MSc Program
Environmental Technology & International Affairs

Contribution of established and alternative desalination technologies as approach to the international water crisis

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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"*Every Human should have the idea of taking care of the environment, of nature, of water*."

His Holiness Tenzin Gyatso,
the 14th Dalai Lama of Tibet

AUTHOR’S NOTE

In the interest of readability the masculine form has been chosen in the text, nevertheless, the details provided refer to members of both sexes.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

%	percent
°C	degree Celsius
‰	per mille
approx.	approximately
bn.	billion
CA	California
CESR	Centre for Environmental Systems Research
d	day
dm^3	cubic decimeter
e.g.	exempli gratia
ED	electrodialysis
et al.	et alii / aliae / alia
etc.	et cetera
ETIA	MSc Program Environmental Technologies and International Affairs
FL	Florida
GTZ	Gesellschaft für Technische Zusammenarbeit
GWI	Global Water Intelligence
IDA	International Desalination Association
kJ	kilojoule
km^3	cubic kilometer
kW	kilowatt
kWh	kilowatt hour
L	liter
m.	million
m^2	square meter
m^3	cubic meter
MD	membrane distillation
MDG	Millennium Development Goal
MED	multi-effect distillation
mg	milligram
MGD	million gallons per day
mm	millimeter
MSc	Master of Science
MSF	multi-stage flash

n	amount of substance
n.d.	no date
no.	number
p	pressure
P	Person / Inhabitant
pp.	pages
ppm	parts per million
R	universal gas constant
RO	reverse osmosis
T	temperature
U.S.	United States of America
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Emergency Fund
USD	U.S. Dollar
V	volume
VC	vapor compression
vol.	volume (literary)
W	watt
WHO	World Health Organization

ABSTRACT

This Master's Thesis deals with the circumstances of the global water scarcity, which doubtlessly can be called a global water crisis, which is affecting various regions of our world and over a billion of people, and desalination as a potential solution, or part of the overall solution, to this growing problem.

The background of the world's water is discussed, explaining basic chemical and physical coherences, reviewing the hydrological cycle and showing geographical concerns of its distribution, extraction and consumption, also including the interdependencies of population and water.

Different applications of membrane processes and thermal desalination methods are presented and the potential for certain processes by means of technological improvements and the combination with renewable energy sources is presented. The excessive use of fossil fuels in general, and for the power supply for desalination plants in this very example does cause significant harm to the environment and accelerates climate change. This is why there is a significant need to employ renewable energy resources to operate desalination plants in a sustainable manner.

Attempts to solve the scarce water situation based exclusively on technology, such as desalination of saline water, will only have a limited impact, due to their environmental considerations and costs. There are certain areas that must be improved on, forming a well balanced mix of water management, including an improvement in the efficiency of water usage, particularly for irrigation, refurbishment of drinking water production and distribution resources, protection of reserves and better pollution control.

1 INTRODUCTION

1.1 Purpose of this thesis

We are virtually living on a water planet with an unimaginably 1.4 billion km^3 of this amazing and unique wet substance distributed all over it. However, this seems like an illusion of plenty, as despite all that water about 1 billion people do not have the most basic access to clean drinking water.

This Master's Thesis deals with the issues of water scarcity and desalination as a prospective solution to the international water crisis. The state of the art of desalination is presented, setting the focus on established desalination technologies and alternatives of using renewable energies for saline water desalination. Through this approach the obvious question shall be addressed, how and if it is possible to make use of the two resources we seem to have in abundance; sun and seawater, in order to address at least part of the needs of the 1 billion of people expressed earlier.

In the course of this research the importance of water was identified, as this thesis ultimately shall raise awareness of the difficile water situation we are facing in our thirsty world and should show established and alternative ways to turn seawater into pure drinking water.

The first part of this Master's Thesis provides background information and definitions on the world's state of water and its scarcity, including the unequal distribution of water and trends for the world's population, and is followed by an overview of desalination technologies.

After a general description of desalination technologies, in the main part of the thesis certain methods are examined more closely, as those look like the most promising solutions, as well as an overview of needed technical improvements and advantages and disadvantages in relation to desalination are presented.

The hypothesis of this thesis will state that a majority of global population lives relatively close to shorelines and therefore would have an seemingly infinite access to water, undrinkable saltwater indeed; yet a much too huge part of the world wide population does not have access to safe drinking water and/or sanitation and ultimately faces water-related diseases and death.

1.2 Methods and literature

The main approach to accomplish this thesis was to set up a descriptive / normative analysis of the portrayed situation of water in today’s world, the usage and distribution of seawater, the current state of the art of desalination technology and furthermore the application of seawater together with sunlight - through solar desalination or the use of renewable energy sources - to counteract the world’s water crisis. This approach is primarily based on literature review.

The literature research was carried out by the review of scientific books, publications in international journals, e-books, research papers, conference papers, thesis’ and dissertations, handbooks, secondary literature and online sources of official institutions with a reliable background. Furthermore, some informal personal communication substantiated the ideas used in this thesis.

2 THE WATER PLANET

2.1 Water on Earth

Although at first glance we are living on a water planet, we are also living in a "*world of salt*", as Shiklomanov (1999) calls it (Shiklomanov, 1999).

The oceans are the main reservoir in our hydrological cycle and amount for 97.5% of all water on Earth; however this seawater is too salty to drink or to use for watering crops. That leaves 2.5% as freshwater, which is the water that we account on for our survival. However of this amount about two thirds are frozen as ice caps, snowfields as glaciers. Thus, less than 1% of the planet's total water is in a readily usable form, as groundwater, surface fresh water, and rain (Withgott, 2008). This concept is also displayed in Figure 1 and the major stocks of water on Earth are detailed in Table 1.

Having this relation in mind, the words that the English poet Samuel Taylor Coleridge used in his *Rime of the Ancient Mariner* appear nowadays even more suitable than during its first publication in 1798, when he wrote: "*Water, water, everywhere, nor any drop to drink*" (Pearce, 2006).

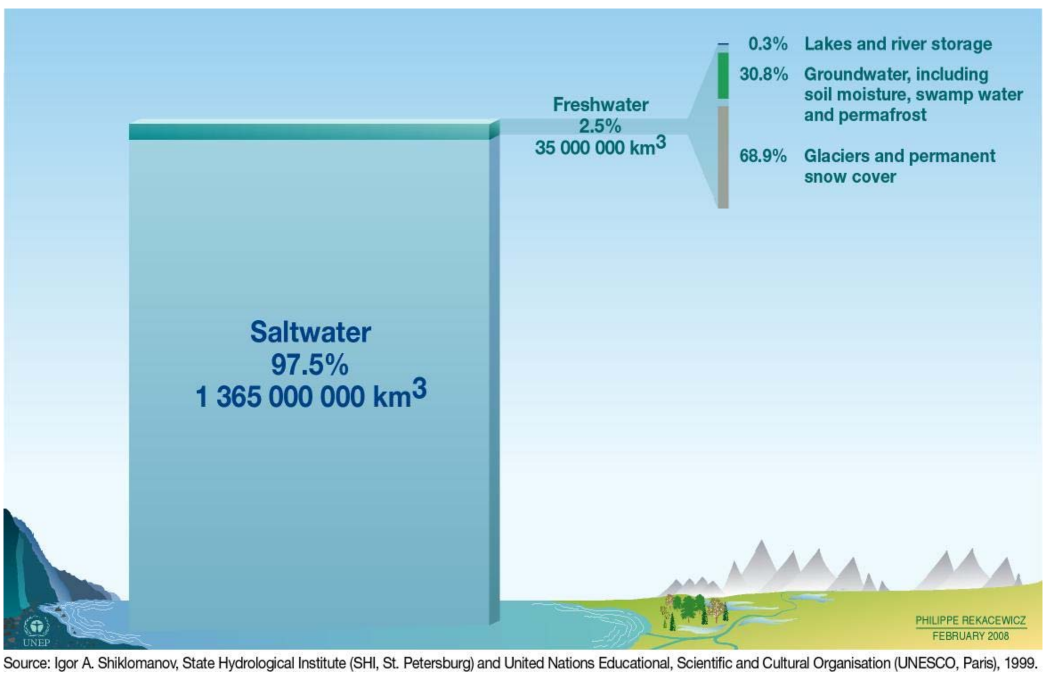

Figure 1: A world of salt (Shiklomanov, 1999)

	Distribution Area (10^3 km^2)	Volume (10^3 km^3)	Percent of Total Water (%)	Percent of Fresh Water (%)
Total water	510,000	1,386,000	100	
Total freshwater	149,000	35,000	2.53	100
World oceans	361,300	1,340,000	96.5	
Saline groundwater		13,000	1	
Fresh groundwater		10,500	.76	30
Antarctic glaciers	13,980	21,600	1.56	61.7
Greenland glaciers	1,800	2,340	.17	6.7
Arctic islands	226	84	.006	.24
Mountain glaciers	224	40.6	.003	.12
Ground ice/permafrost	21,000	300	.022	.86
Saline lakes	822	85.4	.006	
Freshwater lakes	1,240	91	.007	.26
Wetlands	2,680	11.5	.0008	.03
Rivers (as flows on average)		2.12	.0002	.006
In biological matter		1.12	.0001	.0003
In the atmosphere (on average)		12.9	.0001	.04

Table 1: Major stocks of water on Earth (Shiklomanov, 2009)

2.1.1 Chemical and physical properties of water

This section gives an overview of water as chemical substance, a very special substance indeed. In its pure liquid form water is colorless, odorless, tasteless and virtually incompressible (Williams, 2001).

Williams (2001) calls water "*unquestionably the lifeblood of the Earth*" (Williams, 2001) and emphasizes that "*no animal or plant life would exist without it*" (Williams, 2001). Falkenmark (2009) refers during his foreword in *The World's Water* to water as "*the bloodstream of both the biosphere and the social sphere*" (Gleick et al., 2009).

Although water is most common chemical on Earth (Williams, 2001), it is also one of the most unusual, for example it is the only compound to become less dense when it changes from liquid to solid (Glanville, 2008). Furthermore, from chemical perspective water is an oxide of hydrogen and is the only chemical compound that can be found in all three physical stages in nature: solid, liquid and vapor (Williams, 2001) and the only compound that becomes less dense when changing form liquid to solid state. Water has its highest density at 4°C. This density anomaly of water is important for many natural processes, e.g. being the reason that ice formation starts at the surface of water bodies and not at the bottom (Glanville, 2008).

Water is a unique liquid, featuring very high specific heat, very high heat of evaporation, high melting heat and acting a an universal solvent (Kroiss, 2010a). Through those unique chemical and physical properties all known life depends on water (Glanville, 2008).

Water plays a life sustaining role for almost all creatures on Earth and is essential for many biological activities, as listed by Williams (2001), including:

- Metabolism (i.e. always takes place in aqueous solutions);
- Transport of substances (e.g. blood plasma);
- Photosynthesis
- Transport of heat (e.g. acting as heat conductor) and temperature control (e.g. sweating);
- Lubrication (e.g. mucus, synovial fluid);
- Support (hydrostatic skeletons) (Williams, 2001).

2.1.2 Hydrologic cycle

According to Williams (2001) water on Earth can be divided into:

- Surface water, including standing (e.g. oceans, lakes, reservoirs) and running (e.g. rivers),
- Groundwater, and
- Rainwater through precipitation (e.g. in the form of rain, dew, fog, hail, sleet or snow) (Williams, 2001).

All water from those three categories is connected in one compassing single natural cycle, called the global water cycle, or global hydrological cycle, in which water moves from the oceans and the land to land and back to the oceans again continuously (EPA, 2009), as displayed in Figure 2, where also the rough figures for global precipitation, evaporation, evapotranspiration and runoff are stated.

The hydrologic cycle is sustained and begins as water moves from the ocean's surface to the air above through evaporation and by evaporation and evapotranspiration from the land, which creates clouds in the atmosphere, holding the evaporated water. Later those clouds release the water again as rain or snow fall. Once the water reaches the land, it begins its journey back to the sea, either through groundwater or surface water flow, which can vary largely in timing (Vigil, 2003). Accordingly, water is continuously moving through the biosphere by evaporation, condensation, precipitation and transpiration, all driven by the sun’s radiation. 80% of the total precipitation falls directly back into the oceans (Williams, 2001).

During the cyclic movement only tiny fractions are present, seemingly stored, as running surface water; approximately 0.0002% of the total water is present in rivers or streams at any given moment in time (Williams, 2001). Falkenmark (2009) accentuates that the distinction between *green water*, for the water bound in soil, and *blue water*, for the water in rivers and aquifers is getting customary in the water community (Gleick et al, 2009).

The hydrological cycle will be of special interest in chapter 3.2, when it is displaying the principle of thermal desalination technology, through precipitated evaporation and condensation.

A quarter of the total terrestrial evapotranspiration and more than half of runoff that is geographically and temporally accessible is nowadays used by humans. The construction of new dams could advance the accessible runoff by about 10% over the next three decades; however population is predicted to rise by more than 45% during the same timeframe, as also shown in Figure 7. Also, most land surface suitable for rain-fed agriculture is already developed and in production (Postel et al., 1996).

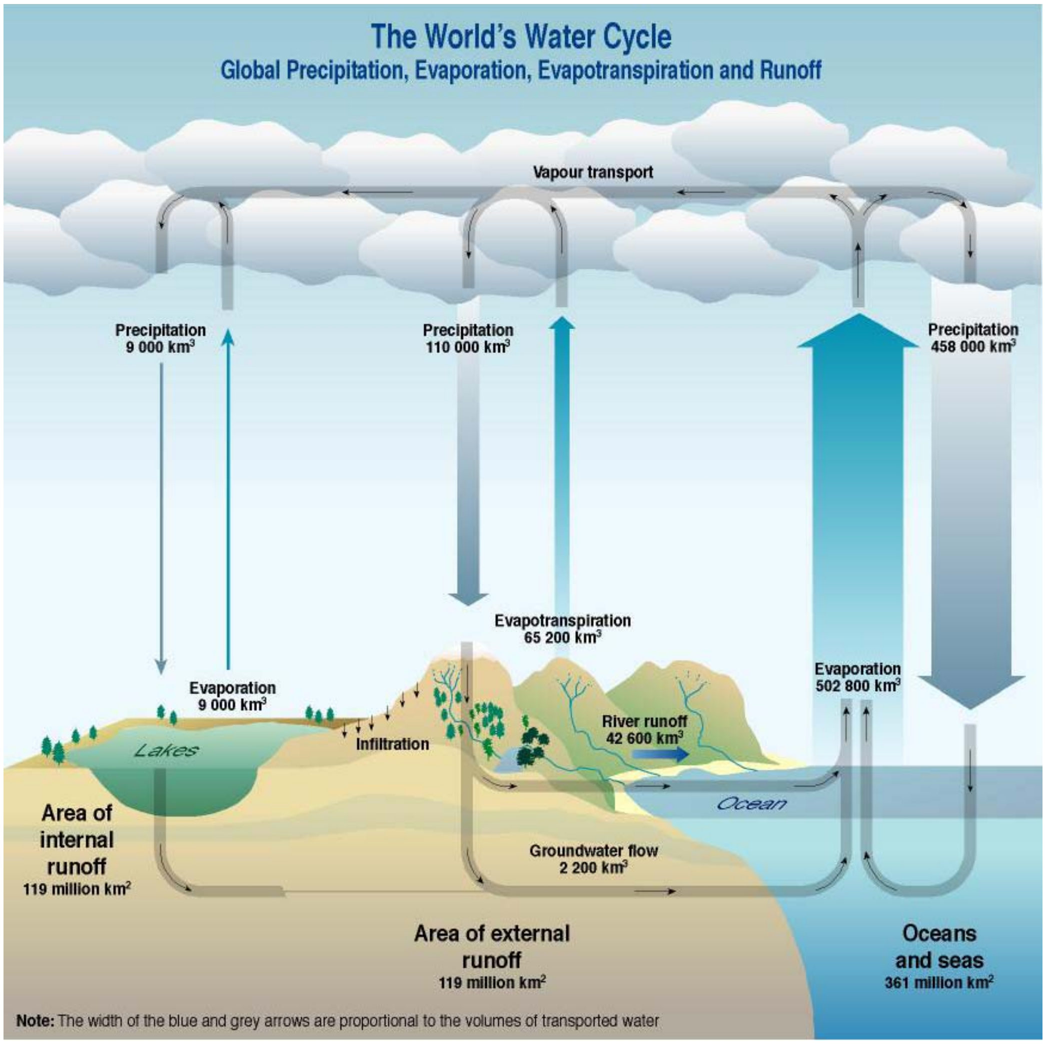

Figure 2: Global water cycle (Shiklomanov, 1999)

Talking about the water circuit it is important to stress the crucial difference of water being used from fresh water sources and water being extracted from groundwater stocks. According to Connor (2009) 20% of the total amount of water being used is derived from groundwater sources and this share is incredibly increasing, especially in arid regions. One further distinction has to be made in terms of ground water, as groundwater can be categorized into two groups: the non-renewable or also fossil aquifers and the renewable ground water sources. The non-renewable sources make up for less than 1% of available water. Still some countries such as Algeria, Saudi Arabia or Libya heavily depend on this non-renewable source as the main source of water which is drastically decreasing (UNESCO, 2009).

This distinction is also crucial for further implications of the use of desalinated water. Desalinated water will definitely not increase the storage of fossil water storage, but can be restored into the renewable fresh water circuit.

2.1.3 Geographical water distribution

As listed in Table 1 there are almost 1.4 bn. km^3 of water existent on Earth, however only one hundredth of one percent is considered easily accessible for human use, which again is very unevenly distributed between the Earth's regions (UNEP 2008). This can clearly be seen in Figure 3, showing the water availability in the recent past, and in Figure 4, showing the water availability for the year 2050.

As an example, Austria is a rich land, also in terms of freshwater resources. Of an annual availability of water of 84.3 bn. m^3 only 3% are actually extracted but not consumed (Mueckstein, 2007). Nearly all the water extracted is returned back into the waters. Evapotranspiration from agricultural land and forests and evaporation from the other areas results in a regional *loss* of water of roughly one half of the available fresh water. Relating to the total available fresh water in the country the drinking water supply represents only about 5‰ (Kroiss, 2010b). In 2006 the average Austrian daily drinking water consumption per capita was less than 150 liters, including industrial use this figure increases to 260 liters per capita (Mueckstein, 2007).

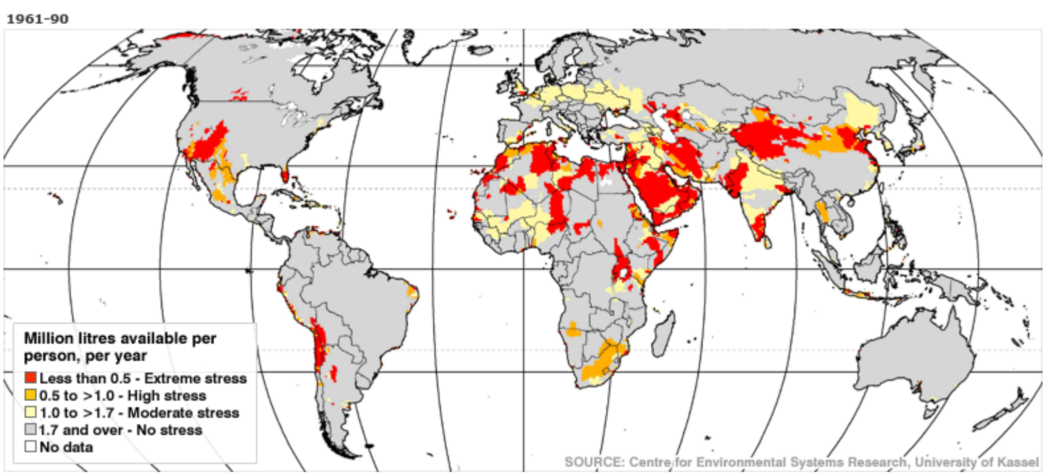

Figure 3: Water availability 1961 - 1990 (CESR, 2010)

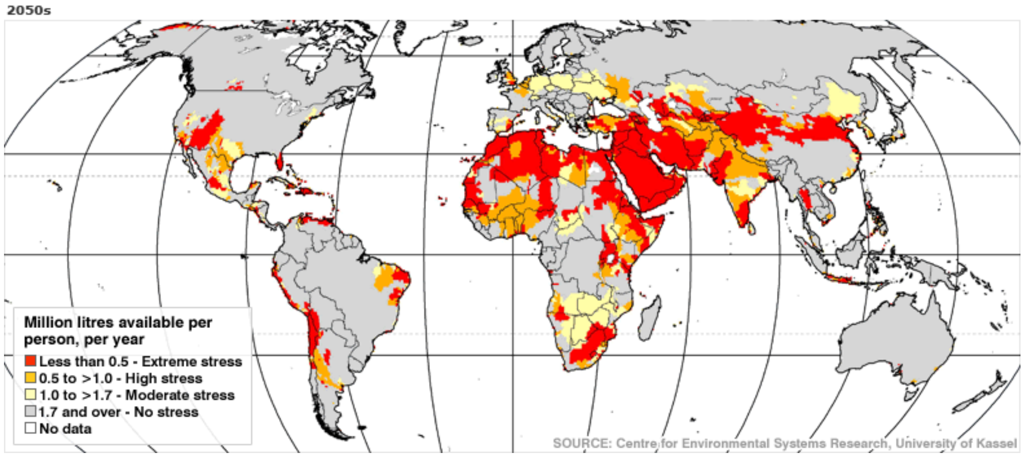

Figure 4: Water availability 2050 (CESR, 2010)

The water withdrawal per person is relating to several socio-economic factors, e.g. population and climatic characteristics. The definition of withdrawal, which is also used in literature, refers to water taken from a water source for use, which does not refer to the water being consumed (Gleick, 2009).

An analysis performed by UNESCO (1999) indicates that in the year 2000, more than half of the world's freshwater withdrawal and 70% of the freshwater consumption took place on the Asian continent, as the world's major irrigation land is located there. There are growth rates in annual global water withdrawal expected between 10 and 12% every 10 years, corresponding with approx. 5,240 km^3 by 2025 (UNESCO, 1999). The current level of water withdrawal per person in m^3 per year is displayed in Figure 5.

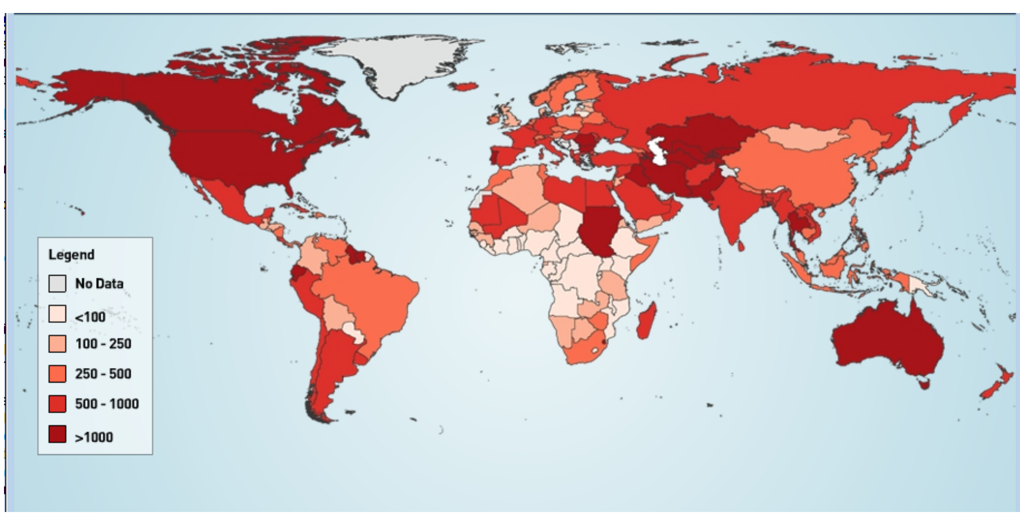

Figure 5: Water withdrawal per person [m³/year] (AQUASTAT, 2010)

In Table 2 some salt concentrations of different water sources are stated, respective to their geographic location.

Water source or type	Approximate salt concentration (ppm)
Brackish water	500 – 3,000
North Sea (near estuaries)	21,000
Gulf of Mexico and coastal waters	23,000 – 33,000
Atlantic Ocean	35,000
Pacific Ocean	38,000
Persian Gulf	45,000
Dead Sea	300,000

Table 2: Salt concentrations of different water sources (OTV 1999 and Gleick 1993)

2.1.4 Water scarcity

According to the United Nations Environment Programme water scarcity occurs, when "*the amount of water withdrawn from lakes, rivers or groundwater is so great that water supplies are no longer adequate to satisfy all human or ecosystem requirements, resulting in increased competition between water users and other demands*" (UNEP, 2008).

Many less developed countries are threatened by freshwater shortages as in several countries the growing population have depleted reservoirs and the larger number of people overwhelm supplies of drinking water. Mexico City, for example, could not supply enough water to its inhabitants for several times in 2009, because of low levels of rain fall, coupled with inadequate infrastructure and a rapidly growing population, worsened by untreated waste that caused the threat from waterborne diseases like cholera (Gore, 2009).

To classify the water availability of certain states the United Nations are ranking countries according to the following classification (UNEP, 2008):

Water scarcity: less than 1,000 m^3/person/year

Water stress: 1,000 to 1,700 m^3/person/year

Water vulnerability: 1,700 to 2,500 m^3/person/year

The UN estimated that by the year 2025 almost all sub-Saharan countries will face water vulnerability, and even worse many countries will even experience water stress or water scarcity, as displayed in Figure 6 (UNEP, 2008).

Palaniappan and Gleick (2009) coined the term of *peak water*, following the established terminology relating to the Hubbert curve for oil production over time. The comparable point of peak water is that we are running up against natural limits of availability or human use of freshwater (Gleick et al., 2009).

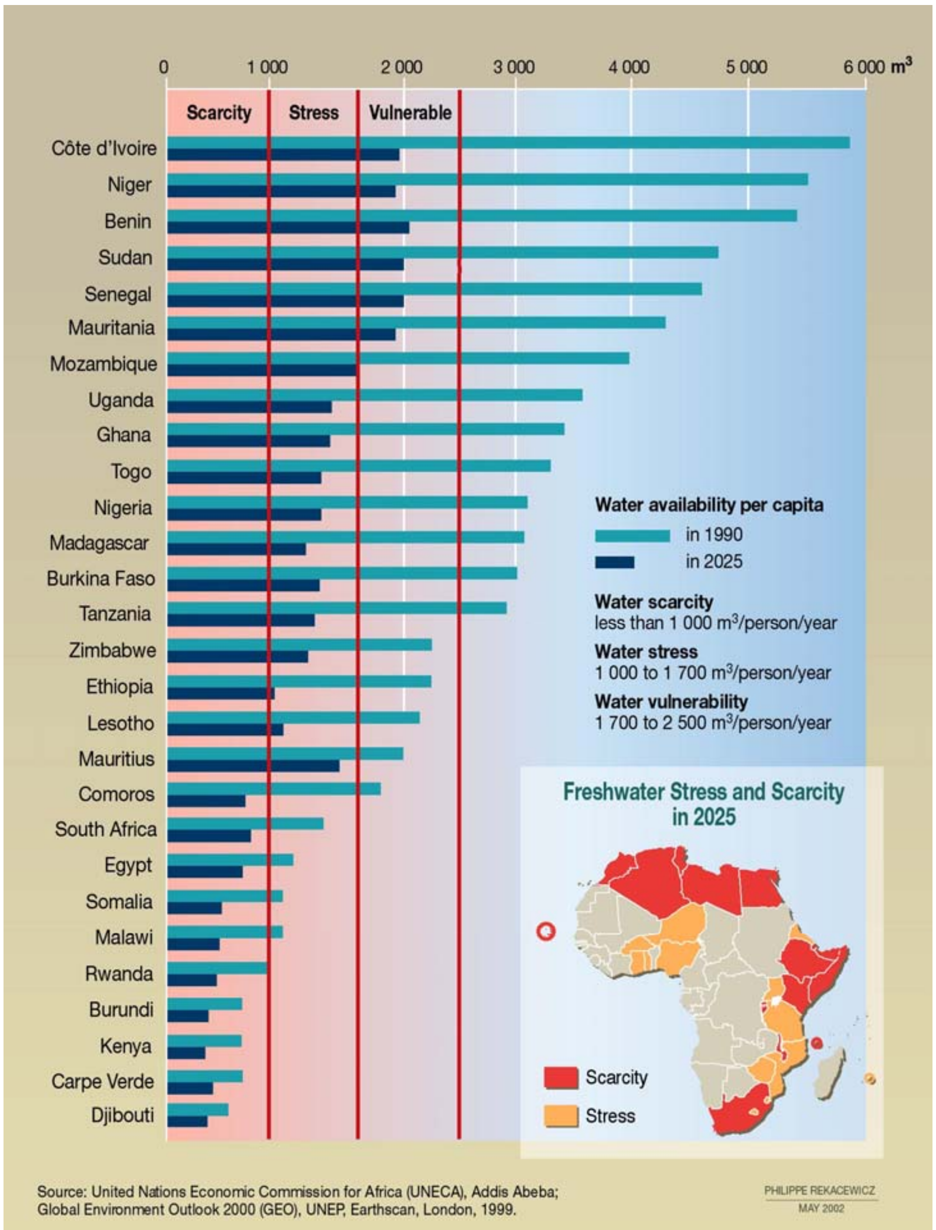

Figure 6: Water availability for selected African countries (UNEP, 2008)

The Water Development and Management Unit of the Food and Agricultural Organization of the United Nations (2010) names the following as contributors to water scarcity:

- Imbalances between availability and demand,
- Degradation of groundwater and surface water quality,
- Intersectoral competition, and
- Interregional and international conflicts. (FAO, 2010)

According to the Food and Agricultural Organization of the United Nations there is no global water scarcity as such by definition; however an increasing and worrying number of regions are chronically short of water, as displayed in Figure 3 and Figure 4.

In particular in the Middle East and North Africa water is a scarce resource. Since 1960 the available water per person has fallen constantly and the expected growth in population will further reduce the available water (Brauch, 2007). Global climate change will aggravate this problem to provide adequate water and food for the population in these regions (Bazzaz, 1994).

While in 1995 Portugal, France and Greece used a maximum of 20% of the total available water, countries like Spain, Italy, Morocco and Algeria used up to 40% and in Tunisia, Libya and Egypt the usage was well over 40%. In the year 2025 all five named North African countries will suffer from water stress or even water scarcity and will have access to less than 1000 m^3 of water per capita and year (Brauch, 2007), which would still be plenty for drinking water need only, however 1000 m^3 of water per capita and year is the minimum amount needed for food production (Kroiss, 2010b).

Toedtling (2010) is pointing out that it would be wrong to think that water stress is exclusive to regions in Africa and Asia, where it might be more obvious, compared to Europe, but which will also be affected by water stress more and more in the future. Amongst other problems, some parts of Europe operate inefficient water supply infrastructure and e.g. France and Spain are losing about 30% of their water during transportation due to poor supply networks. The European Union has identified the water challenges and needs to take political action now, to avoid a European future of water scarcity (Toedtling, 2010).

2.2 Human development and water

2.2.1 Worldwide population

Even when considering only the UN medium predicted worldwide population growth rate the world might have 9 billion inhabitants until 2050, or even 11.5 billion, when considering the UN high prediction (UN, 2004).

The rapidly increasing worldwide population, as displayed in Figure 7, is stressing the existing water resources and is putting pressure on many governments to provide additional water supplies, for which inter alia desalination can be a viable option (Western Australia Water Corporation, 2006).

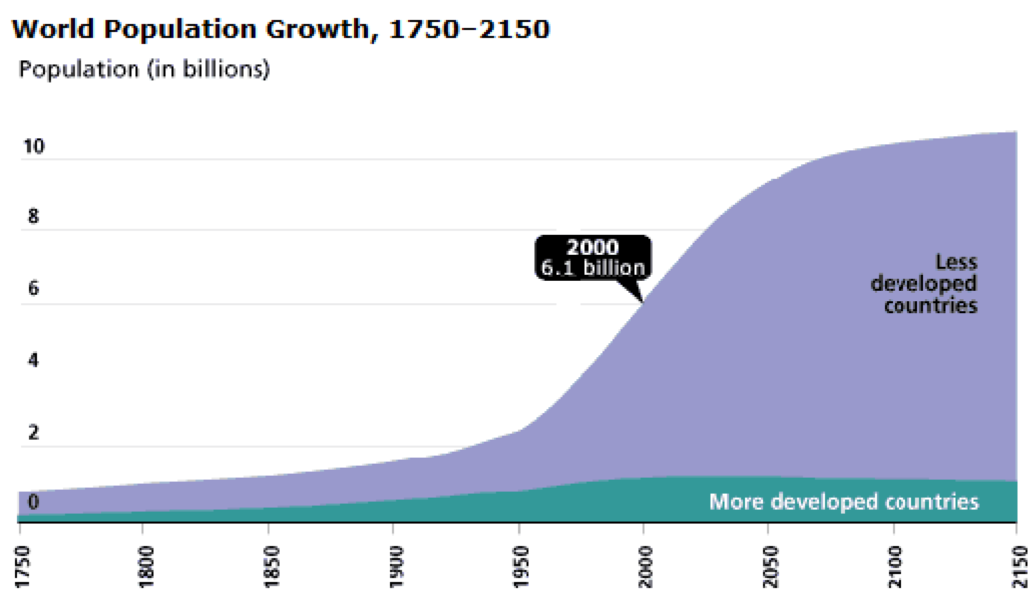

Figure 7: World Population Growth, 1750 - 2150 (UN, 2004)

Half the world's population is nowadays living in urban areas and megacities are booming, many of which are located at coastlines and river mouths, with the result that the majority of the world's population is living within 100 km of the sea (UNESCO, 2009), visualized in Figure 8. Two thirds of the world's population is even living in a range of 50 km to an ocean shoreline (BBC, 2009). The situation will be exacerbated as rapidly growing urban areas place heavy pressure on neighboring water resources, rising the potential for an increase in water related conflicts in the future, comparing with 2.2.5.

For these costal cities desalination is an obvious option for the provision of drinking water, if affordable. However improved water management and increased efficiency of water use has to be a priority (UNESCO, 2009).

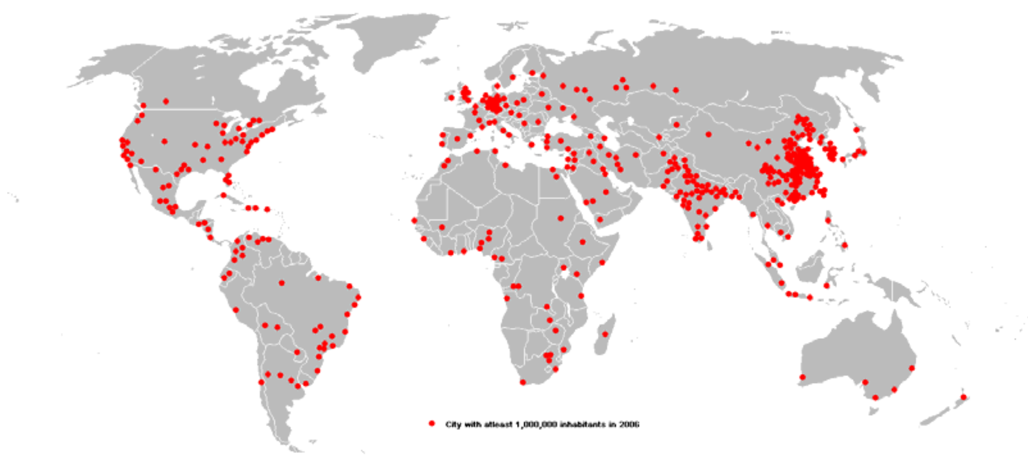

Figure 8: Cities with at least 1 m. inhabitants in 2006 (Saadat, 2007)

2.2.2 Trends in global water use

According to the Food and Agricultural Organization of the United Nations world wide water usage has been growing at a rate more than twice as fast as the population increase during the last century. At the given rate**,** within the next 15 years "*1,800 million people could be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under stress conditions."* (FAO, 2010)

The trends for water use in Figure 9 show that global water use for agriculture, domestic use and also industry will continue to increase at a steady rate.

A clear distinction has to be made between water extraction and water consumption. Not all the water extracted is actually used. Shiklomanov (1999) defines the final use of water as *consumption*, respectively as a condition when water can no longer be reused (Shiklomanov, 1999). As seen in Figure 9 the proportion of water being used and extracted varies from sector to sector. Interestingly, domestic households as well as the industry merely hold a minimum percentage of water being consumed, in relation to the agricultural sector where most of the water extracted is also consumed.

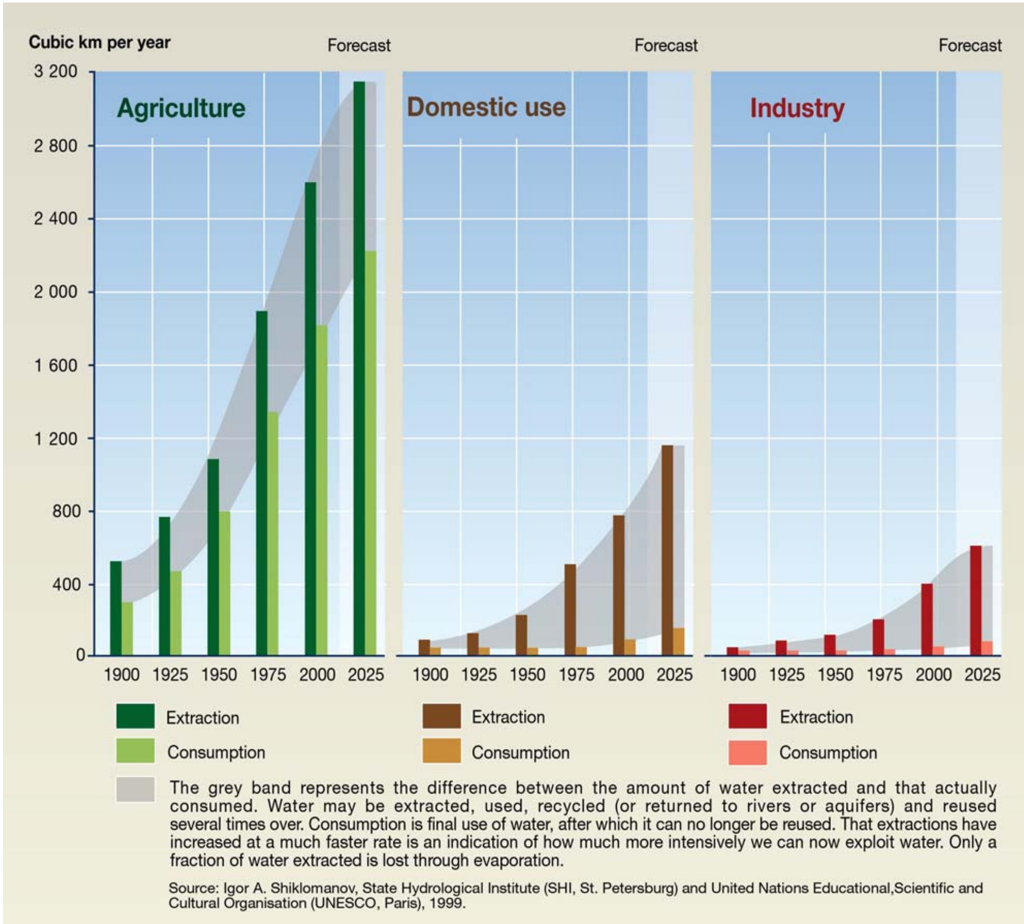

Figure 9: Trends in global water use (Shiklomanov, 1999)

2.2.3 Water aspect in UN Millennium Development Goals

The linkage between safe water supply and public health is crucial and obvious. Especially developing countries have to face the consequences of water-related diseases which are divided into three main groups:

- Water-borne diseases, including e.g. cholera and typhoid, which are caused by ingestion of contaminated water,
- water-washed diseases mainly focusing on hygiene related diseases, and
- water-based diseases coming from parasites living in water (Gleick, 2005).

For the sake of completeness it is necessary to further mention vector-borne diseases. Breeding sites for mosquitoes are preferably areas of standing water. Vectors, such as e.g. mosquitoes, spread a wide range of dangerous diseases such as malaria, dengue, yellow fever, St. Lois, Japanese B encephalitis, etc. (Blake, 1989).

Fidler (2009), lead advisor for health policy to the Worldbank, believes that many items that are influencing the health status of a population, can not be corrected by the health system itself, e.g. economical progress, education, water and hygiene, therefore these controlling systems need external support (Fidler, 2009).

Especially people in developing countries suffering from water shortage are likely to turn to unsafe sources of water, which increases the probability to increase the prevalence of water related diseases (Blake, 1989). Therefore water and especially the free access to safe drinking water and sanitation should be one of the global community's first priorities.

Gleick (2002) is listing estimates of water-related mortality from various sources in the public literature, where a wide range of estimates is stated, varying from 2.2 to 12 millions deaths per year, see Table 3. The majority of water-related fatalities are small children that got infected by virulent, but preventable, diarrheal diseases (Gleick, 2002).

Source	Deaths per year
World Health Organization, 2000	2.2 million (diarrheal diseases only)
World Health Organization, 1999	2.3 million
WaterDome, 2002	more than 3 million
World Health Organization, 1992	4 million
World Health Organization, 1996	more than 5 million
Hunter et al., 2000	more than 5 million
UNDP, 2002	more than 5 million
Johannesburg Summit, 2002	more than 5 million
Hinrichsen et al., 1997	12 million

Table 3: Estimates of water-related mortality (Gleick, 2002)

The Millennium Development Goals (MDG) were established by the United Nations to tackle the most urgent issues in improving the lives of the world's poor. Water plays a vital role in achieving all eight goals, especially when focusing on eradicating poverty (UNESCO, 2009).

The priority of safe drinking water and sanitation is mostly reflected in the MDG Goal Number 7, Target 7C:

"*Reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation*

7.8 Proportion of population using an improved drinking water source

7.9 Proportion of population using an improved sanitation facility" (UNDP, 2000).

The MDGs were set up in the year 2000 to reach certain goals of human development by the year 2015. As today, there are only five more years left to act by the global community to achieve these objectives and to find out if the targets for drinking water and sanitation are likely to be reached until 2015.

According to the MDG Report 2010 (2010) published in June 2010 the prospects for the targets focusing on safe drinking water and basic sanitation are slightly optimistic, implicating a positive trend, but are still not met yet in some regions. Especially Eastern Asia showed a positive development by increasing 30% of improved access to drinking water. Coming last in terms of safe drinking water is the Oceania region, showing no progress over the last 20 years and only 50% of population using improved water sources (UN, 2010).

The United Nations (2010) conclude in their Millennium Development Report that "*the world is on track to meet the drinking water target, though much remains to be done in some regions*" (UN, 2010). Figure 10 below shows the achievement in water and sanitation in relation to the Millennium Development Goal 7C and states the estimated year of fulfillment for various regions of the world.

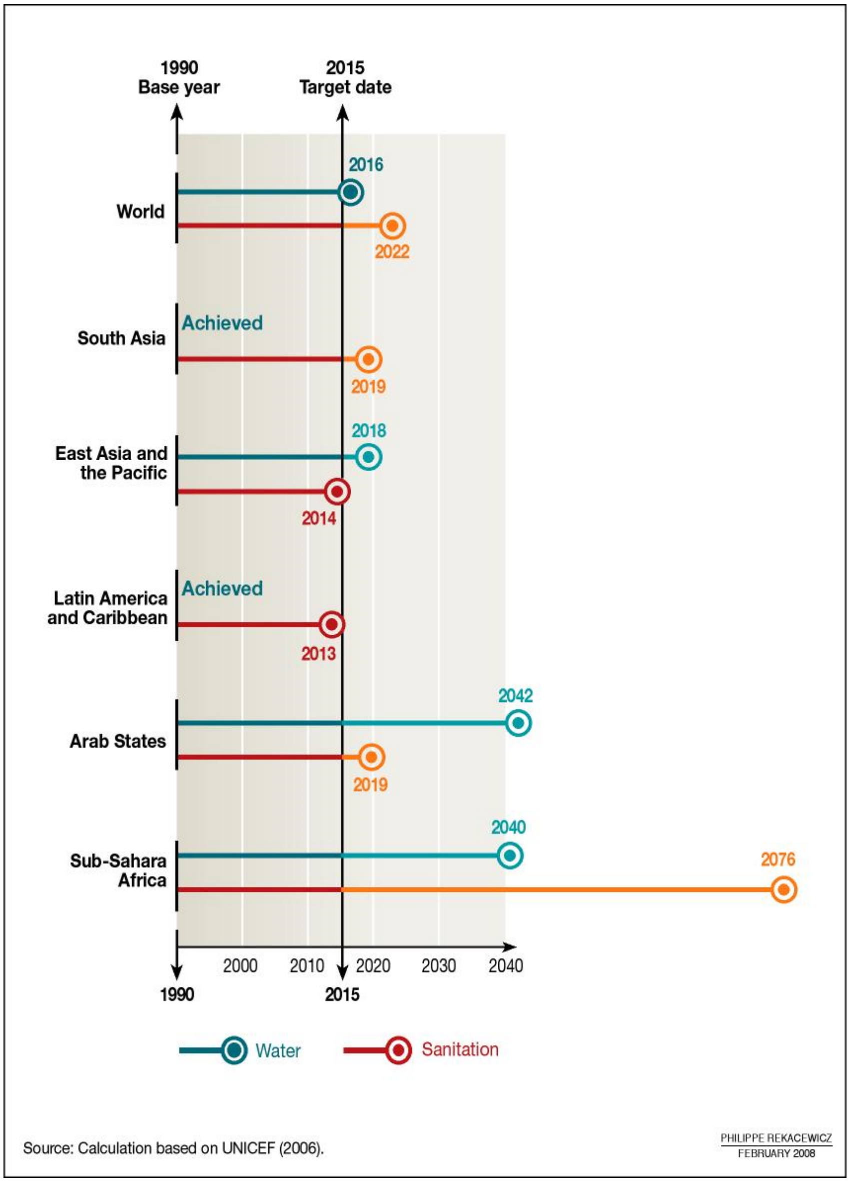

Figure 10: Achievement of the water and sanitation MDG (UNICEF, 2006)

Although at the moment the MDGs for water and sanitation have a fair chance to be met by 2015, it can only be a partial success for policy makers. By definition these goals are reached when there is a reduction by half the proportion of people without sustainable access to safe drinking water and basic sanitation. Hence the other half of affected people still struggles with access to these basic needs. Even if the trend is positive towards more access to safe drinking water and sanitation, according to Gleick (2005), approximately 32 million people will still die due to water-related diseases by the year 2020 (Gleick, 2005).

The European Commission (2008) also sees the achievement of the Millennium Development Goals jeopardized because global climate change could devastate years and years of international development work and is calling for political reactions (European Commission, 2008).

A graphical overview of the worldwide status of MDG target 7.8 and 7.9 for the year 2004 is available at Figure 11, which shows that the lack of access to clean water remains a burden for the poorest countries, and Figure 12, where access to sanitation is a worrying situation for almost all developing countries (UNEP, 2008).

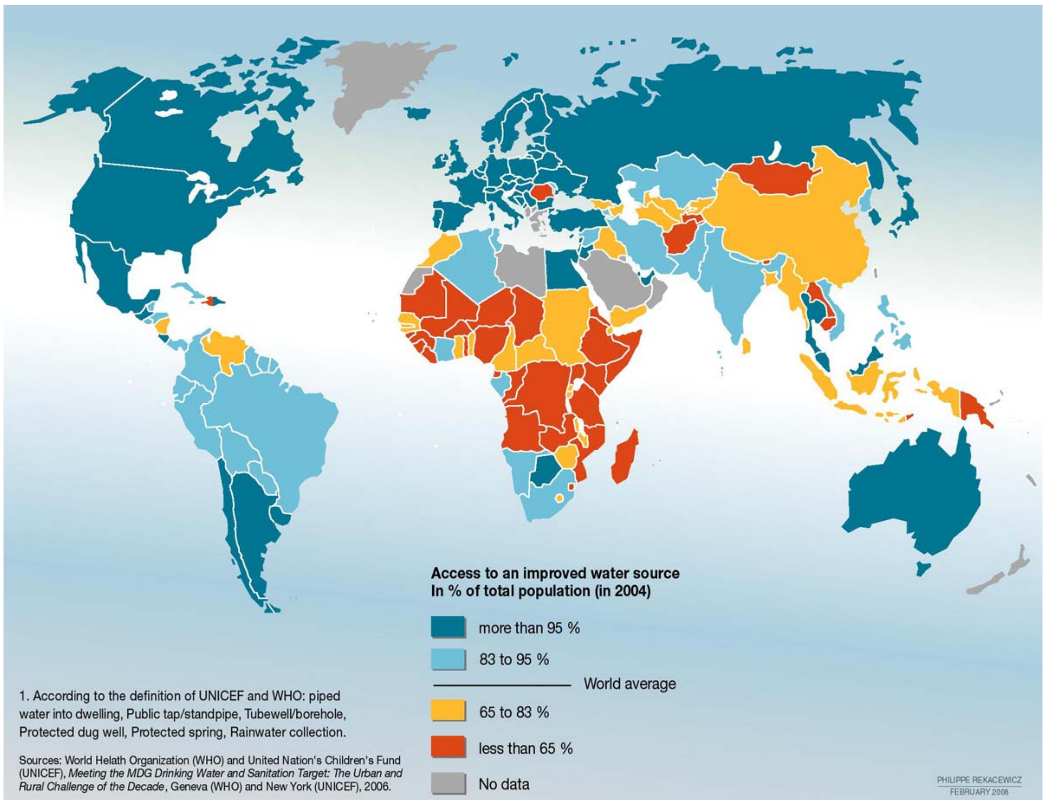

Figure 11: Access to an improved water source in % of total population in 2004 (WHO and UNICEF, 2006)

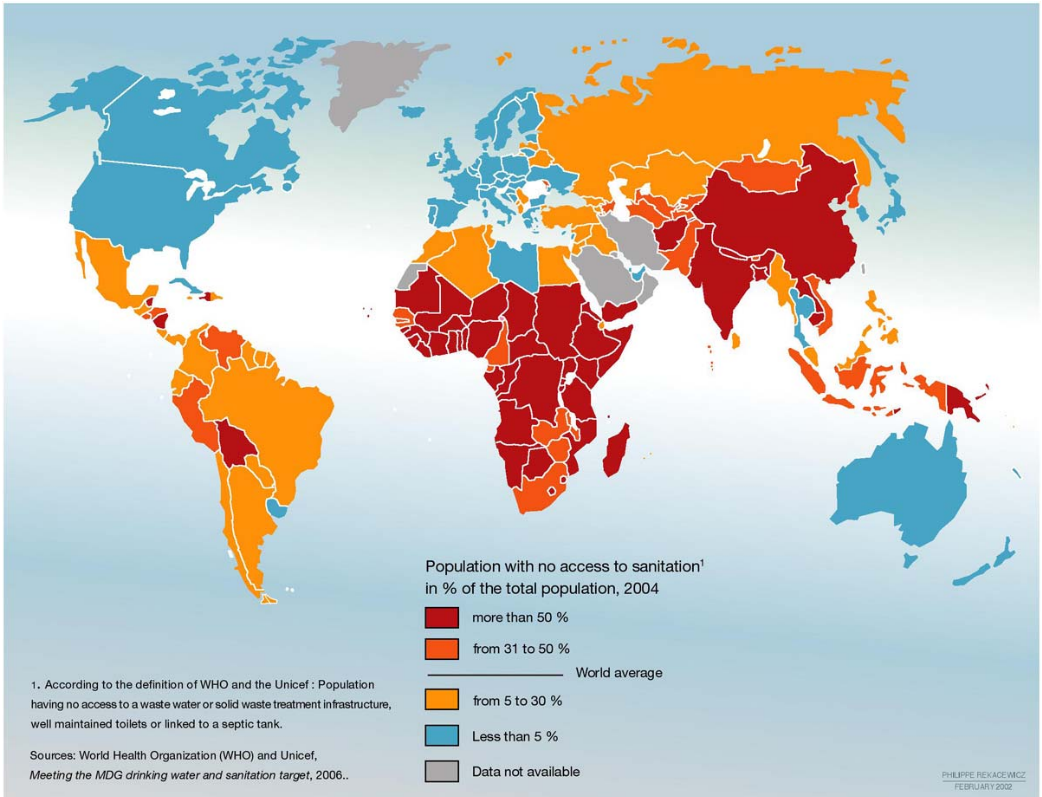

Figure 12: Population with no access to sanitation in % of total population in 2004 (WHO and UNICEF, 2006)

2.2.4 Water as a Human Right

Former UN Secretary General Kofi Annan highlights in the UN report *the right to water* that *"access to safe water is a fundamental human need and, therefore, a basic human right. Contaminated water jeopardizes both the physical and social health of all people. It is an affront to human dignity*" (WHO, 2003).

According to Article 25 of the Universal Declaration of Human Rights (1948) "*Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family*" (UN, 1948).

The right to water is not mentioned separately in the Universal Declaration of Human Rights, however Article 25 implicates health as a human right which includes health related aspects such as water, food, nutrition, housing, etc. (WHO, 2003).

Relating to this diverseness of aspects an important differentiation in water use should be made between the water needed for drinking water only, drinking water consumption, which includes hygienic use, and water for food production.

The relating amount of water needed per person and year lists as follows:

- 1 m^3 for drinking water only,
- 30 to 50 m^3 for drinking water consumption, including hygienic use, and
- at least 1000 m^3 for food production, which can increase substantially depending on the share of meat in the total food production (Kroiss, 2010a).

Access to water is essential to well being and health and might therefore be implicitly included in the declaration. Scanlon et al. (2004) are not satisfied with the including remark on water as an essential part of health and therefore being a human right. Consequently Scanlon et al. (2004) demand the recognition of water as a stand-alone human right. In line of argumentation are the facts that without water several fundamental rights could never be realized, such as right to life, food, self-determination, adequate standard of living, housing, education, etc. Furthermore, a legal right to water would acknowledge the environmental dimension and especially the water-related dimension of human rights. It would provide more effective protection of the valuable good and provide a legal framework to support a better and effective development of jurisprudence to further claim accountability of governments and responsible institutions (Scanlon et al., 2004).

In November 2006 the Human Rights Council of the United Nations by reaffirming the Universal Declaration of Human Rights decided to request the Office of the United Nations High Commissioner for Human Rights "*to conduct, within existing resources, a detailed study on the scope and content of the relevant human rights obligations related to equitable access to safe drinking water and sanitation under international human rights instruments*". This was formally handed in as decision 2/104 under the topic of Human rights and access to water. Till date there has not been an official adaptation to the Universal Declaration of Human Rights, nevertheless the procedural right to water is codified in several human rights and environmental instruments, as listed in Table 4 (OHCHR, 2006).

	Right to participation	Right to information	Right to effective remedy
Universal Declaration of Human Rights (1948)	Art. 21	Art. 19	Art. 8
American Declaration of the Rights and Duties of Man (1948)	Art. XX	Art. IV (freedom of expression)	Art. XVII
European Convention (1950)*		Art. 10	Art. 13
CERD (1965) **	Art. 5	Art. 5(d)(vii) (freedom of expression)	Art. 6
ICCPR (1966)***	Art. 25	Art. 19	Art. 2(3)
CEDAW (1979) ****	Art. 7	Art. 14(2)(b), 16(1)(e)	
African Charter on Human and People's Rights (1981)	Art. 13	Art. 9	Art. 7
World Charter for Nature (1982)	Art. 23	Art. 21(a)	Art. 23
Convention on the Rights of the Child (1990)	Art. 12	Art. 13	
Rio Declaration on Environment and Development (1992)	Pr. 10	Pr. 10	Pr. 13
Agenda 21 (1992)	Ch. 23	Ch. 8	Ch. 8.18
Draft Declaration of Principles on Human Rights and the Environment (1994)	Art. 18	Art. 15	Art. 20
IUCN Draft Covenant on Environment and Development (1995)	Art. 12(4)	Art. 12(3)	Art. 12(5)

* European Convention for the Protection of Human Rights and Fundamental Freedoms

** International Convention on the Elimination of All Forms of Racial Discrimination

*** International Covenant on Civil and Political Rights

**** Convention on the Elimination of all Forms of Discrimination against Women

Table 4: Procedural rights to water as codified in several human rights and environmental instruments (Scanlon et al., 2004)

2.2.5 Water conflicts

It is expected that in the timeframe from 2006 – 2020 certain migration and transmigration issues in the Euro-Mediterranean and North African region will gain on importance, based on water conflict and water cooperation scenarios.

An example of explosive nature might be that until 2050 a water conflict, and in an extreme case a war on water, between Egypt and certain states along the Nile can not be excluded, if the water supply for Egypt might be significantly reduced due to actions from upstream countries making use of the Nile as well. (Brauch, 2007)

In a study about the destabilization and conflict potential due to prognosticated environmental changes in the region of South Eastern Europe and North Africa the following ten scenarios were ranked highest, of which many are directly or indirectly linked to a secure water supply:

- Desperation and survival
- Migration
- Protest and civil war
- Transmigration
- Diaspora
- Combating desertification
- Response on catastrophes / disasters
- Solutions to local water and soil utilization
- Water conflict and water cooperation in along the Nile
- Conflict in Euro-Mediterranean migration (Brauch, 2007)

The Oregon State University has compiled data for all water related conflicts that occurred globally since the 1960s and has found 37 cases of reported violence between states over water, of which 30 cases were happening in the Middle East, and more than 500 cases of water conflict events in the public. Within the same timeframe over 200 water treaties were negotiated between countries (UNEP, 2008).

According to Wolf (2006) the majority of water conflicts occurring during this duration were related to changes in the volume of water flow, followed by disputes over water infrastructure, such as dams and canals. Water quality was only accountable for about 5% of all conflict events analyzed (UNEP, 2008).

3 METHODS OF DESALINATION

In this chapter first an overview of different desalination methods is given, with a focus on the most wide-spread methods. The existing methods are analyzed to provide an overview, however, only the main desalination methods will be discussed in detail within this thesis.

The availability and provision of good quality water is a big concern for many authorities on local, regional and national level, which forms a world-wide crisis, despite the vast amount of water present on Earth. To counteract this situation, Mathioulakis (2006) refers to the application of water cleaning methods, or desalination of seawater or brackish water (Mathioulakis, 2006).

3.1 Definition

Williams (2001) defines desalination as "*the purification of brackish (slightly salty) or salty water by the removal of dissolved salts by processes such as distillation, reverse osmosis, deionization, electrodialysis or freezing*" (William, 2001).

Reviewing the possible solutions to counteract the depletion of fresh water Withgott et al. (2008) address solutions to regulate supply and demand amongst others and also mentions *"another supply-side strategy … to develop technologies to find or 'make' more water"* (Withgott et al., 2008). Desalination is seen as the best-known technological approach to increase supply of fresh water, by removing salt from seawater or other water of marginal quality (Withgott et al., 2008).

3.2 Principle of Desalination

Desalination plants have in common that they separate saline water into two water streams, namely the:

- fresh water, with a low concentration of dissolved salts, and
- the concentrate, also called brine stream, which is containing the dissolved salts (Western Australia Water Corporation, 2006).

Figure 13 shows a simplified diagram of a desalination process, where the fresh water is indicated as *pure water* and the concentrate is indicated as *salt water*.

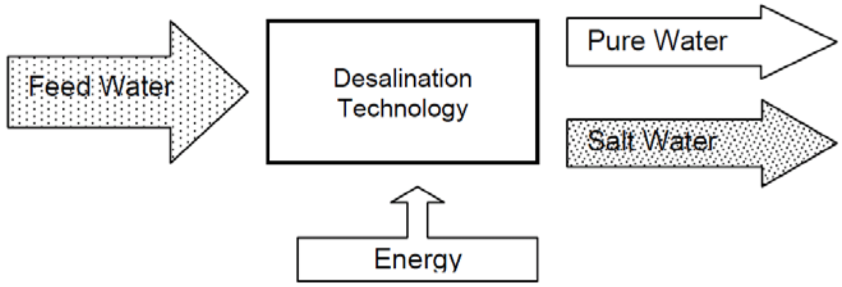

Figure 13: Desalination Process Diagram (Green and Schwarz, 2001)

All desalination processes have in common that they need energy to operate, as displayed in Figure 13, however can be operated by a number of different technologies separating the saline water. As those technologies evolve, desalination is becoming a more economically viable option for many countries. It offers different possibilities depending on the chosen output, from drinking water provision for small island communities to substantial water supply for large cities or even for irrigation, like being used in parts of Spain and the United Arab Emirates (Western Australia Water Corporation, 2006).

Former US president John F. Kennedy (1961) emphasized already the importance of desalination, by stating that "*if we could ever competitively, at a cheap rate, get fresh water from salt water, then it would be in the long-range interests of humanity, which would really dwarf any other scientific accomplishments*" (Kennedy, 1961).

According to Gleick et al. (2006) "*there is no best method of desalination*" (Gleick et al., 2006), as there is a wide variety of technologies providing effective removal of salts from water. Conclusively, the choice for a certain process depends on:

- site-specific conditions (e.g. salt content, source of water, energy sources)
- economics
- quality demanded from end user
- local engineering and skills (Gleick et al., 2006).

These main processes can be divided into two groups:

- thermal or distillation process, see chapter 3.4, and
- membrane or filtration process, see chapter 3.5 (Gleick et al., 2006).

All commercial desalination methods require a physical/chemical pre-treatment of raw seawater to avoid scaling, foaming, corrosion, biological growth, and fouling. They also require a chemical post-treatment (Kalogirou, 2008).

3.3 Overview of desalination methods

An overview of desalination methods is given in Table 5, featuring the most frequently used kinds of desalination.

Technology	Description	Characteristics
Multiple Stage Flash (MSF)	Heated water is fed into low-pressure vessel, where water *flashes* into vapor, which condensates and is collected as pure water. Heat from condensing vapor is captured and used to heat up feed water.	Uses heat. Suitable for medium to large-scale application.
Multiple Effect Distillation (MED)	Water is heated until boiling and vapor collected as pure water. Heat from condensation is captured to supply heat for next stages.	Uses heat. Suitable for medium to large-scale application.
Solar Stills	Temperature of salt water is elevated by the use of solar energy, which enhances evaporation. Condensate is captured as pure water.	Uses solar energy / heat. Simple and independent set-up. Appropriate for small-scale application.
Vapor Compression (VD)	Water vapor gets compressed to cause condensation as pure water. The heat from condensation is used to heat feed water and generate vapor.	Uses electricity. Simple and reliable operation makes it attractive to small to medium scale application.
Electro Dialysis (ED)	Salt is forced through membrane by electric current, thus it gets separated from the feed water.	Uses electricity. Generally only used for brackish water.
Reverse Osmosis (RO)	Pure water is forced through membrane, thus it gets separated from the feed water.	Uses electricity. Appropriate for any scale.

Table 5: Major Desalination Technologies (Green and Schwarz, 2001)

3.4 Thermal Process: Distillation

The method of the thermal process, or distillation, mimics the natural water cycle, see chapter 2.1.2, by hastening evaporation of the seawater by heat and afterwards condensing the water vapor again (Withgott, 2008). It is identifiable that during evaporation of sea water only the fresh water vapor and other volatile compounds enter the atmosphere, whereas minerals, mainly salts in this case, and other impurities stay behind in the ocean. These build-ups of minerals have made the oceans salty, over time (Vigil, 2003). Hereby, the water cycle uses energy from the sun to naturally remove salt from seawater, constantly feeding back fresh water to rivers and lakes (Glanville, 2008).

In the simplest approach of distillation water is heated under atmospheric pressure to its boiling point at 100°C. When making use of using vacuum distillation at less than atmospheric pressure the boiling point of water can be reduced, relating to the ideal gas equation ($pV = nRT$). On account of the reduced temperature energy is saved. While reducing the pressure to 25% of normal pressure, water will boil at 65°C, and at 10% of normal pressure even at 45°C. This fact is also made use of during multiple boiling, where a series of vessels are operated successively at lower temperatures and lower pressures. The process of multi-stage flash distillation, see chapter 03.4.1., is the most common thermal desalination process, using this principle. Also multiple-effect distillation and vapor-compression distillation are methods of distillation (Gleick et al., 2006).

3.4.1 Multi-stage flash distillation (MSF)

The greatest amount of thermal distillation capacity worldwide are multi-stage flash distillation plants, which can produce high quality fresh water with salt contents below 10 ppm, even from saline water with concentrations up to 70,000 ppm total dissolved solids. This is about double the amount that average seawater would have, as compared in Table 2 (Gleick et al., 2006). During the MSF process heated seawater flows as a stream through the bottom of a vessel containing up to 40 evaporation chambers, each of which featuring a slightly lower pressure than the previous one. Because of the lowered pressure the heated seawater starts boiling immediately when entering each new stage and therefore being vaporized into steam, also called *to flash* into steam, as represented in Figure 14 (WHO, 2006). The evaporation occurs from the bulk liquid and not on a heat-exchange surface, like with some similar distillation methods, e.g. Multiple-Effect Distillation, hence scale is limited and makes MSF an attractive option (Birkett, 1999).

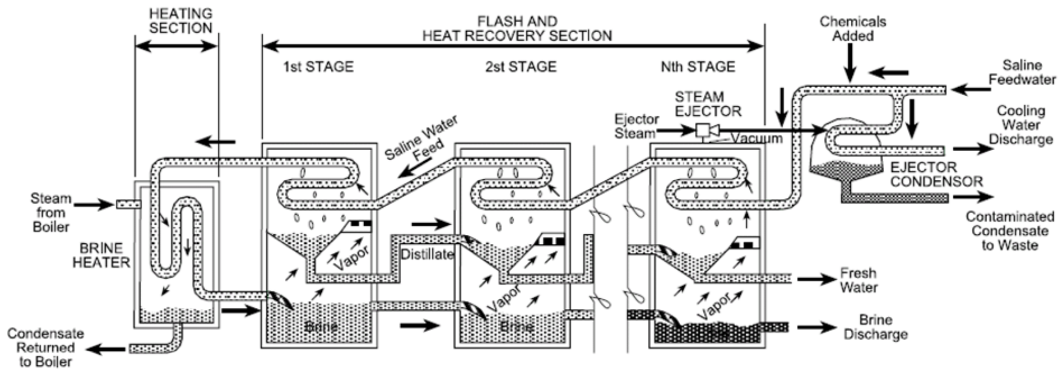

Figure 14: Diagram of a Multi-stage flash plant (USAID, n.d.)

3.4.2 Multiple-effect distillation (MED)

Similar to Multi Stage Flash distillation the process of Multiple-effect distillation occurs in a series of steps, in this case called *effects*. Each consecutive effect operates at a lower pressure and temperature than the one before, to facilitate further vaporization (Buros, 2000). The feed water is heated by steam from a boiler and a part of the feed water vaporizes in each effect, before the remainder is passing to the next effect (Green and Schwarz, 2001). This arrangement can be observed in Figure 15.

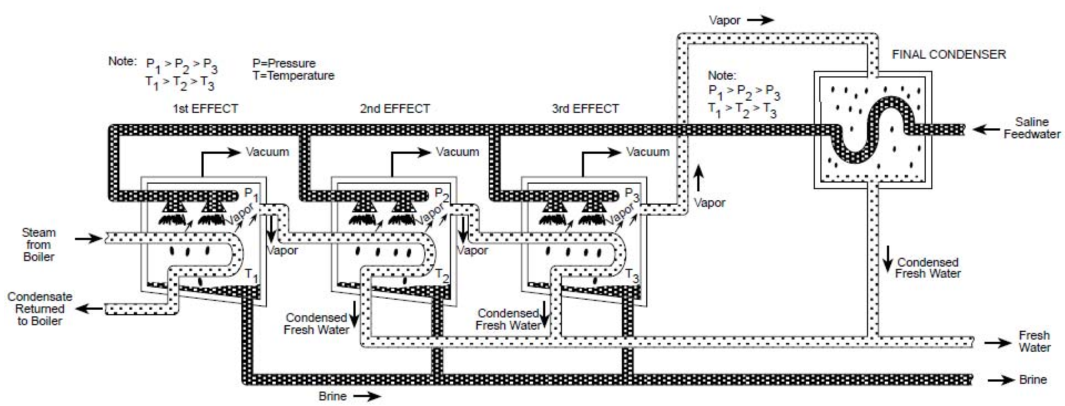

Figure 15: Diagram of a Multiple-effect distillation plant with horizontal tubes (USAID, n. d.)

A number of early desalination plants practiced the MED method, but MSF units took over, because of better performance against scaling, which is still one of the main problems with MED plants. However, as progress is made about minimizing scaling and corrosion, interest in the MED process might be revived (Buros, 2000).

Given that MED plants are large and complex they have the disadvantage that they require skilled operation and maintenance (Green and Schwarz, 2001).

3.4.3 Vapor-compression distillation (VC)

In the method of vapor-compression distillation water vapor is compressed by the use of a compressor and this high-pressure vapor is consequently condensed into pure water while the heat released is used for vaporization of additional water. An important advantage of VC applications is that the do not need a heat source and can operate with solely electrical or mechanical energy, as the mechanical compressor usually is electrical or diesel driven. Correspondingly the process has a high reliability and relative simplicity and is favored for small and medium applications (Green and Schwarz, 2001). If used in large scale application VC is usually combined with other processes as MED.

To run the VC process steam ejectors and mechanical compressors are used in the compression cycle, as indicated in Figure 16 (Buros, 2000).

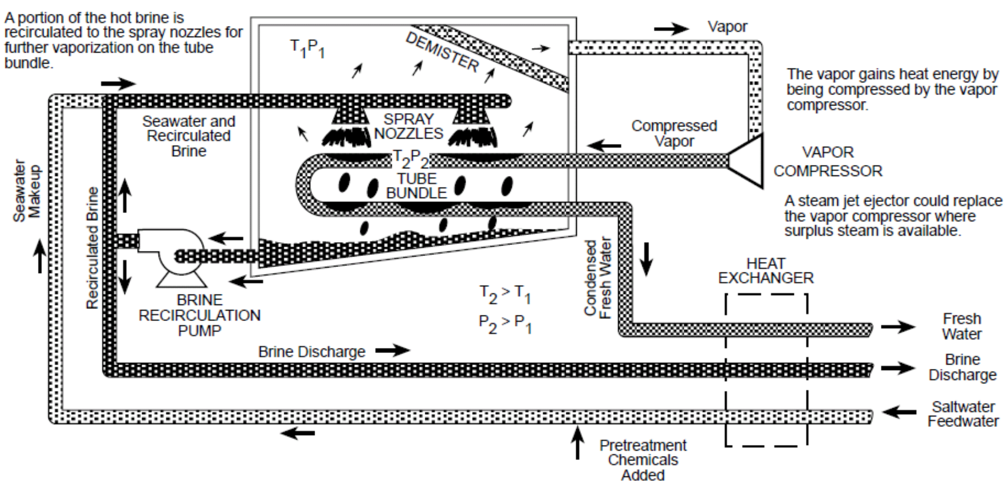

Figure 16: Diagram of a mechanical vapor compression unit (USAID, n.d.)

3.5 Membrane processes: Filtration

In nature, the separation of salts is regulated by membranes, e.g. in the process of dialysis and osmosis, which occurs in the human body (Buros, 2000).

In desalination, membrane or filtration technologies involve forcing of water through membranes to filter out salt and certain other impurities. The most common type of this approach is reverse osmosis, see chapter 3.5.2 (Withgott, 2008), with electrodialysis, see chapter 3.5.3, being the second commercially important desalting process (Buros, 2000).

Each of those two processes uses membranes with the ability to differentiate and selectively separate saline water into fresh water and condensate, see Figure 20.

No heating is necessary for membrane processes, however the pressurization of the feed water is energy intensive (Western Australia Water Corporation, 2006).

3.5.1 Membrane processes in brackish water desalination

Both, the reverse osmosis and electrodialysis process, are more effective with brackish water and also waste water, as the energy required depends on the salinity of the feed water (Buros, 2000). Consideration about the context of use of brackish water desalination shall be stated by the following example. Kroiss (2010) notes that desalination of brackish water causing sea water intrusion to the ground water normally results in an increase of the salinity of the brackish water as it contributes to lower the ground water level, naming the Gaza Strip as example (Kroiss, 2010b). Abu-Maila and Abu-Maila (1991) stated already more than 20 years ago that the water deficiency in the Gaza Strip is significant and can not be made up from local supplies. Salinity of the aquifer in Gaza Strip increases with depth and over-pumping means that seawater intrusion into the aquifer is significant (Abu-Maila and Abu-Maila, 1999). Nowadays the use of about 40 brackish water desalination plants accelerate the intrusion of sea water into the aquifer, with the result that most of the water wells in Gaza Strip have high salinity, some areas reaching a chloride average from more than 500 mg/L up to 2,500 mg/L (Ahmed, 2007). In such cases it is at least more sustainable to desalinate sea water directly and use well treated waste water, which has a comparatively low salinity, to replenish the ground water. However, if brackish ground water is caused by the contact of the ground water with soluble material in the soil, the previous arguments do not apply (Kroiss, 2010b).

3.5.2 Reverse Osmosis (RO)

Osmosis is a process where a substance is passing through a membrane from the side of a lower concentration to the side of higher concentration of a given solution, see Figure 17.

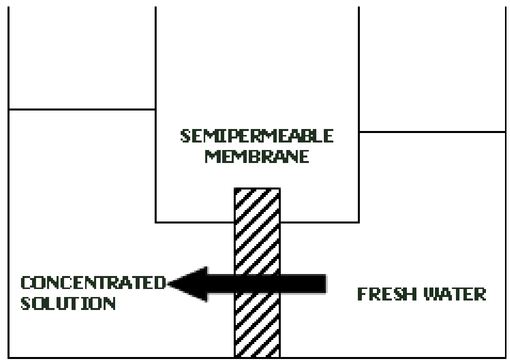

Figure 17: Osmosis: Normal flow from low to high concentration (Applied Membranes, 2007)

In a reverse osmosis (RO) process the solvent's movement is in the opposite direction as during osmosis, which means that the solvent molecules (water) move though a semi-permeable membrane from the area of a higher concentration to the side of a lower concentration, as shown in Figure 18. This can only be achieved by applying a pressure that is greater than the osmotic pressure to the side of the solution.

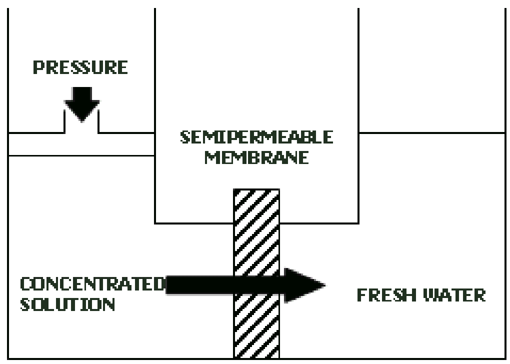

Figure 18: Reverse Osmosis: Flow reversed by application of pressure to high concentration solution (Applied Membranes, 2007)

Applying such pressure is an energy intensive process and the energy requirements are depending on the concentration of salts in the feed-water (Williams, 2001). However, compared with thermal distillation processes, reverse osmosis has the advantages of using less energy and also has lower investment costs, amongst a high share of recovered product water with up to 55% and the modularity of the systems (Teplitz-Sembitzky, 2000). There is no heating phase necessary for this kind of desalination and the major energy requirement comes from pressurizing the feed water (Buros, 2000).

Yet, there are the disadvantages of membranes that they are sensitive to scaling and fouling and that the process can face high costs for maintenance and repair. Thus, there is a risk of disruption in the water supply and lower product water quality (Teplitz-Sembitzky, 2000). The process of reverse osmosis is accountable for the majority of global desalination capacity, as shown in Figure 22, and the basic components of a reverse osmosis plant are shown in Figure 19 below.

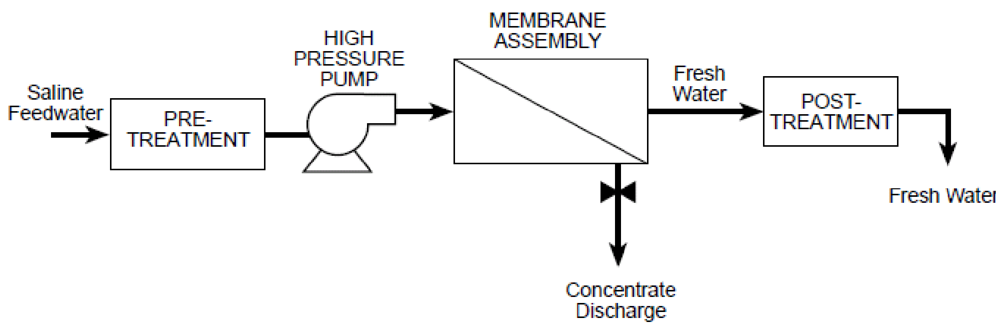

Figure 19: Basic components of a reverse osmosis plant (USAID, n.d.)

According to Gary Crisp, an engineer for the Water Corporation of Western Australia, seawater reverse osmosis has matured into a viable alternative to thermal desalination during the last ten years until 2007 (Schirber, 2007).

Glanville (2008) is reworking the ideal gas equation (PV = nRT) to calculate that the osmotic pressure for seawater with a nominal salt concentration of 3.5% is around 30 bar. This must be overcome to be able to push seawater through a reverse osmosis membrane, thus typical pump pressures to operate reverse osmosis desalination plants range from 55 to 81 bar (Glanville, 2008).

3.5.3 Electrodialysis (ED)

In the process of Electrodialysis an electric current forces dissolved salts through membranes, which keeps the salt stream separated from the product water. This membrane process directs the flow opposite to reverse osmosis, as shown in Figure 20. Pretreatment of the feed water is needed to that extend that small debris must be filtered out to avoid clogging of the membrane (Green and Schwarz, 2001).

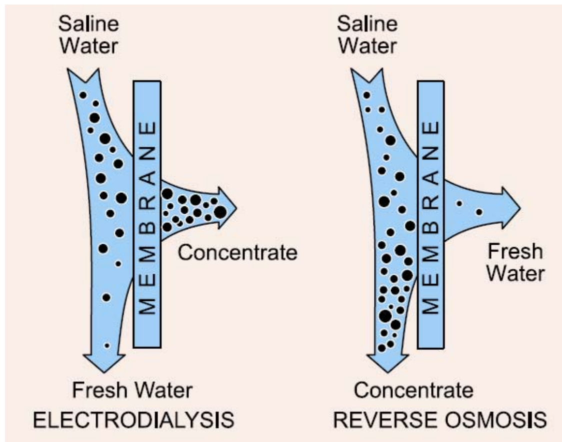

Figure 20: Comparison of electrodialysis and reverse osmosis (Buros, 2000)

The ED process makes use of the following principles to operate:
Most salts get ionic, when dissolved in water, being positively charged as cations, or negatively charged as anions. The cations will migrate to the anode, while the anions will migrate to the cathode. Importantly ED membranes can be constructed to permit selective passing of either one of those ions (Buros, 2000). A schematic overview of the components of an ED plant is provided in Figure 21.

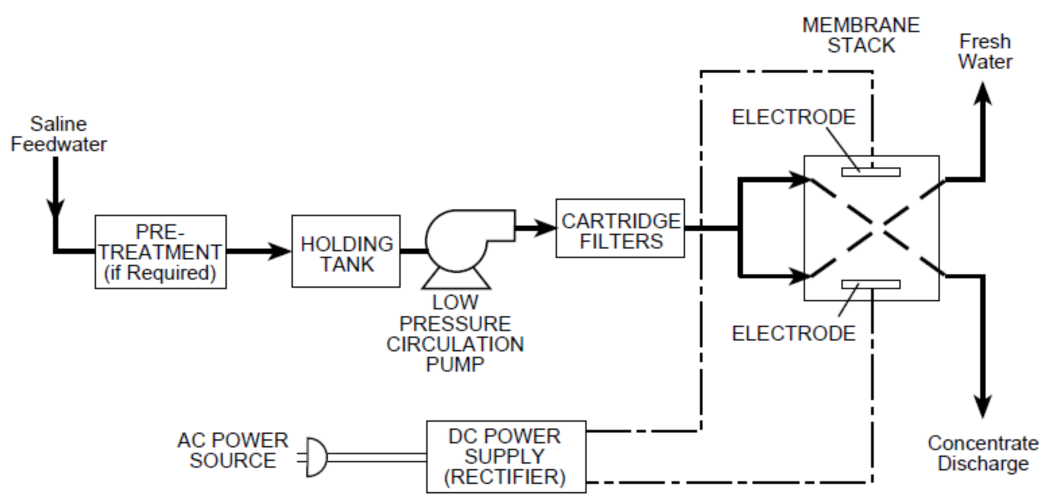

Figure 21: Components of an electrodialysis plant (USAID, n.d.)

3.6 Other desalination methods

Saline water can be desalinated in a range of different processes, including membrane distillation, ion-exchange resins, and freezing, as presented below. None of these methods has gained much commercial success, accounting together for less than 5% of global capacity, as shown in Figure 22. However, some of these options can be beneficial in certain cases, or even preferable (Gleick, 2006).

3.6.1 Membrane Distillation (MD)

The membrane distillation (MD) process combines the use of distillation and membranes. Essentially, saline water is heated up to facilitate the production vapor, which is exposed to a membrane, which passes water vapor, but not water in liquid form. On the other side of the membrane the water vapor condensates on a cooler surface and accumulates as fresh water (Buros, 2000).

Membrane distillation was introduced commercially in the 1980s, thus so far, has only been realized in a few places, as this method needs more space and more pumping energy per unit of product water, as the main desalination methods. However, Gleick (2006) sees also advantages to this process, like its simplicity and the requirement for only small temperature differentials to operate. A probably good application for the membrane distillation method could be where inexpensive low-grade thermal energy is available, e.g. from solar collectors or close-by industry, which could hold future potential for this process (Gleick, 2006).

3.6.2 Ion exchange

In the Ion exchange method resins are used to remove ions from the feed water. Those resins are comparatively expensive and the higher the concentration of dissolved solids, e.g. salts, the more often they need to get regenerated and changed, which makes this process economically not feasible compared with other applications, like RO and ED. However, for lower concentrations of salinity such systems could prove effective, e.g. when applying a final treatment to waters being processed with RO or ED beforehand (Birkett, 1999).

3.6.3 Freezing

When ice crystals are forming, dissolved salts are naturally excluded from the ice formation, therefore also cooling saline water to form ice crystals can be used to perform desalination, simply by melting the frozen water again.

The advantages of desalination by freezing are a lower theoretical energy requirement for single stage operations, reduced corrosion potential and less scaling problems. The disadvantages however include that ice is mechanically difficult to handle, move and process (Buros, 2000).

3.7 Worldwide capacity and plants

With an increase of 6.6 million m³/d within one year, the global desalination market has grown at a record rate, totaling at a capacity of 59.9 million m³/d at the end of 2009. This was the biggest rise in a single year that the worldwide desalination capacity experienced, which was made possible due to 700 new plants that were going online, including the largest in the world, the 880,000m³/d Shoaiba III project in the Kingdom of Saudi Arabia. At the end of 2009 there were 14,451 desalination plant installed (WaterWorld, 2009), showing a significant rise from 13,000 desalination plants at the beginning of 2008 (Kranhold, 2008), with a further 244 plants being contracted or under construction (WaterWorld, 2009). Those installed plants are located in a total of 155 countries all around the globe, with the biggest number of plants installed in the Kingdom of Saudi Arabia, the United States of America and the United Arab Emirates, as displayed in Figure 23 (International Desalination Association, 2006).

All desalination methods presented in chapter 3 have a respective worldwide desalination capacity as indicated in Figure 22 below.

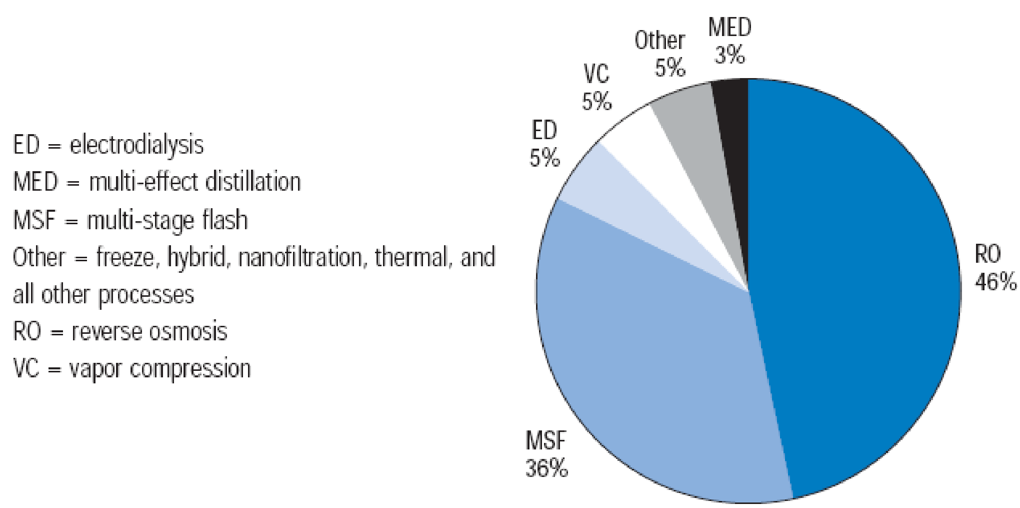

Figure 22: Global desalination capacity by process (Wangnick/GWI 2005)

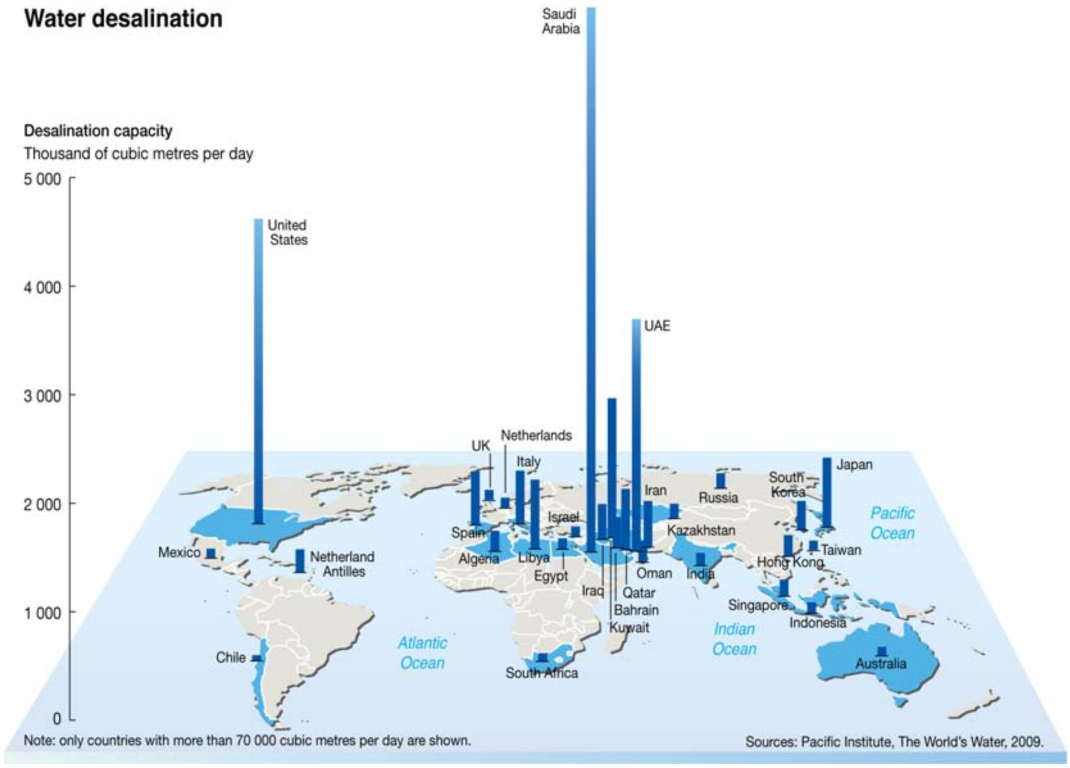

Figure 23: Water desalination capacity worldwide (Gleick et al., 2009)

The worldwide desalination capacity by source water is presented in Table 6 below.

Water source	Share of worldwide installed capacity [%]
Seawater	56
Brackish	24
River	9
Waste water	6
Pure	5
Brine	< 1

Table 6: Global desalination capacity by source water (Wangnick/GWI, 2005)

4 POTENTIAL OF DESALINATION AS SOLUTION TO THE GLOBAL WATER CRISIS

In this chapter the potentials of desalination as solution to the worldwide water crisis are considered. Needed technological improvements to advance the global desalination processes are discussed. In chapter 3 an overview of the worldwide capacity of desalination is stated, which is now followed by scenarios to show the potential of desalination in combination with renewable technologies to establish their sustainable share in the global framework.

Further a cost comparison of various desalination methods is stated and finally the advantages and disadvantages of desalination are highlighted, including costs, energy demand, environmental considerations and health concerns.

4.1 Technological improvements

Commercial competition, urgency to reduce costs and advances in technology have triggered that the options available for the desalination of saline water continue to improve (National Academy of Sciences, 2004).

According to Kranhold (2008) Southern California water officials observed that conditions have changed and confirmed that improved technology is making desalination more competitive, since cost have been cut by half during the past decade, however further improvements are necessary to promote further applications of desalination (Kranhold, 2008).

Recent reviews recommend that research shall focus on several areas, including the overview stated below (National Academy of Sciences, 2004):

Water quality sensor development: Better sensors that are able to perform a fast and inexpensive water quality analysis and that can identify pathogens are needed, in order to have a more effective application of filters and chemicals and thus reduce membrane fouling. Such improvements would be beneficial to all desalination methods, as those sensors would allow more effective post treatment (National Academy of Sciences, 2004).

Improved filtration: Such filters as nanofiltration and ultrafiltration membranes can be used as pretreatment steps for both membrane and distillation systems, as they can remove compounds in the feed water, thus increasing overall productivity (National Academy of Sciences, 2004).

Improved heat-transfer materials: Heat-transfer surfaces are often fabricated of expensive corrosion-resistant materials, e.g. titanium or high-grade steel. Additional research is required to provide reliable and effective surfaces from non-metallic or polymeric materials, which could reduce capital costs (National Academy of Sciences, 2004).

Improved intake methods: Many current intake methods, especially for large desalination plants, impinge seriously on marine life and improved intake methods shall lower this impact (National Academy of Sciences, 2004).

Membrane integrity improvements: Mechanical damage from sediments, as well as oxidation by chlorine or metals are some of the main reasons that could cause failures, which are expensive outages and could also allow pathogens or contaminants to impair the water quality. This could be prevented by better durability and integrity of membranes and would increase system performance and thus reduce costs. Additionally, membrane selectivity could increase the flexibility of a system, through membranes that are capable of removing specific containments selectively (National Academy of Sciences, 2004).

Reduced scaling: Mainly thermal desalination processes are often affected by scaling that is formed by substances like carbonates and sulfates, when they precipitate out of solution. The formation of gypsum is one of the main concerns, which can form from aquatic solutions when 95°C are approached and as a consequence can coat surfaces like pipes and tubes. As a result of scaling the effectiveness of desalination processes is reduced, by restricted flow, reduced heat transfer, and coated membrane surfaces. Essentially scaling is difficult to remove and increases costs. The most adaptable way to reduce the formation of scale is to keep temperatures, thus the boiling point, low (Gleick, 2006). Other means of reducing scaling is to introduce additives that inhibit crystal growth, reduce salt concentrations in the feed water, use seeding to form particles, or to remove the scale forming particles in pretreatment. Once scale has formed it need to be removed by chemical or mechanical means (BKG, n.d.).

Reduced membrane fouling: Organic and inorganic materials can cause fouling of the membranes, which reduces membrane life and permeability. Both cause an increase of the overall costs. Currently efforts to limit fouling include pretreatment of source water, addition of membrane-cleaning chemicals and operational adjustments, which are all costly and innovations in this area are still needed. However, due to the wide variety of feed water qualities it is a hard task to achieve complete resistance to fouling (National Academy of Sciences, 2004). Wherever water even with very low concentrations of organic or inorganic impurities gets into contact with a surface, this will result in the formation of a biofilm, caused by autotrophic and/or heterotrophic bacteria. Biofilm control is therefore one of the mayor challenged using membranes and also a problem with all surfaces in contact with water of nearly any quality and will probably remain a basic problem for all kinds of desalination processes as this is a natural phenomenon (Kroiss, 2010b).

4.2 Desalination by using renewable energy sources

Most of the seawater desalination plants in operation are large centralized or dual-purpose applications, mainly located in the arid and semi-arid regions of the Middle East and the Mediterranean. Such plants are more economical and well suitable for high density population areas, however largely ignoring small poorer communities in less densely populated areas. Those areas do not only lack the access to fresh water, but also in most cases electrical power grid connections or easy access to fossil fuels as well, which leaves renewable energy desalination as a promising solution for fresh water provisioning in such cases to alleviate drinking water shortage (Mathioulakis, 2006).

Until now, alternative energies, such as solar, wind, geothermal and tidal energy have only played a minor role in saline water desalination (Teplitz-Sembitzky, 2000). The present situation does not reflect the obvious advantages of combining renewable energy use and clean fresh water supply through desalination in arid areas, thus such combinations only represent 0.02% of the total desalination capacity installed worldwide in 2006, yet showing an increasing trend (Mathioulakis, 2006).

Possible energy sources for overcoming the power needs for low entropy power from fossil fuel of desalination by using renewable energy sources as shown in Table 7 below.

Energy type	Heat energy	Electric energy
Energy source	Fossil fuel Waste process heat Renewable energy (solar)	Fossil fuel Renewable Energy (Solar, Wind)
Desalination technology	MSF MED Solar Still	VC ED RO

Table 7: Possible energy sources for various desalination technologies (Green and Schwarz, 2001)

The reverse osmosis process is clearly leading amongst all renewable energy driven desalination processes, as displayed in Figure 24.

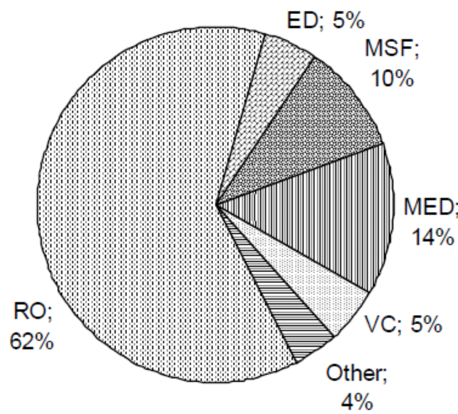

Figure 24: Renewable energy-driven desalination by processes (Mathioulakis, 2006)

The sun is clearly the most important source for renewable energy fueled desalination as solar photovoltaic applications together with solar thermal applications provide 70% of all energy supply, as displayed in Figure 25.

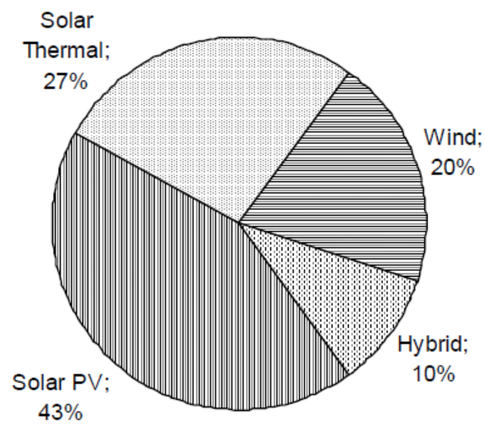

Figure 25: Renewable energy-driven desalination by energy sources (Mathioulakis, 2006)

4.2.1 Solar thermal desalination

The method of solar energy within thermal desalination processes is one of the most promising applications of renewable energies in desalination.

There are two main types of solar desalination processes: direct and indirect collection systems. While the direct method uses solar radiation to produce distillate directly in the collector (e.g. simple solar stills), the indirect collection systems uses two sub-systems, where one is employed for solar energy collection and the other one for the desalination process, e.g. distillation applications using solar collectors or membrane methods using photovoltaic cells and/or solar collectors (Qiblawey and Banat, 2006).

Two of the most promising solar thermal desalination applications are elaborated below: solar stills and solar humidification-dehumidification.

4.2.1.1 Solar stills

Solar still distillations have a very simple structure and solely need for operation the heat of the sun and periodically human labor to refill the salt water, which evaporates from a basin below a clear glass or plastic cover and condenses on this area, before dripping into a pure water collection area at the edges of the application, as shown in Figure 26. In areas with a strong radiation of the sun simple solar stills have proven to produce 2 to 3 L/day of each m^2 of cover area, which sums up to roughly 1 m^3 per year. Despite continuous labor requirements, the independent and simple operation of solar stills makes them a good choice for small-scale, remote installations, with high water transportation costs and unreliable water supply adding to the attractiveness of solar stills (Green and Schwarz, 2001).

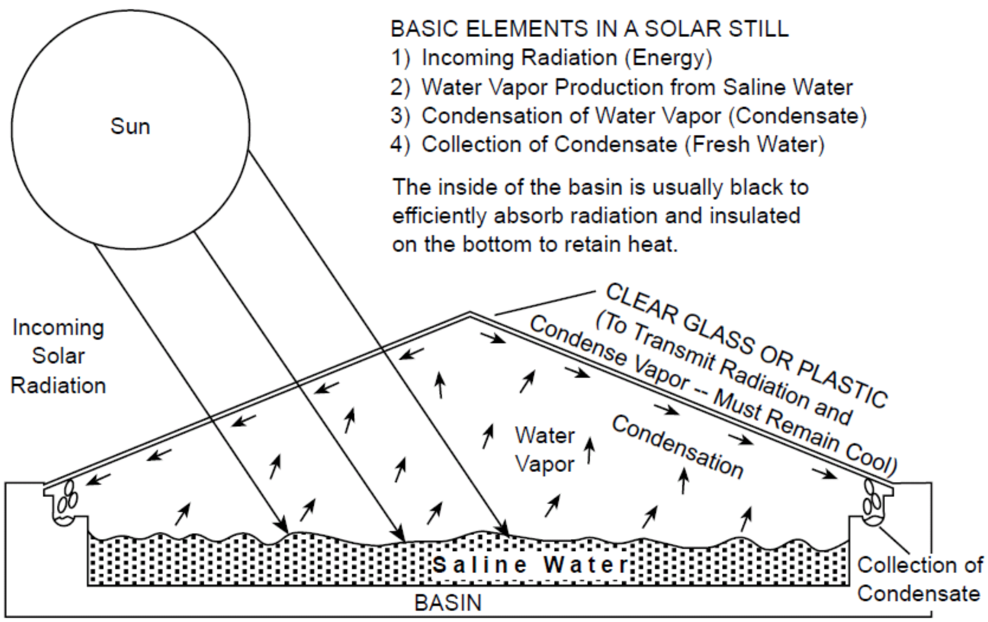

Figure 26: Diagram of a solar still (USAID, n.d.)

Green and Schwarz (2001) summarizes the conditions favoring solar stills as follows: (Green and Schwarz, 2001)

- Salt water is available and other sources are fully exploited,
- Daily water need is only a few m^3,
- Strong sun radiation,
- Unreliable and/or expensive fuel supply,
- Rainwater catchments are impractical (e.g. rainfall less than 500 mm/year),
- Water transportation costs higher than 10 USD/m^3 (Green and Schwarz, 2001).

4.2.1.2 Solar Humidification-Dehumidification

In the humidification-Dehumidification process air is used as a working fluid and therefore possible corrosion or scaling is reduced. This application operates according to the principles of mass diffusion utilizing dry air to evaporate saline water, thus humidifying the air, which can be mixed with significant quantities of vapor. While dehumidifying again, fresh water is produced by condensing the water vapor (Qiblawey and Banat, 2006).

Since a couple of years a new method of desalination gets to the attention of experts. This method is called **Multiple Effect Humidification Dehumidification (MEH)** and makes use of natural convection as a transport mechanism, humidifying the airflow in the evaporator, and then dehumidifying it in the condenser. Ultimately water evaporates and condensates highly efficient within a thermally insulated box. As the system operates at ambient pressure and at temperatures below boiling point the heat and mass transport coefficients are reduced. This is compensated by the use of enlarged surface areas and compressed alignment of the exchange surfaces (Müller-Holst, 2002). A simplified reproduction of this application is given in Figure 27, where saline water is evaporated through solar heat and the produced humidity condensates accordingly. Most of the heat used for evaporation is regained during the condensation as the feed water is preheated (MAGE, 2010).

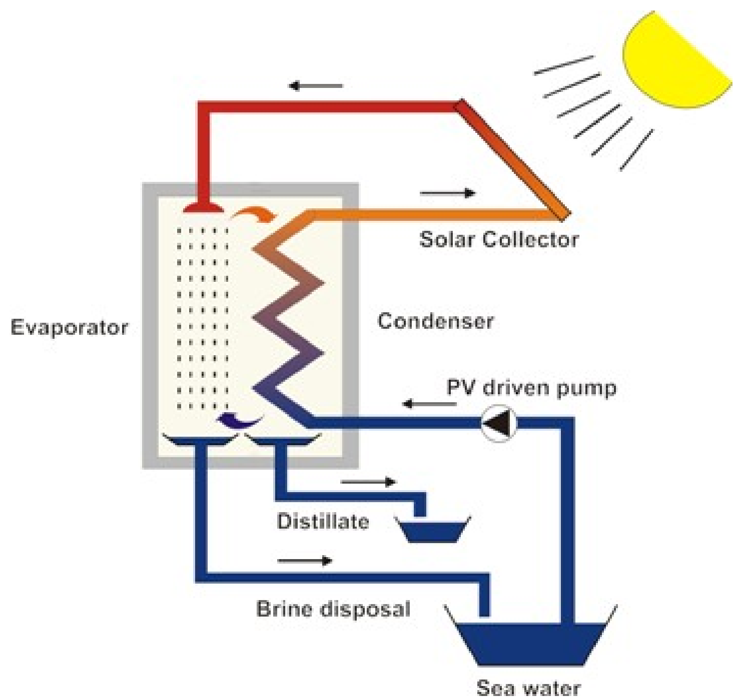

Figure 27: MEH system using solar energy (MAGE, 2010)

4.2.2 Power generation with renewable energies

Instead of using solar energy directly for the thermal process, renewable sources of energy can also be used as power generation for desalination plants, with reverse osmosis being the favorable option. Wind and solar energy have the biggest potential to power RO-plants, while geothermal projects are only suitable for very limited locations, as well as tidal power generation, which is negligible (Teplitz-Sembitzky, 2000).

Teplitz-Sembitzky (2000) states the following two major problems, when considering renewable energies to operate desalination plants are that the costs for power generation from renewable energy sources are relatively high compare with traditional sources, and that wind as well as solar radiation are intermittent sources of energy, while the operation of RO-plants demands the supply of a constant load. A fluctuating load might cause plant components to wear out and more precisely would severely reduce the membrane's life-span, while a constant power supply from renewable energies would demand an energy storage or back-up system, adding extra costs to the project (Teplitz-Sembitzky, 2000).

4.3 Cost statement of desalination methods

Like in almost all undertakings in the industrialized world economics is one of the most important factors determining the ultimate success of a project, similarly economics is determining the extend of desalination (Gleick et al., 2006).

4.3.1 Energy costs

According to research done by Gleick et al. (2006) it is unlikely that the cost of water production through desalination in California will fall below the range of 0.79 to 0.92 USD/m^3 in the foreseeable future, even for large, efficient plants. Similar applies on a world-wide scale (Gleick et al., 2006).

According to Chaudhry (2003) energy is the largest single cost for operating a desalination plant, contributing from on third up to more than one half of the total cost of desalinated water (Chaudhry, 2003).

Referring to USBR and SNL (2003) electrical energy accounts for 44% of the typical costs for a reverse osmosis plant, see Figure 28 (USBR and SNL, 2003). Wangnick (2002) states that thermal plants use even more energy, with an average share of 50% thermal energy and 9% of electrical energy of their total cost distribution, see Figure 29 (Wangnick, 2002).

Taking these percentages into consideration an exemplary increase in energy costs of 25% would result in an increase of the produced water by 11% for RO plants and even 15% for thermal plants respectively. Accordingly the share of desalination costs related to energy will rise as energy prices rise, unless there will be improvements to greatly reduce to actual energy need in desalination (Gleick et al., 2006). The National Academy of Science (2004) states that there is still potential to reduce the energy demand in desalination, however highlights the fact that there are ultimate limits which are limiting energy-efficiency improvements, stating the example that 2.8 kJ is the minimal amount of energy required to remove salt from water by using reverse osmosis, which equals to 1 kWh/m^3 (National Academy of Science, 2004). Industry still has room for improvement as even the most efficient plants are operating at about 4 times of the theoretical minimum, with some older plants using up to 25 times of the theoretically minimal energy input needed. Using an optimistic approach for best practice energy demand of 3 kWh/m^3 and accounting electricity with a price of 0.10 USD/kWh the minimum energy cost for a reverse osmosis plant will be 0.30 USD/m^3, however notably solely for water production, not taking into consideration fixed costs and transport of the produced water. In order to set this figure in comparison there are first-year costs of various reverse osmosis plant summarized in

Table 8 after Gleick et al. (2006).

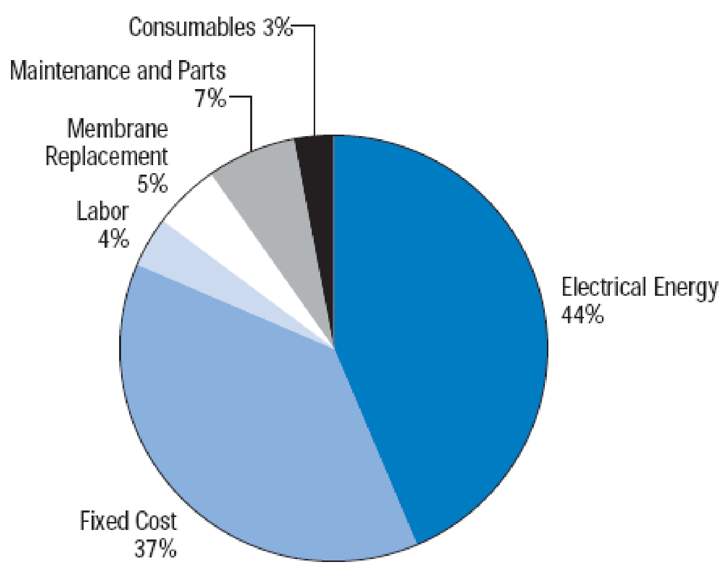

Figure 28: Typical cost for a reverse osmosis desalination plant (USBR and SNL, 2003)

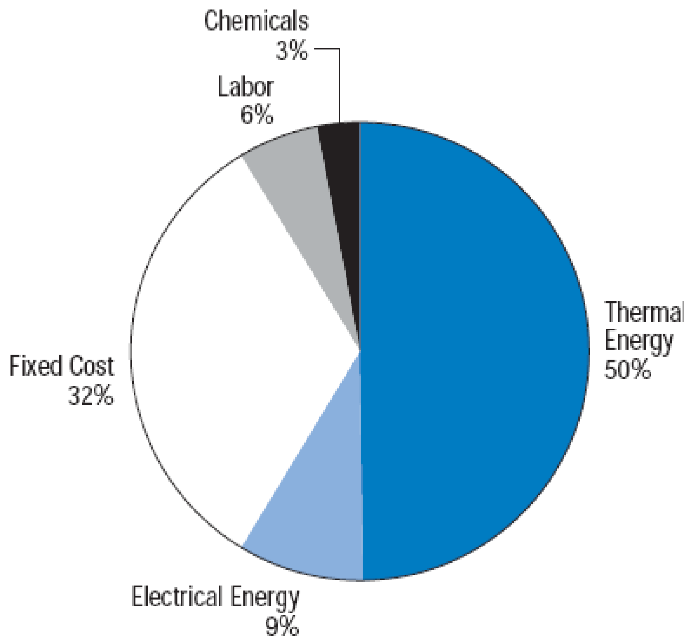

Figure 29: Typical costs for a very large seawater thermal desalination plant (Wangnick, 2002)

Facility or location	USD/m^3	Year of first-year costs
Ashkelon, Israel	0.62	2005
Bahamas	1.48	2003
Carlsbad, CA	0.77	2005
Dhekelia, Cyprus	1.43	2003
Eilat, Israel	0.74	1997
Hamma, Algeria	0.84	2003
Larnaca, Cyprus	0.85	2003
Moss Landing, CA	0.96	2005
Perth, Australia	0.92	2005
Sydney, Australia	1.11	n.d.
Singapore	0.45	2003
Tampa Bay, FL	0.55	2003
Trinidad	0.74	2003

Table 8: Summary of reported first-year cost of produced water for reverse osmosis plants (after Gleick et al., 2006)

4.3.2 Future costs of desalination

Nowadays renewable energies can not yet compete with fossil fuel powered desalination plants, however Mathioulakis (2006) raises the assumption that cost competition should not be the main problem for renewable energy driven desalination plants, because "*a glass of drinking water in remote and arid regions is actually precious and cost can be considered a matter of minor weight*" (Mathioulakis 2006).

Gleick et al. (2006) claim that the long term cost trend has been downward and until recent years many authors expected this trend to continue with hopeful projections and long-term objectives of halving costs by the year 2020, which seems daunting regarding energy prices on the rise and may be out of reach by incremental improvements. Therefore crucial new technologies or breakthroughs in both, material and energy costs, would be needed (Gleick et al., 2006).

Attempts to solve the water shortage based exclusively on technology, such as desalination of sea water, will only have a limited impact due to their cost. We must improve the efficiency of our water usage, particularly for irrigation, refurbish drinking water production and distribution resources, protect reserves and combat pollution (Kroiss, 2010b). This will clearly involve commitment and allotted spending by policy makers.

4.4 Concerns about Desalination

4.4.1 Energy use and greenhouse gas emissions

The high energy demand are the major economic consideration for the operation of desalination plants and consequently the high greenhouse gas emissions are the major environmental thought that need to be considered (Western Australia Water Corporation, 2006).

Glanville (2008) points out that there is a need to reduce the operational energy costs of membrane technology operated desalination plants, also regarding the associated greenhouse gas emissions (Glanville, 2008).

These specifications offer an opportunity for the use of renewable energy sources, as described in chapter 4.2, which however at the moment will still increase the costs of the water produced and therefore may not be suitable in all cases (Western Australia Water Corporation, 2006).

4.4.2 Environmental considerations

For discharging concentrated saline solution into the ocean monitoring is required. To manage this discharge properly a satisfactory dilution of the concentrate needs to be achieved in avoidance of increased salinity to unacceptable levels. The Western Australia Water Corporation (2006) concludes that "*this is generally not a difficult issue*" (Western Australia Water Corporation, 2006).

On the contrary, the UNEP (2010) argues that desalination processes result in the discharge of concentrated brine into the receiving waters, affecting salinity, which is together with temperature a factor that determines the distribution and composition of species in the marine habitat. Ecological changes, such as a shift in species diversity or the potential of colonization of exotic and potentially invasive species could arise, when these parameters are changed over sustained periods. Additionally, UNEP (2010) lists, that many desalination applications require the use of de-scaling and antifouling products, which can contain toxic chemicals and heavy metals, however adding that through good practice and plant maintenance these issues can be well managed (Corcoran et al., 2010).

4.4.3 Health concerns about drinking desalinated water

Having all the technical know-how to actually desalinate water is only of use in case the water produced is not only drinkable, but in fact delivers a safe way of delivering drinking water. Therefore the question has to be asked: Does desalinated water raise any concerns regarding health?

Kozisek (2004) describes that in the early 1980s a WHO report stated that desalinated water causes concrete adverse health effects and should not be recommended as drinking water. Minimum levels of essential minerals should be dissolved in drinking water. Desalinated water is characterized by relatively little amounts of dissolved minerals such as calcium and magnesium which in fact are important to the human well being. Besides the health perspective the inferior aspect of taste should also be taken into consideration, as the so called soft water is often regarded as having a negative taste and being less thirst-quenching, which might reduce customer acceptance (Kozisek, 2004).

During the last three decades desalination techniques have changed and commercially desalinated water is treated with special chemical additives, which leads to a stabilization of the water and an improvement of quality of the desalinated water. Hence desalinated water which is slightly remineralized with e.g. calcium carbonate and can be recommended as drinking water (Kozisek, 2004 and WHO, 2007).

There is no direct harmful effect attested for the consumption of desalinated water, however through consumption of solely desalinated water without any food over a longer duration there is the risk of demineralization of the body. As re-mineralization could prove difficult with simple decentralized desalination units in developing countries, it is also considered to add a minimal amount of saltwater to the desalinated water, especially if there is the risk of malnutrition (Benecke, 2010).

5 OUTLOOK

Economic, social, environmental, and political factors are setting the context for almost all water management and planning issues, and these factors are influencing decisions far more than technological constraints and conditions (National Academy of Science, 2008). In order to reduce the costs of the produced water and to improve process sustainability there is the need for more research and development, improved construction, operation and financing methods and great demand in information exchange between experts and policy makers. According to forecasts Lior (2010) is expecting that the produced water by desalination will at least double in the coming 10 years and that investments of around 60 bn. USD will be made in this sector (Lior et al., 2010). The time-series of global desalination capacity in Figure 30 shows that the installed capacity approximately doubled every ten years since the late 1970s, however Gleick et al. (2006) point out that trends from the past are no indication of future developments (Gleick et al., 2006). Following the International Desalination Association World Congress in Dubai from November 2009 a statement was made that "*seawater leads response to global water crisis*" (WaterWorld, 2009) and the International Desalination Association (2006) even suggests that the market for new desalination capacity is now growing at a rate of 25% per year (International Desalination Association, 2006).

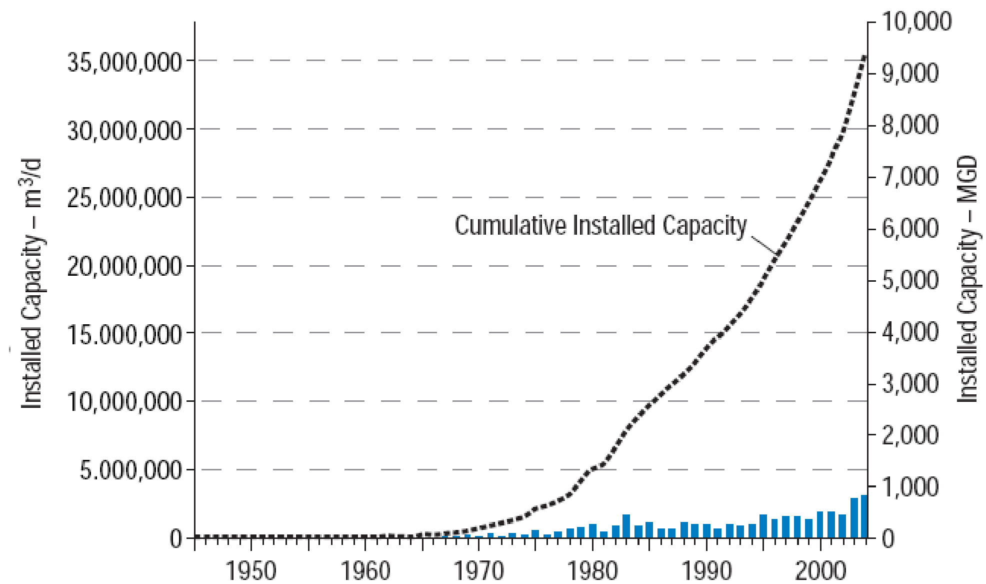

Figure 30: Time-series of global desalination capacity (Wangnick/GWI, 2005)

Agriculture is by far the largest consumer of fresh water, whereat irrigated agriculture is accountable for about 70% of the global freshwater withdrawal. Water scarcity may limit food production and supply and therefore forcing countries into more dependency of food imports and therefore putting pressure on prices (UNESCO, 2009). Relating to the vast water requirements for food production it is likely that desalination will only play a minor role in the water provision for irrigation use. According to Kroiss (2010) the water need for food production of at least 1,000 m^3/P/a, which can increase to far over 2,000 m^3/P/a easily if meat has a significant share in the food produced, is a multiple of the water requirement of human hygiene with around 30 to 50 m^3/P/a and an enormous effort compared with the 1 m^3/P/a that is needed solely for the supply of sufficient water for drinking only (Kroiss, 2010a). Using these figures in a purely theoretical calculation, the more than 60 million m^3 of desalinated water produced every day could provide about 10 liters of pure and safe drinking water to each person on Earth every day; far more than needed to ensure survival. Clearly such an equal distribution is not realizable in everyday practice due to geographical constraints amongst other issues, however shows that the supply of drinking water through desalination is technically achievable. Thus the provision of clean and safe drinking water will not have technical solutions as the limiting factor, but merely the implementation into practice through education, awareness raising and the socio-economic structures (Kroiss, 2010a).

Amongst others, there are two special concepts in water management that gained on importance during recent years, namely the concept of *virtual water,* introduced by Allen in the early 1990s, and the *water footprint* concept, introduced by Hoekstra in 2002, which has been developed in analogy to the *ecological footprint*, that was introduced only few years before. Through a flow in virtual water, which is defined as "*the volume of water required to produce a commodity or service*" (Chapagain and Hoeckstra, 2004), nations can make use of water resources elsewhere in the world by importing virtual water, as opposed to real water. Thus virtual water appears as an alternative water source and when imported is therefore called *exogenous water*. In today's world there is a substantial dependency on water and an estimated 16 % of global water use is for producing goods for export, many of which being exported to nations in arid regions and therefore relieving pressure on the in-country water resources of the importing nation. Closely linked to the concept of virtual water is the concept of the water footprint, which can be assessed for different nations by subtracting all virtual water flows that leave the country and adding all virtual flows that enter the country from the given use of domestic water resources. The virtual water inside various products can be immense, starting from 50 liters of water for one single orange, about 900 liters of water for one kilogram of maize, up to 4,500 liters of water for one beef-steak of 300 grams, just to list a few (Chapagain and Hoeckstra, 2004). Looking at the market prices of those exemplary commodities it becomes obvious that the import of virtual water as opposed to the import of real water or the desalination of saline water is currently also an economically viable option (Kroiss, 2010b) and can be a partial solution to problems of water scarcity for certain regions (Chapagain and Hoeckstra, 2004).

The expected rise in desalination capacity mentioned earlier is however not without consequences in terms of high economic costs, energy requirements, environmental and social implications, thus there needs to be the scope to improve the sustainability of the desalination processes (Corcoran et al., 2010).

Kroiss (2010a) relates the power need of desalination to the worldwide energy demand and states that the supply of drinking water for hygienic use of 30 to 50 m^3/P/a would require 0.02 kW/P (Kroiss, 2010a). Setting the higher figure in relation to the required water needed for drinking only of 1 m^3/P/a the power requirement decreases to 0.0004 kW/P, or 0.4 W/P. The overview in Table 9 compares these values with the energy consumption of selected countries per capita, ranking from the United Arab Emirates as the biggest consumer to Bangladesh with the lowest energy consumption per capita worldwide and shows what kind of fractional amount the provision of drinking water through desalination would mean (World Resource Institute, 2010). However, if desalination is considered to provide water for food production a multiple of this amount has to be provided, mounting to 0.5 kW/P and surpassing the total capabilities of many poor nations.

Energy consumption per capita	
country	kW/P
United Arab Emirates	13.8
Germany	5.6
Zimbabwe	1.0
Bangladesh	0.2

Table 9: Energy consumption per capita (World Resource Institute, 2010)

Kroiss (2010) underlines that the cost-benefit ratio for power consumption to provide safe drinking water, through e.g. desalination, is especially high, as safe water supply leads to considerable savings with healthcare costs and reduced loss of working hours due to water-related illnesses (Kroiss, 2010a). With many other means of power consumption such a high cost-benefit ratio is missing, e.g. when considering that in Germany 0.0306 kW/P are '*lost*' through having household appliances on stand-by mode, which accounts for 0.5% of the total energy consumption in Germany (Umweltbundesamt, 2008).
These comparisons and considerations shall demonstrate that the energy demand for water supply and in particular for desalination is a central problem of these technologies, however those requirements need to be put into context of the bigger picture and thus should also be considered in the notability of desalination's share with climate change issues.

To ensure a sustainable approach for the use of seawater desalination Teplitz-Sembitzky (2000) suggests the use of renewable energies, nevertheless stating that at the moment the adaptation of desalination technologies to renewable energy supplies is still particularly costly (Teplitz-Sembitzky, 2000).
As so often there is not one single solution to a problem, and also the problem of providing sufficient clean and safe drinking water to the world's population needs various combined approaches. Efforts to control the global shortage of clean and safe water based exclusively on technology, such as desalination of sea water for example, will only have a limited impact due to costs and the availability of fossil fuel, which in mid term expectations could be replaced by renewable energies, by direct conversion of solar energy into electrical or mechanical power for example. As most of the countries with severe water scarcity are situated in arid regions with high solar irradiation the perspective seems to be promising. Further the efficiency of water usage has to be improved, particularly for irrigation, drinking water production and distribution resources need to be refurbished, reserves need to be protected and pollution has to be prevented (UNEP, 2008).

6 SUMMARY AND CONCLUSIONS

Water, as well as energy, are probably the most critical parameters for economical and social development and thus are also vital to public and industrial health alike. The race for resources is at least from an energy perspective an obvious spectacle that is carried to extremes on an almost daily basis, by governments, energy companies and also the public. Concerning water scarcity the same fact does not seem that obvious on first sight and while the symptoms of water shortage are easy to identify once immanent, its causes are not. Overexploitation, an exploding population and carelessness together with an insufficient water management brought many regions to the verge of a collapse of their living systems as these completely depend on availability of water.

This thesis shall help with understanding the complex relationship between living systems, water, technology and the environment. Besides various possibilities of technological implementations of desalination methods this thesis also states necessary technological improvements in order to pave the way of a broader acceptance for desalination applications, as well as drawing the background of the coming crisis in international water supply by highlighting the status of water on Earth. However, attempts to satisfy the drinking water needs of the world's population are just one step into a sustainable future, the even bigger one will be the provision of enough and good food for an ever growing population with the given resources. Recalling that an individual needs about 1 m^3 of clean and safe water for drinking per year, the water needed for the same individual's food production accumulates to at least 1,000 m^3 in the same period. Providing this huge amount of water for irrigation will be one of the main problems for generations to come and it will not be possible to solve this by desalination alone.

Although the hydrological cycle is a global phenomenon most issues of water scarcity are local or regional circumstances. Therefore it has to be clear that reduced drinking water use in moderate climatic conditions will not be an important contribution to solving water scarcity problems in arid regions, but local and regional planning and action is needed.

The potential benefits of seawater desalination are great, but the economic, cultural and environmental costs of its wide commercialization remain high as well.

There are certain areas that must be improved on, forming a well balanced mix of water management, including improvements in the efficiency of water usage, particularly for irrigation, refurbishment of drinking water production and distribution resources, protection of reserves and better pollution control.
Water on Earth is leading us to believe in an illusion of plenty, however an illusion that can be turned into reality. There is both in abundance, the Sun's radiation and saltwater on Earth. By some considered the Holy Grail of water supply, desalination is showing the potential for an unlimited supply of water, however with possibly severe environmental and energy related considerations. Clearly the concerns related to a scarce power supply could be relieved by the use of renewable energy sources, however leaving the environmental impacts open, like the discharge of saline concentrate into marine habitat.

According to WHO estimates more than 1 billion people world wide are already lacking access to safe drinking water, with climate change on the one side showing a gloomy picture for many millions more, on the other hand however with the promise of the world community to accomplish the United Nations Millennium Development Goals (MGDs) and thus "*halve the proportion of people without sustainable access to safe drinking water and basic sanitation*" they might be close to salvation – or left alone in the middle of both. The outcome of the MDGs will be known in less than 5 years, however with climate change there is no due date for any results, but the long-term impacts that will be experienced by many generations to come promise to be powerful and serious.

Conclusively I want to repeat the poignant words of Prof. Kroiss, that "*if one wants to work on the quest for safe drinking water, one needs to overcome disregard first and ultimately needs the willingness to act.*"
Finally the question remains, if desalination is "*the ultimate solution to our water problems? No. Is it likely to be a piece of our water management puzzle? Yes*" (Gleick et al., 2006). Now, it remains to be seen how big this piece can be - and will have to be - and how much commitment from the world's leaders we will see to position this piece at the right position in the water management puzzle…

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8 LIST OF TABLES

9 LIST OF FIGURES