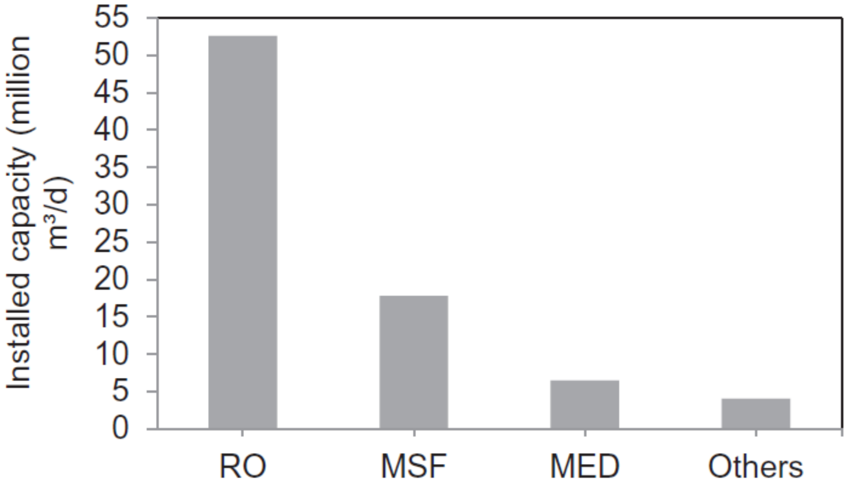


Figure 14 – Total worldwide installed desalination capacity by technology in 2013. [36]

Regarding the origin of the water to be treated, 59% of desalination plants use seawater, 22% brackish water and 9% water from rivers. The use of wastewater has been growing and represents now 6% of total capacity. The remaining 4% use pure water in order to obtain ultrapure water for special applications (e.g. sub and super critical boilers in power plants). [37]

2.2. Multiple effect distillation

The multi-effect distillation is the oldest desalination process. There are references and patents about this process since 1840 and it dominated the market until the appearance of MSF. With the development of MED in recent years there have been improvements with regard to energy consumption, heat transfer area and the gain-ratio allowing this technology to compete technically and economically, with MSF. [38]

The MED process (Figure 17) operates in a number of chambers (often called stages) to increase the energy efficiency of the system. The pre-heated seawater is sprayed against a pipe in the first chamber, which is heated by an external heat source, usually from a boiler or other heat waste source of a thermoelectric plant. When contacting the tubes, the clean water evaporates, and the steam is used as a heat source in the next chamber. The water that does not evaporate (brine) is pumped into the next chamber, and where is again sprayed against the tubes heated by water vapor from the previous effect. The pressure within the chambers are kept below atmospheric pressure level (relative vacuum) in order to lower the boiling point temperature of the water, so that it is not necessary to add additional heat to boil water due to the natural decrease in temperature. This process continues until the temperature is insufficient to evaporate the water, [39] or until the brine has reached not allowed concentration parameters. [40]

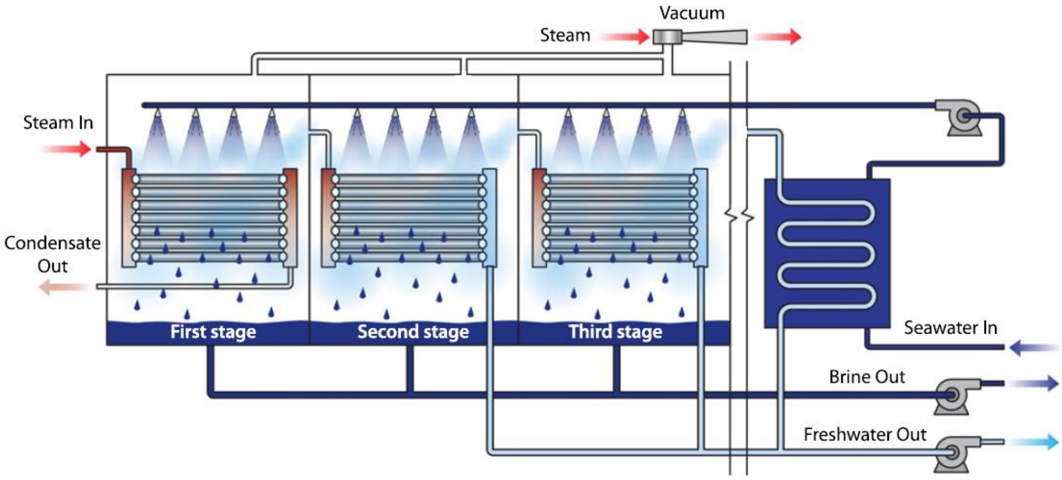


Figure 15 – Schematic diagram of MED unit. [41]

Reducing the boiling temperature of water is important to the reduction of energy costs needed for the process and to prevent fouling in the used equipment, because certain salts dissolved in cold water tend to precipitate when the temperature is higher, as is the case of certain carbonates and sulfates. This means that using this technique there is no need a complex pre-treatment of the salt water. [42]

The number of stages (usually 2-16) is limited by the maximum temperature value in the first effect, which is usually of the order of 70°C. The average capacity varies from 600 to 30 000 m^3/day. [41]

2.3. Multistage flash distillation

MSF is the thermal process for seawater desalination most used nowadays, with an installed capacity of approximately 17.5 million m^3/day. The majority of this capacity can be found in the Middle East, where the heat losses from the large power plants are used as the driving force for the desalination plants. [43]

As in MED, the MSF process operates in a number of chambers (or stages) and each stage is at a lower pressure than the earlier, for successive reduction of pressure boiling temperature. The pre-heated salt water enters a chamber where it will be heated with heat from a boiler or a power plant until it reaches the top brine temperature (TBT), which is usually 90 to 115 °C. Upon entering the first stage, the lower pressure causes part of the hot water to boil rapidly (flash). Hot vapor rises and meets the tubes with salt water on top of the chamber. Due to the lower temperature of the pipes, the steam condenses and the pure, distilled water, precipitates into a reservoir and is redirected to the reservoir of the next chamber. The brine is forwarded to the next stage (at lower pressure) where the process repeats, and so continues until the last chamber (Figure 18).

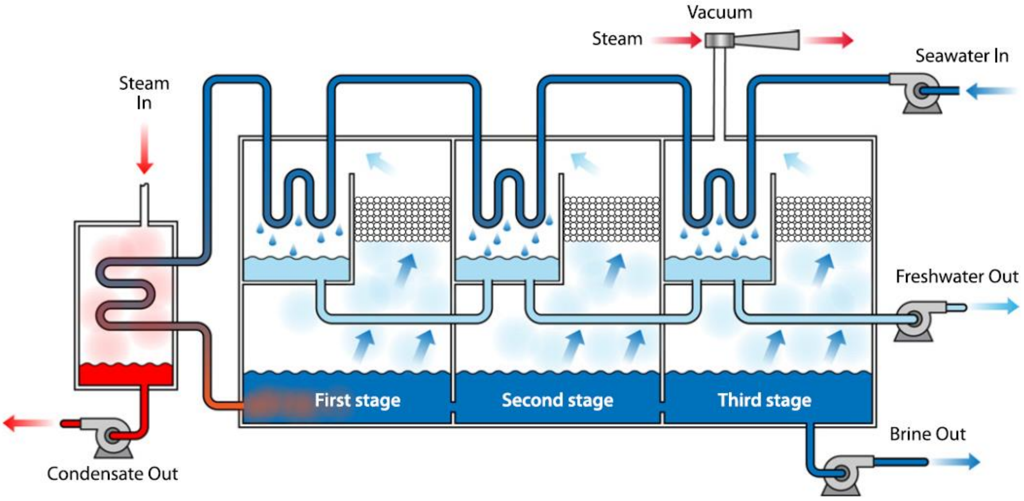


Figure 16 – Schematic diagram of MSF unit. [41]

At the same time that the seawater is used to condense the water vapor in the chambers, it will also get warmer as it passes (within the tube) of the last chamber to the first. Thus when this water reaches the source of thermal energy is already pre-heated thereby the system efficiency is increased.

These systems are used in applications where there is a large demand for water coincident with a relatively large amount of (waste) heat. Large systems may produce between 10 000 and 65 000 cubic meters of water per day. [44]

2.4. Reverse osmosis

The RO process is relatively new, its commercialization began in the early 70s, and is currently the desalination technology most widely used globally. [31] There are two types of RO units, which differ in the type of water to be treated: they are the brackish water *reverse osmosis* (BWRO) and the *seawater reverse osmosis* (SWRO). Due to the large difference in salt concentrations in the feed water, the two kinds of units will also have different operating conditions, used materials, energy needs, and therefore different associated investment and operational costs. But from now on we will focus in greater detail on the SWRO, the main focus of the work.

In membrane processes, materials in the water are retained on a membrane with small pores that freely allows passage of water, but hinders the passage of other materials. The size of these pores will determine the dimensions of the materials that can pass the membrane.

The membrane processes previously presented, *microfiltration* (MF) and *ultrafiltration* (UF), both use membranes with larger pores, and thus can only retain colloidal substances and microorganisms (Figure 19). In *nanofiltration* (NF) on the other hand it is possible to retain micro pollutants and divalent ions (for example: Ca^{2+}, Mg^{2+} e SO_4^{2-}) and this is the reason why it is widely used for water softening applications. [45] The *Electrodialysis* (ED) can be used in the treatment of seawater, however this technology is only economically competitive for the treatment of brackish water, [46] making the Reverse Osmosis (RO) the only suitable membrane technology for seawater desalination.

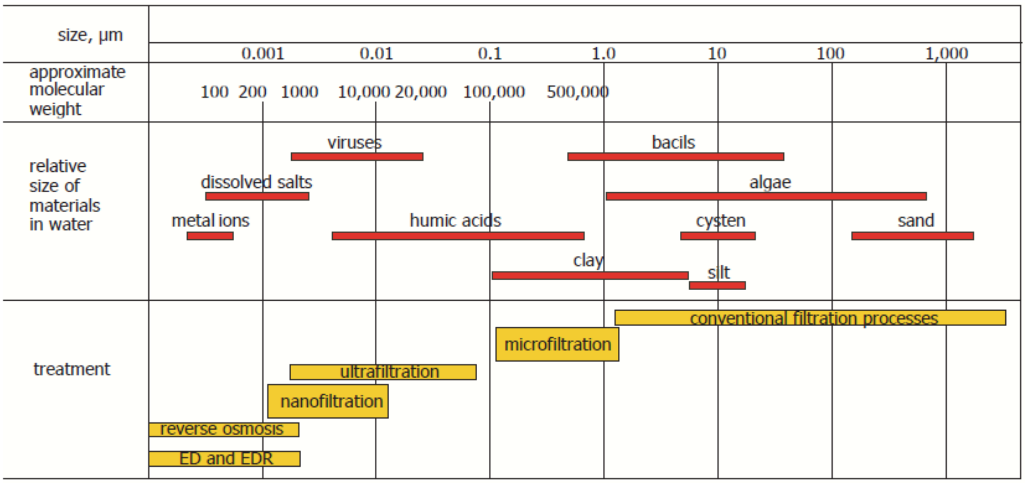


Figure 17 – Membrane processes by size of materials in water. [45]

2.4.1. Principles of operation

2.4.1.1. (Reverse) osmosis

Osmosis is a natural process in which water moves across a semipermeable membrane whose pores allow passage of water molecules but prevents passage of other substances from a hypotonic medium (less concentrated in solute) to a hypertonic medium (highest concentration of solute). This natural processes stops when the same concentration in both media (isotonic) is achieved.

When pure water at the same temperature and pressure is present on both sides of a membrane, there is no flow of water through the membrane. However, when salt is dissolved in one of the sides there will be a flow through the membrane from the pure water side to the salt water side (Figure 20, left and middle) in order to balance the difference in salt concentrations.

When a pressure is applied on the side in which salt was added, a new equilibrium will develop. The extra pressure will result in a reverse flow of water through the membrane, but the salts will not pass. This phenomenon is called reverse osmosis (Figure 20, right).

The minimum pressure needed to reverse the natural flow is called osmotic pressure ($\Delta\pi$) and it depends on the concentration of salts in the water, since the higher salt concentration is the higher is the osmotic pressure.

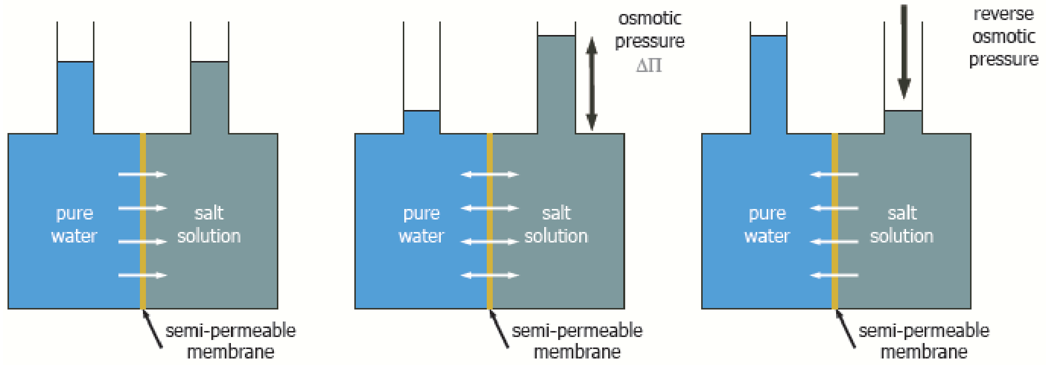


Figure 18 – Principle of osmosis and reverse osmosis. [8]

2.4.1.2. Feed, permeate and concentrate

In membrane filtration processes, three different types of flow are distinguished. The feed flow is separated by the membrane into a permeate flow and into a concentrate flow (brine, waste and retentate designations can be used too) (Figure 21, top). The salt concentration in the feed flow is higher than the salt concentration in the permeate flow and lower than the salt concentration in the concentrate flow.

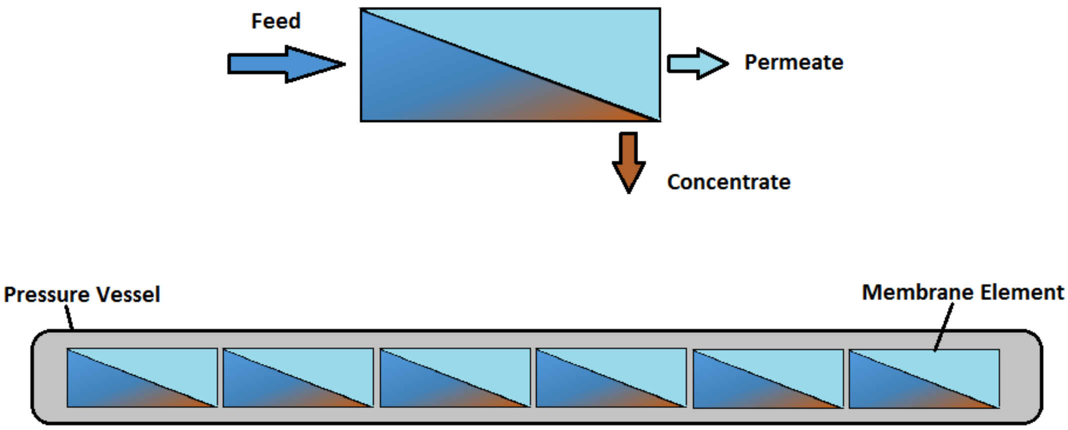


Figure 19 – Schematic drawing of a membrane element (top) and a membrane module (bottom).

Reverse osmosis elements are always operated in cross-flow mode (Figure 22). This means that the feed flow travels parallel to the surface of the membrane and only a small part of the feed flow is produced as permeate (between 1 and 10% per element) [45]. This means that most of the feed water that flows along the membrane surface exits the membrane element as concentrate and enters the next element as feed. To withstand the high operating pressures, a pressure vessel (membrane module) is used. It is not economically feasible to have a pressure vessel for every element and, therefore, two to six elements in series are generally placed in one membrane module, which also allows saving some space (Figure 21, bottom).

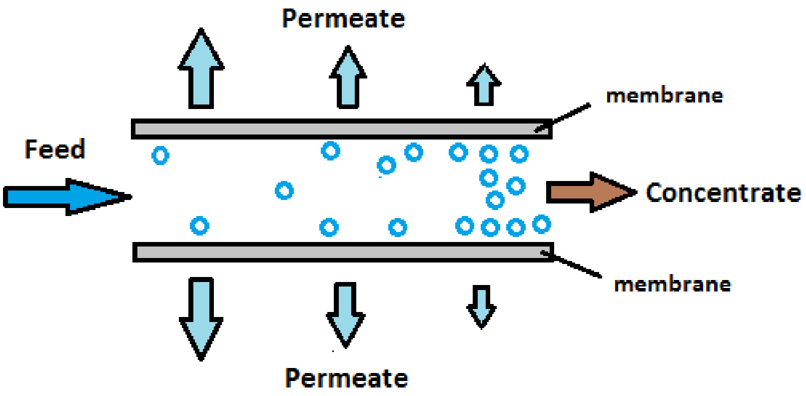
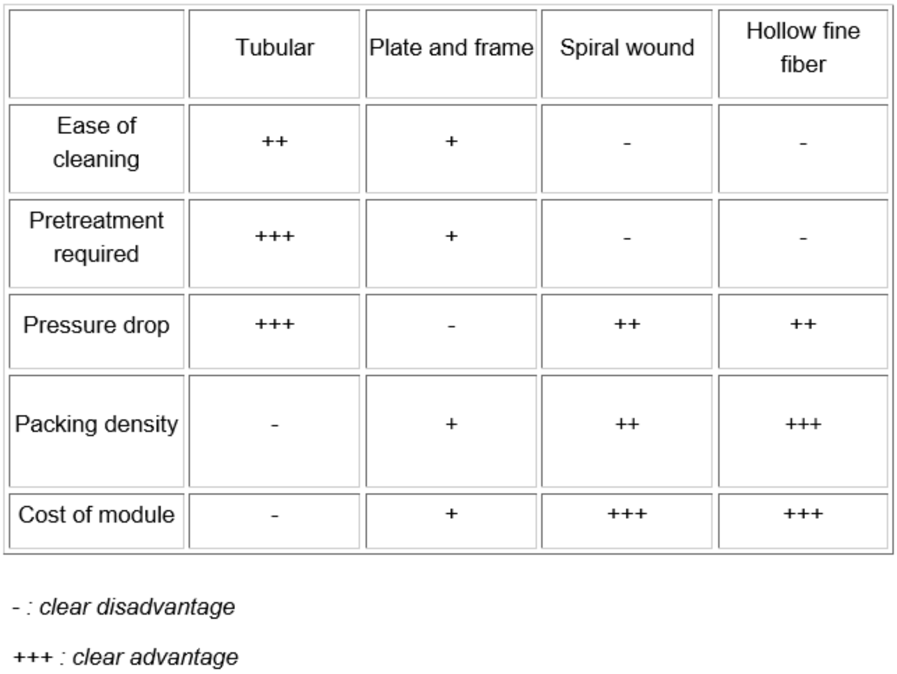


Figure 20 – Schematic drawing of the flow division in a membrane module.

2.4.1.3. Membrane configuration

There are four major membrane configurations on the market for use in reverse osmosis units: *Tubular*, *Plate and frame*, *Spiral Wound* and *Hollow fine fiber*. A comparison of their main features is presented in Figure 23.



	Tubular	Plate and frame	Spiral wound	Hollow fine fiber
Ease of cleaning	++	+	-	-
Pretreatment required	+++	+	-	-
Pressure drop	+++	-	++	++
Packing density	-	+	++	+++
Cost of module	-	+	+++	+++

- : clear disadvantage

+++ : clear advantage

Figure 21 – Comparison between membrane configurations for use in RO units. [47]

The *Hollow fine fiber* design has a packing density (membrane area per unit of volume per element) much higher than the other configurations, in the order of 10 000 m^2/m^3 compared with the < 1 000 m^2/m^3 for the *Spiral wound*, [47] making it the most used until the early 90s, mainly by the largest desalination plants that require a lot of space.

However, the successive reduction of the manufacturing cost of Spiral-Wound elements have caused these elements to become more competitive. Different studies have shown the clear advantages of this configuration compared with the Hollow Fine Fiber for the same operating conditions. (Flow, pressure, feed water quality and recovery rate), allowing the current market dominance

According to *Butt et al.,1997* SW membrane produced excellent quality water (86 ppm) at half the electrical energy cost compared with the HFF membrane which produced 468 ppm water. [48]

Also, according to *Gorenflo et al., 2005* the various design options discussed with spiral-wound elements show significantly better product quality. Depending on feed water and recovery, the savings in power would amount to 4.6% to 18.9% and the improvement in product TDS would be between 15.0% and 77.6% lower permeate TDS. The costs for water would then be $0.06-0.07 lower. [49]

A Spiral Wound configuration element (Figure 24) is composed by a number of membrane sheets twisted around a central permeate collecting tube. Water is fed from one side into a module and it is distributed via feed spacers (supporting layers between membrane sheets) over a membrane element. Once the filtration is made, the permeate flows in spiral direction into the collecting tube.

After passing one element the concentrate enters next element as feed water and the process restarts.

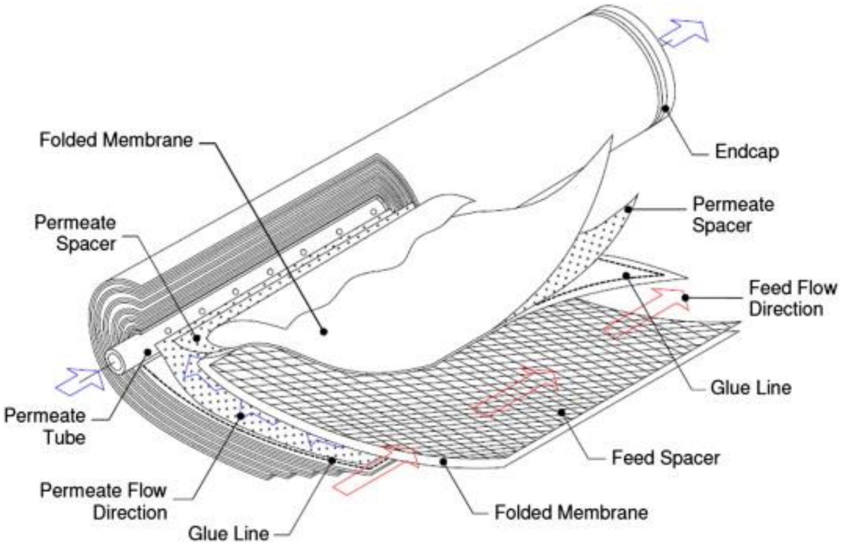


Figure 22 – Composition of a spiral wound membrane element. [48]

2.4.1.4. Concentration polarization and fouling

When a solution passes through a semipermeable membrane, most of the impurities are left behind, making the remaining water more concentrated in the membrane's surroundings, this effect being called *concentration polarization* (Figure 25).

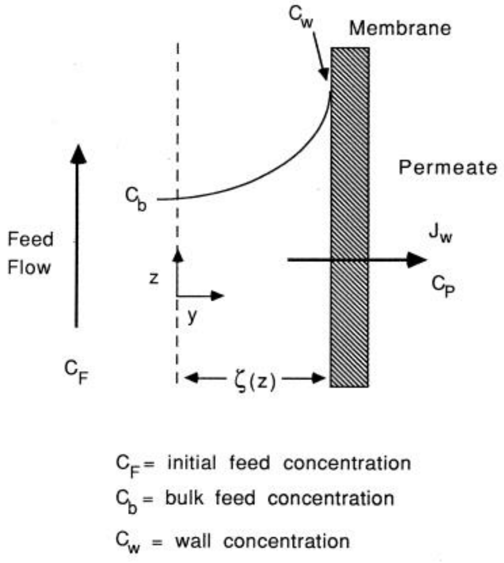


Figure 23 – Concentration polarization concentration profile. [51]

The concentration polarization is a phenomenon inherent to all membrane technology, and its consequence is an increase of osmotic pressure in the affected zone, leading to a reduction of the permeate flow, increased passage of solute by the membrane and greater probability of fouling. [52]

Research indicates, for very high feed flow rates, enough mixing near the membrane surface occurs so that the wall concentration can be assumed equal to the bulk concentration (that is, the boundary layer thickness (ζ (z)=0). However, at lower feed flow rates, the difference between the wall and bulk concentration can be substantial and so the wall concentration must be calculated. [51]

However, the concentration polarization is a phenomenon that is kept unchanged for constant operating conditions and feed water quality and therefore it does not explain the continued decline in the permeate flow regularly observed in a RO system. This evidence suggests that other phenomena besides the concentration polarization are present. The continuous variation of the permeate flux over time is attributed to possible changes in the membrane, caused by species present in the processed solution. These changes are usually related to membrane *fouling*. Figure 26 illustrates the reduction of the permeate flow caused by concentration polarization and membrane fouling.

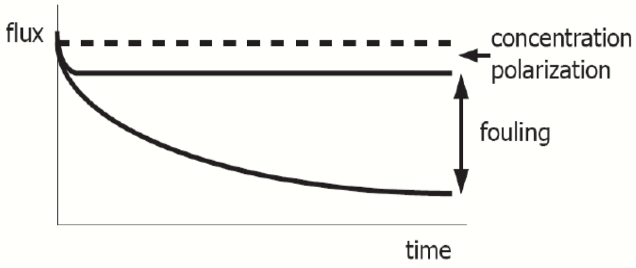


Figure 24 – Concentration polarization and fouling flow profile. [51]

The concept of Fouling refers to the accumulation of particles on the surface or in the matrix of a membrane, which may cause partial (or total) blocking of its pores (Figure 27, left). There are different types of fouling, and they are usually divided into: colloidal fouling; organic fouling; biofouling and scaling. All of them have similar effects on the performance of an RO system, i.e., a decrease in the permeate flow, pressure drop and decrease in salt rejection, leading to negative effects on the capacity and quality of water production and to energy consumption increase. [53]

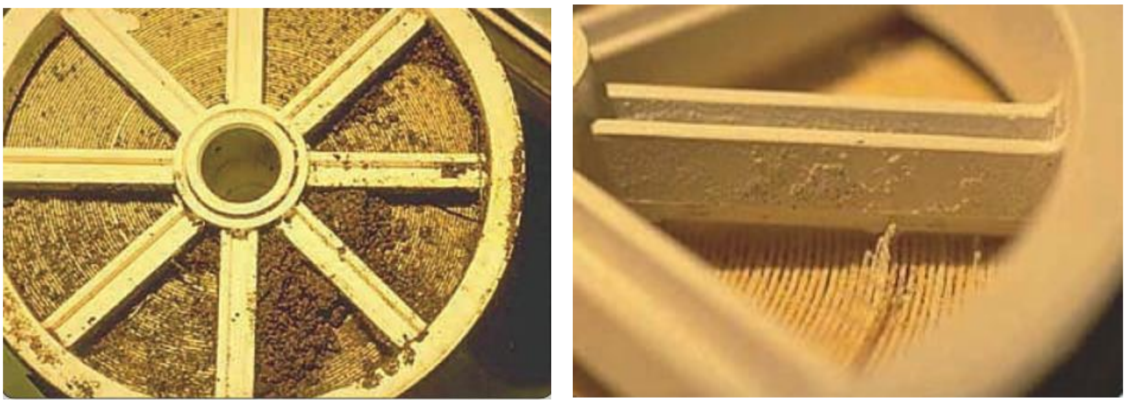


Figure 25 – Effect of fouling in membrane elements. [52]

Although it is considered a type of fouling, the concept of *scaling* is often distinguished from the remaining in the literature. As the water passes from element to element, the non-purified water flow becomes increasingly concentrated which may lead to an extreme situation where the solubility of certain products is exceeded, occurring its precipitation on the membranes' surface, i.e., occurrence of *scaling* (Figure 27, right). This phenomenon usually occurs in the last elements of an RO unit, where the concentrate has the higher salt concentrations, in opposition to what happens with other types of fouling which typically occur in the first element.

Due to the adversities described, in a RO unit, before the water contacts with the membranes, a series of pre-treatment measures are usually taken in order to reduce the fouling and thereby increase system lifetime and performance.

2.4.1.5. RO unit operation

Regarding the methods of operation of a RO the unit is divided into the following blocks, as presented in Figure 28:

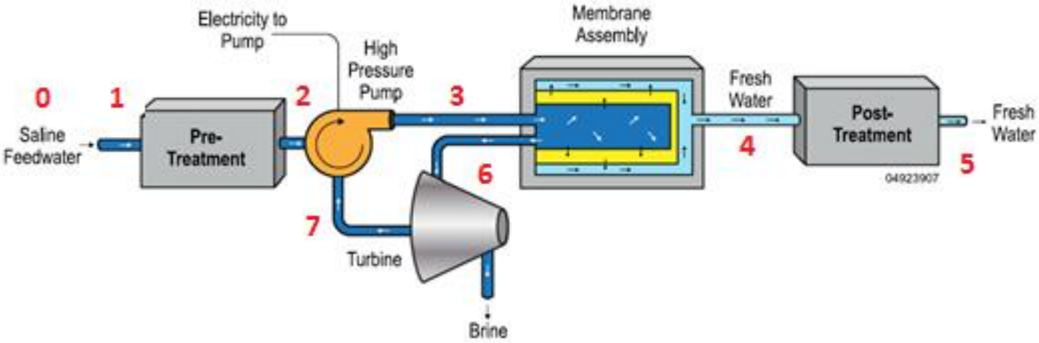


Figure 26 – Schematic diagram of RO system. Adapted from: [41]

0-1: The **feed water** is normally collected from coast/beach wells or directly from the sea (open seawater intake systems). Coast- and beach wells provide better quality water with less turbidity, algae and total dissolved solids than open seawater intakes, but require more space and infrastructures. [55]

1-2: The **pre-treatment block** is one of the crucial steps for successful operation of an RO membrane system. The performance and efficiency of an RO system depends critically on the quality of its feed water. As seen, the impurities in the RO feed water may decrease the membrane performance by cause membrane fouling. The upstream pretreatment must be designed to prevent and minimize these performance losses, and thereby increasing the overall system reliability to achieve the desired permeate flow and salt rejection.
Therefore, in the pre-treatment phase water passes through a series of treatments: suspended solids are removed (sands, clays, algae, etc.) by filtration; chlorine is added as a disinfectant in order to eliminate viruses, bacteria and other micro-organisms; after adding the chlorine the resulting water must be be neutralized, normally using activated carbon (or sodium bisulfite, $NaHSO_3$) to lower its power of oxidation in the membranes; the pH is reduced and antiscalants are added to prevent precipitation of calcium carbonates and sulphates. It can also be used Microfiltration (MF) or ultrafiltration (UF) as pre-treatment and other measures that depend on the quality of the water that will be treated. [56] [45]

2-3: The pre-treated water enters the **pumping system** in which the necessary pressure will be generated to create the desired permeate flow.

3-4: In the **membranes** the vast majority of membranes salts are removed from the feed water. The permeate goes to post-treatment while the concentrate moves to the energy recovery device, or is returned to the sea.

4-5: In the **post-treatment** phase the permeate is disinfected with chlorine, remineralized with calcium and magnesium, pH (≈ 7), boron (< 0.5 mg/L) and other requirements are adjusted according to the type of use and the local law. [57]

6-7: The pressure in the concentrate can be recovered and transferred to the feed water through an **energy recovery device** (an energy recovery turbine or a pressure exchanger for higher recoveries) in order to reduce the energy operating costs of the system.

2.4.2. Fundamentals

2.4.2.1. Mass balance

As shown in (Figure 21, top) the water mass balance for a membrane element is given by:

$$q_f = q_c + q_p \tag{2}$$

where, q_f is the feed flow, q_c the concentrate flow and q_p the permeate flow. All three flows are generally expressed in m^3/h, m^3/day, L/h or L/day depending on their magnitudes.

In addition, the mass balance of the dissolved material can be written as:

$$q_f c_f = q c_c + q_p c_p \tag{3}$$

where, c_f represents the concentration of the dissolved materials in the feed water, c_c the concentration of dissolved materials in the concentrate and c_p the concentration of dissolved materials in the permeate. Concentration is commonly expressed in g/m^3 or ppm, which is its equivalent.

Due to high membrane rejection of salts (> 99.6% in spiral wound elements [58]) concentrations in concentrate flow are much higher than in feed flow, and concentrations in permeate flow are almost neglectable.

The percentage of salt rejected by a membrane, *rejection* (Re), is expressed by the equation (4).

$$Re = \left(1 - \frac{c_p}{c_f}\right) * 100 \tag{4}$$

The recovery ratio (γ) is a measure of the overall production of the system. It is defined as the ratio between permeate and feed flow:

$$\gamma = \frac{q_p}{q_f} * 100 \tag{5}$$

A recovery of 40% means that 40% of the feed flow is produced as permeate and 60% as concentrate. Combining the equations (2), (3) and (5) and assuming a rejection of 100%, thereby eliminating the portion of the concentration of the permeate flux, one obtains equation 6 which relates the concentration factor with the recovery ratio.

$$\frac{c_c}{c_f} = \frac{1}{1-\gamma} \tag{6}$$

For γ = 40% the concentration factor is approximately 1.7 meaning that the concentration of the concentrate flow is about 1.7 times greater than the one of the feed. For γ = 60%, the concentration factor increases to 2.5 and for γ = 80% it grows to 5. This means that an RO unit operating at 80% of recovery with feed concentration around 35 000 ppm, will produce brine with concentrations of about 175 000 ppm.

Due to such amount of concentration, the recovery is limited to about 50% for SWRO, due to the possibility of scaling [8] and because a higher osmotic pressure of the concentrate would imply a feeding pressure greater than the one supported by the pressure vessel. [59]

The recovery of one element is between 1 and 10%, so to increase the overall recovery of the system more elements must be placed in series.

2.4.2.2. Kinetics

The transport properties of a semi-permeable membrane are determined by the permeate ability of the membrane and by a driving force. The flux of the solvent, or permeate flow per membrane area, is directly proportional to the applied pressure and is given by the equation at constant temperature:

$$J_w = L_p * TMP \tag{7}$$

where, J_w is membrane water flux [L/h/m^2], L_p is membrane permeance [L/m^2/h/bar] that depends on the membrane being used [60], and TMP stands for the transmembrane pressure. Flux is usually expressed in *lmh* and pressure in *bar*.

Transmembrane pressure is the net pressure difference over a membrane and acts as the driving force for a membrane process. It is given by:

$$TMP = \Delta p - \Delta\pi = (p_f - \frac{\Delta p_{loss}}{2} - p_p) - \Delta\pi \tag{8}$$

where, p_f is feed pressure, Δp_{loss} is the pressure drop occurring when water moves from the feed to the concentrate, due to friction with the walls of the membranes or tubes, p_p is the permeate pressure and $\Delta\pi$ the osmotic pressure difference.

The osmotic pressure difference over the membrane is given by:

$$\Delta\pi = \frac{\pi_f + \pi_c}{2} - \pi_p \tag{9}$$

where, π_f, π_c and π_p are the osmotic pressures of feed, concentrate and permeate, respectively. The osmotic pressure difference is averaged to be independent of position in the membrane.

Osmotic pressure is a property of a fluid, is dependent of the salt concentration and temperature and independent of the presence of a membrane. It may be calculated by:

$$\pi = \sum \frac{R * T * c_i * z_i}{Mi} \tag{10}$$

where, π is the osmotic pressure (*Pa*), R the gas constant (*J/K.mol*), T the temperature (*K*), c_i the ion concentration (*g/m³*), Mi molecular ion mass (*g/mol*) and z_i the valence of the ion. To compute the osmotic pressure, it is sufficient to take into account only the most important ions: HCO_3^-; SO_4^{2-}; Cl^-; Na^+; Ca^{2+} and Mg^{2+}.

Since the concentration of the salts of the permeate is very low, in the calculation of the osmotic pressure difference in a membrane, π_p can be neglected. Thus, and remembering that the concentration of the concentrate depends on the recovery rate, the following equation is valid:

$$\Delta\pi = \pi_f * \left(\frac{2-y}{2*(1-y)}\right) \tag{11}$$

2.4.2.3. Operation and optimization conditions

As seen, there are plenty of variables that affect the operation of an RO unit. Joining equations (7), (8) and (11) one obtains equation (12), which shows that the flow in a membrane will depend on the feed pressure, on the feed water quality (in terms temperature and salt concentration) and on the recovery rate.

$$J_w = L_p * \left(p_f - \frac{\Delta p_{loss}}{2} - p_p - \sum \frac{R * T_f * c_i * z_i}{Mi} * \left(\frac{2-y}{2*(1-y)}\right)\right) \tag{12}$$

However, there are a number of factors limiting the operation of a RO unit:

-The supply pressure must not exceed the maximum recommended by the manufacturers of the pressure vessels, which is in the order of 60-70 bar.

-The pressure drop per element (Δp_{loss}) also has a maximum recommended, to avoid damage (around 1 bar depending on the manufacturer). [61]

- The recovery should not exceed 50% due to the possibility of scaling [14] and because the osmotic pressure of the concentrate would be too high for the maximum feed pressure. [60]

- The permeate flux should never be very low throughout the system (>15 lmh to avoid increasing concentration polarization, or >35 lmh to avoid fouling). [45] Smaller fluxes leads to lower energy costs because less pressure is required but also leads to decreased quality of permeate. [62]

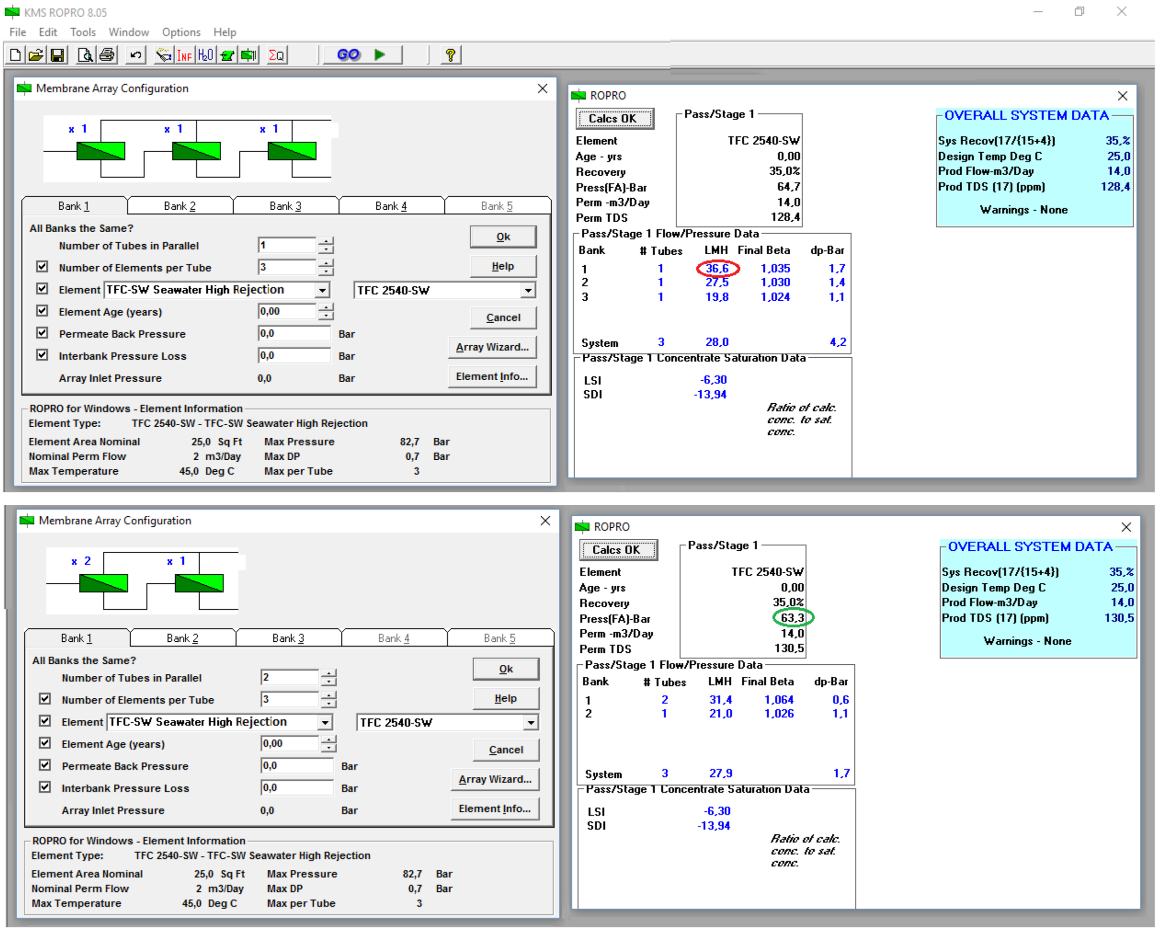
- Higher temperatures of the feed water increases the flux but also decreases the rejection ratio.

The choice of the feed flow (flux times m^2 of membrane) is the only nearly unlimited variable since it depends only on the size and number of elements used and the power of the pump, and so it is only limited by the budget and/or the available area.

Depending on the focus being on either minimizing the capital expenses or minimizing the long-term operational expenses it should be made a careful study of the RO unit operating conditions to achieve an optimization according to the intended purpose.

Several Windows-based software tools for RO systems plant design can be used to simulate RO plants performance for pre-defined variables like: feed composition, flow rates, feed pressure or recovery. This will allow the right choice about the best setting for the intended purpose. The most commonly used software tools are available from the major RO membrane suppliers like Dow, GE Osmonics, Hydranautics, Koch Membrane Systems.

Using the KMS ROPRO 8.05 software, from Koch Membrane Systems, a simulation to determine the feasibility of filtering seawater with 35 000 ppm at 25°C in order to obtain a permeate flow of 14 m^3/day and 35% recovery was done, using two different configurations (Figure 29).



All Banks the Same?

Number of Tubes in Parallel: 1

☑ Number of Elements per Tube: 3

☑ Element: TFC-SW Seawater High Rejection; TFC 2540-SW

☑ Element Age (years): 0,00

☑ Permeate Back Pressure: 0,0 Bar

☑ Interbank Pressure Loss: 0,0 Bar

Array Inlet Pressure: 0,0 Bar

ROPRO for Windows - Element Information

Element Type: TFC 2540-SW - TFC-SW Seawater High Rejection

Element Area Nominal	25,0	Sq Ft	Max Pressure	82,7	Bar
Nominal Perm Flow	2	m3/Day	Max DP	0,7	Bar
Max Temperature	45,0	Deg C	Max per Tube	3	

Pass/Stage 1

Element	TFC 2540-SW
Age - yrs	0,00
Recovery	35,0%
Press(FA)-Bar	64,7
Perm -m3/Day	14,0
Perm TDS	128,4

Pass/Stage 1 Flow/Pressure Data

Bank	# Tubes	LMH	Final Beta	dp-Bar
1	1	36,6	1,035	1,7
2	1	27,5	1,030	1,4
3	1	19,8	1,024	1,1
System	3	28,0		4,2

Pass/Stage 1 Concentrate Saturation Data

LSI	-6,30
SDI	-13,94

Ratio of calc. conc. to sat. conc.

OVERALL SYSTEM DATA

Sys Recov(17/(15+4))	35,%
Design Temp Deg C	25,0
Prod Flow-m3/Day	14,0
Prod TDS (17) (ppm)	128,4

Warnings - None

All Banks the Same?

Number of Tubes in Parallel: 2

☑ Number of Elements per Tube: 3

☑ Element: TFC-SW Seawater High Rejection; TFC 2540-SW

☑ Element Age (years): 0,00

☑ Permeate Back Pressure: 0,0 Bar

☑ Interbank Pressure Loss: 0,0 Bar

Array Inlet Pressure: 0,0 Bar

ROPRO for Windows - Element Information

Element Type: TFC 2540-SW - TFC-SW Seawater High Rejection

Element Area Nominal	25,0	Sq Ft	Max Pressure	82,7	Bar
Nominal Perm Flow	2	m3/Day	Max DP	0,7	Bar
Max Temperature	45,0	Deg C	Max per Tube	3	

Pass/Stage 1

Element	TFC 2540-SW
Age - yrs	0,00
Recovery	35,0%
Press(FA)-Bar	63,3
Perm -m3/Day	14,0
Perm TDS	130,5

Pass/Stage 1 Flow/Pressure Data

Bank	# Tubes	LMH	Final Beta	dp-Bar
1	2	31,4	1,064	0,6
2	1	21,0	1,026	1,1
System	3	27,9		1,7

Pass/Stage 1 Concentrate Saturation Data

LSI	-6,30
SDI	-13,94

Ratio of calc. conc. to sat. conc.

OVERALL SYSTEM DATA

Sys Recov(17/(15+4))	35,%
Design Temp Deg C	25,0
Prod Flow-m3/Day	14,0
Prod TDS (17) (ppm)	130,5

Warnings - None

Figure 27 – RO systems plant design simulation with KMS ROPRO 8.05 software.

When using a configuration with three modules in series (each one with three elements of 2.3 m^2) it is apparent that the flux of the first element (circled in red) is 36.6 lmh, higher than the upper limit of 35 lmh suggested by *Fritzmann et al.,2007*, and this could lead to long-term fouling problems. [55] At the same time the total pressure drop in the system is also somewhat higher (4.2 bar) leading to an increased pressure need (64.7 bar) to achieve the desired permeate flow. When using the configuration with two modules in parallel with one in series, with the same number of elements per module size as above, it appears that the first stage flux is better (from 36.6 to 31.4 lmh). At the same time the overall pressure drop is lower (from 4.2 to 1.7 bar), thus leading to a decrease in the required supply pressure (64.7 to 63.3 bar) and consequently lower energy costs. This shows that, in this example, the last configuration would be more appropriate.

2.4.3. Cost and energy

Cost

The cost of RO desalination has steadily decreased from the commercial introduction in 1970s until today, due to improvements in membrane, pumping and energy recovery systems technology.

Nowadays for large SWRO (between 100 000 and 320 000 m^3/day) the reported water production cost ranged between 0.45 and 0.66 US\$/m^3. For medium SWRO (15 000 to 60 000 m^3/day) between 0.48 and 1.62 US\$/m^3 and for smaller capacity SWRO units (1 000 to 4 800 m^3/day) the cost ranges between 0.7 and 1.72 US\$/m^3. [63]

Typical water cost contributions in an SWRO plant for an estimated lifetime of 25 years, is given in Figure 30.

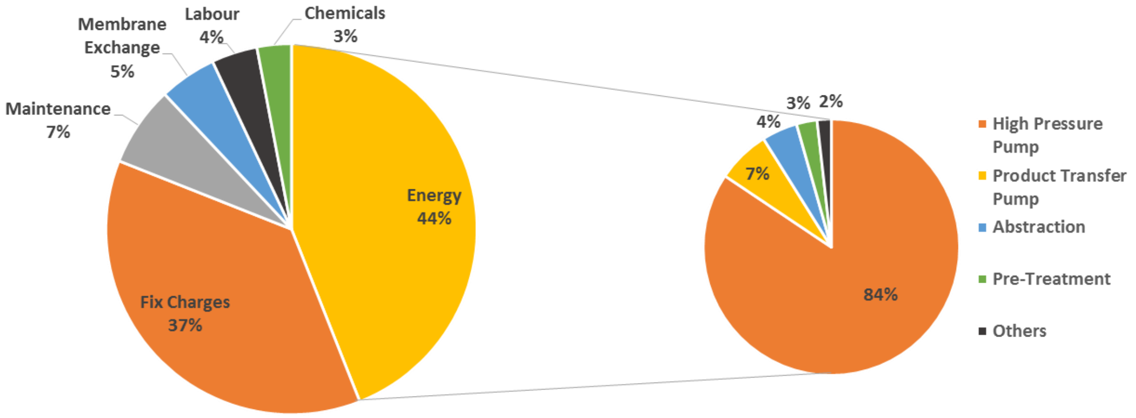


Figure 28 – Water distribution cost in a SWRO plant and energy consumption of different process stages. Adapted from: [55]

Even after all the developments to decrease energy consumption, this is still the major contribution (44%) to the water cost in a SWRO plant. Energy is needed namely for the intake system, the pumping system, pretreatment operation and most importantly to power the high pressure pump (RO_{HPP}).

Fixed charges, or investment cost, include land and equipment acquisition, as well as the plant construction. Standard plant equipment like membrane modules, piping and pumping systems can be easily scaled up, so the bigger the RO unit the smaller the fix charges portion. Fix charges will be paid only once, at the beginning, unless irreversible damage in some equipment occurs. To avoid that, it is important the regular maintenance of the equipment, which amount to about 7% of total investment costs.

Unlike the rest of the equipment, membranes damage cannot be fixed and they must be replaced. Membrane replacement cost depends on the rate at which membranes are damaged, and it generally accounts for about 5% of the overall life cycle cost of an SWRO desalination plant. Normal periodicity for membrane replacement is around 4 years but to hit that mark efficient pre-treatment and cleaning is needed to reduce fouling rate. Using good pre-treatment and cleaning methods requires a large amount of chemicals and, depending of the used method, this usually represents about 3% of the total cost of the plant.

Labor cost has a minor share on overall cost of SWRO desalination plants, nearby 4%. On the other hand, energy consumption is the biggest contribution to the total unit cost with a 44% share.

Energy

As seen, energy has a major role regarding water production cost in an SWRO, in which 84% of the total energy is required to power the RO_{HPP}.

The RO_{HPP} creates the pressure necessary to move the desired water flow through the system. The required pressure, as seen before, is influenced by a lot of factors such as the permeability of the membranes, the concentrations of salts in the water, temperature, recovery rate, module configuration, among others. However the unit operating conditions are maintained practically constant over its lifetime, meaning that the electric power required will be practically the same over system lifetime.

A RO_{HPP} is usually powered by an electric motor connected to the electric network and thus the power required by this engine must be accounted for in what concerns energy costs. It may be calculated by:

$$P_{motor}(kW) = \frac{q_f * p_f}{\eta_{RO_{HPP}} * \eta_{motor} * 600} \qquad (13)$$

where, q_f is the feed flow in L/min and p_f the pressure in bar.

Since the power of the electrical equipment is nearly constant throughout the operating time, and knowing that this type of unit generally runs 24 hours a day, 365 days a year, a gross calculation of the annual energy consumed by the SWRO unit is given by:

$$Energy_{SWRO}\,(kWh) = 8760 * P_{total} \qquad (14)$$

where, P_{total} is the sum of the power of the main electric equipment, in kW.

However, in the desalination context, when referring energy it is more usual to use the term SEC, which is the energy required to produce 1 m^3 of permeate:

$$SEC\,(kWh/m^3) = \frac{P_{total}}{q_p} \qquad (15)$$

where, q_p is the permeate flow in m^3/h

The average reported SEC ranges from 3.7 to 8 kWh/m^3. [63] The consumption may exceed 15 kWh/m^3 for very small sizes units. For a typical size SWRO unit of 24 000 m^3/day, the electricity consumption ranges from 4 to 6 kWh/m^3. This means that a typical size unit needs in a year an average of about 44 GWh of electric energy. Besides, the high cost arising from high energy requirement, energy consumption comes along with an environmental impact associated with the emission of greenhouse gases. This motivated the development of desalination technologies integrated with renewable energy sources. This method is particularly promising in remote areas where the connection to the public electrical grid is either not cost effective or not feasible, and where water scarcity is severe.

Chapter 3 – Case study

3.1. Introduction

This project aims to develop a simple and cost-effective water desalination system for a small Caribbean island where both freshwater and conventional electricity are nonexistent. The proposed system is driven entirely by renewable energy. It uses wind energy to supply, via a hydraulic system, the high pressure pump required to promote the seawater flow through the reverse osmosis system (producing a near constant fresh water flow) and an electric generator. The rate of oil flow in the hydraulic system depends on wind speed, which is highly variable, but the system is designed in order to make the generator operate at constant speed and torque, delivering constant power to a bank of batteries, a mode of operation that is highly important for energy storage. When wind speed is higher than necessary, the excess flow is redirected back to the tank. Solar photovoltaic energy is also used for battery recharging. This contribution is important especially when wind velocities are too low. The electricity will be used by the system to power pumps, sensors, data acquisition and control instruments and by the restaurants of the island to power refrigerators and/or other equipment needed.

The system under study was developed by *SolteQ Energy B.V.* with the support of a higher education institution, *Delft University of Technology* and with the cooperation of three other companies: *Lenntech B.V.* (responsible for the RO system); *Hydroton B.V.* (responsible for the hydraulic system) and *Hoekstra Suwald Technology* (responsible for the wind turbine).

At a first stage, the various parts of the system were carried to Leeuwarden, The Netherlands where they were assembled and some problems with the mechanical equipment were detected. After the resolution of these initial problems, the system was tested for several days under different atmospheric conditions. During these tests the correct operation of the system was verified, and it was also collected an important set of data which allowed to estimate the water production and the electric consumption of the final system, and gather information for future developments.

At the end of this work, the system was being dismantled and shipped to Johnny Cay, Colombia, where hopefully it will provide an average of 5.5 m^3 of freshwater per day and around 20 MWh of electricity per year to the island community.

The chapter 3 will be divided in 3 parts:

- ✓ The island: where it will be given a small intro about the island, as well as its population needs and renewable energy resources.
- ✓ The system: where all system will be described in detail; the used data collecting tools and the performed tests will also be described and the obtained results will be presented and discussed.
- ✓ Production and cost estimation: where the water and energy production will be estimated according to the previous topics as well as the economic viability of the system.

3.2. The Island

3.2.1. Geography and climate

Johnny Cay, a small island with area around 38 000 m^2, is located in the archipelago of San Andrés, Providencia and Santa Catalina (comprising the three main islands with the same name). Johnny Cay is located about 1.5 km from the island of San Andres and this one is located in the Caribbean Sea, about 700 km northwest of the Colombian coast and 200 km from the coast of Nicaragua (Figure 31).

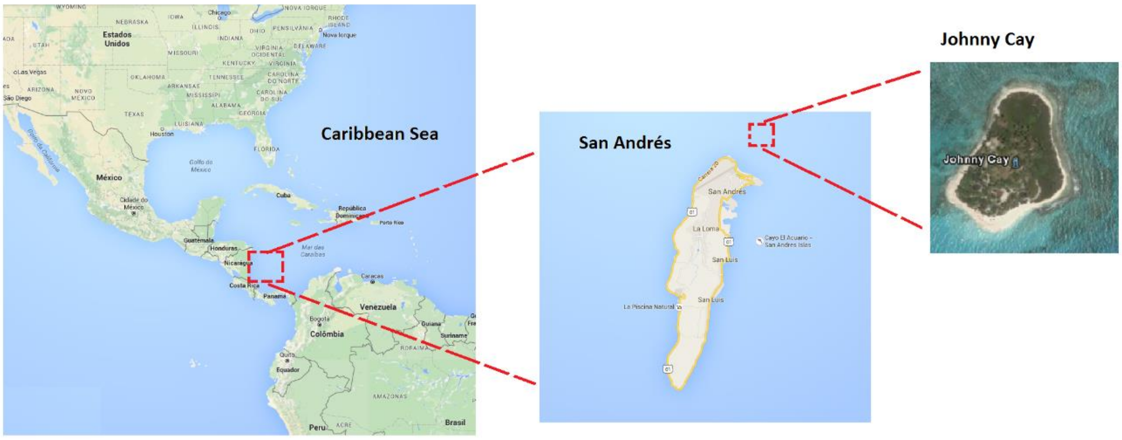


Figure 29–Location of the island of Johnny Cay. Adapted from: [64]

Because of its location in the tropics, the archipelago is characterized by high temperatures, with an annual average of 27.3 °C. The influence of trade winds, which blow from northeast, partly determines the rainy season starting in May, peaking in October and lasting until November December. Annual rainfall reaches on average 1700 mm, 80% of which occurs during these months. High temperatures and winds are combined in a warm semi-humid climate. Despite being located in the open Caribbean Sea, the archipelago is rarely hit by hurricanes and tropical storms. [65]

Johnny Cay is also called Island of Sugar because of its white sand beaches. It is visited daily by tourists and residents coming from San Andrés to relax on the beach or having a deep fried fish with a fresh coconut cocktail served by the few small bars and restaurants around the island. According to the regulation it is not allowed to stay overnight in the island, likewise there is no people living there. [66]

3.2.2. Renewable energy resource

Wind resource

The island in study has no weather stations. The eolic potential was evaluated using data from measurements made at the airport of San Andres island, at a height of 10 m above ground level, in an area with slightly higher altitude than the average sea level.

Figure 32 represents the prevailing wind directions and the average speeds recorded during a 19-year study period.

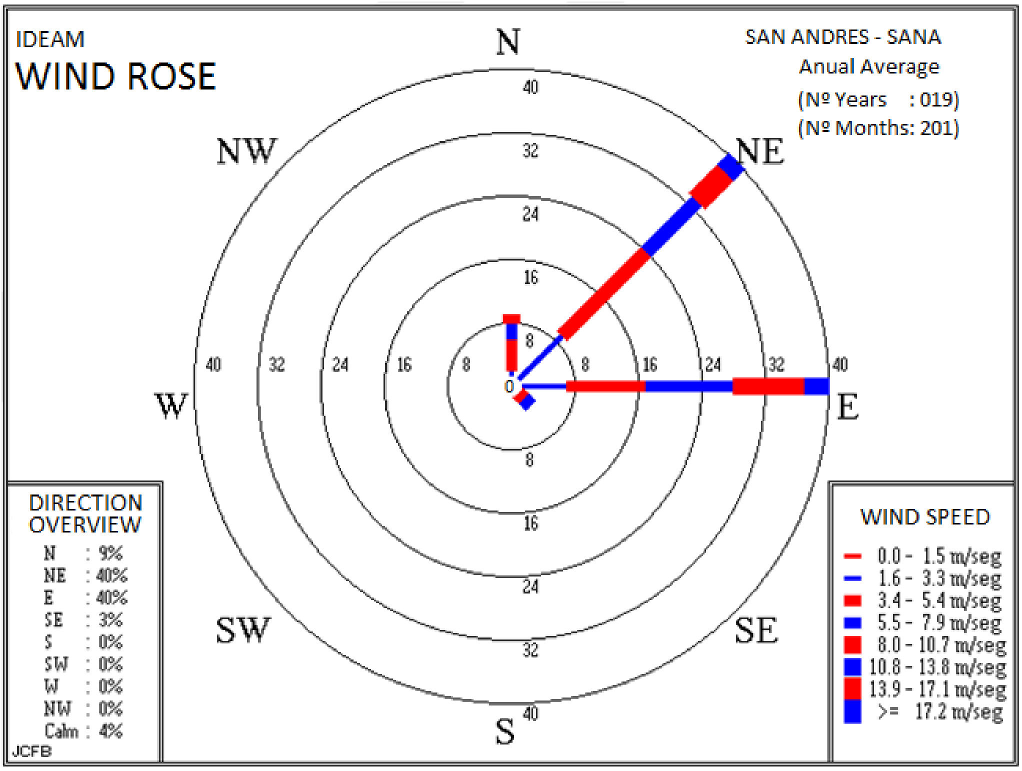


Figure 30 – Annual basis wind profile in San Andés. [67]

It is observed that during 80% of the time the wind blows between the Northwest and East. In Table 3 wind speeds are divided according to the international anemometer Beaufort scale, where it is found a prevalence of speeds in the range 8-10.7 m/s and an average speed of around 7 m/s.

Table 3 – Annual basis wind profile in San Andrés.

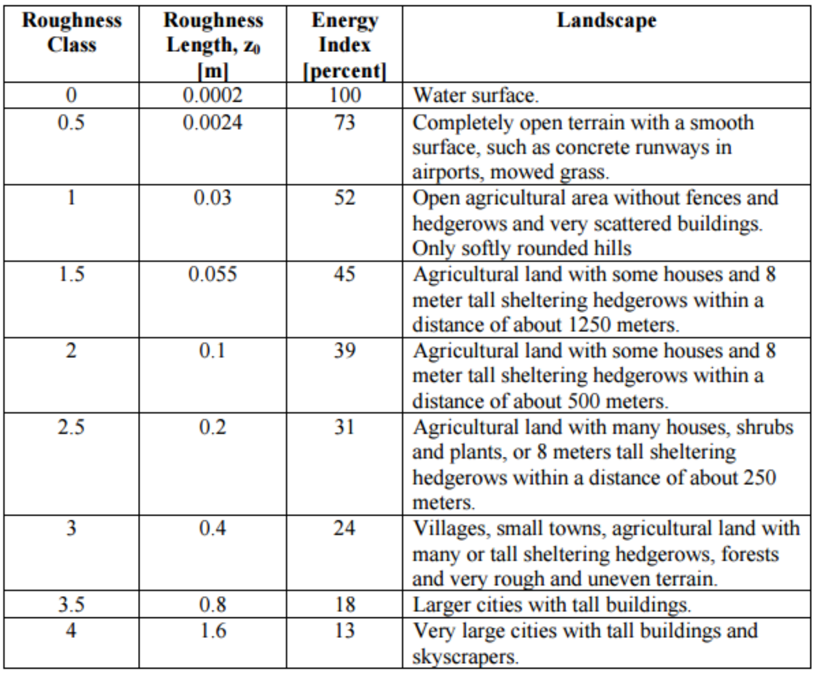
m/s	N	NE	E	SE
0.3-1.5	0,5%	0,0%	0,0%	0,0%
1.6-3.3	5,5%	9,0%	7,0%	0,0%
3.4-5.4	2,0%	0,0%	10,0%	0,0%
5.5-7.9	1,0%	0,0%	11,0%	0,0%
8-10.7	0,0%	15,0%	9,0%	1,5%
10.8-13.8	0,0%	9,0%	3,0%	1,5%
13.9-17.1	0,0%	5,0%	0,0%	0,0%
>= 17.2	0,0%	2,0%	0,0%	0,0%

Ideally, the characterization of the wind resource for energy production should be made based on measurements taken at several points of the surroundings, over a significant number of days and at the same altitude that the turbine rotor will be installed. However, when this is not possible (either for lack of time, financial resources, or any other reason) it is usual the use of the Prandtl law (equation 16) in order to extrapolate the data measured at a lower altitude. [68]

$$\frac{u(z)}{u(z_R)} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_R}{z_0}\right)} \tag{16}$$

where $u(z)$ is the wind speed at the height z, $u(z_R)$ is the speed at a reference height z_R, and z_0 is defined as the characteristic length of the ground roughness, representing a characteristic the ground surface texture.

In what concerns the characterization of the ground roughness, different types of terrain are typically divided into classes, with the corresponding values of roughness length z_0. An example of this type of approach is presented in Figure 33, one of the most used tables in different evaluation studies about wind potential as, for instance, in the preparation of the "European Atlas of the wind".



Roughness Class	Roughness Length, z_0 [m]	Energy Index [percent]	Landscape
0	0.0002	100	Water surface.
0.5	0.0024	73	Completely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1250 meters.
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters.
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 meters tall sheltering hedgerows within a distance of about 250 meters.
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	18	Larger cities with tall buildings.
4	1.6	13	Very large cities with tall buildings and skyscrapers.

Figure 31 – Ground roughness characterization. Adapted from: [68]

For our case study, with an average speed of 7 m/s at a reference height of 10 m in an area characterized by a roughness length of about 0.0024 m, one may conclude, using equation (16), that at the foreseen turbine altitude (15 m) one should expect a value of $u(z)$ of about 7.34 m/s, representing an increase of about 5%. This means that, since the roughness of the chosen location is low, the wind speed variation with height is small, and therefore, the need to install higher towers is not relevant. Furthermore, since the wind speed values given above are divided into groups, they may be considered in the calculations of the wind potential with no great error.

It is also important to determine the seasonal wind speed variability in order to assess any months where production would be substantially lower (Figure 34).

The average wind speed has a maximum in the months of January, February and June leading, very probably, to an increased production time. In contrast, during the months of September, October and November the monthly average speeds are lower than the annual average, so the production may be substantially lower.

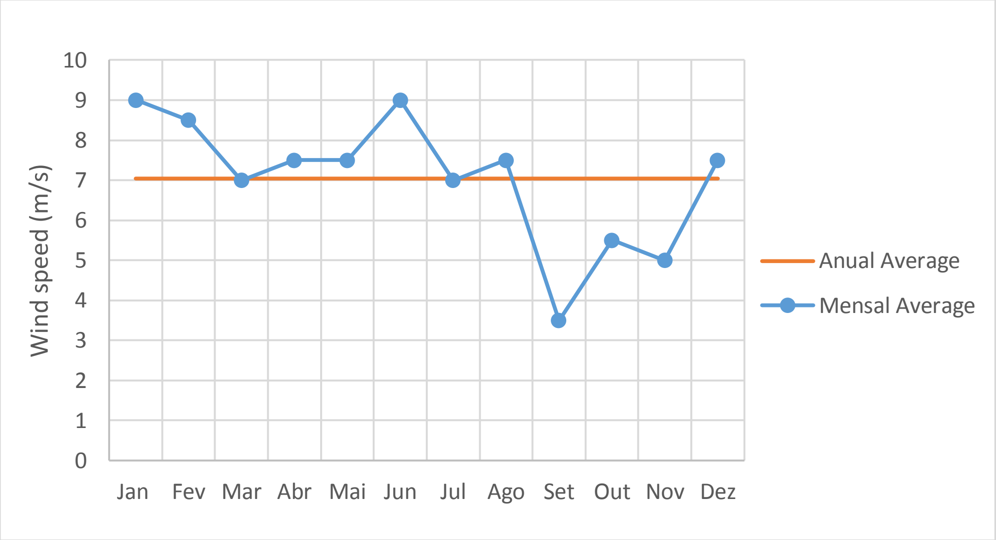


Figure 32 – Average wind speed seasonal variability in San Andrés [66]

Solar resource

Solar resource on the island, according to 22 year measurements taken by the Atmospheric Science Data Center at NASA Langley Research Center for the Latitude 12.599 and Longitude -81.69 are presented in Figure 35.

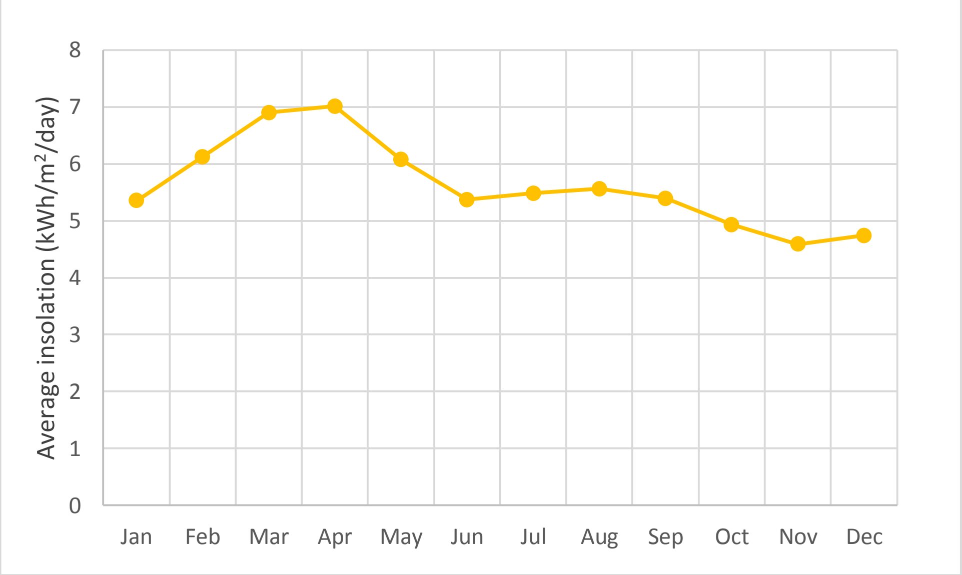


Figure 33 – Monthly averaged insolation incident on a horizontal surface. [69]

The average insolation on horizontal plane has a maximum in the months of March and April, approaching 7 kWh/m^2/day, and a minimum in the last months of the year (5 kWh/m^2/day) due to cloud cover during the wet season. The annual average is 5.6 kWh/m^2/day.

A tilt of solar PV panels relative to the horizontal will not bring great improvement in the average incident radiation on them since the island is located near the equator. However, with increasing slope some months can obtain higher insolation values (Figure 36), and therefore, the inclination must be chosen according to the predicted consumption for each month. Moreover, solar PV system should be sized to meet the needs from the month with less insolation/consumption ratio.

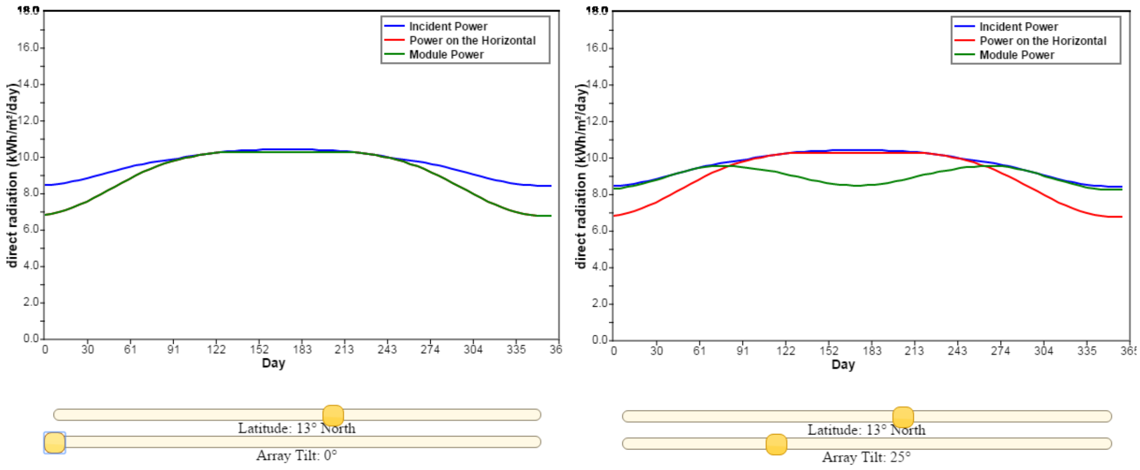


Figure 34 – Effect of latitude and module tilt on the solar radiation received throughout an year without clouds in kWh/m^2/day (the module is assumed to be facing south). [70]

3.2.3. Demand

It is known that demand will depend on the number of tourists present visiting the island, something that is highly influenced by its meteorological conditions. San Andres has a tropical climate with high temperatures, high humidity and only two seasons: the wet season and the dry season. Temperature and humidity do not change much during the year, so precipitation has the major influence in tourism flow. In theory, the higher the precipitation the less the number of tourists.

Figure 37 shows the average precipitation over the year.

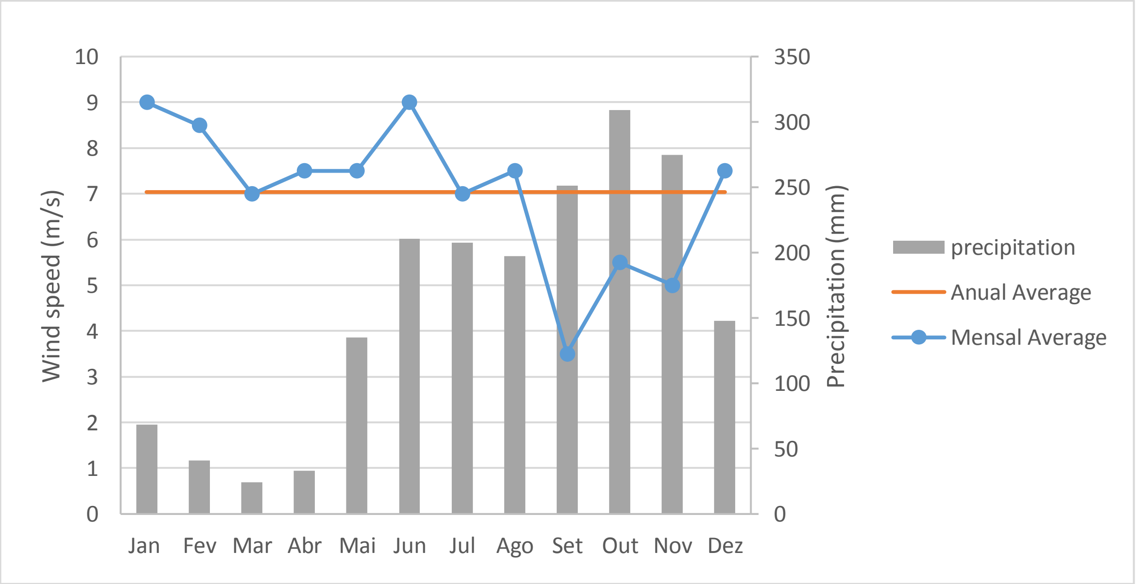


Figure 35 – Wind speed vs precipitation over the year. Data from: [66] [67]

It is seen that the wet season normally starts around June and finishes around November, however during June and July there is an increase in island population because of the adolescent students on vacation [66]. This means that the low season comprises mainly September, October and November, which are, by a lucky coincidence, the months with lower wind speeds. The wind resource annual variability is thus well fitted to the expected demand annual variability.

The most important source of electricity demand in the Island will be the water desalination unit for drinking water production, obviously indispensable, especially in hot areas. Local merchants actually buy all the drinking water in San Andres, store it into bottles, and send them to Johnny Cay by sea. According to the responsible of the water management, the drinking water needs rounds about 330 L/day, a value that corresponds to an average between the low and high season, calculated from an annual average demand of 120 450 L.

Aside from liquid water, ice is also a very important resource on the island. It is used mainly for refreshing drinks and conserving the fish. Ice is also bought in bags with different volumes, and each bag has different ice qualities, i.e.: The 5.44 kg bag, has ice made from drinkable water and the 50 kg bag has ice made from non-drinkable water. On average daily are request is around 540 kg of pure ice and 472 kg of non-pure ice, corresponding to an amount of about 369 380 kg per year (Table 4).

Table 4 – Ice demand in Johnny Cay. Data from: [66]

Type of ice	Bag capacity (kg)	Daily needs (kg/day)	Annual needs (kg/year)
pure	5.44	540	197 100
non-pure	50	472	172 280
	Total	1012	369 380

Johnny Cay has one of the biggest affluences in the tourist sites of the San Andres islands, especially during lunch hours. There are in the island about 15 huts that are used as restaurants, bars and craft sales.

Figure 36 – Typical bar in Johnny Cay. [66]

These huts will also contribute to the island electricity demand. As mentioned before, the island has no electrical network or any other mechanism capable of producing electricity. However, it was asked to all merchants what would be their priority needs once electrical power would be available. The requested equipment, according to their answers, fall in the areas of lighting and refrigeration.

This is quite understandable since more than half a ton of ice per day is needed for refreshing drinks.

The expected electrical consumption, taking into consideration the results obtained from the enquires, is shown in Table 5:

Table 5 – Requested equipment and electrical consumption in Johnny Cay. Data from: [66]

Equipment	Quantity	Power (W)	Total power (W)	Total consumption (kWh/month)[a]
Fridge	11	350	3 850	2 079
Equipment	7	550	3 850	462
Freezer	5	1 016	5 080	1 830
Lights-300W	2	300	600	108
Total			13 380	4 479

The foreseen average monthly energy consumption of all devices is around 4.5 MWh/month (or 53.75 MWh/year) corresponding to a foreseen installed capacity of about 13.4 kW.

3.2.4. Proposed implementation

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[a] According to the report [66] the demand was calculated assuming a scenario of inefficient use by the community. However, the calculation method was not explained.

(pages 55 to 82 are only available in the confidential version)

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Chapter 4 – Conclusion

With this project it was shown that it is possible to desalinate seawater using only renewable energy sources, more specifically, the wind energy. The system can remove from the wind the energy required to produce 8.6 kW of electric power at the same time as it provides the necessary pressure to move 23.8 L/min of seawater though the spiral wound membranes of a SWRO system, producing drinking water at a rate of 8.33 L/min with excellent quality for consumption (TDS = 300 ppm). In future studies it would be important to perform some more experimental tests to determine the power coefficient for different wind speeds and specifically to determine the system startup speed (estimated at 8 m/s). The main advantage of this configuration has to do with the low investment cost. The use of a hydraulic system as a bridge between the wind turbine and the RO instead of electricity makes it simpler and, consequently, economically more viable.

However, in this system, it was also found a series of problems and so some improvements for future projects were suggested. The main problem is due to a foressen system start-up wind speed of around 8 m/s. According to the annual wind regime in the island, that results in 54% of the time during which there would be no water production. In the case study this feature is not a problem since there is overproduction, however this may be a problem in areas with weaker winds making the system less attractive. One way to mitigate this problem would be to create a heat exchange between the sea water intake and the hydraulic oil. This would promote at the same time a decrease in the hydraulic fluid temperature, making it possible to dispense the oil cooler, and an increase in the sea water (feedwater) temperature, decreasing the necessary pressure required by the RO_{HPP} (and thus reducing the start-up speed). A more dramatic solution, since it implies changes in the base system structure, would be to implement multiple RO systems with different pressure levels operating in an on/off mode: when the energy available from the wind is too low, the RO with less capacity would be activated and, with the rise of the available wind energy this unit would be switched off while a second one, with higher capacity, would be switvhed on, and so on. This would make it possible to produce water at different production rates but for longer periods. Finally, an improvement in energy efficiency could be obtained by changing the seawater intake system: since the used pump requires a lot of energy due to the high rotor speeds, a better solution would be to use a conventional pump to raise the seawater to a tank to subsequently be used by the system without the need of an electric pump.

To upscale the system it is important to determine whether it would compensate to use a three bladed wind turbine. The addition of one blade would increase the turbine efficiency but the overall system cost would also increase. The pump connected to the rotor would have to be able to produce higher pressures and/or to pump larger flows and the entire structure would have to be reinforced. All these changes should be evaluated to conclude if this option is a good solution.

On the studied implementation site, the costs of pure water and ice paid by the merchants are quite substantial but with the application of this project we anticipated a 50 % cost reduction for these goods. At the same time, it brings economic benefits to the investors and environmental benefits to the park, since it allows a reduction of about 4 tons of plastic garbage and about 11 tons of emitted greenhouse gases per year, offering a “100 % green" tourist destination in what concerns energy and water.

Finally, the implementation of this system in regions with limited financial resources proves to be a viable alternative to standard desalination systems, because of the low investment cost combined with the free and inexhaustible resource which is the engine of the entire process. In addition, its importance gains an increased strength in a world where most of the population suffering from drinking water shortages is located near a source of water unsuitable for human consumption and where renewable resources are abundant.

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Appendix A - Hydraulic system technical drawing

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Appendix B - RO technical drawing

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