Ecological and economic analysis of seawater desalination plants

Diploma Thesis

by

cand. Wi-Ing. Frank Münk

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Frank Münk
Abstract

This work provides an ecological and economic analysis of seawater desalination plants with focus on the problem of brine discharge into the seas. Based on scientific findings the impacts on the marine ecosystem are displayed and a case study is presented. A review of the public opinion regarding seawater desalination and its ecological impacts is given and regulations concerning brine discharges in different countries are presented and compared. The largest part of this work deals with the techno-economic analysis of investments and measures which enable to reduce the environmental impacts of brine discharges.

The concentrations of different pretreatment chemicals in Multi Stage Flash (MSF) and Reverse Osmosis (RO) effluents are critical for the marine environment. Furthermore, the high salinity of RO effluents as well as the high discharge temperatures and copper concentrations of MSF effluents present a danger. In the Middle East where the most seawater desalination capacities are situated and the ecological risks are highest, however, brine discharges are a non-priority topic and the public opinion is rather uncritical. In Western countries where capacities are still low, in contrast, major opposition has developed against several desalination projects and cost and environmental concerns were raised. Regulations for brine discharges are not directly specified in many countries and directives are set on a case by case basis under consideration of environmental impact assessment reports. Countries like Saudi-Arabia and Oman have more detailed regulations for brine discharge, but these are not stringent enough and do hardly limit the impacts of critical pollutants.

Efficient and economical technologies exist to reduce the impact of brine discharges on the marine environment. Modern physical water pretreatment with Ultrafiltration membranes or sponge ball systems drastically reduces the need for most chemicals. Residual antiscalant chemicals can be replaced by more biocompatible chemicals. Copper pollution is avoided by using corrosion resistant duplex steel components. The impact of high salinity and temperature is mitigated by discharging the brine via multiport diffuser outfalls. The combination of these measures removes critical pollutants from the effluent and significantly reduces the environmental impacts of brine discharges. The costs for the necessary investments are similar to that of conventional plants, even without monetising the benefits of reduced marine pollution. An optimisation model for investment decisions under consideration of environmental impacts of brine discharges is developed in the course of this work.
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<th>Description</th>
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<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
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<tr>
<td>DSS</td>
<td>Duplex Stainless Steel</td>
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<tr>
<td>ED</td>
<td>Electrodialysis</td>
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<td>EIA</td>
<td>Environmental Impact Assessment</td>
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<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>HDD</td>
<td>Horizontal Directional Drilling</td>
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<td>HDPE</td>
<td>High Density Polyethylene</td>
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<tr>
<td>IDA</td>
<td>International Desalination Association</td>
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<td>MAP</td>
<td>Mediterranean Action Plan</td>
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<td>MED</td>
<td>Multi Effect Distillation</td>
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<td>MEDRC</td>
<td>Middle East Desalination Research Centre</td>
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<td>MENA</td>
<td>Middle East North Africa</td>
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<tr>
<td>MF</td>
<td>Microfiltration</td>
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<tr>
<td>Mo</td>
<td>Molybdenum</td>
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<td>MSF</td>
<td>Multi Stage Flash</td>
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<td>NF</td>
<td>Nanofiltration</td>
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<td>Ni</td>
<td>Nickel</td>
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<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluorethylene</td>
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<td>RO</td>
<td>Reverse Osmosis</td>
</tr>
<tr>
<td>SDI</td>
<td>Silt Density Index</td>
</tr>
<tr>
<td>SWRO</td>
<td>Seawater Reverse Osmosis</td>
</tr>
<tr>
<td>TCO</td>
<td>Total Costs of Ownership</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
</tr>
<tr>
<td>THM</td>
<td>Trihalomethane</td>
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<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
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<tr>
<td>UAE</td>
<td>United Arab Emirates</td>
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<td>UF</td>
<td>Ultrafiltration</td>
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<tr>
<td>UNEP</td>
<td>United Nations Environmental Programme</td>
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<tr>
<td>WWF</td>
<td>World Wide Fund</td>
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<td>ZLD</td>
<td>Zero Liquid Discharge</td>
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1. Introduction

As the world population is soaring, the global need for fresh water is steadily increasing. In many arid regions of the world natural fresh water resources like ground water, spring water, rivers and lakes cannot cover the demand any more. The fresh water reservoirs are depleting as more volumes are extracted and consumed than can be replenished by natural processes. Water scarcity can be a major obstacle for economic development and a social and political menace. Particularly the development in arid regions of the Middle East and North Africa is essentially dependant on the provision of new, additional sources of fresh water (World Bank, 2007).

Seawater desalination enables to access the unlimited water resources of the oceans and to provide a reliable, independent source of drinking water at any coastal site. Since the technology became commercially available in the 1960s, it spread continually and constitutes a major constituent of fresh water supply in many arid countries today. In 2005 the global installed and contracted seawater desalination capacity amounted to 27.4 Million m³/d. 76 % of this capacity is concentrated around the Arabian Gulf, the Red Sea and the Mediterranean. Capacities of 11 Million m³/d are currently installed at the Arabian Gulf only. Until 2015 the global capacities are projected to double and new desalination hot-spots in Australia, Southeast-Asia and California are going to emerge (Höpner, et al., 2008).

Due to the highly increasing desalination activities and the concentration of activities on a small number of regions and water bodies, it is necessary to deal with the possible adverse environmental effects of the technology and to develop mitigation strategies at an early stage. A major environmental problem of seawater desalination plants is brine discharge. Brine is the waste stream produced by desalination plants and is usually discharged into the sea. Depending on the desalination process the brine contains a variety of chemicals and corroded heavy metals in different concentrations and may have high salinity and temperatures. The impacts of these pollutants and brine characteristics on the marine environment can be manifold and must be mitigated by technical measures.

Besides the mere ecological and technical point of view, the problem of brine discharges is also a problem of public perception. The prospects of successfully facing the impacts of brine discharges also depend on the environmental awareness of the public and on the importance of desalination for people’s welfare. The stringency of environmental regulations for brine
discharges and their proper enforcement can likewise be reflected by the dependency of a nation on desalinated water.

This thesis aims at analysing the environmental problem of brine discharges from a technical, legal and economic point of view and at presenting feasible and cost-efficient technical solutions in order to mitigate the marine impacts of desalination plants. The necessary information for this work was partly derived from a research stay in the Sultanate of Oman.

The potential harmfulness of brine discharges on the marine environment will first be analysed from the scientific point of view and the most critical pollutants in major desalination processes are identified. The environmental awareness of the public and the public opinion on desalination in a couple of countries will be outlined and differences between the countries are highlighted. In this context, the socio-economic effects of desalination are covered, focusing on growth effects and the importance of desalinated water for the economic development. An overview about regional and national regulations regarding brine discharges is to depict the legal state of environmental protection and to reveal possible shortcomings. The most important task will be to give recommendations for technologies which reduce the environmental impacts of brine discharges. The recommendation will be based on a techno-economic analysis consisting of an evaluation of the mitigation potential for important pollutants, the operational efficiency and a comparison of relevant costs of the technologies. Based on conventional investment planning concepts, an optimisation model for investment decisions under consideration of environmental impacts of brine discharges is developed.
2. Desalination technologies

“Desalination is the process of removing dissolved salts and other chemicals from seawater, brackish groundwater, or surface water” (California American Water, 2004). Over the last decades various technologies have been developed to implement this process. The different types of source water are distinguished by their salinity. Seawater contains the highest level of dissolved salts. Brackish water contains less salt than seawater, but more than fresh water.

The overall procedure of seawater desalination is similar in most cases. Via an intake system seawater is pumped into the plant. It is pretreated by different physical and chemical methods in order to meet the water quality requirements of the plant. The pretreated water enters the desalination unit and is divided into a desalinated product stream and a concentrated waste stream. The highly pure product stream is led to a posttreatment system where the drinking water quality is ensured. Afterwards it can be distributed to the consumers. The concentrated waste stream, commonly called brine, is discharged back into the ocean via an outfall system.

The most important desalination technologies can be divided into two process groups. Thermal processes use heat to evaporate water, leaving the salts behind in the brine. The thermal technology with the highest market share is Multi Stage Flash (MSF). Membrane processes use pressure or electricity to force water through a semi-permeable membrane which blocks salts and other dissolved solids. The main membrane technology is Reverse Osmosis (RO). Almost half of the global desalination capacity which includes all source waters like seawater, brackish water or river water is covered by Reverse Osmosis plants. MSF plants have the second largest share (Fig. 1).

![Share of technologies in global desalination capacity](image)

*Fig. 1 Global distribution of installed desalination capacity by technology (based on Höpner et al., 2008)*
When only seawater desalination capacities are considered, MSF plants account for the highest share of the production (Fig. 2). The share of RO plants has continuously increased in the last years and is predicted to catch up further in the future. The clear lead of MSF technology in the seawater sector is due to its strong predominance in the countries of the MENA (Middle East and North-Africa) region (Höpner, et al., 2008).

![Share of technologies in global seawater desalination capacity](image)

**Fig. 2** Global distribution of installed seawater desalination capacity by technology (based on Glade, 2005)

In the following a basic overview about desalination technology is given, including a description of the different process technologies, a comparison of intake systems and a presentation of typical water pretreatment measures and the related operational problems.

### 2.1 Thermal processes

Thermal processes, also called distillation processes, involve the evaporation and condensation of water. The main field of application is seawater desalination. Because of the high energy consumption, thermal desalination is mainly applied in countries with low energy prices and high energy resources. In most cases thermal plants are operated in cogeneration with a power plant in order to use the released heat in the desalination process. The most important thermal processes are *Multi Stage Flash*, *Multi Effect Distillation* and *Vapour Compression*.

**Multi Stage Flash (MSF)**

Multi stage flash is an old technology reaching back to the 1960s. It enables to produce fresh water with very low salt concentrations (< 10 mg/l) from feed water with salinities of up to 70 g/l (Heather, et al., 2006). MSF units are usually built for capacities of 4,000-57,000 m³/d. The energy consumption is - at 18 kWh/m³ - the highest of all established technologies and more than three times higher than that of an average Reverse Osmosis unit. However, MSF is still a widely accepted technology due to its reliability, the easy process control and the simple layout (Al-Sahili, et al., 2007).
The MSF process consists of several chambers, called ‘stages’, in which salt water is boiled at consecutively lower pressures and temperatures. In a tubing system, the feed water first passes from back to front through the different stages of the plant and is preheated. Then, it enters the so called ‘brine heater’ under high pressure and is heated to the top brine temperature (TBT) of around 90-120 °C (UN ESCWA, 2001). When the salt water enters the lower pressurised first stage, parts of it are boiled, it ‘flashes’. In each of the following stages the pressure is further reduced and more water is transferred into steam. The higher the TBT is, the more consecutive stages can be operated and the more fresh water is generated. This means that the plant efficiency is increasing with the TBT. However, the TBT is restricted by scaling problems which are explained later.

In each chamber, the boiled water condenses at heat exchanger tubes which are used to preheat the feed water. The performance of the heat exchanger units is responsible for the energy efficiency of the plant. The distillate is collected throughout the system and leaves the MSF unit at the last stage. The same applies to the brine which passes from stage to stage at increasing salt concentrations and is extracted at the last stage (Buros, 2000). The configuration of a typical MSF plant with four stages is illustrated in Fig. 3.

![Fig. 3 Schematic of the Multi Stage Flash process with four stages (Lahmeier International, 2003)](image)

**Multi Effect Distillation (MED)**

Multi Effect Distillation is the oldest desalination technology. MED units are usually built for capacities of 2,000-20,000 m³/d and the energy consumption amounts to around 15 kWh/m³ (Al-Sahili, et al., 2007).

The configuration is very similar to MSF. Seawater is boiled in several consecutive steps, called ‘effects’, at decreasing temperatures and pressures. In contrast to MSF, seawater is sprayed directly onto the heat exchanger tubes of each effect at the same time. The water evaporates and the generated vapour of one effect is transferred into the heat exchanger tubes of the following effect where it condensates and causes more water to evaporate (Fig. 4). A boiler generates the steam for the first effect and the vapour of the final stage is used to preheat the feed water. As the water does not evaporate from the bottom of the pressure
chambers like in MSF units but directly on top of the heat transfer tubes, severe corrosion and scaling problems on the tubes are caused. Therefore the TBT must be reduced to values of around 70 °C. Because of these problems and because of the higher costs, MED lost competition against MSF in most applications (Miller, 2003).

**Fig. 4 Schematic of the Multi Effect Distillation process with three effects (Buros, 2000)**

**Vapour compression**

In the case of vapour compression the energy to evaporate the feed water is produced by compressing vapour with a mechanical or thermal compressor. The vapour enters the heat exchanger tubes and the pressure is decreased. At a certain pressure drop the vapour condensates and latent heat is released. Thus, the feed water which is sprayed onto the tubes evaporates and more vapour is generated and compressed.

Vapour compression has a typical energy consumption of 7-12 kWh/m³ which is lower than for other thermal processes. It is a very reliable technology and is mainly used for small desalination capacities of 3,000 m³/d or less. The reason for this is that each stage of the process needs an own compressor and compressors are expensive. Low cost compressors, however, cannot provide enough pressure to operate on several stages. Therefore the process is most often limited to one or a few stages and is restricted to small capacities.

**2.2 Membrane processes**

In contrast to distillation, membrane processes are based on the separation of water and salts via a semi-permeable membrane. The Reverse Osmosis process uses pressure to separate the dissolved salts from the feed water. In the case of Electrodialysis, electricity is used. Reverse Osmosis can be applied for brackish and seawater sources. Many innovations and improvements in membrane efficiency and energy recovery have contributed to the accelerating distribution and growing popularity of Reverse Osmosis systems.
Nanofiltration plants, which are mostly used for brackish water desalination, apply the same technical principle as Reverse Osmosis plants and will not be separately discussed in this context. They will be covered later as a pretreatment system.

**Reverse Osmosis (RO)**

In the RO process the feed water is pressurised by high pressure pumps to up to 80 bars and then passed through special membranes in an enclosed vessel. The membranes selectively block most dissolved solids including salts and let pure water pass. The blocked salts accumulate and are finally discharged. The amount of produced fresh water depends on the applied pressure and on the salt content of the feed water. The energy consumption is increasing with growing membrane pressure. By using recent methods of energy recovery the energy consumption can be reduced to 3 kWh/m³ (Buros, 2000). The typical components of an RO desalination system are illustrated in Fig. 5.

Depending on the application and the feed water characteristics several membrane materials and configurations can be applied. The first successful material on the market was cellulose acetate. Today a mix of cellulose di- and tri-acetate is usually used. However, synthetic polymer materials are increasingly replacing the natural cellulose membranes. This is mainly due to the better salt rejection and the higher durability of synthetic materials. Furthermore, polyamides resist to higher pH ranges and cope better with biological attacks and other feed water pollution. In contrast, they are very susceptible to chlorination.

The two most important membrane configurations are hollow thin fibre and spiral wound membranes. In the hollow fibre configuration many thin fibre tubes (85 µm in diameter) are packed to bundles and placed inside a vessel. As the pressurised feed water flows into the vessel it partly passes through the thin fibre structures and enters the tubes in a desalinated state. Due to the tiny spacing among the fibres tubes (∼ 25 µm), particle trapping is a major danger. Therefore, the feed water quality has to be exactly controlled.

In the spiral wound configuration thin membrane layers are wrapped around a collecting tube. The pressurised feed water is flowing in a spiral between the membrane layers. Portions of it are pushed through the membranes and enter the central collecting tube in a desalinated state. The remaining water concentrates and flows out as brine. Since spiral wound membranes are less loosely packed (several mm) they enable larger flux rates¹ and are less susceptible to particle trapping than hollow fibre configurations. Instead, the thin layers are more sensible to particle erosion and larger flux rates promote particle deposition (Krishna, 1989; Lattemann, et al., 2003).

¹ Membrane flux rates are defined as water volume per membrane area and time unit
Electrodialysis (ED)

Most salts in water are ionic and thus can be deflected by an electric field. In an electrodialysis system the feed water flows into different chambers, divided by alternating cation and anion selective membranes (Fig. 6). As voltage is connected, the anions are flowing towards the positive pole and the cations towards the negative pole. As the selective membranes are installed alternately, anions and cations can only pass one membrane and the next one is impenetrable. Thus, alternating chambers of concentrated and desalinated water are created which are extracted by different tube systems (Buros, 2000).

ED plants are mainly used for brackish water sources, since energy consumption is increasing proportionally with the salt concentration. As no pressure is applied and no water is streaming through the membranes, ED can handle higher levels of particle pollution than RO plants. Thus, less filtration and pretreatment is needed in ED systems (Miller, 2003).
2.3 Intake and pretreatment

Seawater contains substances and particles which are potentially harmful for the desalination components. Biological substances can create fouling, solid particles can cause coagulation and deposition, dissolved solids can cause scaling and material corrosion can be accelerated. Therefore, plant operators carefully choose the intake system, position the intake at the site with the best water quality and look for the most robust materials. In most cases, the raw water quality is not sufficient for plant operation and technical cleaning systems need to be installed. Filters are integrated to purify the water as far as possible and chemicals are dosed to ensure the right water parameters.

Intakes

Open water intakes take the water directly from the sea via pipes which enables a theoretically unlimited raw water stream. The strong water suction poses a risk of impingement and entrainment for fish and other animals. Particles and organisms small enough to pass the screens are sucked into the plant and significantly deteriorate the feed water quality (Heather, et al., 2006).

Beach wells are vertical bore holes constructed on the beach side. They make use of the sandy soil as natural prefiltration and thus deliver a better feed water quality. Besides, the danger of impingement and entrainment is avoided. However, beach wells depend on geological conditions and can only provide limited water volumes which are generally not enough for large plants.

Higher intake volumes can be delivered by Horizontal Directional Drilling (HDD). This technique installs pipelines under the seabed. The water, prefiltered by the geological layers, can be collected in sufficient quantities, independent of waves, currents and tides. But HDD is not suitable for all geologic conditions and is difficult to construct and to maintain. Furthermore, beach wells and HDD pose the risk of salt water intrusion into the ground water (California American Water, 2004).

Pretreatment

When the raw water quality is bad and does not meet the quality criteria of the plant, pretreatment has to be carried out in order to avoid operational problems. Chemical pretreatment is the most commonly used technique for seawater desalination plants (Lattemann, et al., 2003). Chemical treatment is applied to solve and avoid the following problems:

- Suspended particles
- Fouling
- Scaling
Intake and pretreatment

- Corrosion
- Foaming

Suspended particles in the feed water contaminate and block the RO membranes. The particles have to be forced to form bigger agglomerations so that they can be filtered with dual media and cartridge filters (Fig.7). This is usually done by adding coagulation chemicals like ferric chloride or polyelectrolytes to the water. Besides, turbines or propellers can be used to achieve mechanical flocculation through slow mixing (UN ESCWA, 2001).

Fouling is caused by organic material in the feed water, most likely fine unfiltered particles and bacteria which settle on surfaces and start growing. They cause blockage and destruction of RO membranes and reduce the heat transfer and the process efficiency in MSF plants. Fouling is usually fought by continuously adding biocides, most commonly chlorine, to the feed water which restricts biological growth. In order to stop all biological activity shock-chlorination with higher dosages is carried out in regular intervals.

Scaling occurs when the solubility of dissolved salts is exceeded and the salts are starting to precipitate. As result of the desalination process the concentrations of salts are rising and eventually reach the solubility limits. Calcium carbonate scales form quickest. Solubility levels are decreasing with rising temperatures which poses an additional problem for thermal plants. Scale formation reduces the RO membrane performance and supports fouling. In MSF plants scale formation promotes corrosion and reduces the heat transfer and thus the overall operating efficiency. In order to control scale formation, acids and antiscalant chemicals are dosed. When calcium sulphate scales form, they cannot easily be removed by antiscalants. Due to this reason the MSF process temperatures are restricted to about 115 °C.

Fouling and scaling cannot be completely avoided by means of regular pretreatment. Fine films will form eventually. Therefore, regular chemical cleaning with acids and a mix of other chemicals has to be carried out additionally.

Corrosion is a major problem in MSF plants. It is promoted by high temperatures, high salinity, oxygen and chlorine. Particularly copper-nickel alloys which are applied due to their good heat transfer capacities are vulnerable to corrosion. In order to maximise the protection of the sensitive metals, anti-corrosive chemicals are dosed and the feed water can be depleted of oxygen by using so called oxygen scavenger.

Foaming is an exclusive problem of MSF plants. It occurs when dissolved organics concentrate on the water surface due to the water movement. Foam increases the danger of salt intrusion into the distillate and is therefore tried to be avoided by using antifoaming agents. These reduce the tension in the surface water and destroy the surface films.

The typical chemical pretreatment steps for MSF and RO plants are summarised in Fig. 7.
A new approach to pretreatment are membrane filtration systems (Van der Bruggen et al., 2002). Depending on the pore sizes of the membranes, different sizes of particles can be filtered and different pressures have to be applied (Fig. 8).

**Microfiltration (MF)** removes particles of down to 0.1 μm. This includes suspended solids, algae, emulsions and some bacteria. The energy consumption is relatively low as only small pressures are applied.

**Ultrafiltration (UF)** removes substances down to 0.01 μm which comprises dissolved macromolecules, colloids, viruses and smaller bacteria. Pressures of up to 5 bars have to be applied.

**Nanofiltration (NF)** has the finest pores of down to 0.001 μm. NF even removes hardness ions (e.g. Ca, Mg), dissolved organic carbon and a fraction of the salts. It works similar to RO units, but at significantly lower pressures.
2.4 **Case study: Barka plant, Oman**

As the most common desalination technologies have been discussed, a specific desalination plant shall be outlined in order to get an idea of a typical plant design and the operational data. In the following the Barka seawater desalination plant, situated in the Sultanate of Oman, is covered. The presented data has been collected during a visit of the plant and through conversation with the commercial manager and an operating engineer.

The Sultanate of Oman is situated at the south-east of the Arabian Peninsula, at the entrance to the Arabian Gulf. The Muslim country with a size about that of Germany has around three million inhabitants. Most of them live in the north-eastern coastal belt and in the capital area of Muscat. At the moment, four major sea water desalination plants (Al-Gubrah, Barka, Sohar and Sur) and numerous small brackish water plants in the inland are operated in order to cover the fresh water demand of Oman. The location of the seawater plants is shown in Fig. 9.

![Location of major Omani seawater desalination plants](image)

**Fig. 9 Location and capacities of major Omani seawater desalination plants (1 US-gallon = 3.785 litre)**

Barka is the third largest plant of the country and is located about 65 km West from Muscat City. It is owned by a private investor, the AES Corporation. Barka is a standard middle size MSF plant which is operated in cogeneration with a power plant. Cogeneration plants are the prevalent type in the Gulf region.

Barka is powered by natural gas. The steam turbines produce 450 MW of electricity and the MSF desalination unit accounts for a fresh water production of 91,200 m³/d. The intake
system consists of four pipes of 1.2 km length (Fig. 10) and a diameter of 2.2 m. The overall intake flow rate including cooling water amounts to 126,500 m³/h and is taken from a water depth of 10 m. The brine is blended with the cooling water and is discharged into the sea via a submerged offshore outfall. The outfall comprises four pipes of 650 m length which lie 8 m deep under the water surface. The outfall pipes are equipped with multiport diffusers in order to enhance the dilution rates after discharge. The minimum distance between intake and outfall is 800 m in order to avoid the recirculation of concentrated water to the intake.

Barka uses the typical chemical pretreatment steps which are usually applied in MSF plants. To prevent fouling, hyperchlorine is dosed at a constant level of 3 mg/l. Besides continuous chlorination, shock chlorination is effected in regular intervals. A phosphate-based antiscalant is used at a concentration of 1.5 mg/l. Antifoaming agents are used but the dosages could not be investigated. Regulations determine that the brine temperature at the point of discharge must be limited to 10 °C above the ambient value and the salt concentration of the brine must be restricted to 2 g/l above ambient. In case of accidental overdosing of chemicals, additional cooling water can be mixed to the brine and an emergency mixing system is available.

All in all, it can be concluded that the Barka plant is operated in a modern and transparent way. Precautions are taken to reduce environmental impacts and the national regulations for brine discharge are met according to the information obtained. The chemical pretreatment methods used in the Barka plant are typical for current MSF plants. The outfall system with multiport diffusers can be considered as superior to the prevailing open sea outfalls from an ecological point of view.

![Fig. 10 Sketch of intake and outfall system of the Barka desalination plant (Abdul-Wahab, 2007)](image)
3. Environmental impacts

Seawater desalination provides safe drinking water for regions with severe fresh water shortages and can help to protect and relieve the ground water resources from extensive usage. However, desalination is also accompanied by some negative effects on the environment:

- Land usage
- Energy consumption
- Brine discharges

The problem of land usage is connected with every major industrial project. Seawater desalination plants are situated at coastal sites which are a particular sensitive environmental habitat with many social, economic and recreational functions. The search for an appropriate plant location has to be carried out with great care in order to minimise differing interests.

Despite great achievements in reducing the overall energy consumption, particularly for Reverse Osmosis plants, desalination remains an energy-intensive process. Since most of the energy is taken from fossil sources and global warming becomes a problem of great urgency, the CO$_2$-production caused by desalination plants is another important environmental problem. In the Middle East, where most desalination capacities are situated, fossil energy is particularly cheap and thus, energy saving is less profitable. But at the same time, an immense amount of energy in these countries is delivered by the sun. Research projects currently tempt to find efficient and reliable solutions for solar-driven desalination (DLR, 2007). These would reduce the emissions of CO$_2$ and other air pollutants. However, greenhouse gases are a complex problem without geographical borders and have to be fought all around the world. Solutions to the air pollution problem will not be the focus of this work.

Instead, the concentration shall be shifted to the impacts of the desalination effluent. This by-product of the desalination process is concentrated salt water containing a mixture of chemicals used during plant operation. The composition depends on the desalination process, the operational parameters, the component materials and the pretreatment measures used. The brine is usually rejected directly into the sea. This chapter describes the effects of the brine discharges on the marine environment and presents a case study.
3.1 Impacts of brine discharges

A couple of aspects are relevant in order to carry out a comprehensive impact analysis of brine discharges. Physical properties like salinity and temperature play a role. Both of them change the effluent density and thus, influence its flow characteristics and the impact area. Besides, the different types of pretreatment and cleaning chemicals as well as corroded metals must be considered. In the following the different impact categories are analysed under consideration of differences between the two main technologies MSF and RO.

Salinity

The salinity of most oceans lies at about 35-40 g/l. The salinity of desalination effluents depends on the recovery rate and can highly exceed the natural ocean levels. The recovery rate of a desalination plant is defined as the ratio of produced fresh water volume to the feed water volume. The higher the recovery rate, the less brine volumes are generated, but the higher brine salinities are reached.

\[
\text{Recovery rate} = \frac{\text{Fresh water volume}}{\text{Feed water volume}}
\]

The recovery rate of RO plants usually lies at 40-64 % (Lattemann, et al., 2008). At a recovery rate of 50 % e.g., the brine salinity would be double that of the natural ocean salinity. MSF plants have recovery rates of about 10 % and often dilute the concentrate with cooling water prior to discharge. Thus, the discharge salinity usually is only about 1.05 times higher than the feed water salinity (Höpner, 1999). Due to the higher salt levels, RO effluents have a higher density and rather affect the benthic species whereas MSF effluents rather affect the open water organisms. The dilution speed of the discharged brine decreases with growing density differences between brine and the receiving water. Thus particularly RO brines can keep critical salinity levels over a larger area of the water body.

Several studies indicate that constant salinity levels above 45 g/l alter the benthic community and reduce the diversity of organisms. Most organisms can cope with short salinity peaks of up to 50 g/l and can adapt to long-term variations of 1-2 g/l. Some organisms have very low levels of tolerance. For corals the salinity of 43 g/l can already be lethal (Lattemann, et al., 2003). Typical RO brine significantly exceeds the indicated tolerance levels and must be classified as dangerous until it is sufficiently diluted.

High salinity also increases the water turbidity and can disrupt the photosynthesis process. Less sunlight and higher salt concentration lead to the extinction of plankton species and reduce the variety of other immobile organisms. The tolerance varies greatly between the different species. The same applies to fish. Less tolerant species will be deprived of their natural habitat and will vanish from the place of impact (Miri, et al., 2005).
A study investigated the impact of salinity on Posidonia oceanica, a Mediterranean sea grass which houses a high diversity of species and has important functions for the marine ecology. At a salinity of only 39.1 g/l significant effects on the vitality of the plant were documented. Salinity levels of 40 g/l and above caused significant effects on plant mortality and salinity of 45 g/l led to a 50 % mortality rate after 15 days. These levels can easily be reached around the discharge location of desalination plants (Höpner, et al., 2008). For many other ecosystems, the exact effects of increased salinity on marine organisms are still not entirely investigated. Detailed analysis is lacking and further research is needed.

It was suspected that the high desalination activities in the semi-enclosed Arabian Gulf might even lead to an overall salinity increase of the Gulf water. This danger, however, can be ruled out as the high natural evaporation rates in the Gulf generate much more significant overall salinity changes than the totality of desalination activities (Höpner, 2008). In areas with high evaporation rates species have adapted to the natural salinity variations. But the high local salinity levels around the discharge location, especially for RO plants, clearly exceed natural levels and pose a threat for a variety of species.

**Temperature**

The brine temperature of RO plants is only insignificantly higher than ambient values and can be neglected. Instead, MSF plants generate high thermal emissions and discharge the concentrate at a maximum of 10-15 °C above ambient, after dilution by cooling water. The discharged stream is a multiple of the mere brine volume and is likely to float on the water surface due to the high temperature and the lower salinity increase (Lattemann, et al., 2003).

Increased temperatures reduce the oxygen solubility in water. Significant decreases in oxygen levels can be toxic for species. In winter the temperature rise can boost biological activities. In summer it can be lethal to unadjusted and immobile organisms (Danoun, 2007). Thermal impact is generally a minor problem in hot regions where large annual temperature changes are a natural phenomenon. The highest stress will last on the environment in temperate countries which is not used to quick temperature changes (Höpner, 1999). However, the experimental data for different species is still very low. Temperature is an essential parameter of water quality and species have preferred temperature ranges. Significant long-term alterations can be harmful and cause organisms to die-off (Höpner, et al., 2008).

**Antifouling additives**

The most commonly used antifouling additive is chlorine. It is a broad-effect agent and can have equally broad impacts on marine organisms. Moreover, chlorine is highly reactive and provokes dangerous chemical reactions, most important the halogenations of organic compounds. Both MSF and RO plants use chlorine or hyperchlorite to prevent fouling. A typical dosage is 2 mg/l. For shock chlorination, several times this value is added for a shorter period.
In RO plants using polyamide membranes dechlorination of the feed water is carried out in order to protect the membranes. However, minor residual chlorine levels can still be present in the brine and the problem of the toxic halogenated organic compounds remains (Höpner, 1999). Sodiumbisulfite which is commonly used for dechlorination reacts to harmless products but may cause critical oxygen depletion if overdosed.

Nevertheless, the impacts of chlorine are more significant for MSF plants since usually no dechlorination is effected. Besides, MSF plants require larger feed water volumes which increase the loads of chlorine and its by-products. One can assume that 10-25 % of chlorine concentration in the feed water (equal to 200-500 µg/l) can approximately be measured in MSF effluents. Concentrations in the mixing zone of MSF plants were reported to be around 100 µg/l. The mixing zone is the area around the discharge location in which the brine and its constituents are diluted to ambient or given threshold values.

At an assumed effluent concentration of 250 µg/l, the daily chlorine input of major MSF plants into the Arabian Gulf is calculated to amount to 21,900 kg (cf. Appendix B).

Chlorine is proven to be toxic at concentrations of a few micrograms only. The photosynthesis process of plankton can be seriously reduced at concentrations of only 20 µg/l. At levels of 50 µg/l the composition of marine organisms can change and their variety is reduced. The known lethal values for fish species range between 20 and several hundred µg/l (Lattemann, et al., 2003). Fig. 11 depicts toxic chlorine concentrations for a range of species by means of the LC50 indicator1. It can be seen that the reported chlorine concentrations in MSF effluents and in the mixing zone are acutely toxic for many of the examined marine organisms.

Fig. 11 Chlorine toxicity levels for a range of marine species (Höpner, et al., 2008)

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1 The LC50 test measures the concentration of a chemical which is lethal to 50 % of the tested species after a certain time span (usually hours). It is an acute toxicity test which does not depict the possible long term effects of lower concentrations.
Halogenated organic compounds, most important trihalomethanes (THM), are typical by-products of chlorine addition and the result of reactions with hypochlorite. Besides in MSF effluents, THM can also be present in RO effluents if it has formed prior to the dechlorination process step. The concentrations are much lower than for chlorine but toxic concentrations might be reached. Moreover, the chronic effects of THM are not known and synergic effects must be taken into consideration. THM is proven to have carcinogenic effects on animals (Lattemann, et al., 2008).

**Antiscaling additives**

*Polyphosphats* were the earliest antiscalcing agents but they are on the retreat because of two main disadvantages. Their stability is reduced at temperatures above 90 °C which makes them impractical for most thermal applications. Furthermore, polyphosphates are major macronutrients which can cause eutrophication. As a consequence, algae growth rates may soar, leading to deteriorating raw water quality, frequent filter problems and growing need for antifouling agents.

Today the most commonly used agents are *polymeric antiscalants*, particularly the agent Belgard EV. Typical dosages are 2 mg/l. Only one study about Belgard EV has been carried out reporting that no accumulation in algae and fish was detected and that the agent is ecologically safe (Höpner, 1999). Toxic concentrations are usually by an order of magnitude of 1-3 higher than typical dosage levels. However, considerable loads are discharged into the seas. An estimated antiscalant load of almost 62,000 kg/d is discharged into the Arabian Gulf (cf. Appendix C). Thus, the degradability rate of antiscalants becomes of environmental interest. Belgard EV is only degraded by 18 % in 35 days. Other agents reach much better degradation in the same time, e.g. Flocon 100 (52 % in 35 days). Substances with good biodegradability should be chosen in order to avoid possible long term effects. Polymeric antiscalants might reduce the concentrations of essential trace metal ions in the seawater, but this process is still not entirely investigated (Höpner, et al., 2008).

Some RO plants also use *sulphuric acid or hydrochloric acids* at 20-100 mg/l in order to avoid scaling, resulting in a feed water pH of 6-7. The acidic solution should be neutralised as far as possible prior to discharge to the sea (pH ≈ 8.3).

**Antifoaming additives**

Commonly used antifoaming agents are polyglycols and fatty acids with typical dosages of about 0.1 mg/l. The dosage depends mainly on the raw water quality and its seasonally changing organic composition. Antifoaming additives are considered non-toxic. Polyglycols have a good biodegradability. They can transform into a polymerised state which is more persistent in the environment but due to the low concentrations used in desalination plants, polyglycols are of little concern for the marine environment (Lattemann, et al., 2003).
Corrosion products and anticorrosive additives

Heavy metal discharge as a consequence of corrosion is a main concern in MSF desalination plants because of the high temperatures involved. Depending on the materials used for the heat exchanger tubes and vessels, copper, nickel, iron, zinc and other heavy metals are corroded and discharged (Höpner, 1999). The prevailing alloy for the heat exchanger tubes is copper-nickel which has poor corrosion resistance and accounts for the highest heavy metal pollution in MSF plants. In RO plants, non-metal materials and stainless steel are predominating. There are traces of iron, nickel, chromium and molybdenum in the RO effluent, but the concentrations remain non-critical.

The average $copper$ background concentration of the oceans lies at a minimum of 0.1 µg/l. Copper concentrations in MSF effluents were reported in the range of 15-100 µg/l. The tolerance towards copper pollution is not yet entirely known for all species. Copper can be toxic at higher concentrations, causing enzyme inhibition in organisms and reducing growth and reproduction (Miri, et al., 2005). Fig.12 illustrates the toxicity levels for a range of marine organisms. Although the discharged concentrations can be high above natural levels in the mixing zone, the risk of acute toxicity is generally low.

Instead, there is a higher risk of accumulation and long term effects. Copper compounds tend to settle down and accumulate in the sediments. They can be absorbed by benthic organisms and even be transferred into the food chain eventually. With respect to bioaccumulation, the discharged loads instead of the concentrations become the main point of concern. A conservative estimation calculates that copper loads of 292 kg/d are rejected into the Arabian Gulf by major MSF plants (cf. Appendix D).

![Fig. 12  Copper toxicity levels for a range of marine species (Höpner, et al., 2008)](image)

Nickel is contained by up to 30 % in the Cu-Ni heat exchanger alloys and is less toxic than copper. No real data exists about discharge concentrations, but they are believed to be much lower than for copper. The U.S. Environmental Protection Agency (EPA) calls for a
maximum concentration of 8.2 µg/l for long term exposure. With proper dilution at the discharge point most effluents are likely to reach this level after a short area around the outfall. Nickel is quite mobile in water, but the majority of the load will accumulate in the sediments around the outfall. Adverse effects of accumulation cannot be excluded.

It should be kept in mind that the corrosion rates will most likely increase during the process of acid cleaning although no specific data is available. Additionally, low pH values make the discharged metals more mobile and thus, more harmful for the environment.

Stainless steel materials comprise mainly iron and lower rates of chromium, nickel and molybdenum. The toxicity and overall discharge concentrations are believed to be harmless. Concentrations might augment through pitting and failing process control.

One strategy used to fight corrosion is to reduce the oxygen levels of water during the desalination process. Sodium bisulfite, the chemical also used for dechlorination in RO processes, can be applied as oxygen scavenger in MSF plants. In water sulfite is oxidised to sulfate which is a harmless seawater component. Other corrosion inhibitors like benzotriazole are particularly used during chemical cleaning (Lattemann, et al., 2003).

**Coagulants**

The need for coagulation of suspended solids is an RO-specific problem. Ferric chloride at dosages of 1-30 mg/l or polyelectrolytes like polyacrylamide at about 1-4 mg/l are usually added to the intake water in order to enhance coagulation. The dosages are correlated to the amount of suspended particles in the water. In most plants the agglomerated particles are filtered by media filters and periodically backwashed into the sea.

Coagulants are non-toxic in the concentrations applied in RO plants. Iron is a natural seawater constituent and polyacrylamide is a non-priority pollutant. Problems are only posed by the possible disturbance of photosynthesis processes due to an increase in turbidity during backwash of the coagulated sludge and by coagulant enrichment in sediments. The Ashkelon RO plant in Israel (330,000 m³/d) doses 3 mg/l of ferrous coagulant and produces a highly turbid, red coloured effluent during backwash which is effected every hour for 10-15 minutes. This might be eased by treating or diluting the backwash with feed water prior to discharge. Sludge treatment is carried out in modern RO plants in Australia and the United States. Land deposition of the filtered sludge is an alternative but adds an estimated 1-5 US-cents/m³ to the water price (Höpner, et al., 2008).

**Chemical cleaning**

Despite all pretreatment measures RO membranes and MSF tubing systems and boilers are cleaned periodically in order to remove residual deposits. Acidic solutions (pH 2-3) are used to remove metal oxides, scales and inorganic colloids. Alkaline solutions (pH 11-12) are applied for removal of biofilms as well as organic and inorganic colloids. The necessary
volumes of cleaning solutions are higher for MSF plants. It must be assumed that in most cases the spent cleaning solutions are discharged into the sea without treatment. This should at least be done by gradually mixing the cleaning solution with the brine.

The extreme pH values of cleaning solutions can be a threat to the marine ecosystem depending on the discharged volumes and the degree of degradation at the discharge point. LC$_{50}$ mortality for certain fish species in an HCl solution of pH 2-2.5 is reached after 48 hours. Residual acidity and alkalinity are usually quickly neutralised by seawater.

Other threats are posed by the additives which are dosed to the cleaning solutions. These differ according to the desalination process. When it comes to MSF plants the chemical impacts are comparatively low as only corrosion inhibitors like benzotriazole are dosed. The concentrations discharged into the sea are difficult to estimate because dosages and discharge methods for cleaning wastes are unknown. Benzotriazole has low toxicity but is quite persistent and slowly degraded in seawater. It tends to adsorb at suspended matter in an acidic environment and thus can accumulate in the sediments. The tendency for accumulation in organisms, however, is low.

With regard to the chemical cleaning process of RO membranes, a much more diverse and more harmful mix of chemicals is used. The agents commonly recommended by most membrane manufacturers are:

- disinfectants like formaldehyde and isothiazole
- sulfonate detergents like sodium dodecylsulfate (NA-DDS)
- complexing agents like Ethylene Diamine Tetraacetic acid (EDTA)

Disinfectants are biocides used to remove biological films from membranes and are acutely toxic for the marine environment. In the case of formaldehyde, LC$_{50}$ levels of only 0.1 mg/l were found for certain species. A seawater volume of more than 58,000 m³ would be exposed to lethal concentrations if a common disinfection solution with 1 % formaldehyde is applied.

Detergents are used for the removal of colloids. They disrupt the intercellular membrane system in organisms. Toxicity is in the middle range, with LC$_{50}$ levels of NA-DDS ranging between 1-10 mg/l for many marine species. Pretty good degradability at 80% in a couple of days is documented.

Complexing agents reduce the water hardness and remove scale deposits. EDTA has low toxicity but is poorly degradable at only 5 % in three weeks.

Although the RO cleaning volumes are much lower than the MSF volumes, the toxicity of its constituents makes RO cleaning solutions far more dangerous for the marine ecosystem (Lattemann et al., 2003; Höpner et al., 2008).
Results

From the analysed data the following conclusions about environmental impacts of brine discharges can be drawn:

- The marine environment is affected by physical and chemical properties of desalination effluents. Impacts can be caused by pollutant concentrations and loads.
- Pollutant concentrations cause acute impacts within a local mixing zone until they are decreased to harmless or ambient levels. The acute impact zone depends on the dilution rate of the brine in the receiving water.
- Pollutant loads can cause chronic impacts and long term effects if the accumulation rate surpasses the natural decomposition rate. Chronic impacts are not necessarily restricted to a zone around the outfall but can occur in the whole water body.
- Increased salinity and temperature cause local problems. The impact of salinity is more critical for RO plants due to the higher recovery rates. Increased temperature is an environmental problem of thermal plants.
- Antifouling chemicals like chlorine are highly toxic, but are mainly an acute problem within the mixing zone of MSF plants.
- Antiscaling chemicals are non-toxic, but some agents are poorly degradable and might cause chronic impacts due to load accumulation.
- Coagulants are non-toxic, but may disturb the photosynthesis process as they increase water turbidity. Antifoaming additives are non-toxic and generally well degradable.
- Heavy metal discharge due to corrosion is a major problem in MSF plants. Copper is the only critical element in terms of discharged loads and possible impacts. It can be acutely toxic to a certain degree but mainly generates load problems through accumulation. Other heavy metals may also be toxic but are discharged at non-critical concentrations.
- The pH values prevalent during chemical cleanings are toxic if directly rejected. The chemical mix used for RO membrane cleaning can have highly toxic local effects as well as long term impacts due to poorly degradable constituents.
- The ecosystem of water bodies with high desalination activities and low water exchange like the Arabian Gulf or the Red Sea are particularly endangered. Large parts of the shorelines can be affected and load accumulation risks are higher. Low water depths, sensitive coastal ecosystems and significant pollutant discharges make the Arabian Gulf the most endangered water body (cf. Appendix A-D).
- The complete spectrum of impacts provoked by desalination effluents is still not entirely known and tolerance or toxicity levels have not been examined for all concerned marine species. Furthermore, complex synergy and cumulative effects of different pollutants add another uncertainty factor to the real extent of environmental impacts. Thus the results of present studies should be treated as a minimum impact.

All in all, environmental impacts of brine discharges cannot be neglected and further research is needed to validate and extent the current knowledge. Table 1 summarises the results about marine impacts of RO and MSF plants.
A classification is now to be established for the pollutants in order to display their potential harmfulness in MSF and RO processes (Table 2). The classification considers the outlined results about toxicity, degradability, applied dosages and process relevance. The following ranking seems appropriate:

### Table 2 Potential harmfulness of major pollutants in MSF and RO effluents

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>MSF</th>
<th>RO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very critical</td>
<td>Chlorine</td>
<td>Cleaning solution</td>
</tr>
<tr>
<td>Critical</td>
<td>Temperature, Antiscalants, Copper, THM</td>
<td>Salinity, Antiscalants, THM</td>
</tr>
<tr>
<td>Less critical</td>
<td>Salinity, Cleaning solution, Nickel</td>
<td>Coagulants</td>
</tr>
<tr>
<td>Non-critical</td>
<td>Antifoaming, Other metals</td>
<td>Temperature, Metals</td>
</tr>
</tbody>
</table>

This classification will be consulted for the ecological assessment of mitigation technologies in Chapter 6. Highest efforts should be undertaken to reduce or avoid the discharge of pollutants classified as ‘critical’ and ‘very critical’.
3.2 Case study: Sur plant, Oman

The possible impacts of desalination effluents on a specific marine ecosystem are illustrated at the example of the Omani seawater desalination plant near Sur (Fig. 9). The presented data has been acquired during personal conversation with Dr. Michel Claereboudt, associate professor from the Department of Marine Science and Fishery at the Sultan Qaboos University in Muscat. Dr. Claereboudt investigated the marine impacts of the Sur plant on behalf of the Omani environmental consulting company ‘HMR Consultants’ and issued a report in 2006.

At that time the Sur desalination plant was a small-sized RO facility with a production capacity of 12,000 m³/d. The exact recovery rate of the plant is not known. At an assumed rate of 40-50% a discharged brine volume of at least 250 m³/h with a salinity of twice that of the feed water can be expected. The brine was discharged via an open sea pipe of about 20 cm in diameter next to the shoreline.

The impact zone of the discharged brine was visible as a shimmer on the water surface and covered an area of about 100 m². At the bottom of the sea, in vicinity of the outfall, a large coral reef was situated. Several ten meters after the outfall - the distance needed for the dense RO plume to sink to the sea bottom - the corals started to be seriously damaged or were already dead. A clear transition zone between dead and still healthy corals became visible, as can be seen in Fig. 13. The pictures also display the high turbidity of the water in the impact area. The dead coral zone extended over an area of several hundred meters in length and width. Corals are known to react very sensitive to pollution and alteration in the living conditions. According to Mr. Claerboudt they are highly sensitive to salinity changes which must have been the main effect for the die-off. The chemical dosages of the plant are not known and an additional impact through chemicals could not be excluded.

![Fig. 13 Impact of the Sur plant effluent on a nearby coral reef: Transition to the impact zone (left) and close-up view of dead corals within the impact zone (right) (courtesy of Michel Claerboudt)](image)

The Sur plant case shows that even small desalination plants with low discharge volumes can have alarming impacts on the marine environment. Obviously the large variety of marine ecosystems reacts differently and has different sensitivity and tolerance levels towards brine...
discharges. These differences must be considered when planning and conducting desalination activities.

Höpner et al. (1996) presented a list which ranks 15 coastal subecosystems according to their sensitivity (Table 3). Criteria for the classification were the sensitivity towards desalination effluent characteristics, the water exchange capacity and the natural recovery potential. The higher the number of the ecosystem the more sensitive it reacts and the more adverse effects have to be expected from desalination activities.

Table 3 Coastal subecosystems and characteristics ranked according to their sensitivity (based on Höpner et al., 1996)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Subecosystem</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>High energy oceanic coast, rocky or sandy, with coast-parallel currents</td>
<td>plenty of oxygen, nutrients and energy; efficient biodegradation</td>
</tr>
<tr>
<td>2.</td>
<td>Exposed rocky coasts</td>
<td>good water exchange in all areas</td>
</tr>
<tr>
<td>3.</td>
<td>Mature shorelines</td>
<td>low particle accumulation through high sediment mobility</td>
</tr>
<tr>
<td>4.</td>
<td>Coastal upwelling</td>
<td>high water exchange, but seasonally limited</td>
</tr>
<tr>
<td>5.</td>
<td>High energy soft tidal coast</td>
<td>still high sediment mobility, but accumulation tendency in certain areas</td>
</tr>
<tr>
<td>6.</td>
<td>Estuaries and estuary-similar systems</td>
<td>seasonally changing water quality and turbidity</td>
</tr>
<tr>
<td>7.</td>
<td>Low energy sand-, mud- and beachrock-flats</td>
<td>limited water exchange; house many species and tend to accumulation</td>
</tr>
<tr>
<td>8.</td>
<td>Coastal sabkahs</td>
<td>exposed to wind, dust and solar radiation; rarely capable of degradation</td>
</tr>
<tr>
<td>9.</td>
<td>Fiords</td>
<td>shelter for many sea animals; limited exchange and tendency to oxygen deficits</td>
</tr>
<tr>
<td>10.</td>
<td>Shallow low-energy bays and semi-enclosed lagoons</td>
<td>endangered by load concentrations; low water exchange</td>
</tr>
<tr>
<td>11.</td>
<td>Algal (cyanobacterial) mats</td>
<td>lower sensitivity, but reactions to many stress factors are still unknown</td>
</tr>
<tr>
<td>12.</td>
<td>Seaweed bays and shallows</td>
<td>sanctuary for breeding animals; tendency to load concentration; sensitive</td>
</tr>
<tr>
<td>13.</td>
<td>Coral reefs</td>
<td>shelter for a big variety of species; many species with high sensitivity</td>
</tr>
<tr>
<td>14.</td>
<td>Saltmarsh</td>
<td>sensitive macrophytes and animals; very vulnerable to load concentrations</td>
</tr>
<tr>
<td>15.</td>
<td>Mangrove flats</td>
<td>rapid decline through pollution and changing conditions; plants and animals can hardly tolerate any pollution</td>
</tr>
</tbody>
</table>

As can be seen coral reefs are ranked at the 13th place and are characterised by high sensitivity. This categorisation correlates well with the observed impacts in the shown case study. Desalination outfalls should be situated far away from subecosystems of the last ranks.
In order to analyse the numerous conceivable impacts of desalination projects and to avoid severe environmental effects in advance, environmental impact assessments are usually conducted.

### 3.3 Environmental impact assessment (EIA)

Environmental impact assessments are a method of evaluating the adverse environmental and socio-economic effects of industrial projects. Benefits and disadvantages of the project are weighed out against each other and mitigation measures are recommended to cope with the adverse effects. The results are presented in an EIA report and constitute a decision basis for national authorities to grant or dismiss a project or to impose restrictions on it.

In most countries EIAs for desalination plants are carried out prior to the project start. However, until now there is no generally admitted EIA procedure or global standard for desalination plants. Consulting companies all over the world, e.g. HMR Consultants in Oman, use their own methods. Common guidelines would be highly preferable in order to standardise the EIA procedure and in order to make the EIAs comparable. In the course of the Mediterranean Action Plan (MAP) the United Nations Environment Program (UNEP) issued a general guideline on EIA procedures and recommended contents. The MAP proposal comprises ten assessment steps for desalination projects covering all aspects of environmental and socio-economic importance (UNEP MAP, 2003):

1. **Land use and site selection**, considering
   - Different interests in coastal land use (recreational, social, etc.)
   - Environmental disturbances on soil, water and air during construction
   - Impacts on the local habitats during operation

2. **Energy use alternatives and air quality**, considering
   - Atmospheric emissions including greenhouse gases and acid rain pollutants
   - Risk of accidents due to fuel transports and handling

3. **Sea water intake**, considering
   - Risk of entrainment and impingement of marine organisms
   - Disturbance of marine life during construction
   - Risk of salt water intrusion into the ground water

4. **Brine and chemical discharges**, considering
   - Potential impacts of salinity, thermal discharge, chemicals, etc. on the marine environment
5. **Combination of the waste stream with other discharges**, weighing up
   - Positive dilution aspects of brine stream blending with cooling or sewage water
   - Additional thermal and chemical stress through brine stream blending

6. **Oceanographic conditions and use of dispersion models**, including
   - Assessment of currents and effluent mixing behaviour
   - Risk assessment for surface and benthic organisms as a result of the plume

7. **Transboundary effects**, considering
   - Possible effects outside the focused area through accumulation and persistence of substances
   - Global effects of local environmental decline

8. **Potential growth of water demand**, evaluating
   - Upcoming development and the necessity for desalination

9. **Socio-economic impacts including impact on the citizens**
   - Benefits like safe, reliable drinking water and ground water protection
   - Risks like changing consumption pattern towards water waste and misuse

10. **Pre- and post-operational monitoring programmes**
    - Important tool to assess the accuracy of predictions made by EIA
    - Pre-operational monitoring provides data of the initial state of the ecosystem
    - Post-operational monitoring gives comparable impact data after the operation start

Impacts of brine and chemical discharges are dealt with in item 4 and partly in item 7 of the procedure. Land use, sea water intake and air pollution are other major environmental topics covered by the assessment. Specific ecological and geographical characteristics of the proposed plant site, the shoreline and the ocean are considered in the assessment.

Besides the environmental aspects, the concerns and interests of residents and water consumers as well as the economic benefits and possible drawbacks for the region are evaluated. The public opinion and the socio-economic effects of desalination are covered in the following chapter.
Public opinion

Public acceptance of or opposition against desalination plants depends on many factors. The importance of desalination for the development of a country and the magnitude of water scarcity play an important role for the public opinion. The general environmental awareness of the people, financial aspects of desalination projects and the social function of coastal areas are other influencing factors. Accordingly the opinions and the approval of desalination differ around the globe. This chapter provides an overview over different regions and countries.

4.1 Public opinion

Public acceptance of or opposition against desalination plants depends on many factors. The importance of desalination for the development of a country and the magnitude of water scarcity play an important role for the public opinion. The general environmental awareness of the people, financial aspects of desalination projects and the social function of coastal areas are other influencing factors. Accordingly the opinions and the approval of desalination differ around the globe. This chapter provides an overview over different regions and countries.

4.1.1 MENA region

The MENA region is characterised by high water scarcity and quickly growing populations in many of the countries. The production of clean and sufficient drinking water is essential and has become an industrial sector of upmost importance. All capacities are currently extended.

Tolba et al. (2006) conducted a survey which investigated the public opinion of the Arab world towards environmental issues. Between November 2005 and March 2006 3,876 citizens from 18 countries of the Arab League were questioned. 60 % of the respondents declared that the state of the environment had deteriorated in the past ten years and only 30 % thought it had improved.

65 % considered sea, coastal and lake pollution to be a major problem and 27 % considered it to be a minor problem. Considering all topics, sea and coastal pollution was only ranked the 8th most urgent problem on the environmental agenda as can be seen in Fig. 14. The share of respondents who considered sea pollution a major problem was considerably higher in countries with long coasts e.g. Morocco (96 %) and Saudi-Arabia (85 %). Oman and UAE (both 68 %) were in the middle field.

Drinking water was indicated as a major problem by 69 % of the respondents and as a minor problem by 17 % (Fig. 14). The share of people who did not consider drinking water supply to
be a major problem was considerably high in countries with the highest water scarcity which are all highly dependent on desalinated water (41% in Qatar, 35% in Oman and Kuwait, 31% in UAE). In countries such as Iraq and Sudan where many people do not have access to sufficient water, in contrast, drinking water constitutes a major problem according to the vast majority of the respondents.

95% of the informants agreed that their country should do more about the environment but only 68% were willing to pay taxes for the sake of environmental protection.

![Fig. 14 Assessment of environmental problems according to respondents in MENA countries (Tolba et al., 2006)](image)

The study shows that seawater pollution is considered a major environmental issue by the majority of people in Arab countries, but not one of the most urgent ones. Sensitivity towards the drinking water problem correlates with the undersupply of the population, not with the scarcity of natural water resources. Countries with the highest desalination capacities rate the drinking water problem the least critical. This indicates that seawater desalination is a well accepted technology for drinking water production in these countries. Environmental concerns, criticism or even opposition concerning desalination plants in Arab countries cannot be derived from this study.

**Saudi-Arabia**

Saudi-Arabia possesses a total desalination capacity of currently 3,000,000 m³/d and additional 6,000,000 m³/d are planned to be installed within the next 20 years (Global Water Intelligence, 2004). The Saudis pay low for their water although it is very expensively produced and transported. Public concern or resistance against desalination is not reported. Instead the highly inefficient Saudi-Arabian water management in general is criticised by
external observers. The WWF criticised that the country combines very low water prices with the highest production and distribution costs worldwide. Traditional water use restrictions have been abandoned and highly unproductive agricultural farms in desert areas in the interior are irrigated with ground water. Thus desalinated water for domestic use has to be provided via pipelines over hundreds of kilometres from coastal locations. The World Bank criticised the subsidised energy prices which favour inefficient desalination technologies in the kingdom, notably thermal desalination (WWF, 2007).

**Israel**

Israel is also highly dependent on desalinated water since extensive agricultural activities and recurring droughts have accelerated the depletion and contamination of ground water resources. The world’s largest RO desalination plant with a capacity of 320,000 m³/d is situated in Ashkelon.

Israelis are getting increasingly concerned about the pollution of the marine environment but the focus is much more on industrial sewage than on desalination effluents. The fears of ocean pollution are partly based on the possibility of rising water prices due to deteriorating quality of intake water for desalination plants. Specific concerns about scheduled desalination plants are mainly politically motivated, e.g. as result of plans to build a channel between the Red Sea and the Dead Sea in order to supply more water for Jordan.

**Oman**

Oman might be exemplary for the Gulf States when it comes to the public opinion towards desalination. A stay in the country provided the opportunity to talk to different Omani around the capital area in 2007. When asking the Omani, among them university students, professors and ordinary people, about their opinion on desalination and the possible adverse effects, the answers were almost unanimous. The Omani evaluated desalination plants as essential for the country and for their own life. They could not imagine any alternative to desalination since the ground water resources were too small and unreliable. Most of the questioned people were not aware of possible adverse effects and could not imagine any impacts of desalination plants unless maybe air pollution. This might be due to a lack of knowledge about the technology. When pointed to the possible side effects, most people agreed that such effects should be avoided but that desalination would anyway remain indispensable. When visiting two MSF plants, the plant operators assured that they would stick to the environmental regulations which they believed to be sufficiently stringent. All in all, hardly any of the interviewed persons uttered major concerns regarding desalination, but most agreed that the impacts of brine discharges should be restricted.

Dr. Abdul-Wahab from the Department of Mechanical and Industrial Engineering at the Sultan Qaboos University in Muscat investigated the environmental awareness of the Omani public and their willingness to protect the environment in 2007. 425 people in the Muscat
governorate area from different educational backgrounds were questioned for the survey. The study examined three aspects (Abdul-Wahab, 2008):

- Environmental knowledge
- Environmental attitudes
- Environmental behaviour

The basic environmental knowledge of the respondents was generally low and more than half of them gave incorrect answers to basic questions like the chemical composition of the atmosphere. They were more knowledgeable about local environmental problems and international environmental problems such as climate change.

Environmental attitudes reflected the opinion on the state of the environment and the satisfaction with environmental protection by the government and were found to be overall positive. However, most respondents requested the government to do more about the environment. Only a minority thought that the individuals should take more responsibility for environmental protection.

The environmental behaviour was revealed to be low. Only around 40% were willing to change their lifestyle in order to protect the environment.

The question of seawater desalination was not included in the survey which might reflect the low local sensibility for the problem. The results on environmental behaviour indicate that the willingness to restrict the lifestyle in order to save water resources is probably low. The reported deficiencies in environmental knowledge might explain that Omanis do not know about possible environmental impacts and thus do not have reservation towards the desalination technology. Another answer could be that the Omani desalination capacities are still too small to show any obvious detrimental effects. There are only four major plants on the long north-eastern coast which leads directly into the Arabian Sea. Pollutant accumulation and impact multiplications like in the semi-enclosed Arabian Gulf are less probable.

Summary

All in all, no public opposition or major reservations against desalination plants based on environmental concerns were found in MENA countries. The most important reason seems to be that desalinated water is an inherent part of many people’s life and that many countries are highly dependent on it. Besides, a lack of knowledge about the desalination technology and its possible impacts might explain the findings. In countries like Oman, where the seawater desalination capacities are still low, the potential impacts are not visible at first glance. The public attitude might change if the environmental impacts rise to an extent which would significantly interfere with people’s standard of living.
4.1.2 Western countries

A different picture arises in the so called Western countries. The traditionally high environmental awareness and the existence of alternative water sources and water saving options lead to a more controversial debate about desalination.

United States

In the U.S. the states Texas, Florida and California suffer from the most serious water scarcity and account for the highest desalination capacities in the country. Public opinion about desalination differs.

Texas is primarily relying on brackish water desalination. Most seawater projects were dismissed because of the high expenses and not because of strong public opposition.

Florida is the state with by far the highest installed desalination capacity in the United States, but predominantly relies on brackish water desalination. The first major seawater plant of the country was built at Tampa Bay. It was designed to produce 95,000 m³/d but it never reached this capacity due to filter and membrane failures. Financing problems and contractor bankruptcies led to long delays in the construction phase and prevented proper operation. In 2005 the plant eventually had to be closed for two years since the chemical pretreatment system did not meet the water quality standards of the RO membranes.

In a survey issued by the Tampa Bay Water company in 2005 only 4 % of the respondents supported a focus on desalination in order to meet the drinking water needs of the region. 47 % were not willing to pay more than 10 US-$ per month in addition for the development of new water supplies like desalination plants. Another 20 % were not willing to pay anything at all (Tampa Bay Water, 2005). The negative experiences with seawater desalination at Tampa Bay also fuelled controversial debates at the west coast.

California is predicted to emerge as one of the new desalination hotspot within the next decades. 15-20 major seawater desalination plants with a total capacity of 1,700,000 m³/d are planned until 2030, covering 6 % of the state’s water supply by that time (Höpner, et al., 2008).

In 2002 a public opinion poll of 601 Californian voters issued by the West Basin Municipal Water District found that 70 % favoured desalination as future drinking water option. The reduced dependence on imported water, improved quality of local water supplies and increased water availability for environmental and agricultural use were given as main reasons for the approval (Miller, 2003).

In 2004 the San Diego County Water Authority conducted a study about the public opinion on seawater desalination. The results for desalination were quite favourable as Fig. 15 illustrates (San Diego County Water Authority, 2004).
Fig. 15 Results of an opinion poll on seawater desalination in San Diego County (San Diego County Water Authority, 2004)

70% of the respondents thought that seawater desalination generally is a good idea and only 14% explicitly disagreed with the idea. Desalination supporters primarily listed the large water supplies in close proximity and the function as possible backup source as an advantage. Those who opposed desalination were mainly concerned about a possible contamination of the product water and secondly about the high costs. Only 8% of the opponents had environmental concerns. When asked directly about environmental implications 46% believed that desalination would not be harmful to the ocean environment. Only 20% believed that desalination could be harmful to the ocean. Most of them worried that seawater desalination alters the salinity of the ocean, has general bad impacts on the environment and disturbs the natural balance. Only 6% listed chemicals as potential harm for the ocean life (Fig. 16).

When it comes to the construction of a concrete plant in the San Diego County even 75% stated they would favour the project and only 7% were opposed, with costs being the primary concern. However, the share of people who were ‘unsure’ about environmental impacts (34%) or claimed to ‘need more information’ was significant and indicates that many citizens believe not to have enough knowledge to entirely assess the risks of desalination plants or that they are sceptical. But altogether the polls indicate that public concerns about seawater desalination are moderate and a large majority favours the technology.
However, Californian minds seem to change when it really comes to implementing specific projects. None of the large scheduled desalination projects in California easily got the necessary approvals or was started in time. Due to strong public opposition and regulatory obstacles the construction and operation starts of many plants were delayed and some projects were completely dropped. Until now none of the large projects has been finished.

The 189,500 m³/d RO plant in Carlsbad in San Diego County was scheduled to begin construction in 2005 and to be finished in 2008. Despite the high theoretical approval rates in San Diego County resulting from the presented poll it took much longer to get adequate approval rates in the municipality as well as state level authorisations (WWF, 2007). As a result constructions will not be completed until 2010.

Even harder battles with local communities had to be fought at Huntington Beach where another 189,500 m³/d RO plant was to be built. The construction start was scheduled for 2004 and operation start for 2006. But when the project was announced strong citizen movements arose, e.g. the activist group ‘Residents for responsible desalination’. A clear statement and the main motivation of the group can be found of its website (RFRD, 2008): “We believe seawater desalination should not replace conservation or reclamation and reuse of water, and should not harm the ocean environment, should not damage local property values, neighbourhood residential communities, or our tourist economy, and should not diminish local public control of our vital water resources. We believe that the Poseidon proposal for Huntington Beach fails on all these points.” Besides, many letters of annoyed residents who are concerned about a decline in living standards caused by the plant can be found on the website. Due to the rigorous public opposition the construction start of the Huntington Beach plant was delayed to the year 2007 and the completion is expected for 2009.
The reasons for opposition against specific desalination projects in California are manifold. But most public concerns are based on environmental and cost arguments as the following selection shows (WWF, 2007; RFRD, 2008):

- Unacceptable environmental impacts of the desalination units expected
- Cogeneration of most projected plants with coastal power stations using ‘flow through cooling intakes’ → controversial as these are likely to be harmful for the marine environment
- Urban water saving, enhanced water recycling and efficiency improvements in the agriculture sector should be preferred
- Doubts in the cost-effectiveness of desalination
- Possible taxpayer subsidies for financing the energy costs
- Projected privatisation of most plants provokes losses of public ownership and control
- Fears of coastal overdevelopment
- Devaluation of the coastal area and decreasing tourist activities
- Increasing noise and air pollution

To conclude, passionate commitment for civil rights and ecological campaigns has a long tradition in the U.S. public. It seems that the high theoretical approval rates for seawater desalination are dropping when it comes to the realisation of a specific project. Even if opposition is only based on a minority of the population or some annoyed residents, the movements are obviously capable of substantially delaying major projects. The Californian experience can translate to other states if they decide to embrace large scale desalination plans. Unless the desalination industry cannot dispel the major cost and environmental concerns about desalination plants it seems to be difficult for the technology to gain ground in the United States.

Spain

Spain has a renowned desalination industry with customers around the world. The country disposes of the largest desalination capacity in the Western world with current capacities of more than 1.6 million m³/d. But despite its long and strong tradition, desalination is not an entirely uncontroversial topic in Spain.

The country has highly invested in desalination to secure its water supply. Critics say that this is too costly and unnecessary and call for improvements of the bad water management instead. Spain is using more than one fifth of the desalinated water for its highly subsidised agriculture which is more than in any other country. It is more accepted in the public to build a desalination plant for supplying the agriculture than for supporting tourism and urban development. Despite the large supplies with desalinated water farmers still continue to illegally access the groundwater in order to save costs. Operation start of Europe’s largest seawater RO plant in Carboneras had to be delayed due to funding disputes with local farmers. Obviously, opposition is grounded on the high water prices although desalinated water is already strongly subsidised by the government. On the other side a boom of tourist
Public opinion

Estates can be noticed throughout the country which eventually also has to be supplied by costly desalination plants.

The New Water Culture Foundation, a Spanish non-profit organisation, demands more reasonable desalination policies. The foundation calls for improving the water management, slowing down the capacity extensions and conducting full environmental assessments of each desalination plant. Furthermore, desalination sites shall be restricted to industrial areas and zero discharge plants should be taken into consideration (WWF, 2007). Zero discharge plants enable desalination without brine discharges and will be covered in detail later on.

It can be seen that the debates in Spain are concentrating on costs, environmental impacts and possible mitigation measures. It is not a debate about the usage of desalination but about the extent of usage and the preferred fields of application.

Australia

A survey among a representative number of 1000 Australians about their perception of desalination and water recycling was conducted by the University of Wollongong in 2007. When asked about their main concerns regarding desalination, high costs, environmental burden and health-related topics were mentioned. Costs and environment were the most urgent issues for the interviewees.

When asked directly about the environmental impacts of desalination, 81% were aware of the high energy consumption of the plants. Desalination was perceived as less environmentally friendly than recycled water. A majority of 69% believed that desalinated water is healthy. But 24% believed it is purified sewage and 20% agreed that it contains endocrine disruptors which could affect fertility. This reflects the ignorance about the topic.

However, the overall acceptance for desalinated water was higher than for recycled water. A majority of respondents would prefer the use of desalinated water for close body contact like bathing or drinking and chose recycled water for purposes like watering the garden or irrigation of parks (Dolnicar et al., 2007; Birnbauer, 2007).

When it comes to specific projects the differing opinions about desalination in Australia abound. The scheduled desalination plant in Sydney was controversially debated. When the plant was first proposed in 2005 the State premier himself denounced it as “bottled electricity”. The ‘Sydney Community United against Desal’, an activist group made up of scientists, engineers and environmentalists, formed to oppose the Sydney plant. They called for more water recycling and improved water management instead.

A survey revealed that almost 60% of the Sydneysiders opposed the desalination project. Only 34% were in favour of the plant and even half of the proponents preferred to invest in water reuse and recycling instead. Two thirds of the respondents were worried about the greenhouse gas emissions. Due to strong opposition from environmentalists, the unpopularity in the community and the discovery of additional ground water resources, the project was dropped in 2006 (Frew, 2005; Davis, 2006). It was not before 2007 that the government pushed through the project and launched the construction start of a plant with much smaller capacity than usually planned.
In other regions of the country like Queensland and Perth desalination projects have been implemented without major delays and hesitation. The RO plant near Perth with a capacity of 123,000 m³/d was the first major plant to start operation and is currently the only one. The reason for the quick project implementation was that the water supply could not keep pace with the fast, uncontrolled urban development. Water management was badly organised and the time for demand side adaptations had run out as. In order to quiet the ecological minds relatively high attention was paid to environmental issues when designing the Perth plant (WWF, 2007).

**Summary**

Public opinion about seawater desalination in Western countries is ambiguous. Whereas a majority of people in relevant countries generally favours desalination, the community approval rates often drop when a specific project is announced or when people are getting directly concerned. Environmental and cost concerns are most commonly raised. A certain ignorance can be detected since many people do not know what to expect from desalination. Opponents often demand to intensify the water saving efforts and to concentrate on natural water resources. Nevertheless, after significant initial opposition several major projects are on the way or already running in California and Australia. Spain is only debating about the extent of desalination application.
4.2 Socio-economic effects

Evaluating the socio-economic impacts of desalination projects is an important part of an EIA study. The following positive and negative effects of desalination plants are generally conceivable (UNEP MAP, 2003):

Positive effects

- Desalination may raise the living standard by providing a better access to water and a source of clean and reliable water which is independent of the climate situation and other external influences.

- Water shortages can be a limit for population and economic growth. Desalination can create wealth by increasing the possibilities for agricultural production, industrial activities and tourism in countries with water scarcity. This may raise the overall income in the region. Even some direct jobs and income can be expected from a desalination plant.

- Desalination may be a solution to some environmental problems in regions where the natural water resources are already vastly exploited. Unsustainable water exploitation can cause effects like desertification which result in a decline of people’s living standard. Desalinated water can reduce the pressure on natural resources and restore sustainable water consumption.

- Limited water can be the root of heavy conflicts between consumers, agricultural and industrial sectors or between people of different ethnics and social classes. It was often anticipated that the wars of the 20th century will be fought about water, not oil. Desalination may help to ensure stability and peace in water scarce regions.

Negative effects

- Desalination activities can entrain other industrial and infrastructural activities and lead to overdevelopment of coastal areas and structural inequalities within the country. Inland locations might be cut off from large supplies unless costly and complex transportation over large areas is taken into consideration. Migration of people from rural inland areas to the coastal suburban centres may be accelerated and overpopulation of coastal regions can intensify.

- The use of desalination can lead to water misuse and wastage by creating the impression that water is sufficiently available and that capacities can easily be enlarged. Unsustainable consumption pattern may arise and lead to additional environmental burden and the need for water capacity extensions.
Adverse environmental impacts of desalination can involve social and economic problems. Deteriorating seawater and air quality may result in the loss of recreational areas and possible health problems. The fishery industry can suffer from reduced fish populations and the tourist industry can suffer from environmental pollution and industrial activities in coastal areas.

Relying to a large extent on seawater desalination can create dependencies. In the case of chemical accidents or oil spills which affect the intake zone, the plant would have to be shut down and water supply might collapse. Besides the large energy consumption makes desalination plants vulnerable to energy cuts.

It is plausible that desalination plants promote effects like improved access to safe water, rising living standards and economic growth. But in reality these socio-economic effects are influenced by a variety of factors and the real share of desalination is difficult to measure. The following analysis is to investigate how desalination is connected to some of the observed effects.

Water availability

Table 4 shows the values of water scarcity and access to safe water in selected MENA countries and lists the per capita GDP for each country (DLR, 2007).

- Water scarcity is defined as the ratio of total water use to natural water availability. The more the value exceeds one hundred per cent the higher is the need for additional water sources.
- Access to safe water is defined as share of the population with access to a sufficient amount of water from safe sources like household connections, boreholes, wells, etc.

<table>
<thead>
<tr>
<th>Country</th>
<th>Water scarcity (%)</th>
<th>Access to safe water (%)</th>
<th>GDP per capita(^1) (US-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egypt</td>
<td>106</td>
<td>72</td>
<td>1,506 (2006)</td>
</tr>
<tr>
<td>Libya</td>
<td>720</td>
<td>68</td>
<td>9,900 (2007)</td>
</tr>
<tr>
<td>UAE</td>
<td>1488</td>
<td>100</td>
<td>23,700 (2005)</td>
</tr>
<tr>
<td>Qatar</td>
<td>538</td>
<td>100</td>
<td>70,754 (2007)</td>
</tr>
<tr>
<td>Oman</td>
<td>132</td>
<td>92</td>
<td>13,190 (2006)</td>
</tr>
<tr>
<td>Yemen</td>
<td>157</td>
<td>30</td>
<td>(\approx 650)</td>
</tr>
</tbody>
</table>

\(^1\) Data derived from the German foreign ministry website
It can be seen that none of the listed countries can exclusively rely on natural water resources to cover the total demand. All countries have to provide additional sources of water in order to keep pace with the demand. If no other natural sources are available the only means is to import water or to generate capacities of desalinated water.

UAE, Libya and Qatar suffer from the highest water scarcity. Nevertheless UAE and Qatar manage to provide access to safe for 100 % of the population whereas a country with much lower water scarcity like Egypt only manages to supply enough water for 72 % of the population. The small states UAE and Qatar may be a special case. But it is obvious that the access to sufficient water supplies is directly correlated to the wealth of a country (expressed in per capita GDP), independent of the magnitude of water scarcity. Countries with the lowest per capita GDP also have the lowest access rates to safe water.

Similar to the other rich Gulf countries, Oman relies on several large seawater desalination plants in order to cover the water demand of the more densely populated coastal regions and reaches a water access rate of 92 %. Neighbouring Yemen which has about the same size and population and virtually the same climatic conditions as Oman is much poorer and can only adequately supply 30 % of the population.

The possible consequences of water scarcity become obvious in the case of Yemen. In the last ten years many conflicts about water and land have been reported in the country. In 1999 the Al Thawra newspaper reported the death of six people and seven injured after clashes between two tribes which were triggered by disputes about water and agricultural land. In the same year the Al Shoura reported that sixteen villagers had been killed in a conflict with state troops because they did not want to share well water with neighbouring villages (World Bank, 2007).

From the outlined figures it can be concluded that seawater desalination definitely improves the water availability and the access to safe water in arid countries and thus contributes to a high living standard of the population. However this effect is only visible in rich countries. The poorest countries obviously cannot afford the high investments relevant for desalination. Consequently the water access levels in poor countries remain low, even if the water scarcity is less severe. The cited World Bank report assessed, however, that desalination is becoming increasingly viable for poorer countries whereas it was in exclusive use of high income countries in the past.

**Growth effects**

The EIA conducted for the *Carlsbad desalination plant* in San Diego County, CA included an evaluation of possible growth-inducing impacts of seawater desalination. The county was previously relying mainly on imported water, surface reservoirs, water reuse and conservation efforts. The EIA outlined possible growth effects of the project and distinguished between direct growth-inducing effects like new employment and related development projects and indirect growth-inducing effects like extension of urban services to the outskirts, extension of infrastructure or removal of obstacles to growth.
The San Diego County Water Authority (CWA) investigated growth effects of the Regional Water Facilities Master Plan and concluded that seawater desalination can provide reliable, but not guaranteed, shortage free water for the future population. Seawater desalination “neither supports nor encourages growth to a deeper degree … and is therefore not inherently directly growth-inducing” (City of Carlsbad, 2005). Desalination may induce indirect growth effect, but many other components like infrastructural facilities, educational facilities, employment opportunities, electricity and emergency services also play an important role. The districts which would receive water from the Carlsbad plant are not likely to change their land use plans, growth or population projections only because of a new mix of overall water supplies, according to the CWA. Consequently, major growth effects of a desalination plant within the City of Carlsbad cannot be expected.

A similar conclusion about population growth is drawn in the case of the Huntington Beach desalination project in Orange County, CA. The population of Orange County will grow, even if desalination is not applied. The Huntington Beach plant would provide water for 250,000 additional people, but the natural growth rates project 500,000 more citizens in 2020. Desalination would only accommodate the inevitable growth which planning institutions in Orange County have projected for the next decades. The Californian Department of Water Resources affirmed that “growth isn’t driven by water supply. If it were, Humboldt County (in rainy northwest California) would be the state’s fastest growing area” (City of Huntington Beach, 2005).

The California Coastal Commission judged instead that water supplied by desalination plants may at least remove the primary constraint for growth in some coastal areas of California. Determining growth effects based on desalinated water in a special area, especially when effects of a single plants shall be measured, is believed to be very difficult since water from one source is not exclusively going to one customer area. The growth-inducing impact of a particular desalination plant depends on its service area, the state growth plans and the interconnection of water supplies. It is emphasised that densely populated states like California sometimes even make efforts to limit growth-inducing effects of projects (California Coastal Commission, 2004).

The WWF report on desalination concluded that freshwater supply is the limiting factor for community growth in California. The unlimited supply of desalinated water would cause unsustainable growth. California’s multiple development control mechanisms prevent such effects. Instead, particularly in regions of the Mediterranean and the Middle East a high correlation between desalination activity and unsustainable urban and tourism growth and high levels of environmental pollution was detected. Experiences show that environmental pollution is accelerated when additional water supplies such as desalination capacities are offered in an area of unregulated development. Therefore, effective land use planning schemes need to be established prior to the application of large scale desalination (WWF, 2007).

Many cities in the MENA region suffer from water shortages and the competition between rural and urban areas about water is increasing. “Water scarcity is becoming a major barrier for economic development” (DLR, 2007) in the region.
The capital area of Sana’a in Yemen is a spectacular example for severe water shortages. 13,000 water wells have been constructed in an uncontrolled and unsustainable manner in this area in order to meet the water demand of the population. As a consequence, the groundwater levels are decreasing by 3-5 m/a (Foster, et al., 2006). Although Yemen does not seem to have the financial means to conduct large scale desalination at the proposed Red Sea sites, calculations show that it might be less rewarding and even more expensive to do nothing. Seawater desalination at the Red Sea for 2 million Yemeni people would cost around 4 Billion US-$. The current situation of water scarcity and groundwater depletion produces economic costs of 1.4% of the Yemeni GDP, equalling 210 Million US-$/a, according to World Bank calculations. Divided by the excessively used water volumes, depletion costs of 0.08 US-$/m³ have to be added to the normal water costs of 0.50 US-$/m³ (Table 5). If the costs of environmental degradation caused by groundwater depletion (90 Million US-$/a) are additionally considered, the total water costs are increased by another 0.04 US-$/m³. The resulting total water costs of 0.62 US-$/m³ might be higher than the desalinated water costs and thus, desalination plants may be profitable even for Yemen.

As outlined in Table 5 the costs of groundwater depletion in other MENA countries are even higher than in the case of Yemen. The calculated total water costs in Algeria and Jordan clearly exceed the water costs of efficient desalination plants. Consequently, desalination can be theoretically rewarding for poorer nations with high water scarcity, when all economic aspects of water use are evaluated.

<table>
<thead>
<tr>
<th>Table 5 Costs of water depletion and resulting total water costs in selected MENA countries (based on DLR, 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Lost GDP (Mil. US-$/a)</strong></td>
</tr>
<tr>
<td>1,080</td>
</tr>
<tr>
<td><strong>2. Overused volumes (Mil. m³/a)</strong></td>
</tr>
<tr>
<td><strong>3. Depletion costs [1./ 2.] (US-$/m³)</strong></td>
</tr>
<tr>
<td><strong>4. Production costs (US-$/m³)</strong></td>
</tr>
<tr>
<td><strong>5. Total water costs [3.+ 4.] (US-$/m³)</strong></td>
</tr>
</tbody>
</table>

However, the limits of seawater desalination must equally be stressed. Due to the high operating costs and the high sensitivity towards energy prices, the use of desalination in poor countries is restrictive. The above shown costs of overuse could also be reduced by less cost-intensive water supply strategies. Besides, seawater desalination is mostly restricted to domestic use. It is not competitive to the usually low water costs in the agricultural sector and will not develop any significant growth impulses in this sector. This aspect further restricts the economic benefits for poorer countries which usually have a high agricultural share on the total economy. Furthermore, economic growth through seawater desalination will generally be restricted to coastal areas as the costs for pumping freshwater into inland territories...
increases with the distance. Because of these limits, desalination is “unlikely to resolve the fundamental mismatch between supply and demand in water” (DLR, 2007).

Malta can serve as a good example for the growth effects of desalination. The small arid island is quite wealthy, but dependent on tourism. In the 1980s the island was suffering from a chronic lack of water in the summer months, resulting in the deterioration of tourism business and industrial decline. The water scarcity had significant adverse effects on the economy, foreign exchange earnings and finally on investment and employment. The situation improved when the country was embracing the construction of several new RO desalination plants. Together with an upgrade in tariffs in order to avoid water misuse, the economic crisis was overcome. In the case of Malta, water scarcity was the prime obstacle for economic development and the investment in desalination was highly beneficial for the economic growth of the country (Riolo, 2001).

Similarly high dependence on desalination can be observed on the Canary Islands. 50% of the population relies on desalinated water and the production of water is directly linked to economic growth. On islands with desalination plants the tourist numbers are higher and keep growing. According to the Head of the Canary Islands Water Centre, the environmental impacts of desalination on the islands are minimal compared to the socio-economic growth they trigger. The most severe environmental challenges are set by the growth itself. It must be controlled and organized in a sustainable way (Hernández-Suáres, 2003).

**Results**

Seawater desalination has obviously improved the access rates to water and triggered (possibly unsustainable) economic growth in rich MENA countries. In Western countries with moderate climatic conditions the growth effects of desalination cannot definitely be detected and may not even be desired like in California. The economic development on islands which have specialised on tourism can be boosted by desalination as examples from Malta and the Canaries have shown. In each case growth effects will be limited to coastal regions unless inefficient water transport systems are installed. Due to the high costs, desalinated water will mostly be restricted to domestic application.

Due to the high investment and energy costs, however, the social and economic benefits of desalination are not or only restrictively applicable for poorer countries, even if current water overuse and depletion generates higher economic costs.
5. Regulatory aspects

An important way to control and restrict adverse environmental impacts of seawater desalination plants is to put up appropriate national laws or transnational agreements. These may regulate the brine discharge management, set up discharge limits or impose environmental standards and conditions mandatory for receiving operating permits. With respect to the worldwide desalination activities, the regulatory situation is very diverse and unclear. No common standards exist as each country has own water regulations which are more or less publicly accessible. Most regulations are abstract and do not apply specifically to desalination plants, but to industrial effluents in general. The following chapter gives an overview and comparison of regional and national regulations relevant for seawater desalination effluents in order to assess the level of regulatory protection of the marine environment.

5.1 The LBS protocol

The industrial activities around the Mediterranean coast have steadily increased in the last decades. The total desalination capacity amounted to 3.4 Million m³/d in 2005, mainly operated by Spain, Algeria and Libya (Höpner, et al., 2008).

In 1996 the amended version of the Protocol on the Protection of the Mediterranean Sea against Pollution from Land-Based Sources (LBS Protocol) was issued by the UNEP. The protocol was a result of the ‘Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean’ (Barcelona Convention). The LBS protocol defines a regional legal framework for dealing with the different kinds of marine pollution and aims at restricting the impact of all land-based activities on the Mediterranean Sea.

The central assignment of the protocol is documented in Article 5, § 1: “The Parties undertake to eliminate pollution deriving from land-based sources and activities in particular to phase out inputs of substances that are toxic, persistent and liable to bio-accumulate, listed in Annex I.” For this purpose, the contracting parties shall elaborate and implement national and regional action plans, under consideration of “the best available technique and the best environmental practise”. Desalination effluents are implicitly included in Article 6, § 1 which
states that “Point source discharges … shall be strictly subject to authorization or regulation by the competent authorities of the Parties” (UNEP MAP, 2003). Under the terms of Article 7, § 1 the contracting parties commit themselves to formulate and adopt common guidelines, standards and criteria dealing with, amongst others,

- the length, depth and position of pipelines for coastal outfalls, taking into account, in particular, the methods used for pretreatment of effluents
- the quality of seawater used for specific purposes that is necessary for the protection of human health, living resources and ecosystems,
- specific requirements concerning the discharged quantities of the substances listed in Annex I, their concentration in effluents and methods of discharging them,

Annex I includes pollutants which are to be regulated in the national legislations. The list comprises all pollutants relevant for desalination processes, including biocides and their derivatives, non-biodegradable detergents, compounds of nitrogen and phosphor, thermal discharges, acid or alkaline compounds, heavy metals and their compounds and non-toxic substances which have an adverse effect on the oxygen content or on the physical or chemical characteristics of the seawater. The authorisation of any discharge depends on compliance with standards arising from the requirements of the above mentioned aspects of article 7.

Some quality standards for pollutants have already been jointly adopted by the parties. Measures relevant for desalination plants are the so called “Measures for the control of pollution by zinc, copper and their compounds” (1996) and the “Measures for the control of pollution by detergents” (1996). They set a water quality objective of 8 µg/l and an effluent limit of 500 µg/l for total dissolved copper. The use of detergents shall be restricted to those which are at least 90 % biodegradable in order to reduce the input of non-degradable substances into the sea. Detergent input must further be restricted in identified hot-spot areas. The level of detergents in coastal recreational areas must be monitored, as well as the detergents level in effluents, when possible. Member countries are free to apply stricter regulations in their national legislations (UNEP MAP, 1996).

In order to be legally binding for all countries the LBS protocol must be ratified by at least 15 of the 21 Mediterranean countries. It has been ratified by 13 countries until now. The important desalination countries Libya and Algeria did not join the protocol yet (UNEP, 2008).

The original LBS protocol from 1983 has already fully entered into force. The only important difference to the amended version in the relevant chapters is that it divides pollutants into those which should be eliminated (Annex I) and those which should be strictly limited (Annex II). All the above mentioned pollutants are included in Annex II except for special biocides and phosphoric antiscalants. Thus, the amended version is more stringent than the original one.
5.2 EC Water Framework Directive

In 2000 the European Commission (EC) issued a new Water Framework Directive in order to improve the quality of European waters endangered by the impacts of point sources. The directive follows a ‘combined approach’ by limiting the direct emissions from point sources as well as by setting environmental quality standards. All point sources in member states have to meet both Emission Limit Values (ELV) and Environmental Quality Standards (EQS). Thus, the direct emissions of a plant as well as possible accumulation of pollutants and long-term effects on the water body are sought to be limited.

However, application problems arise since the directive does not define where, relative to the point source, the EQS criteria start to apply. They might apply directly after the point of discharge making the EQS identical to the ELV, or at the next sensitive area in reach, e.g. a beach. Furthermore, the directive does not state how to monitor if the EQS values are met by the point sources.

Jirka et al. (2004) recommended a precise mixing zone regulation in order to define after which distance the EQS standards turn into effect. Besides, the importance of predictive models which depict mixing and transport processes in order to establish a link between point emissions and long range concentrations of pollutants is underlined. Only if such tools are available, the combined approach is administrable. The development of interfaces for the coupling of hydrodynamic models for near and far field predictions has been dealt with in the diploma thesis by Niepelt (2007).

The numerous ways of interpreting the EQS standard may provoke very different applications within the European community. An interpretation which defines the EQS value ‘as near as possible’ would be highly restricting and neglects necessary mixing areas. An application ‘after complete mixing in the water body’ or ‘after completion of initial mixing’ would expose vast areas to the pollutant plume, undermining the main goal of the combined approach. Therefore, a mixing zone definition is highly important in order to make the Water Framework Directive an efficient water protection regulation for desalination effluents.

Concrete ELV and EQS values for pollutants relevant to desalination were not found within the European legislation. Appendix IX of the Water Framework directive refers to other EC-directives which in turn refer again to other codes or authorise the different member countries to establish own limit values. Six so-called daughter directives have been issued on the EC-level which set limit values and quality objectives for 18 substances, e.g. mercury and cadmium discharge (European Commission, 2008). Further regulation is delegated to the member states.
5.3 **United States**

The U.S. Environmental Protection Agency (EPA) is the federal environmental institution of the United States. The agency has not issued any specific regulations concerning the disposal of desalination wastes, but some regulations contain relevant guidelines. These guidelines can be mandatory for the entire country, but in most cases they delegate the legislative responsibility to the states.

Federal guidelines depend on the discharge method used. For surface water disposal, the Clean Water Act (CWA) applies. It regulates the disposal of substances into surface and ground waters. Section 402 of the CWA specifies that any plant discharging directly into U.S. waters must have a NPDES (National Pollutant Discharge Elimination System) permission which can be issued by the EPA or by the states. The NPDES defines the maximum permitted pollutant concentrations in the effluent based on water quality standards and technically possible mitigation measures. Thus, the pollution limits and the prerequisites for receiving an NPDES permission may be different for each desalination plant and subject to a detailed project analysis.

EPA publishes the so called National Recommended Water Quality Criteria (Table 6) which define threshold values for pollutant concentrations in surface waters. The criteria are not legally binding but serve as a guideline for the state legislations. The states are using the recommended EPA values and other advisory information as guidelines for their pollutant regulations. (Mickley, 2006).

The national Water Quality Criteria consist of the CCC (Criterion Continuous Concentration) and the CMC (Criterion Maximum Concentration) value. The CCC value is a water quality standard and defines the maximum concentration of a pollutant for long-term exposure. The CMC value is the effluent standard and defines the maximum concentration for brief exposure (Lattemann, et al., 2003). Table 6 lists the Water Quality Criteria for selected pollutants. Only a few substances relevant for desalination plants have been regulated by the EPA.

### Table 6  Selected U.S. EPA Water Quality Criteria for seawater (based on EPA, 2006)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>CMC (µg/l)</th>
<th>CCC (µg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>13</td>
<td>7.5</td>
</tr>
<tr>
<td>Copper</td>
<td>9.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Nickel</td>
<td>74</td>
<td>8.2</td>
</tr>
<tr>
<td>Zinc</td>
<td>90</td>
<td>81</td>
</tr>
<tr>
<td>Chromium</td>
<td>1,100</td>
<td>50</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.5 – 8.5</td>
</tr>
</tbody>
</table>

California is the state with the highest capacity projections for seawater desalination. There is no special Californian regulation for concentrate disposal of desalination plants at the moment. Thus, the Californian NPDES programme for conventional water treatment plants
applies for plants with discharge to surface water. The programme refers to the Porter-Cologne Water Quality Control Act which is the central section for water quality within the Californian water code. The act outlines water quality objectives and regional water quality control plans in a qualitative way, but does not specify any concrete limit values. These are set on case-specific basis. After consideration of the specific plant data and relevant regulations, the California Regional Water Quality Control Board (CRWQCB) decides about the permit for surface discharge which is valid for five years.

5.4 **State of Victoria, Australia**

No relevant water regulations were found for Australia in general. The regulation of the state of Victoria regarding waste water discharges shall be exemplarily highlighted. This regulation applied for the feasibility study of the seawater desalination plant near Melbourne, scheduled to be constructed in 2009. According to the Coastal Management Act of Victoria, the development of coastal land requires the consent from the Minister of Planning and must be compatible with the coastal management programme.

As stated in the Environment Protection Regulations (1996), any project comprising the discharge of waste from a point source onto any land or into any water is subject to approval prior to construction and subject to license by the Environment Protection Authority (EPA) prior to operation (Melbourne Water, 2007). All potential impacts on the marine environment are dealt with by the State Environment Protection Policy (SEPP) and its Schedules. The policy seeks to secure the beneficial uses of the environment by licensing, monitoring and auditing discharges by industrial facilities. The hierarchy of avoiding, reusing and recycling wastewaters applies prior to discharge. In order to get an approval for a plant it must be ensured by means of posttreatment that the discharge does not pose a risk to the beneficial uses of the environment. If the treatment is not effective, the EPA may authorise a mixing zone. Unlike the EC-regulation, the Victorian authorities incorporate the idea of a mixing zone into the water regulations and give the following definition: “A mixing zone is an area of a waterway or waterbody where the receiving water environment is detrimentally affected by a waste discharge” (EPA Victoria, 2003). It is an area with exactly defined boundaries in which specified environmental quality objectives can be exceeded. The mixing zone regulation places the economic benefit of the discharger and ultimately that of the community above the beneficial uses of the environment, but only if the risks are calculable and only for the smallest necessary area. The operators have to prove that the quality objectives are met beyond the mixing zone. Quality objectives are set on an ad-hoc basis, depending on the respective project and the affected ecosystem. For Port Phillip Bay, one of the possible sites of the Melbourne desalination plant, the SEPP Schedule F6 requires a water quality objective for salinity variation of not more than 5%. Operators must demonstrate that the project does not jeopardise the beneficial uses of the bay which include the natural ecosystems, commercial and recreational fishing, and contact recreation.
Western Port, a second possible plant location, is addressed by SEPP Schedule F8 which defines quality objectives for salinity variations of 1.0 g/l from ambient. The same beneficial uses as in Port Phillip Bay apply, with emphasis on the protection of the largely unmodified aquatic ecosystems (Melbourne Water, 2007).

5.5 Saudi-Arabia

The principal environmental legislation for the kingdom of Saudi-Arabia is issued by the Presidency of Meteorology and Environment (PME, 2001). Appendix 1 of the regulation contains environmental protection standards for water bodies. These standards intend to influence location, design and operation of industrial facilities. The performance standards for direct discharge define the maximum pollutant concentrations in any waste water at the end of the outfall prior to discharge to coastal waters. A mixing zone must be defined for each discharge and the extent of the zone is defined by the Presidency on a case by case basis. Receiving water quality standards apply at the edge of the mixing zone and beyond for the average discharge concentrations of 30 days. They are defined as maximum deviation from local standard conditions. The regulation for relevant pollutants is summarised in Table 7.

Table 7 Discharge and water quality standards for Saudi-Arabian waters (based on PME, 2001)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Discharge standard</th>
<th>Water quality standard*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>case by case</td>
<td>1 °C</td>
</tr>
<tr>
<td>pH</td>
<td>6-9</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>15 mg/l</td>
<td>5 %</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.5 mg/l</td>
<td>5 %</td>
</tr>
<tr>
<td>Copper</td>
<td>0.2 mg/l</td>
<td>5 %</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.2 mg/l</td>
<td>5 %</td>
</tr>
</tbody>
</table>

* maximum deviation from ambient values

Appendix 2 of the regulation describes guidelines and standards for EIAs of industrial and development projects. An EIA has to be conducted for every major industrial project. The auditing process for the EIA depends on the classification of the industrial project. Desalination plants are classified as ‘projects with serious environmental impacts’ which is the category with the highest expected impacts. The EIA has to include:

1. Description of the project and its objectives
2. Status of the surrounding environment (including marine environment)
3. Impact assessment on the environment (including marine and coastal environment)
4. Assessment of significant impacts and presentation of possible mitigation measures
5. Summary of significant impacts after mitigation measures

Al-Jubail is a major Saudi city at the Arabian Gulf and houses one of the largest seawater desalination plants of the world, the Al-Jubail MSF plant with a capacity of 1.54 Million m³/d. The Royal Commission for Al-Jubail issued a local environmental regulation which applies to the city area and the adjacent waters of the Arabian Gulf (RCJ, 1999).

The regulation defines average monthly discharge standards for effluents which are identical to the values of the national regulation listed above, except for total dissolved solids (25 mg/l). Besides, maximum discharge standards are defined allowing higher concentrations of copper and nickel (0.5 mg/l), chlorine (2.0 mg/l) and total suspended solids (40 mg/l) for a restricted period of time. The water quality standard is set to 0.01 mg/l of chlorine, 0.1 mg/l of copper and a temperature rise of 3 °C, but these standards must only apply for 10 % of all water samples.

The data shows that the Al-Jubail discharge and water quality standards are less stringent than the national standards. It is unknown if the regulations of Al-Jubail can be overwritten by the national legislation. Other important pollutants relevant to desalination effluents, e.g. antiscalants, have not been regulated in none of the codes.

5.6 Oman

The Omani Ministerial Decision No. 159/2005 copes with “Promulgating the bylaws to discharge liquid waste in the marine environment”. It is the core legislation for liquid waste discharges into the sea and is based on the “Law to monitor marine pollution”, promulgated by Royal Decree No. 34/74, and the “Environment protection and pollution control law”, promulgated by Royal Decree No. 114/2001.

The ministerial decision defines liquid waste as “any liquid containing environmental pollutants discharged into the marine environment from land or sea sources”. As stated in Article 5, “no liquid waste shall be directly or indirectly discharged in the marine environment without obtaining prior license”. The license is issued by the Department of Inspection & Environment Control and depends on the following conditions. First, the plant operators must reuse or recycle the liquid waste, destroy hazardous components or mitigate impacts by environmental treatment, if this is feasible in an appropriate way (Article 7). Second, they have to provide a detailed description of the characteristics of the liquid waste (Article 8) and the waste has to conform to the discharge limits of pollutants specified in Annex 1 (Article 9). Third, they have to provide information about the discharge location, such as physical and biological characteristics of the seawater and recreational or other usages of the concerned shoreline (Article 10).

The maximum concentrations for selected substances in the effluent according to Annex 1 of the regulation are as follows:
Besides the discharge limits, a mixing zone of 300 m in diameter around the outfall is specified. Within the mixing zone no marine life at the seabed may be destroyed. Beyond the mixing zone

- the ambient water temperature must not be increased by more than 1 °C (weekly average)
- the average ambient salinity must not be changed by more than 2 g/l
- the average dissolved oxygen level should not be reduced by more than 10 %

Moreover, some constructional targets are set for plants. The outfall pipes must not be installed less than one metre from the lowest tide line. The discharge pipes must be located in a place where it is impossible for the waste plume to hit corals and seaweed at the bottom. Due to the results of the Sur plant case study (cf. Chapter 3.2), the proper application of the latter regulation must be questioned.

For the selection of the discharge site and the construction of the outfall, information about wind speed and direction for one month, low and high tide currents in an area of 1 km around the outfall and the average sea depth in the same area should be included. Besides, multiport diffuser pipes are recommended to be installed in order to improve the brine dilution.

For those violating any of these regulations, the penalties of the Environment Protection & Pollution Control Law shall be applied.

### 5.7 Results and interpretation

The LBS protocol provides a legal framework for the protection of the Mediterranean Sea from point sources which is to be specified in the national legislation of the member countries. The protocol requires the member states to find common guidelines and regulations for the discharge of a variety of pollutants. However, the protocol only contains qualitative declarations without any specific standards, except for copper and detergents. There is a large margin of interpretation for the implementation. Appropriate laws by member countries based...
on the protocol were not found. The more stringent amended version of the protocol has not been ratified by important African nations and thus, has not yet entered into effect.

The EU does not provide any legislation for desalination plants and effluents. The EC water framework directive only regulates that both emission limit values as well as water quality standards for pollutants from point-sources must be established. The lack of a proper mixing zone definition impedes the practical use of the directive. The definition of limit values and quality standards is delegated to the member states. However, no regulations of EU member countries for relevant pollutants or desalination plants could be found.

Few of the covered MENA and Western countries have regulations dealing with desalination plants in particular. Most of them define discharge standards for temperature, chlorine, copper and pH, but regulations for other important factors like salinity, antiscalants and the chemicals used in cleaning solutions are lacking in almost all cases. The Omani legislation at least includes salinity and temperature limits for effluents, a distinct mixing zone definition and constructional standards for plants. Saudi-Arabia also defines a mixing zone and requires an EIA for each desalination project. Australia has not issued any detailed regulation and defines environmental standards on an ad-hoc basis for each desalination project. The U.S. EPA publishes a couple of general recommended water quality criteria, but no specific federal or state regulations for desalination plants exist.

However, unspecific regulations cannot automatically lead to the conclusion that the environmental protection standards are low. Australia and the U.S. are well known for high environmental standards. The great environmental awareness of the public in these countries is another driving force for an environmentally sensible handling of desalination technology. A sound EIA study was conducted for each major desalination project in Australia and the United States. Discharge standards and other requirements for plant operation will be set based on the EIA findings. Exact values or standards were hardly found. The discharge design requirements for the scheduled SWRO plant in Sydney e.g. enable that no salinity increase of more than 1 g/l above ambient will be reached beyond a mixing zone of 50-75 m (cf. Chapter 6.1.5).

On the other side, specific regulations are no guarantee for their proper application in reality. Effluent standards for copper and chlorine were included in most of the covered country legislations and are compared in Table 9.

### Table 9 Regulatory effluent standards for chlorine and copper in selected countries

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>U.S. (EPA)</th>
<th>Saudi-Arabia</th>
<th>Oman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine (µg/l)</td>
<td>13</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>Copper (µg/l)</td>
<td>9</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

Obviously the U.S. standards are far more stringent than those of the two Middle Eastern countries. It seems that the EPA has defined the limits with respect to the sensitivity and toxicity values of marine organisms (cf. Fig. 10, Fig. 11), whereas Saudi-Arabia and Oman have defined limits which are very close to typical concentrations in desalination processes. Chlorine concentrations in desalination effluents were found to be around 200-500 µg/l and
copper concentrations in MSF effluents around 15-100 µg/l (cf. Chapter 3.1) which fits well into the regulatory values. These values have proved acutely toxic for a variety of marine organisms. Thus, the outlined standards of the two MENA countries do neither contribute to reduce the impacts of copper and chlorine in typical desalination effluents, nor do they create incentives to reduce the pollutant concentrations and invest in mitigation technology. Realistic limits for brine discharges might lie in between the two extremes, but should tend to the ‘no effect’ values established by the U.S. EPA.

According to the World Bank, the environmental institutions in MENA countries are generally weak and the experience with environmental assessments of individual desalination projects is low. The activities of the numerous desalination plants around the shallow Arabian Gulf remain uncoordinated and unregulated. A World Bank expert claims that to his “best knowledge, no strategic environmental assessment of brine discharges into the Arab Gulf … has been undertaken today” (Schiffler, 2004). Other sources notice that comprehensive standards for brine disposal in Gulf countries are lacking because the interface between industry and regulators is not yet well established. Current regulatory efforts of the countries are concentrating on the definition of plant-specific mixing zones (Alameddine, et al., 2007).

The Arabian Gulf is the water body which is most threatened by desalination. Strategic discharge regulations adopted by all Gulf countries would be highly desirable and needed, but seem to be far from realisation. According to the revised information, the individual countries are still struggling to establish their own regulation which has proved to be less stringent than might be needed in the covered cases.
6. Techno-economic analysis

This chapter is supposed to analyse technologies and measures which enable to mitigate the impacts of desalination plants on the marine environment. First, the technologies are introduced and their ecological and technical efficiency is evaluated. Subsequently, the costs of major technologies will be analysed and compared to conventional systems. A decision support approach for assessment and selection of environmental investments is presented. Finally, recommendations are given for the best investments to reduce marine impacts under ecological and economical aspects.

6.1 Technologies reducing marine pollution

There are several conceivable measures to mitigate the marine impacts of desalination plants. The market success depends on the question if these measures are technically efficient, economically and easy to implement. Three main approaches exist to mitigate the marine impact of desalination plants:

- Reducing the salt concentrations and temperature differences of the brine
- Reducing the need for chemicals and additives
- Reducing corrosion of plant components

Mitigation measures can take effect at the intake, in the operational process or at the outfall. They can constitute an alternative pretreatment or a material choice. In the following, some promising technologies are discussed and their mitigating potential is assessed.

6.1.1 Sub-seabed intakes

One essential step to reduce the impact of chemicals on the marine environment is to improve the feed water quality of the plant. The better the feed water quality the less chemicals are needed in the pretreatment process. Furthermore, a more economical operation can be
expected because the reliability of the plant components is increased and the process stability is improved. As has been shown in Chapter 2.3 beach well intakes have the advantage of supplying better feed water quality than open sea intakes. But they have limited stream capacities and therefore are not suitable for large seawater plants. A solution to this problem is Horizontal Directional Drilling (HDD). This technique can provide high intake volumes by introducing drains into water permeable layers under the seabed. Fig. 17 illustrates the HDD intake design (California American Water, 2004).

![Fig. 17 Sub-seabed intake via Horizontal Directional Drilling (California American Water, 2004)](image)

A commercial implementation of sub-seabed intakes via HDD is the Neodren system. It enables to deliver intake flows of 80,000 m$^3$/d to 400,000 m$^3$/d from a small coastal location (Peters, et al., 2006). A desalination plant in San Pedro del Pinatar in Spain with a capacity of 172,800 m$^3$/d is entirely fed by a Neodren intake. From a position at the coast, drillings of more than 600 m towards the sea can be conducted. Depending on the necessary flow volumes, numerous bore holes are drilled which fan out under the sea (Fig. 18). A minimum distance must be kept at the end of the drills in order to avoid interference between the hydraulic streams. After the drilling the intake pipes are placed into the bore holes. The seawater is prefiltered by the geological layers of the seabed and enters the system through perforations in the last section of the pipes. The system is restricted to water permeable soils such as sand or gravel soils (Catalana de Perforacions, 2006).

![Fig. 18 Neodren intake system with a fan of horizontal drains (Peters, et al., 2007)](image)

The feed water quality of a RO desalination plant with Neodren intake and an intake volume of 8,640 m$^3$/d was analysed in a long-term trial at the coast of Barcelona in an area with
highly turbid water. Samples from five different days show that the turbidity of the seawater was reduced by up to 91.4% (on average 64.8%) and that the feed water always reached stable low values, independent of the raw water conditions. The turbidity reflects the content of suspended matter in water which causes fouling of RO membranes in long-term operation (Peters, et al., 2007).

Similar effects were found for the values of Total Organic Carbon (TOC)\(^1\). Table 10 lists the TOC values of the RO feed water which were reached with the Neodren intake at different sampling days. The results show that Neodren delivered a good and stable feed water quality with a TOC of around 1.5 mg/l, independent of the initial seawater values. The same positive results were obtained with Neodren systems at eight other sites.

Table 10  TOC values of samples in open sea and with Neodren filtrate (Peters et al., 2006)

<table>
<thead>
<tr>
<th>Sampling day</th>
<th>14.03.</th>
<th>29.03.</th>
<th>26.04.</th>
<th>03.05.</th>
<th>18.05.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater (mg/l)</td>
<td>3.42</td>
<td>2.05</td>
<td>1.67</td>
<td>1.68</td>
<td>1.75</td>
</tr>
<tr>
<td>Neodren (mg/l)</td>
<td>1.36</td>
<td>1.52</td>
<td>1.6</td>
<td>1.35</td>
<td>1.59</td>
</tr>
<tr>
<td>TOC reduction (%)</td>
<td>60.2</td>
<td>25.9</td>
<td>4.2</td>
<td>19.6</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Since organic matter and suspended solids are responsible for fouling and scaling in RO membranes, the reduction of these particles, as has been found in the tests, enables to reduce the dosages of the respective chemicals. In combination with a micro-bubble flotation and an ultrafiltration unit, even a dramatic reduction of the needed chemicals was observed. The micro-bubbles are introduced into the feed water, attach themselves to suspended particles and float them to the surface where they can be easily removed.

Besides the better feed water quality, the application of Neodren intakes has the following advantages (Peters, et al., 2006):

- No physical effects on the shoreline and the benthic community during construction in contrast to open intakes on the seabed
- No danger of entrainment and impingement of marine organisms
- The quality of intake water is not affected by the dynamic action of the sea, which allows for a more stable plant operation without frequent adaptations of chemical dosages
- The frequency of chemical cleaning is reduced, which prolongs the lifetime of the RO membranes

Disadvantages of Neodren intakes may be the soil disturbance caused by drilling and excavation and the risk of possible salt water intrusion into the groundwater aquifers.

\(^1\) TOC counts organic matter in sea water, consisting of living and dead particulate matter and dissolved molecules. It is an indicator of water quality. For RO applications, water usually requires pretreatment when a TOC of 3 mg/l is exceeded (Lattemann, et al., 2003).
Dr. Thomas Peters, Neodren expert and independent consultant for membrane technology and environmental engineering, was questioned in order to validate and specify the Neodren benefits. According to his statement, the feed water quality is improved to an extent that no chlorination or any other antifouling measure is needed and only little flocculation and antiscaling chemicals must be dosed in most of the currently running plants. Cleaning intervals for the RO membranes are increased 4-6 times and the lifetime of the membranes is enhanced. The Silt Density Index (SDI)\(^1\) of the feed water is lower than five in all Neodren operated plants. An SDI < 5 is acceptable for RO membranes and guarantees very low fouling rates (Applied Membranes Inc., 2008). Furthermore, the advantage of stable operation at constant feed water quality, independent of the weather and water situation and without the risk of entrainment of any material or organisms, was underlined.

Dr. Peters specified the example of the Spanish RO plant in San Pedro del Pinatar. One of the RO units uses a Neodren intake and the neighbouring sister unit uses an ordinary open sea intake. Both units (each 65,750 m\(^3\)/d) run stable, but the open sea unit operates on two stages of multimedia filters and conventional chemical pretreatment, whereas the Neodren plant only needs one single sand filter without any further chemical treatment.

These findings have not yet been published, but seem to be realistic due to the great test results about feed water quality.

All Neodren systems are currently used in RO plants. Application in MSF plants is theoretically possible but as thermal plants do not need highly pure feed water, the operational need for Neodren is less strong than for RO. Additionally, lower recovery rates and higher average capacities in MSF plants require higher intake volumes which could poses design problems and add to the capital costs of Neodren.

### 6.1.2 Alternative Pretreatment

The idea of alternative pretreatment is to replace conventional chemical pretreatment by physical alternatives which provide the same or even better feed water quality, especially for the demanding RO membranes. The most promising technology is membrane pretreatment with ultra- or nanofiltration. These have pore sizes small enough to remove most troubling substances from the intake water.

**Ultrafiltration**

As outlined by Czolkoss (2006), a modern advanced pretreatment design for seawater RO plants only consists of a UF membrane unit without complicated chemical dosing systems. UF membranes block particles of down to 0.01 µm in diameter and are physically cleaned by

---

\(^1\) The Silt Density Index (SDI) measures the rate of suspended solids and colloidal material in the feed water. It is an indicator for the fouling potential of a water source.
regular water backwashes. The removed deposits are filtered by a backwash filter and are discharged to the sea. If operated in ‘dead end mode’, which is a maximum flux mode with regular backwashes, the energy consumption of UF membranes can be kept as low as 0.1-0.3 kWh/m³ (Peters, 2005). Similar to RO membranes, there exist spiral wound and hollow fibre configurations. In spiral wound configurations, accumulating particles between the layers can cause heavy fouling and scaling problems. The hollow fibre configuration somehow lacks the mechanical stability for an efficient backwash of the filtrate.

The newly developed Multibore membranes combine stability with good cleanability as well as good fouling and scaling resistance and thus, are the best choice for UF pretreatment. Multibore membranes consist of a bundle of small fiber cables which are inserted into a collecting tube. Each fibre cable consists of seven capillaries with pore diameters of 0.02 µm. The seawater enters the capillaries and is desalinated by being pushed through the fibre cables into the collecting tube. The duration between backwashes usually varies between 15 and 30 minutes.

Experiences with UF pretreatment in a couple of regular and pilot SWRO plants showed that a feed water SDI < 3 can be reached in most cases. The average RO trans-membrane pressure (TMP) which reflects the pressure resistance and thus the energy consumption of the plant is also reduced due to the good feed water quality. An additional flocculation dosage is recommended to further improve water fluxes and SDI levels.

The advantages of UF with respect to conventional pretreatment can be summarised as follows (Wolf, et al., 2005):

- Filtration of suspended particles, colloidal materials, algae and bacteria
- Reduction of RO membrane fouling and cleaning frequency, because SDI levels below 2.5 are reachable
- Life extension of RO membranes
- Lower consumption of operational and cleaning chemicals (except antiscalants)
- Facilitated operation through constant feed water quality
- Higher RO membrane output
- More robustness and flexibility towards quality variations of the intake water
- Shorter intake pipes in shallow waters possible because seawater quality is less critical

In the case of the Tampa Bay SWRO plant in Florida, the conventional pretreatment system with coagulation, filters and chemicals could not entirely meet the RO quality criteria of the manufacturer (SDI < 4) and produced fluctuating feed water quality (cf. Chapter 4.1.2). This led to fast fouling and destruction of the RO membranes. In contrast, test runs with a UF hollow fibre membrane system at Tampa Bay produced excellent feed water quality at a constant basis, independent of raw water quality. The applied UF membrane with the brand name ZeeWeed1000® outperformed the conventional system on a broad basis (Table 11). The SDI always remained below 2.5 and the average RO output could be increased. Bacteria were filtered by more than 5 log (99.999 %) which documents the potential of reducing fouling problems and avoiding antifouling chemicals. The RO cleaning frequencies were increased up to six times and thus, the annual membrane replacement rate also dropped.
Table 11  Pretreatment performance of the ZeeWeed 1000® UF membrane compared to a conventional system (based on Wolf et al., 2005)

<table>
<thead>
<tr>
<th></th>
<th>ZeeWeed 1000® UF hollow fibre membrane</th>
<th>Conventional filtering and chemical system</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDI</td>
<td>&lt; 2.5 (100% of time)</td>
<td>&lt; 4 (30% of time)</td>
</tr>
<tr>
<td>Feed water quality</td>
<td>Consistent</td>
<td>Fluctuating</td>
</tr>
<tr>
<td>Average RO flux</td>
<td>~ 18 l/m²h</td>
<td>~ 14 l/m²h</td>
</tr>
<tr>
<td>Bacteria</td>
<td>&gt; 5 log removal</td>
<td>n.a.</td>
</tr>
<tr>
<td>Virus</td>
<td>&gt; 4 log removal</td>
<td>n.a.</td>
</tr>
<tr>
<td>RO membrane replace</td>
<td>~ 10 % per year</td>
<td>~ 14 % year</td>
</tr>
<tr>
<td>RO cleaning frequency</td>
<td>~ 1-2 times per year</td>
<td>~ 4-12 times per year</td>
</tr>
</tbody>
</table>

A general performance comparison of UF pretreatment and conventional chemical pretreatment was issued by experts from Taprogge. The company is market leader for solutions optimising the water circuits in industrial facilities and has expertise in intake and pretreatment systems for desalination plants.

Table 12 summarises the important findings of the comparison. The excellent removal of bacteria by UF pretreatment is confirmed. Environmental impacts of UF are evaluated to be low due to the reduction of chemicals. Moreover, the advantages of operational stability and full automation are highlighted and lower RO investments are predicted due to the higher output rates per unit.

Table 12  Performance comparison of conventional and UF membrane pretreatment (based on Dickhaus, 2005)

<table>
<thead>
<tr>
<th></th>
<th>Conventional pretreatment</th>
<th>UF pretreatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria</td>
<td>No barrier</td>
<td>4-6 log reduction</td>
</tr>
<tr>
<td>Virus</td>
<td>No barrier</td>
<td>3-4 log reduction</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>No barrier</td>
<td>&gt; 99 % reduction</td>
</tr>
<tr>
<td>Particular TOC</td>
<td>No barrier</td>
<td>&gt; 99 % reduction</td>
</tr>
<tr>
<td>Silt Density Index</td>
<td>3-5</td>
<td>&lt; 1-2</td>
</tr>
<tr>
<td>Footprint</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
<tr>
<td>Automation</td>
<td>Restricted</td>
<td>Fully automated</td>
</tr>
<tr>
<td>Operational stability</td>
<td>Dependent on raw water quality</td>
<td>Membranes deliver stable RO feed water quality</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>High (continual chemical addition)</td>
<td>Low (chemicals only for extraordinary membrane cleaning)</td>
</tr>
<tr>
<td>Influence on RO investment</td>
<td>Standard</td>
<td>Lower RO capacities needed (ca. -15%)</td>
</tr>
<tr>
<td>Influence on existing plant</td>
<td>Restricted RO output</td>
<td>Increased RO recovery due to better feed water quality</td>
</tr>
</tbody>
</table>
Pearce (2007) reported that chemical pretreatment requirements are minimal if a coagulant is dosed to the UF feed water. A case study of an RO plant with UF pretreatment at the eastern Mediterranean Sea revealed that continuous chlorine and sodium bisulphite addition is redundant and the RO cleaning frequency can be reduced to once a year. Even the coagulant dosage is only about 43% of the dosage in conventional operation.

An RO pilot plant in China using UF hollow fibre membrane pretreatment could even be operated without any use of chemicals during the whole experimental period which took several months. This was attained by carefully optimising the UF-RO operational parameters. Maximum RO product flows and optimum UF pretreatment reliability were found for UF backwashes of 30 seconds duration at every 40 minutes. With regular backwashes, the UF system delivered excellent feed water quality and constant flow rates, at an SDI < 3 in 95% of the time. Consequently, the RO membrane performance was high and stable and no pressure drops or flow rate decline in the RO system could be observed (Xu, et al., 2007). These findings give rise to great optimism for the role of UF pretreatment as environmental mitigation strategy for SWRO plants. The applied procedures in the Chinese example should be pursued in other plants.

To sum up, all reviewed studies agree that UF membranes are a reliable and efficient pretreatment option for seawater RO plants and outclass current conventional pretreatment systems by providing far superior feed water quality and operational advantages. The potential ecological benefits are significant since the use of most chemicals can be clearly reduced or avoided. UF pretreatment for MSF plants, however, has not been reported in any study. Similar to sub-seabed intakes, this might be due to the fact that MSF does not require highly pure feed water and that much more UF membranes would be necessary for the high MSF intake volumes. Nevertheless, application of UF pretreatment in MSF plants could have similar environmental advantages like in RO plants.

**Nanofiltration**

Nanofiltration membranes have pore sizes down to 0.001 µm, enabling them to filter not only suspended solids and bacteria but also scale forming hardness ions and a fraction of the Total Dissolved Solids (TDS). In contrast to UF, NF membranes cannot be backwashed due to their technical layout. Thus, particles can accumulate on the surface and make NF susceptible to fouling and scaling, similar as RO membranes (Violleau, et al., 2005).

Hassan et al. (1998) analysed the first set-ups of RO and MSF pilot plants with nanofiltration pretreatment. No chemicals or only reduced dosages were used during the test runs. However, it is uncertain if chemicals could be removed from the NF feed water. Probably the reduction of chemicals only referred to the RO feed water. RO membrane performance in the NF-SWRO process was found to be superior to that of conventional pretreatment. Due to the excellent NF permeate quality the RO membranes could be operated at 20-30 bars only, without any deterioration in RO permeate quality. At
RO pressures of 40 bars, the recovery ratio was increased to 48 % compared to 16.7 % with conventional pretreatment.

A NF-MSF system was safely operated for 66 days at a top brine temperature of 120 °C without addition of any antiscalping or antifoaming chemicals. The concentrations of the important scale forming ions Ca$^{2+}$ and SO$_4^{2-}$ in the RO feed water were reduced by 81 % and 93 % respectively. This would even enable to operate on higher top brine temperatures of up to 160 °C and thus, with higher overall plant efficiency.

Applied to the 56,800 m$^3$/d Jeddah SWRO plant, the NF pretreated RO membranes achieved a 60 % recovery rate compared to only 35 % in standard operation. RO membrane output increased from 2370 m$^3$/h in the conventional system to 4056 m$^3$/h (Fig 19). The overall energy consumption dropped by 25 % with NF pretreatment.

![Fig. 19 Comparison of flow rates in the conventional SWRO system with 35 % recovery (above) and in the NF-SWRO system with 60 % recovery each (below) (based on Hassan, et al., 1998)](image-url)

Test runs at the Jeddah plant indicate that the NF membranes completely remove turbidity and bacteria, efficiently remove scale forming ions by up to 98 % and lower the TDS by over 50 %. Thus an excellent feed water quality for RO membranes is provided and the operation is facilitated. The plant performance is enhanced and the use of pretreatment chemicals in the RO feed water can be completely abandoned or drastically reduced. However, it was not clear if and how much chemicals were needed for the NF feed water.

Leading Edge Technology Ltd. (LET) applied NF pretreatment at the Layyah MSF plant in UAE. By reduction of the feed water hardness, the top brine temperature could be increased by 20 °C to 125 °C without scale formation. This translated into a water output increase of 30 %. The use of chemicals in the MSF process was significantly reduced, but periodic shock chlorination, acid dosing and scale inhibitors were dosed to the NF feed water. However, the overall consumption of chemicals was reported to be reduced (Awerbuch, 2007).

Eriksson et al. (2005) reported that the Umm Lujj plant in Saudi-Arabia installed a special nanofiltration membrane in 2000 which proved excellent for pretreatment in both RO and thermal plants. At reasonable flow rates the fouling of NF membranes could be largely reduced and the cleaning frequencies were moderate. However, the NF feed water at the Umm Lujj plant was still dosed with acid, antiscalants (4 mg/l) and disinfectants (4 mg/l).

As long as NF membranes cannot be operated without or with low chemical dosages, the ecological advantage of chemical savings in the RO unit is clearly undermined. The amount of necessary antifouling or antiscalping additives seems to depend on the flow rates and on the...
pressures of the NF modules. Only coagulants and antifoaming agents which are low priority pollutants can definitely be removed when using NF pretreatment. Resistant NF membranes have to be developed before they can replace conventional pretreatment.

Sponge ball technique

Sponge balls are a physical cleaning method developed to remove deposits from the tubes in MSF plants. The flexible rubber balls with a diameter slightly above the tube diameter are continuously circulated through the tubing system, thus cleaning the tubes from fouling and scaling products. This is particularly important for the heat exchanger tubes which influence the energy efficiency of the plant. The sponge balls can be removed anywhere in the plant where appropriate filters are installed.

According to Taprogge consultants, sponge balls are successfully applied in several MSF plants in Saudi-Arabia. The pretreatment system can be economically designed, consisting of cost-efficient microfilters and the sponge balls. The use of antifouling chemicals is completely redundant. Antiscalants at about half the usual dosage and moderate antifoaming addition is sufficient to guarantee smooth operation in combination with sponge ball application. Thus, the dosages of antiscalants are reduced from 3 mg/l to about 1-1.5 mg/l (Taprogge, 2008). Every couple of years cleaning of tubes and distillers with acid is carried out which can be completely neutralised prior to discharge.

Sponge ball cleaning was tested in the Al-Jubail II and the Jeddah III MSF plants in Saudi-Arabia. The test report concluded that tube cleaning by circulating sponge balls along with the use of antiscalants proved to be the most effective and economical means to avoid fouling and scaling of internal surfaces of tubes in MSF distillers. Cost savings were caused by reduced additive dose rates and energy savings of up to 40 %. These are the result of improved heat transfer due to efficient tube cleaning.

Similar results were found for the 117 MSF distiller systems operated by the Saline Water Conversion Corporation (SWCC). The combination of sponge balls and antiscalant, used in all these distillers, was found to be the most cost efficient procedure to avoid tube scaling. It allowed lowering of antiscalant rates without formation of scales. Even the top brine temperature could be increased in a couple of plants (Hamed et al., 2001; Hamed et al., 2002).

UV treatment

Lattemann & Höpner (2007) mentioned the use of UV irradiation as alternative pretreatment method. A wavelength of 200-300 nm damages the DNA structure of microorganisms and can be applied for disinfection of the intake water. Easy handling and the avoidance of storage and disposal of chemicals are advantages of UV pretreatment. But on the other side, highly reactive substances like free radicals are produced which may form by-products in unknown variety and quantity.
With respect to UV treatment only one report was found which stated that UV irradiation, in combination with 5 µm filters, did not measurably reduce fouling (Koyuncu, et al., 2006). It must be supposed that UV treatment is not an effective pretreatment method.

“Green” additives

When chemical addition cannot be avoided, the use of so-called “green” chemicals should be considered. Green chemicals fulfil some minimum environmental requirements and thus are less harmful for the marine ecosystems. The OSPAR Commission (Oslo and Paris Commission) which is the regulatory body for the protection of the marine environment in the North-East Atlantic has issued the PLONOR list. The list contains chemicals which ‘Pose Little Or NO Risk’. In order to get an entry on the list, two of the following three criteria have to be met and in any case the biodegradability must be higher than 20 % in 28 days (Ketsetzi, et al., 2008):

- Biodegradability: > 60 % in 28 days
- Toxicity indicators: LC_{50} or EC_{50} > 1 mg/l for inorganic species and > 10 mg/l for organic species
- Bioaccumulation: Log (partition in octanol/water) < 3

One example for a ‘green chemical’ is an inulin-based polymer which turned out to be an efficient silica scale inhibitor. It could keep silica soluble up to a concentration of about 300 mg/l. Since inulin is of vegetable origin, no adverse effects on the marine environment are expected.

A recently developed chemical which meets the PLONOR requirements is the antiscalant PAP-1. It has a biodegradability of 58.3 % after 20 days and shows very good results for the inhibition of magnesium and calcium scales. The agent is considered non-toxic and environmental friendly. Growth rates of algae were not affected by different dosages of 1-9 mg/l (Li, et al., 2006).

6.1.3 Material selection

Thermal desalination plants operate in extremely corrosive environments consisting of salt water, vapour and a mixture of aggressive chemicals including acids. Due to the high temperatures, mainly metals are applicable for most plant components. Copper-nickel alloys are traditionally used as heat exchange surfaces in thermal plants due to their good heat conductivity characteristics.

As copper-nickel alloys possess very low corrosion resistance, copper discharges are one of the largest sources of pollution in MSF plant. Discharged concentrations are further increasing during exceptional stress through acid cleaning. Furthermore, local corrosion is intensified by pitting and crevice corrosion. In the Arabian Gulf the annual copper input from MSF plants is
Material selection

estimated to amount to 73-485 t (Lattemann, et al., 2003). Solutions can be provided by the
development and application of materials which have higher corrosion resistance and are less
toxic.

Al-Odwani et al. examined the corrosion behaviour of a number of materials which are
commonly used or have the potential for future application in MSF plants, including two
copper-nickel alloys (Cu-Ni 90-10 and Cu-Ni 70-30), two stainless steels and one titanium
material. The materials were tested up to 300 days under typical thermal plant conditions, in
brine and vapour environment at temperature ranges of 50-90 °C. The Cu-Ni 90-10 compound
performed worst, with average corrosion rates of 0.017 mm/a. Cu-Ni 90-30 contains more of
stress resistant Nickel and thus, got better result with an average of 0.0032 mm/a. Titanium
outclassed both copper-nickel alloys with a maximum corrosion rate of only 0.00076 mm/a,
measured in the first 30 days of the test. Later on, corrosion rates were even lower due to the
formation of an extremely resistant titanium oxide layer.

Even titanium was outranked by the two stainless steels in the test row. The steels were
mainly alloyed with chromium, nickel and molybdenum. Molybdenum increases the
resistance against general and local corrosion. Chromium highly improves the corrosion
resistance in chloride solutions. The stainless steel material with the lower concentrations of
alloying elements had corrosion rates of lower than 0.0003 mm/a under almost all conditions.
After 300 days of test run, signs of initiating pitting were visible. The higher alloyed steel had
maximum initial corrosion rates of 0.0007 mm/a. These were rapidly decreased to under
0.0001 mm/a through formation of oxide layers. Signs of pitting were not visible. The
observed corrosion rates for stainless steels were close to the minimum measurable dimension
(AI-Odwani, et al., 2006).

All in all, the test showed the superior corrosion resistance of stainless steel and titanium
materials compared to conventional copper-nickel alloys (Fig. 20). It should be noted that the
test runs were held in aerated environment. Since MSF plants are usually operated in
daerated environment, the copper-nickel alloys might have performed better. Nevertheless,
they cannot compete with the shown alternatives.

![Corrosion rates of Cu-Ni 90-10, Cu-Ni 70-30, titanium, low and highly alloyed stainless steel (from left
to right) in brine and vapour at different temperatures (AI-Odwani et al., 2006)](image)

Fig. 20   Corrosion rates of Cu-Ni 90-10, Cu-Ni 70-30, titanium, low and highly alloyed stainless steel (from left
to right) in brine and vapour at different temperatures (Al-Odwani et al., 2006)
Al-Malahy et al. investigated the corrosion behaviour of three differently alloyed stainless steels, a nickel based compound and titanium under conditions relevant to SWRO plants, with temperatures of 25-40 °C and salinity of 35-55 g/l. They found that titanium showed superior corrosion resistance compared to the other materials under these conditions.

Superior corrosion resistance of stainless steels can not only be reached by high concentrations of alloying metals, but also by so called **duplex stainless steels**. These steels have a mixed austenitic-ferritic microstructure which provides twice the strength of conventional austenitic steel. Thus, thickness and weight of plant components can be reduced. Furthermore, same or superior corrosion resistance is attained at lower alloying levels. Conventional high end corrosion resistant stainless steels contain about 20 % Cr, 18 % Ni and 6 % Mo, whereas duplex grades only need about 25 % Cr, 7 % Ni and 4 % Mo for the same performance. Depending on the requirements, the grade of alloys can be reduced to values such as 21.5 % Cr, 1.5 % Ni and 0.3 % Mo (Olsson, et al., 2007).

In 2004 duplex steels were introduced as evaporator shells of thermal plants for the first time. Several plants in the Middle East and North Africa successfully adopted the concept. The application potential reaches from highly demanding parts like heat exchange tubes to less critical components like product water processing units. In SWRO plants operators had previously relied on highly alloyed stainless steels to meet the material requirements in the high pressure parts of the system. But the duplex steels are gaining ground in modern plants and are for example used for energy recovery units or high pressure pipe sections in new high-tech plants like Ashkelon (Israel), Singapore and Perth (Australia).

Stainless steels and titanium materials have similar, but lower thermal conductivity coefficients than traditional copper-nickel alloys and seem to be inferior for heat exchange applications in thermal plants. The thermal conductivities are 47 W/mK for Cu-Ni 90-10, 29 W/mK for Cu-Ni 70-30 and 16.7 W/mK for titanium. However, all experiences from power plants and other industrial sectors agree that no decrease in heat transfer capacities could be detected when shifting to titanium or stainless steel elements. Presumably, other properties like film formation tendency and fouling grades play a more important role for heat transfer than the mere elemental conductivity.

Besides, material conductivity is generally increasing with lower wall thickness. The higher corrosion resistance of duplex steels or titanium enables this reduction in wall thickness. The overall heat transfer of titanium tubes is similar to copper-nickel tubes with twice the wall thickness (Scheffler, et al., 2008). The thermal conductivity of typical duplex steel grades is slightly higher than that of titanium (Aalco, 2008). Thus, titanium and duplex steels are appropriate for the application as heat transfer elements.

Another promising material option for MSF plants are polymeric materials, e.g. PTFE (Polytetrafluoroethylene) and HDPE (High Density Polyethylene). Compared to traditional metal materials, polymers show various advantages for desalination plants such as the simple, light-weight installation, low costs, low scaling tendency and excellent resistance against corrosion and chemicals. Pollution through corrosion and corrosion inhibitors can be completely avoided with polymers. But the application in thermal plants is still restrictive, as the thermal extension is ten times higher than for metals and most polymers are aging at high temperatures. Besides, drawbacks of polymers are the poor thermal conductivity (30-750
times lower than for metals) and the reduced strength (Glade, 2007). Particularly for heat transfer surfaces, copper-nickel and, to a lower extend, aluminium brass and titanium are dominating.

An innovative solution might be polymer film heat transfer elements, made of HDPE or PP (Polypropylene). At a film thickness of only 20-50 µm, thermal conductivity of polymers competes with copper-nickel alloys of 1 mm thickness. In an experimental procedure several layers of these films were welded in order to form polymer heat transfer tubes. Experiments found that the tubes were able to withstand a pressure of several bars. Furthermore, the films last as well as, or even better than titanium. The low material costs would enable to extend the heat transfer area, leading to energy savings (Scheffler, et al., 2008). However, problems with the stability of the polymer tubes have to be overcome and the production process still is highly experimental.

Very few practical experiences with polymers as heat exchanger material are available due to the remaining technical problems, but also due to conservative customer behaviour. In contrast, polymers are used as reliable material in RO plants for a long time. Only in the high pressure sections the polymer durability is too low and metal materials are preferred (DLR, 2007).

To conclude, corrosion resistance and environmental impacts depend on the material selection and are an almost exclusive issue in thermal plants. Material stress in RO units is lower and ecologically harmless solutions like stainless steel and polymers exist. In thermal plants the requirements regarding corrosion can be met by highly alloyed stainless steel, duplex stainless steel and titanium. All materials have minimum corrosion rates and thus, minimum disposal rates via brine discharge. Duplex stainless steel might be preferable to highly alloyed stainless steel because the lower concentrations of alloying elements further reduce the risks for the environment. Titanium tends to accumulation, but is non-toxic.

### 6.1.4 Posttreatment

Chlorine is one of the most hazardous pretreatment chemicals. In cases where its application cannot be prevented, dechlorination is a simple and effective method to avoid adverse effects. This step should be a compulsory part of the environmental strategy and not only an operational necessity in RO plants in order to protect the membranes. A harmless neutraliser is sulphur dioxide. Although overdosage can lead to pH reduction in the treated water, the acidic products are quickly neutralised by seawater alkalinity (Lattemann et al., 2003; Höpner et al., 2008).

The problem of metal discharge can also be solved by posttreatment. Many different technologies like precipitation, complexation, adsorption or biosorption exist to remove metal cations from a liquid:

- By means of precipitation, some metals can be selectively removed. Iron and manganese e.g. precipitate through addition of lime into the fluid.
Discharge options and design

• Complexing agents are metal binding materials like the water-soluble polymer carboxymethylcellulose. It has good complexing qualities for copper and nickel cations which are of particular environmental relevance in MSF plants. Up to 99% of the copper concentration can be complexed and subsequently ultrafiltrated.
• Adsorbing materials like activated carbon might be an efficient method of removing metals and other hazardous components from brine. New synthetic adsorbing agents possess high adsorbing capacities and selectiveness.
• Certain success was achieved with biosorption of copper cations by a special biomass. Further research is needed to investigate the effects on other metal ions.

6.1.5 Discharge options and design

Discharge options

Brine disposal is a major environmental problem of seawater desalination plants. If a feasible and efficient alternative to ocean disposal could be found, the entire problem of marine pollution would be solved. Conventional disposal methods of desalination plants comprise:

• Disposal to surface water
• Disposal to sewer
• Deep well injection
• Evaporation ponds
• Land application, e.g. irrigation

Disposal to surface water comprises discharge to rivers, lakes, the ocean and other water bodies. It is the most common practice since most plants are situated next to surface water. Sewer disposal uses the existing infrastructure of a waste water treatment plant. The discharged brine must comply with the maximum sewer and plant treatment capacity as well as the wastewater quality characteristics. Deep well injection means the insertion of brine into a deep aquifer under the groundwater layers and depends on suitable geological conditions. Evaporation ponds are areas of land where brine is disposed and evaporated by solar heat, leaving the salts behind. Land application enables the reuse of desalination effluents for irrigating lawns, parks and agriculture. It depends on the tolerance of plants towards salinity and the conformance with water quality standards for irrigation.

The most widely used disposal methods in the USA are surface water discharge (45%), sewer discharge (27%) and deep well injection (13%). The statistic considers 234 nanofiltration, brackish and seawater desalination plants of more than 100 m³/d capacity. With focus on desalination plants with capacities larger than 25,000 m³/d, more than 40% discharge to surface water and another 40% inject to deep wells (Mickley, 2004). Factors like plant size, increasing regulations and public concerns are limiting the disposal options and challenging the search for a technically, environmentally and financially feasible method. The discharge
Discharge options and design

Volumes are a particularly limiting parameter for seawater desalination plants. The advantages and disadvantages of typical concentrate management options are summed up in Table 13.

**Table 13  Comparison of brine disposal options for desalination plants (based on Alameddine et al., 2007; Moch, 2007; Department of natural resources and mines, 2003)**

<table>
<thead>
<tr>
<th>Disposal method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Surface water discharge | - Can handle large volume  
                       - Water body promotes dilution  
                       - Often least expensive option  
                       - Possible dilution and combination with power plant discharge            | - Adverse impacts on marine environment  
                       - Dilution depends on local hydrodynamic conditions                        |
| Sewer disposal        | - Dilution through waste stream  
                       - Uses existing infrastructure  
                       - Possible beneficial treatment                                              | - Restricted capacity depending on sewage plant  
                       - Must meet sewer quality standards  
                       - Still discharged to surface water                                           |
| Deep well injection   | - No marine impacts  
                       - Good option for smaller inland plants                                      | - Only cost efficient for larger volumes  
                       - Maximum capacity hard to assess  
                       - Dependent on suitable, isolated aquifer structure  
                       - Danger of groundwater pollution                                             |
| Evaporation ponds     | - No marine impacts  
                       - Possible commercial salt exploitation  
                       - Low technological and managing efforts                                      | - Strongly restricted capacity  
                       - Large areas of land necessary  
                       - Only in dry climate with high evaporation  
                       - Risk of soil and groundwater pollution  
                       - Disposal of unusable salts needed                                           |
| Land application      | - No marine impacts  
                       - Alternative water source for irrigation of tolerant species                | - Only for smaller discharge flows  
                       - Possible adverse impact of chemicals and pollutants on plants  
                       - Risk of soil and groundwater pollution  
                       - Storage and distribution system needed                                       |

The comparison shows that the alternatives for large seawater desalination plants are quite restricted. *Evaporation ponds* for large flow streams would require gigantic areas of land which are costly to prepare and to maintain. Economies of scale would be very low. Evaporation ponds also pose a considerable risk to soil and groundwater and are dependent on climate conditions. Therefore they are mainly applied for small brackish water plants in arid regions.

*Land application* of brine is also restricted in scale. Large volumes necessitate huge, complex distribution systems. Moreover, the effluent might have to be treated in order to meet the quality standards for land application and in order to avoid the risk of groundwater and soil pollution.

*Deep well injection* might be an option for seawater plants. But excellent geological conditions are needed in order to store large volumes of effluents without any leakage or
Discharge options and design

Discharge design

The optimisation of the discharge design helps to mitigate the environmental impacts of ocean disposal. The prime design objective for outfall systems is to reach the highest possible effluent dilution in the receiving water. The higher the dilution rates are the smaller is the impact area of concentrated salts, pollutants and elevated temperature, at least for all non-accumulating substances. A proper discharge design is particularly important for low energetic water bodies where the natural dilution rates are low. Attaining a certain dilution rate in a given radius around the outfall might be obligatory in order to meet mixing zone regulations.

The concentration of a pollutant after discharge depends on the initial discharge concentration, the concentration in the ocean and the level of dilution (Mickley, 2006). Where

\[ y = \text{discharge concentration} \]
\[ x = \text{receiving water concentration} \]
\[ i = \text{dilution number} \]
\[ d_i = \text{pollutant concentration after } i^{th} \text{ dilution} \]

The pollutant concentration after \( i^{th} \) dilution is defined as:

\[ d_i = \frac{y + i \times x}{i + 1} \]
Assuming the following example for the purpose of illustration:

The ocean salinity is set to $x = 38 \text{ g/l}$. An RO plant with a recovery rate of 50% discharges its effluent at a salinity of $y = 76 \text{ g/l}$ into the ocean. The regulatory authority calls for a maximum salinity deviation of 2 g/l above ambient beyond the mixing zone. It is to be investigated what dilution performance the discharge design has to provide in order to meet the regulatory target. Calculations show that

$$ d_{18} = \frac{76 \frac{g}{l} + 18 \cdot 38 \frac{g}{l}}{18+1} = 40 \text{ g/l} \quad \rightarrow \quad i = 18 $$

Consequently, the regulations are met if at least an 18-fold dilution can be effected within the mixing zone. This means that ocean water amounting to 18 times the volume of the discharged brine must be mixed up.

A simple way to provide good effluent dilution and to minimise the environmental effects is to discharge into a highly energetic sea location where no sensitive ecosystems are in reach. This aspect should be given high priority when searching for an appropriate plant site. If the hydrodynamic qualities of the sea are not sufficient, it should be checked whether the effluent can be diluted with cooling water or wastewater effluents from neighbouring plants. If such methods are not available or the dilution is still insufficient, the discharge design must be optimised.

The dilution process can be divided into a primary jet dilution in the so-called near-field and a subsequent natural dilution in the far-field. Jet dilution mainly depends on the outfall geometry, the discharge velocity, the discharge angle and the density difference between brine and seawater. The natural dilution is influenced by waves, currents and diffusion processes. The dilution rates increase with decreasing density differences between effluent and seawater, which argues for blending prior to discharge.

Besides open surface discharge, sub-merged outfall pipes are a commonly used discharge option. Multiport diffuser outfalls consist of a submerged pipeline and a diffuser section with several ports (Fig. 21) which can be installed in unidirectional or alternating direction, amongst others. Multiport diffusers improve the dilution by increasing the pressure and velocity of the discharged brine as well as by increasing the contact area with the surrounding seawater. The efficiency depends on the number of ports and the space between each other. The lower the interaction between the different port plumes and the smaller the port diameter, the higher are the dilution rates (Einav, et al., 2002).

The EIA study for the SWRO plant in Sydney, which is projected to have a maximum capacity of 500,000 m³/d, investigated possible discharge designs for the plant. Simulations incorporating local coastal data were carried out in order to determine the design with the best near-field dilution performance. Finally, a multiport diffuser system, situated 250-300 m offshore in water depths of 20-30 m, was recommended. The diffuser ports are installed at 25 m distance from each other and are positioned at angles of 60° from horizontal. The brine exits the diffuser ports at a velocity of 7 m/s and at a salinity of 65 g/l. Within a mixing zone of 50-75 m, the salinity of the plume is decreased to values that do not deviate more than 1 g/l.
Discharge options and design

from ambient values (≈ 36 g/l) (Sydney Water Corporation, 2005). This equals a dilution rate of 28. Hence, the outfall design enables to limit the critical brine concentrations to an area of no more than 75 m. This example highlights the mitigation potential of multiport diffusers.

Fig. 21 Layout of an outfall pipeline with multiport diffuser (Bleninger, 2007)

Alameddine et al. (2007) developed design recommendations for the discharge of thermal effluents, based on simulation results of the CORMIX modelling tool. For open surface discharges, the width of the channel is recommended to be increased and the height of the discharge point should be reduced in order to enhance the horizontal spreading of the plume. However, the open surface discharge proved inadequate to achieve acceptable dilution rates in most cases.

The mixing performance of submerged single port outfalls is improved by splitting the concentrate up into several outfall pipes with adequate space among each other. However, simulations showed that the best dilution rate was reached by multiport diffusers. A tenfold dilution rate was achieved within a 300 m mixing zone.

Bleninger et al. (2008) found that the submerged discharge at offshore locations and at high velocities provides a high mixing efficiency for negatively buoyant jets. After examination of recent data and simulations with the CORMIX jet integral model, discharge angles of 30° to 45° above horizontal were recommended. These provided better offshore transport of the effluent during low current activities and reached better dilution rates at the point of impingement with the seabed. However, more experimental data and more accurate modelling, particularly of the far-field mixing process, is needed to confirm these results.

Obviously, the recommendations about the best outfall design for brine discharges are differing. Depending on the applied mathematical modelling tools and the underlying assumptions, different ‘optimal’ discharge angles, velocities and maximum dilution performances are calculated. The reliability and accuracy of the applied simulation models has to be improved in order to give more secure recommendations about an optimal discharge design under certain conditions. This task is currently subject to research projects.
6.1.6 Zero Liquid Discharge

The concept of Zero Liquid Discharge (ZLD) systems is to avoid liquid waste products through appropriate process steps. For desalination applications, it means that all feed water is converted into drinking water or evaporated during the process, leaving only dry, solid constituents behind. ZLD incorporates the potential of providing desalinated water without any brine discharges and impacts on the marine environment. Solid wastes can more easily be treated and e.g. disposed in landfills. Besides, recovery and commercial use of salts and other valuable minerals might be taken into consideration.

A typical ZLD system for desalination plants consists of a conventional RO unit and a subsequent heating unit, e.g. a multi effect evaporator which dewater the RO brine. More energy efficient, however, are brine concentrators which compress the produced vapour and reinset it into the vessel to generate more vapour. They consume approximately ten times less energy than single effect evaporators, at evaporation rates of 90-98 %. Another option is to pass the concentrate into a crystalliser after initial evaporation. In the crystalliser, the brine is rotated in a vortex and forms a crystal mineral cake which can be dewatered in a centrifuge or a filter press to a solid state (WHO, 2007).

The higher the recovery rate of the RO unit, the less energy must be used to dewater the brine. Thus, conventional MSF plants are not suitable for ZLD as the brine concentration is too low.

Unlike in other industrial sectors, ZLD has not yet established itself in the desalination industry. Major drawbacks are the complexity of the systems and the costs. About 150 industrial facilities mainly in the power industry operate on ZLD basis in the United States. Only a couple of feasibility studies have included the ZLD option for desalination plants. No single desalination plant in the USA used ZLD in 2006. Until now, traditional disposal options are applied in more than 98 % of the cases (Mickley, 2006).

A study issued by the Middle East Desalination Research Centre (MEDRC) underlines the advantages of ZLD for small home-use water treatment systems in the MENA region. Besides saving valuable water through 100 % recovery, no saline waste water has to be discharged to the drain in contrast to conventional systems. Zero-liquid systems for home-use will soon be commercially available (MEDRC, 2005).

In contrast, commercial offers for large-scale seawater desalination ZLD systems are rare. The German company I.E.S. states to have a “scientifically-proven ecological profitable solution to the worldwide seawater desalination problem of harmful waste brines” (I.E.S., 2007). The proposed zero discharge recycling system (Fig. 22) extracts water and valuable minerals like table salt, magnesium chloride, potassium chloride and gypsum. After a conventional RO unit, the brine is passed to a self-sustaining softening system where it is decalcinated in order to avoid scale formation. The softening unit does not require any chemicals or energy. Afterwards, the brine enters a thermo distillation unit and is dried up to a salt concentration of 180 g/l. The highly concentrated brine flows back into the softening unit where the saturated sorbents are recovered. Then, it passes through recovery systems for mineral by-products, which are not further specified. The final step takes place in the
crystallisation chamber which leads to dry products. The entire process with an exemplary intake flow rate of 1488 m³/d is illustrated in Fig. 22. The RO unit recovers 528 m³/d of water, with another 600 m³/d of water being extracted in the thermo distillation unit. 2160 kg/d of gypsum, 50400 kg/d of table salt and 10800 kg/d of magnesium-potassium concentrate are extracted in the mineral recovery units. The overall recovery of potable water amounts to 75 % of the input water.

According to the manufacturer, the advantages of the system are:

- No chemicals needed during the recycling process
- Ecologically safe as no brine is rejected
- Profitable operation because salts and minerals are recycled in commercial quantities
- System can be applied to any desalination technology
- System can be attached to any plant capacity without any limitation
- The water output of regular plants is doubled

However, in a personal conversation with I.E.S no cost details on the system could be given, nor could any success story be presented since the system has not yet been applied to a real desalination plant. I.E.S claimed that this is due to marketing problems, not to technical problems and that they have thoroughly tested the concept.

Without any confirmation, it is questionable if the outlined system can operate in a profitable way. According to Mickley (2006), zero liquid discharge is the most costly of all disposal options. Furthermore, it remains to prove if the system can really be efficiently applied to any
existing seawater desalination plant of any capacity. It is also unclear, if salts can be commercially used if they are extracted from chemically contaminated brine, and it is unknown how useless solid waste or residual constituents denominated as ‘other products’ would be disposed.

Many questions regarding zero discharge solutions for seawater desalination plants remain unclear. But because of the immense ecological advantages of such systems, the developments should be carefully watched and research efforts for an effective and cost-efficient design should be intensified. Until now, it must be supposed that such a design does not exist yet.
6.2 Economic assessment of mitigation technologies

After having identified a couple of promising technologies to reduce the marine impacts of brine discharges and having assessed their ecological and technical efficiency, the financial burden of these systems shall now be analysed in order to evaluate their commercial applicability and viability in current seawater desalination plants. It should be noted that general financial statements about desalination technologies are difficult to make since costs are highly case-specific. The fact that desalination projects are usually planned and run by consulting companies, which treat customer data confidential, has further hampered the search for financial data in the course of this work. The following chapter presents the findings about costs of major mitigation measures.

First, the general cost structures of desalination plants shall be shortly introduced. The most important cost indicator for desalination plants are unit costs. Unit costs reflect the totality of costs and liabilities of a desalination plant, distributed per unit of produced water (usually m³). This equals the price which customers have to pay for one unit of desalinated water.

Unit costs have significantly decreased in the last years. Costs for MSF plants have decreased at an average of 6 % since the 1970s. The costs for SWRO were reduced by two thirds in only ten years. A SWRO plant on the Bahamas e.g. produced at a price of 1.27 US-$/m³ in 1995 whereas the Singapore plant, currently the most efficient one, produced water at the price of only 0.42 US-$/m³ in 2005. These unit cost reductions were mainly caused by the advancements in membrane technology and economies of scale. Unit costs thus depend on the desalination technology and the production capacity, but also highly on local factors like energy costs, capital costs or input water quality (Ebensperger, et al., 2005).

Fig. 23 provides a comparative illustration of typical cost distributions of SWRO and MSF plants, specified as share of unit costs. The data is derived from two exemplary middle-size plants with capacities of both 40,000 m³/d.

![SWRO cost composition](chart1.png) ![MSF cost composition](chart2.png)

**Fig. 23** Cost distributions of the Israeli SWRO plant Sabha A and the Libyan MSF plant Tripoli West II (based on Ebensperger et al., 2005)
It can be seen that the share of capital costs is considerably higher for MSF plants, which reflects the higher construction costs for thermal desalination plants. The share of energy costs is also significantly higher for the energy-intensive MSF process and contributes only about one quarter to the RO costs. Other operational costs like maintenance and labour are usually higher for membrane processes due to the greater operational complexity. Membrane replacement is a unique cost unit for membrane plants.

All in all, RO has lower unit costs than non-subsidised thermal plants since the energy consumption is much lower (Dore, 2005).

Environmentally friendly technologies which are analysed in the following affect the unit costs in several ways. First of all, the market price of the technology adds to the capital costs of the desalination plant. Since most technologies directly interfere with the operational parameters and influence the system efficiency, as has been shown in the previous chapter, environmental investments can influence the operating costs of a plant by changing the overall energy consumption, chemical consumption, need for maintenance, membrane replacement rates and labour intensity. Because of the numerous influencing factors, investments must be compared by a comprehensive cost indicator. Besides unit costs, the concept of Total Costs of Ownership (TCO) is commonly used. The TCO comprises all capital and operating costs of a desalination plant over its whole lifetime. An investment is financially favourable if it reduces the TCO of an existing plant. The best investment among several alternatives is the one with the lowest TCO.

**Sub-seabed intakes**

The Neodren intake system provides good feed water quality and reduces the need for pretreatment and cleaning chemicals in RO plants, as has been shown in the previous chapter. These technical characteristics generate the following cost advantages (Peters et al. 2006):

- Reduced costs for chemicals and for infrastructure and logistics related to chemicals
- Reduced costs for RO membrane replacement due to extended membrane lifetime
- Reduced energy consumption due to pressure reductions in the RO membranes as result of improved feed water quality

In personal conversations the financial viability of the Neodren intake compared to conventional open sea intakes was affirmed by Dr. Peters. According to his experience with existing plants, the capital costs of Neodren including installation are partly higher than that of open sea intakes. But due to the cost advantages listed above, the TCO with a Neodren system is lower. Additionally, the sub-seabed location avoids costly operation stops caused by blockage of intake screens or particle intrusion.

These are quantitative cost estimations. Dr. Peters could not back the statements by explicit numbers due to confidentiality reasons, but was eager to publish his data within the next years in order to underline the advantages of Neodren intakes.

Until then, the cost assessment of Neodren must be handled with care. The operational cost advantages are plausible, as they are directly linked to the documented technical benefits.
However, they depend on the quality of the filtering layers in the seabed and thus, are subject to variations. Additionally, the capital costs which include drilling and other soil works are site-specific and as such, cannot be clearly specified. All in all, lower TCO with Neodren systems cannot be generally confirmed and must be determined in a case-specific in-depth analysis.

**Ultrafiltration**

Although ultrafiltration has proven in numerous tests to be a superior pretreatment method for seawater RO plants, its application has until now been restricted to a couple of plants around the world. A main obstacle has always been the allegedly higher operating costs compared to conventional pretreatment systems. But as latest studies show, even cost aspects argue for ultrafiltration.

Knops et al. (2007) analysed the cost-efficiency of a UF pretreatment system for RO plants, equipped with a newly developed UF membrane. They conclude that the TCO of the plant with UF pretreatment (79-88 US-cents/m³) is 2-7 \% lower than with conventional pretreatment (85-90 US-cents/m³).

Looking at the single cost units, the capital costs of pretreatment were 10-20 \% higher because of UF membrane purchases. The operating costs of pretreatment were measured 25-50 \% lower with UF, as result of the trade-off between high chemical savings and additional costs for UF membrane replacements. Total pretreatment costs were reduced by 0-20 \%. The costs for RO cleaning and replacement which usually make up about 6 \% of the TCO were lowered by 30-40 \% due to UF operational benefits. Other fixed costs were reduced by 4 \% because of the smaller footprint of UF systems and reduced offline times due to less RO membrane replacement. Energy savings and higher flux rates through UF were difficult to assess and thus, were assumed to be equal for both systems. Summing up all cost units, a small cost advantage for UF pretreatment was calculated (Fig. 24).

**Fig. 24** Comparison of TCO for a SWRO with conventional and UF pretreatment (Knops et al., 2007)
Wolf et al. (2005) compared the economics of a UF pretreatment system with hollow fibre membranes and a conventional system with two stage sand filters and chemical treatment. Because of the large dependence of cost results on external factors like raw water quality and financial terms, the exact test parameters were specified. The pretreatment systems were compared for a SWRO plant with a capacity of 74,000 m³/d and poor, highly variable raw water quality with a salinity of 35 g/l and an SDI > 6. Interest rates of 6.5 % and energy costs of 0.045 US-$/kW/h were assumed. Comparing the TCO revealed another small lead for UF pretreatment, as Fig. 25 illustrates.

The TCO added up to 0.582 US-$/m³ for the UF system and 0.592 US-$/m³ for the conventional one. The investment costs were comprised of investments in the desalination system (lower for UF), investment in the pretreatment system (higher for UF) and infrastructural investments (equal). The UF lead was mainly generated by slightly smaller total investment costs, lower RO membrane replacement and lower staff costs due to more reliable operation. It is unclear, however, why the costs for chemicals were not decreased significantly, although substantial reductions in chemical use can be expected from UF pretreatment.

Additional cost savings which have not been included in the calculations refer to the intake structures. Due to the good UF filtering qualities the feed water can be taken from close to the shore. No long intake pipes are needed to access deeper waters where the raw water quality is better. The poorer the raw water quality, the higher cost advantages of UF can be expected.

Pearce (2007) presented another UF cost analysis. In a general study the average costs of UF pretreatment and conventional systems were compared. It was found that the capital costs for UF pretreatment systems were 20-50 % higher. On the other side, the potential for cutting RO membrane replacement costs was about 33 % and the total amount of RO membranes could be reduced by up to 25 % at adequate TDS levels, due to flux rate extension. Besides, costs
for chemicals were considerably reduced and space savings of up to 33% may also translate into capital cost savings. Last but not least, higher operation hours per year as well as much more reliability and failure resistance at variable feed quality and weather conditions (often not considered) added to the cost advantages of UF pretreatment. The energy consumption was similar to conventional systems.

A case study in the Eastern Mediterranean Sea was outlined. It can be considered as a conservative study since the operational conditions were comparatively favourable for conventional pretreatment. The raw water quality was relatively good and stable so that only a single stage of dual media filters was needed in the conventional system. UF pretreatment, however, has highest cost advantages at poor quality feed water. Moreover, cost advantages through flux rate increases with UF systems were restricted by the high feed water salinity of 38 g/l. The chemical cost comparison was based on the fact that continuous disinfection with UF pretreatment is redundant and that coagulant dosages could be reduced by 57%. The study covered three different scenarios. The first case depicts the costs of conventional pretreatment with three RO membrane cleanings per year. The other two scenarios were based on the assumption that UF pretreatment is used and that two or only one RO membrane cleaning per year is carried out. The total costs of the three cases are summarised in Table 14.

Table 14  Results of pretreatment cost comparisons under conservative conditions (based on Pearce, 2007)

<table>
<thead>
<tr>
<th>Costs (US-cents/m³)</th>
<th>Conventional (3 RO cleans/a)</th>
<th>UF pretreatment (2 RO cleans/a)</th>
<th>UF pretreatment (1 RO clean/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating days per year</td>
<td>346</td>
<td>347.5</td>
<td>349</td>
</tr>
<tr>
<td>Capital cost share</td>
<td>33,01</td>
<td>33,87</td>
<td>33,72</td>
</tr>
<tr>
<td>RO replacements</td>
<td>3,51</td>
<td>2,33</td>
<td>2,32</td>
</tr>
<tr>
<td>UF replacement</td>
<td>0</td>
<td>1,96</td>
<td>1,95</td>
</tr>
<tr>
<td>Cartridges</td>
<td>0,45</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Chemical use</td>
<td>2,10</td>
<td>1,15</td>
<td>0,74</td>
</tr>
<tr>
<td>Energy, maintenance &amp; labour</td>
<td>51,01</td>
<td>50,79</td>
<td>50,58</td>
</tr>
<tr>
<td>Total costs</td>
<td>90,08</td>
<td>90,10</td>
<td>89,31</td>
</tr>
</tbody>
</table>

The results show that additional capital and UF replacement costs can be financed by the savings in RO replacement and chemical use. Each annual RO membrane cleaning which can be saved, saves a total of 0.8 US-$/m³ in the case of UF pretreatment. The case study confirms that UF is commercially competitive or favourable, even under conservative conditions with operational advantages for conventional pretreatment. Besides, additional cost savings are enabled by the reduced downtime, due to more stable feed water quality, as well as by the lower footprint. Both aspects have not been taken into considerations in this study and would improve the UF cost balance.
Nanofiltration

Hassan et al. (1998) outlined cost calculations for the Jeddah 2 SWRO plant in Saudi-Arabia, which was operated with and without NF pretreatment. The total energy consumption with NF was 25% lower than in conventional operation and the RO recovery rate was increased to 60% at the same time. However, increasing the recovery rates also involves higher investments into additional intake pipes. Independent of the assumed prices for energy and under consideration of all relevant costs including the capital costs for NF membranes, the economic analysis revealed that the NF-SWRO plant produced at about 27% lower unit costs than the conventional SWRO plant. This may result in a significant drop in water prices. The cost advantages with NF pretreatment were mainly due to plant efficiency increases, energy consumption decreases and chemical savings. With capacities of 31,977,504 m³/a, the water output of the NF-SWRO increased by 71%.

Cost savings can also be expected from NF-MSF systems, but have not been covered in detail. Avoiding scale formation with NF pretreatment enables higher top brine temperatures, which leads to higher plant efficiency and reduction of energy costs.

Eriksson et al. (2005) cited reports about the Umm Lujj SWRO plant in Saudi-Arabia stating that the plant could be operated at 29% lower unit costs including amortisation when using NF pretreatment. The single cost units, however, are not known. In two pass RO mode which combines two consecutive RO units, however, the costs were still 10% lower than in NF-RO mode. It is concluded that NF pretreatment is economical in cases with poor raw water quality where RO membranes with conventional pretreatment experience excessive fouling and have poor performance. In order to minimise the unit costs, NF-SWRO should be operated with high RO recovery rates.

According to MEDRC (2001), the operating costs of NF pretreatment are about 1.0 US-cent/m³ for labour, 2.0 US-cents/m³ for membrane replacement, 1.5 US-cents/m³ for chemicals and parts and costs for energy consumption of about 1.2 kWh/m³. The capital costs add up to around 8.6-10.0 US-cents/m³, depending on the amortisation. These costs must be considered as theoretical and do not reflect real operational costs of specific plants.

Other sources severely doubt in the viability of NF pretreatment. Experts at Taprogge consider NF membranes to be much too costly and do not see any potential for cost reductions in the future due to the low market share.

Material selection

Raw material prices play an important role for material selection and for capital costs of a desalination plant. The trend is to minimise nickel consumption, as the nickel price has soared from 7 US-$/kg in 2002 to 55 US-$/kg in 2007. The copper price also increased by 400% to 9 US-$/kg in the last five years (Glade, 2007). These are significant commercial disadvantages for copper-nickel alloys. Titanium, with costs of 90 €/kg in 2007 and high lead times (Scheffler, et al., 2008), is no cost-efficient alternative either.
The higher corrosion rates are expected, the more material has to be used for plant components. This has created overweight designs of MSF plants with high investment costs per volume of up to 3,000 US-$/m³ in the past. The replacement of simple carbon steel by stainless steels end of the 1990s reduced the investment costs to 1,200 US-$/m³. Besides investment costs, better corrosion resistance also lowers the costs caused by system downtimes, maintenance works and material replacement (Al-Odwani, et al., 2006). The same logic applies when looking at cost advantages of titanium and stainless steels compared to copper-nickel. Whereas the tube thickness in MSF plants has to measure 1-1.2 mm for copper-nickel materials, only 0.4-0.7 mm are sufficient for titanium tubes which translates to material savings of 60 % (Glade, 2007).

The price of stainless steel depends to a large extent on composition and concentration of the alloying materials chromium, nickel and molybdenum. Duplex stainless steels have multiple cost advantages. Firstly, the content of the critical cost intensive alloying materials nickel and molybdenum is reduced by at least 60 % and 33 % respectively, compared to conventional corrosion resistant stainless steels. Secondly, as the strength of duplex steels is double that of conventional steels, less material has to be used. Thus, material costs are saved and lower component weight can cause cost savings during construction. For storage tanks made of duplex steel, material savings of 34 % were reported.

As early as in 1993 the cost advantages of duplex steels in MSF plants have been published at an IDA conference, but the desalination industry did not adopt the concept until 2003. Today, a couple of thermal plants in the MENA region, but also SWRO plants in Australia and Singapore, have installed the material and were able to reduce capital and maintenance costs (Olsson, et al., 2007). The premium duplex steel 2205, which has the same high corrosion resistance as highly alloyed austenitic grades like the stainless steel 904L, had a listed raw material price of 10 US-$/kg in 2007. For comparison, the same price must be paid for a conventional middle class stainless steel with far worse corrosion properties (Baek, 2007).

Polymer elements constitute the cheapest material option of all. They are already widely applied in SWRO plants. If innovative ways were found to apply polymers in thermal plants as well, significant cost reductions would be possible. Costs for heat transfer pipes amount to an estimated 40 % of the capital costs of a typical MSF plant, and the distiller shells to another 40 %. This underlines the cost potential for polymer solutions in heat transfer elements. The material costs of heat transfer elements made up of HDPE or PP are 2-3 orders of magnitude below that of titanium or copper-nickel tubes. Simple installation and construction as well as low scaling tendency can generate further cost advantages (Scheffler, et al., 2008).

Besides material costs, the heat conductance plays an important role in influencing the costs of thermal plants, as it directly influences the energy consumption. The total conductance of heat transfer units equals the product of heat transfer area and specific material conductivity. The choice of an optimal level of conductance provokes a trade-off between rising capital costs and increasing energy consumption, as Fig. 26 illustrates.
With growing conductance, the energy consumption is decreasing, but the investment costs for heat transfer materials are growing. In conventional systems, the high capital costs of heat transfer materials lead to minimal costs of water in point A and only allow for the installation of a conductance of C. Innovative polymer materials have much lower investment costs which results in a significantly lower straight line of capital costs (dashed). Thus, the curve of total water costs (dashed) is much smoother than the original one and trends in direction of the x-axis. Now the minimal costs of water are at point B which corresponds to a higher conductance of D. Consequently, the newly applied polymer materials would lower the costs of water by E minus F. Thus, by applying cost efficient heat transfer materials, more conductance can be reached, leading to higher plant efficiency and lower water costs. This argues for polymer materials or inexpensive stainless steel solutions.

Discharge options

As has been shown in the previous chapter, viable discharge options for large-scale seawater desalination are surface water, sewer disposal and possibly deep well injection. General cost statements for discharge and outfall options are difficult to make as they highly depend on site-specific properties and variable factors, such as:

- Conveyance costs, including pumps, pipeline material and trenching works on land and in the water
- Outfall design, including pipes, risers, diffuser ports, etc.
- Land costs and availability
- Climatic conditions
- Varying regulatory requirements and enforcements
However, experiences and studies show that surface water disposal is cheapest discharge option for most desalination plants. This particularly applies to seawater desalination plants with large discharge volumes (Mickley, 2006). The main cost factors of surface water disposal are conveyance costs, costs for outfall construction and costs associated with monitoring of environmental effects of the concentrate. Outfall costs depend on the outfall size, the material, the effluent salinity level and resulting dilution requirements, amongst others. Using an already existing outfall makes surface water discharge even more cost-efficient. The cheapest outfall design will be an open sea outfall with one pipe. In the case of submerged outfalls, the costs are rising with the water depth and the length of the pipes. Sewer disposal can be a low cost option for low discharge volumes. Apart from conveyance, the costs mainly consist of the fees which must be paid for connection to the sewage plant and for treatment of the effluents. These costs increase with growing flow rates. It might also be an affordable option for larger plants, if the fees are moderate. The capital costs for deep well injection are higher than for surface and sewer disposal. Hence it is restricted to larger flow streams in order to benefit from economies of scale. Capital costs depend on depth and diameter of the well and geological conditions, amongst others. Furthermore, pretreatment of the brine prior to well injection might be needed. For safety reasons, an alternative disposal option should be provided in cases of maintenance, testing or failing of the well. These aspects would significantly add to the overall costs. The operating costs are low. Generally, costs of deep well injection are difficult to predict and include several uncertain factors. The approximate capital costs of drilling, conditioning and monitoring a well for a tube of 50 cm diameter and a depth of 1,000 m are estimated to be 4.5 Million US-$. Assuming another 50,000 US-$/a for operating costs, costs in the order of magnitude of a few US-cents would add to the unit costs.

Fig. 27 gives an illustrative comparison of the approximate capital costs of typical discharge options, depending on the effluent volumes. It can be seen that surface water and sewer discharge have least capital costs and that these costs only slightly increase with the effluent flow rates.
The costs of multiport diffuser systems are not necessarily higher than a standard pipe of comparable length. The cheapest multiport design is a simple pipe with holes drilled into the sides. But this raises the danger of seawater backflow or organism intrusion, particularly for intermittent streams. A series of ports equipped with valves should be the preferred design. Valves regulate the concentrate stream by means of pressure and cost about 600 US-$ for a 3-inch valve and 1,500 US-$ for a 12-inch valve. Several design alternatives might be possible to meet the required dilution. In this case, designs with shorter diffuser lines and smaller ports have usually proven to be less expensive (Mickley, 2006). Submerged multiport diffusers are expected to be cheaper than single submerged outfall pipes in the Arabian Gulf region. Since multiport diffusers enable more rapid mixing of the effluent, the length of the outfall pipes can be shorter without posing risks for the coastal environment and coastal activities. Conventional outfall pipes have to reach out further into the sea in order to ensure sufficient dilution. Thus, they are more expensive in the shallow water of the Arabian Gulf (Alameddine, et al., 2007).

Zero Liquid Discharge

The Zero Liquid Discharge option is more expensive than all conventional discharge options. This is primarily due to the high capital and energy costs. In the case of municipal membrane effluents, ZLD is only applied when no other option exists because of the cost reasons (Mickley, 2006).

An exemplary calculation for ZLD costs presumes a moderate effluent flow rate of only one Million Gallons (3,785 m³) per day and an operation time of 20 years. Capital and energy costs of concentrator and crystalliser alone, without considering disposal costs of the solid waste, lead to total annual costs of 4,142,400 US-$ . This translates to immense unit costs of 3.0 US-$/m³, which is 600 % more than the total unit costs of current efficient seawater desalination plants. Since energy costs are making up for more than 3.5 Million US-$ of the total annual burden, no significant economies of scale can be expected from ZLD. There might be same savings through high-end energy recovery tools, but at these cost magnitudes, no chance of commercial application is visible.

Mickley (2004) compared the operating costs of three ZLD system designs, including a thermal evaporator plus evaporation ponds (1), a high recovery RO plus thermal evaporation plus evaporation ponds (2) and a high recovery RO plus evaporation ponds (3). Option 3 turned out to be most cost-effcient. Cost savings of about 40 % compared to the alternatives were calculated due to the absence of energy-intensive evaporators. Options 2 and 3 require the use of chemicals in the RO process, so that costly sludge disposal must be included in the calculations.

In order to become more cost-efficient, ZLD must make use of salt recovery and commercial exploitation. Technologies already exist to selectively remove salts. Other trends might help to make ZLD more competitive in the future:

- Technologies to replace the energy-intensive thermal units are currently in development
• Lost water through low recovery rates in conventional discharge processes is becoming more precious
• Environmental concerns will rise with deteriorating source water quality
• Environmental regulations for open water discharge will become more stringent

ZLD might benefit of these trends, but it is not possible to state when and even if it will be financially competitive to conventional discharge options for large-scale seawater desalination.

The German company I.E.S. claims to have developed a profitable ZLD system for all desalination volumes by extracting minerals and salts in commercial quantities during the process. However, concrete figures are neither available in any publications, nor could they be provided in personal conversations with the manufacturer.
6.3 Results and interpretation

From the analysed data and sources, the following results about the efficiency of mitigating technologies can be presented. All findings are displayed in comparison to a conventional seawater desalination plant design consisting of an open sea intake, chemical pretreatment, copper-nickel elements (for MSF heat exchange), conventional stainless steels (RO) and surface water discharge.

**Sub-seabed intakes**, namely the Neodren system, proved to provide good feed water quality for RO plants, provided that appropriate filtering layers like sand or gravel are available in the coastal area. TOC and turbidity were significantly reduced to stable non-critical levels. Experiences show that current plants run at an SDI < 5 and that the need for pretreatment chemicals is significantly reduced. Antifouling agents are dispensable, coagulants and antiscalant chemicals are reduced and chemical cleaning intervals of RO membranes are enlarged by 4-6 times (≈ 80% less chemical cleaning). Single sources report that average capital costs for Neodren intakes are higher, but that TCO is generally lower due to cost savings related to reduced chemicals, reduced membrane replacement and improved operation reliability. These cost advantages cannot be verified. Application of sub-seabed intakes for MSF plants seems to be less efficient from a technical and financial viewpoint.

**UF pretreatment** has been extensively tested in numerous pilot plants and regular plants and has proved to deliver excellent feed water quality for RO plants. An SDI < 3 can often be attained. Most covered plants ran stable without antifouling chemicals, at moderate coagulation and antiscalant dosages and at least four times lower RO membrane cleaning frequencies (≈ 75% less chemical cleaning). A Chinese pilot plant could even be operated stably and efficiently without dosage of any pretreatment or cleaning chemicals, only by optimisation of the UF-RO operational parameters. Different studies prove that UF pretreatment is also financially competitive to conventional pretreatment. Higher capital costs for UF membranes are financed by chemical savings and lower RO replacement needs. The TCO was equal or lower than for conventional systems in the covered cases. Thus, UF pretreatment combines technical, ecological and financial advantages for RO plants.

The use of **NF pretreatment** is not well documented. A couple of tests confirm that NF boosts the recovery rates of RO and MSF plants due to the excellent filtering qualities. Chemicals for RO feed water are not needed. But it must explicitly or implicitly be concluded from the test descriptions that chemicals have to be dosed instead into the NF feed water in order to avoid fouling and scaling of NF membranes. Thus, the environmental efficiency of NF pretreatment is undermined. It might be overcome by process optimisation and development of more robust NF membranes in the future. Cost calculations from two SWRO plants in Saudi-Arabia reported unit cost reductions of 27% and 29% by application of NF pretreatment due to energy savings and RO efficiency improvement. NF pretreatment seems to be most cost-efficient when operating at high recovery rates and at poor feed water quality.
**Sponge balls** were found to be an effective method to reduce fouling and scaling in MSF tubing systems. Together with the dosage of moderate antiscalants, antifouling chemicals can be avoided. The plant efficiency may be slightly increased. Numerous MSF plants in Saudi-Arabia already use sponge ball cleaning. The combination of sponge ball cleaning and antiscalant dosing is reported to be the most cost-efficient pretreatment solution in these plants.

**“Green” additives** offer an ecologically compatible alternative to conventional pretreatment chemicals. Especially the search for green antiscalants was successful. Agents like PAP-1 are non-toxic, provide excellent biodegradability and showed encouraging results in scale inhibition. Even more common antiscalants like Flocon 100 have good biodegradability. The costs of these agents could not be investigated. Due to the low share of chemicals in unit costs (cf. Fig. 23), the use of green antiscalants is not expected to cause any decisive changes of unit costs.

**UV radiation** has not proved to be an efficient pretreatment measure and is hardly covered in any publication.

**Stainless steel and titanium** materials were found to provide excellent corrosion resistance in MSF and RO plants. Severe heavy metal pollution by traditional copper-nickel alloys in thermal plants can be avoided with these materials, whereas the lower thermal conductivities do not necessarily pose an operational problem. Newly developed **duplex steels** provide the same high corrosion resistance as regular stainless steels at much lower alloying concentrations and twice the strength. Experiences with duplex steels in newly built thermal and RO plants are highly positive. With high raw material prices for nickel, copper and titanium, stainless steels are the most cost-efficient metal materials for desalination plants. Among the stainless steels, duplex steels are most economical as they have lower alloying concentrations of costly nickel and molybdenum. Due to the higher strength of duplex steels, less material is required and wall thicknesses can be reduced which enables the application as heat transfer elements.

**Polymers** have the best resistance against chemicals and corrosion of all materials and are most cost-efficient. HDPE and PP proved to be efficient and enduring heat transfer materials in single test series, but are still experimental. Stability remains a problem and the conductivity is decreasing with the number of used polymer layer. However, due to the low material costs, larger heat exchange surfaces could be installed.

**Posttreatment** measures can mitigate potential adverse effects of the brine prior to discharge. Harmless neutralisers exist to remove residual chlorine from the effluent. Several chemical and adsorbing options are conceivable to remove heavy metals. However, these measures do complicate the process and avoiding heavy metal corrosion should be preferred.

Sea disposal is the only discharge method practicable for all capacities of desalination plants and it is generally the most cost-efficient option. It requires low investments and has moderate operational costs. The impact area of brine discharges can be minimised by increasing the dilution rates. Submerged **multiport diffusers** proved to provide good dilution rates. They are affordable and not much more expensive than conventional outfall pipes, particularly under
bad mixing conditions in the surrounding sea. Optimisation of the discharge design, e.g. outfall geometry, discharge angles and velocities, further improves the dilution process. Discharge angles of 30-45° above horizontal were recommended for negatively buoyant effluents.

The Zero Liquid Discharge concept has not yet proven to be viable for large scale seawater desalination. Despite claims about alleged availability of effective systems for all desalination capacities, technical questions remain unanswered and commercial competitiveness must be highly doubted. Until now, experiences have shown that ZLD is the most expensive discharge option of all, generating unsupportable unit costs mainly because of the high capital and energy costs of current systems. Nevertheless, future developments and research should be carefully watched because of the huge potential environmental benefits and the option of salt and mineral recovery. MSF effluents are not suitable for ZLD due to the low concentrations.

The environmental benefits and costs of major mitigation technologies, in comparison to conventional seawater desalination systems, are summarised in Table 15.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Environmental benefit</th>
<th>Financial expenses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sub-seabed intake (RO)</td>
<td>SDI &lt; 5, no antifouling chemicals, antiscalant and coagulation chemicals reduced, chemical cleaning intervals 4-6 times higher</td>
<td>Higher investment costs, lower operating costs → lower TCO (?)</td>
</tr>
<tr>
<td>2. UF pretreatment (RO)</td>
<td>SDI &lt; 3, no antifouling chemicals, antiscalant and coagulation chemicals reduced, chemical cleaning intervals at least 4 times higher, operational optimisation might replace all chemicals</td>
<td>Higher investment costs, lower operating costs → slightly lower TCO</td>
</tr>
<tr>
<td>3. NF pretreatment</td>
<td>No chemicals for desalination unit, instead for NF membranes (?)</td>
<td>Unit cost reductions and higher recovery rates</td>
</tr>
<tr>
<td>4. Sponge balls (MSF)</td>
<td>No antifouling chemicals, slightly less antiscalants</td>
<td>Lower pretreatment costs, most cost efficient method for many MSF plants</td>
</tr>
<tr>
<td>5. Green additives</td>
<td>Biocompatible, non-hazardous antiscalating chemicals</td>
<td>Unknown costs, no significant cost increases expected</td>
</tr>
<tr>
<td>6. Titanium components</td>
<td>Excellent corrosion resistance</td>
<td>High raw material prices and high lead times</td>
</tr>
<tr>
<td>7. Stainless steel components</td>
<td>Excellent corrosion resistance</td>
<td>Moderate prices, depends on grade of alloying materials</td>
</tr>
<tr>
<td>8. Duplex steel components</td>
<td>Excellent corrosion resistance</td>
<td>Low prices due to low alloying concentrations</td>
</tr>
<tr>
<td>9. Polymer materials</td>
<td>Superior corrosion resistance</td>
<td>Lowest material price</td>
</tr>
<tr>
<td>10. Multiport diffuser &amp; discharge design</td>
<td>Improved dilution performance → impact area reduced</td>
<td>Similar to submerged outfalls, more cost-efficient in shallow low energy waters</td>
</tr>
<tr>
<td>11. ZLD (RO)</td>
<td>No marine impacts at all, possibly solid waste to dispose</td>
<td>Much too expensive, uncompetitive until now</td>
</tr>
</tbody>
</table>
It can be concluded that a couple of cost-efficient technologies exist to considerably reduce or avoid the major pollutants in desalination effluents. Sub-seabed intakes, UF and NF pretreatment as well as the different metals can be considered as alternative applications with respect to their environmental benefits. Strategies of how to determine the best environmental investment among several alternatives are discussed in the following.
6.4 **Environmental investment decisions**

This chapter gives a theoretical analysis of decision support systems for investment planning with focus on relevant desalination investments. First, a conventional investment planning method is described and explained by giving an example. Then a basic model for investment planning under consideration of environmental impacts of brine discharges is developed and its practicability for the investment decisions in the context of this work is evaluated.

**Conventional investment planning for desalination plants**

In order to draw a conclusion about the profitability of an investment, conventional investment planning methods usually compare two main elements:

1. *Capital costs* include the unique costs for acquisition, installation, construction, etc.
2. *Operating costs* consider all recurring costs of an investment. They can be directly related to the investment, e.g. costs for maintenance, spare parts, labour, etc. But an investment also causes indirect cost effects, as it influences the operational parameters of a plant. For example, the investment in NF pretreatment can result in lower overall energy consumption because lower RO membrane pressures are needed. All operational changes must be entirely monetised in order to make operating costs comparable.

The investment with the lowest capital and operating costs or the highest cost savings is chosen. For desalination issues, the means of comparison usually are unit costs (US-$/m³). The unit costs of a desalination plant usually reflect the totality of costs and equal the water price, unless water production is subsidised or any of the input factors is subsidised. In this case the unit costs and thus the water price are lower than the totality of costs.

The capital costs of investments in desalination plants are distributed over its whole lifetime in order to keep the water price at a reasonable, competitive level. The amortisation method is a commonly applied mathematical method of translating the capital costs of an investment into regular payments over a given time. The costs of money are considered by compounding the payments via an interest rate (Díaz-Caneja, et al., 2004).

Where

\[ a = \text{annual amortisation rate} \]
\[ I = \text{investment} \]
\[ n = \text{number of amortisation years} \]
\[ i = \text{interest rate} \]

The annual amortisation rate of an investment \( I \) for a total of \( n \) years at a given interest rate \( i \) is defined as
In order to translate the capital costs of an investment into unit costs, the annual amortisation rate is divided by the average annual production capacity of the desalination plant.

A fictitious investment in a new UF pretreatment system with capital costs of 10,000,000 US-$ for membranes, installation, etc. shall be supposed. The system shall be integrated into an 80,000 m³/d SWRO plant with a lifetime of about 20 years, at a given interest rate of 6 %. The annual amortisation rate of the investment would amount to:

\[
a = \frac{I \cdot (1+i)^n}{(1+i)^n - 1}
\]

Costs of 859,717 US-$ must be amortised every year for the UF investment. At an average operating period of 360 days per year, the plant has an annual water production of 28.8 Million m³. Consequently, the UF capital costs add 2.9 US-cents/m³ to the unit costs of the desalination plant.

The operating costs of the investment like additional energy costs, membrane replacement costs, labour and maintenance costs are calculated on a yearly basis and converted into unit costs. Assuming 500,000 US-$ of direct operating costs per year result in 1.7 US-cents/m³.

The UF investment also causes savings in operating costs. These consist of chemical savings, the reduction of RO replacement costs due to provision of better feed water quality, decreased energy consumption of the RO modules due to lower pressure requirements, etc. Altogether, the cost savings might account for 300,000 US-$/a which corresponds to 1.0 US-cents/m³. Summing up the capital and operating burden of the UF investment yields the total costs of 3.6 US-cents/m³ which is the reference value for comparison to alternative investments (Table 16). Alternative investments (e.g. a different type of UF membrane) with total costs of less than 3.6 US-cents/m³ would be favourable to the described investment.

<table>
<thead>
<tr>
<th>Table 16 Cost calculations for a fictitious UF investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>annual (US-)</td>
</tr>
<tr>
<td>Capital costs</td>
</tr>
<tr>
<td>Operating costs</td>
</tr>
<tr>
<td>Savings in operating costs</td>
</tr>
<tr>
<td>Total costs of investment</td>
</tr>
</tbody>
</table>

The cost comparisons between membrane and conventional pretreatment covered in Chapter 6.2 (cf. Fig. 23 & 24, Table 14) are based on this concept of calculation under summarised under the term of TCO. However, this method has some disadvantages:
- A precise data base for all cost figures and operational parameters is needed. In the case of desalination projects, this can only be provided in a detailed analysis through assessments by consultants and engineers or after test runs.

- Some aspects of investments are difficult to monetise and cannot be included. This is e.g. the lower probability for system shutdowns or the improved and facilitated process control for desalination plants when using membrane pretreatment technologies.

- The concept does not consider all environmental costs and possible environmental impacts of investments.

The last aspect is the most important one for this work. Environmental costs are commonly divided into internal and external environmental costs (cf. e.g. Madu, 2001). Conventional investment planning usually only covers internal environmental costs of investments. These are operational costs which have to be borne by plant operators and which can be assigned to environmental issues, e.g. certificate costs for CO$_2$ emissions, costs for wastewater management and monitoring, wastewater disposal fees, fines for violating regulations or exceeding regulatory limits, etc.

However, it is not known if internal environmental costs have been included in the cost comparisons of technologies presented in Chapter 6.2. They might be included in one of the cost groups labelled as chemicals, labour or energy, but have not been directly mentioned in the cost compositions.

External environmental costs reflect environmental impacts which are caused by industrial activities but which are not paid for since no price for the damage exists. Such impacts can be e.g. the degradation of natural resources, water pollution, dying of species, changes in quality of life, etc. External effects of investments are not included in conventional investment planning. They have to be monetised and assigned to the polluter or the originating source in order to provide a comprehensive cost analysis.

Brine discharges of seawater desalination plants can cause internal and external environmental costs. Thus, the discussed mitigation technologies (Table 15) may reduce both internal and external costs. A possible way of integrating external environmental costs of brine discharges into the decision making process is presented in the following.

### Including environmental impacts of brine discharges

The following approach presents a proposal for including the environmental impacts of brine discharges into the investment decision. For simplicity reasons, the approach only considers the external effects on the marine environment.

Assuming a set of investments $i$ to choose from. The best investment minimises the sum of total costs of ownership and external environmental costs:

$$\min \ TCO_i + EEC_i$$
where TCO depicts the totality of capital and operating costs of an investment which includes internal environmental costs. The external environmental costs are caused by the impact of a desalination effluent on the marine environment. The total impact depends on the discharged pollutants, the pollutant intensity, the impact area and the sensitivity of the receiving ecosystem towards the respective pollutant.

- The relevant pollutants are salinity, temperature, the different chemicals and heavy metals. Höpner (1999) e.g. identified ten main pollutant groups in desalination effluents which might be adopted in this context. If needed, the groups can be split up to more detail, e.g. from a chemical group level (antiscalants) to a chemical agent level (Belgard EV).

- The pollutant intensity is the concentration of the pollutants or the temperature of the effluent at the point of discharge into the receiving marine ecosystem.

- For the definition of an environmental sensitivity scale, one could refer to the 15 subecosystems outlined in Table 3. A sensitivity coefficient assigns a number to each combination of pollutant and ecosystem, reflecting the potential harmfulness of the pollutant on the respective system. Elaborating these sensitivity numbers would be a task for biologists. Table 17 gives an example of a possible sensitivity scale.

Table 17 Definition of an exemplary sensitivity scale depending on the pollutant and the receiving ecosystem

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>...</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollutant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>...</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>...</td>
<td>35</td>
</tr>
</tbody>
</table>

- The dilution factor depicts the dilution rate attained after a certain mixing zone. Thus, technical efforts to improve dilution and to minimise the impact area can be considered.

Defining the following variables:

- \( Pollutant \ p \): 1...n [-]
- \( Pollutant \ intensive \ t \): 0...∞ [mg/l, °C]
- \( Ecosystem \ s \): 1...m [-]
- \( Sensitivity \ coefficient \ q \): \( \mathbb{N} \) [1/mg/l; 1°C]
- \( Environmental \ cost \ factor \ c_e \): 0...∞ [US-$]
- \( Dilution \ factor \ d \): \( \mathbb{N} \) [-]
- \( Regulatory \ limit \ values \ R \): 0...∞ [mg/l, °C]
The resulting marine impact for a specific ecosystem can be expressed as the product of pollutant intensity $t$ and respective sensitivity coefficient $q$, summed up over all pollutants and divided by the dilution factor:

$$\frac{1}{d} \sum_{p=1}^{n} t_p \times q_{ps}$$

This term depicts the impact value which is caused by the operation of a desalination plant with a given configuration and can be altered by environmental investments. The impact value must be monetised in such a way that the decline of values for the society through marine pollution is properly expressed, for example by means of a cost factor $c_e$. This approach is similar to the certificate costs for CO$_2$ emissions which reflect the environmental costs of one emitted unit of CO$_2$. Finding an appropriate cost equivalent for marine pollution is a task for economists.

When defining the TCO as the sum of capital ($c_c$) and operating ($c_o$) costs, the optimisation approach for finding the best combination of mitigation investments for brine discharges can be defined as follows:

$$\min c_{ci} + c_{oi} + \left( c_e \times \frac{1}{d} \sum_{p=1}^{n} t_p \times q_{ps} \right)_i \quad \forall i$$

s. t. $t_p \leq R_p \quad \forall p$

The investment or the sum of investments which minimises the above term constitutes the optimal investment decision for mitigating the impacts of brine discharges, from an ecological and economic point of view. The constraint in the second row ensures that all investments or combination of investments are ruled out which do not meet the regulatory limit values $R$ for the different pollutants.

The approach demonstrates that a lot of precise data about plant parameters, impacts, marine environment and the different costs must be available in order to conduct a sound environmental assessment of investments reducing brine discharges. This data can only be provided by profoundly analysing a scheduled project or a running plant and the respective ecosystem. For the course of this work, a more qualitative way of assessing the identified mitigation technologies and giving investment recommendations has to be applied.
6.5 Recommendations

Recommendations for the best available technologies to reduce impacts on the marine environments are given separately for RO and MSF plants. The recommendations will be based on the combined assessment of:

1. **Ecological efficiency** which describes the potential of reducing both the internal and external environmental costs and is measured by the reduction of critical pollutants
2. **Financial efficiency** which includes capital and operating costs and is measured by the TCO or other cost units depending on the available data

The assessment of the ecological efficiency will be based on the classification of critical pollutants outlined in Table 1 and the potential of the respective technology to reduce the use of the different pollutants (Table 15). The assessment of the financial efficiency will be based on the findings about costs, summarised in Table 15.

**Recommendations for RO plants**

For RO seawater desalination plants the following mitigation technologies come into question:

- **Sub-seabed intake, UF pretreatment, NF pretreatment, green additives, titanium components, stainless steel components, duplex steel components, polymer materials, multiport diffuser, ZLD**

ZLD can be ruled out because the costs are too high and no working application exists yet. NF pretreatment is ruled out because environmental benefits are doubtful and the ecological efficiency is probably low.

Sub-seabed intakes and UF pretreatment both reduce the dosages of cleaning chemical (very critical), chlorine and thus THM (critical), antiscalants (critical) and coagulants (less critical) and can be considered as alternatives. UF provides better SDI levels and has the potential of operating on lower chemical dosages than plants with sub-seabed intakes. Besides, UF does not depend on geological conditions and is not more costly than conventional pretreatment whereas the costs of sub-seabed intakes are not yet well investigated. Therefore UF pretreatment is generally recommended. However, the natural feed water filtration with sub-seabed intakes is an effective system and should be evaluated in the specific case. A combination of sub-seabed intake and UF might have a better ecological efficiency than the single application. But as both applications provide similar operational and cost advantages, the TCO of a plant with both systems is expected to be higher than the gain in ecological efficiency could justify.

The use of antiscalants may not be completely avoided by UF pretreatment. Commonly used antiscalants like Belgard EV have been evaluated as critical pollutants. They should be
replaced by green antiscalants like PAP-1 or other agents with good biodegradability. The costs of green antiscalants are not expected to cause decisive changes in unit costs.

Polymer materials are commonly used in many RO plant components. In high pressure sections where polymers are not applicable, duplex steels should be used. Duplex steels have the same performance, but are cheaper than conventional stainless steels and even much cheaper than titanium. All these materials are harmless due to the low corrosion rates.

Multiport diffusers should be installed in every case, since they reduce the impact of salinity which has been classified as critical pollutant. Besides, multiport diffusers limit the impact area of all other residual pollutants in the effluent. The costs are case-specific, but are not expected to be significantly higher than conventional submerged outfalls. Every additional cost-efficient measure to decrease the brine concentrations before or after discharge into the sea should be considered, e.g. discharge design optimisation, pre-dilution, etc. These efforts are denominated as ‘dilution enhancement’.

Consequently, the recommended mitigation technologies for RO plants, under ecological and economical aspects, are:

1. UF pretreatment
2. Green antiscalants
3. Duplex steel components (if polymers are not applicable)
4. Multiport diffuser, dilution enhancement

By means of this combination of technologies, all critical RO pollutants can be reduced or avoided without major cost increases:

- chlorine and THM (critical) is avoided
- antiscalants (critical) and coagulation (less critical) agents are reduced
- residual antiscalants are replaced by harmless alternatives
- the annual use of cleaning chemicals (very critical) is considerably reduced
- heavy metal discharge is infinitesimal
- impact area of salinity (critical) and other residual pollutants is reduced

Recommendations for MSF plants

For MSF seawater desalination plants the following mitigation technologies come into question:

NF pretreatment, sponge ball technique, green additives, titanium components, stainless steel components, duplex steel components, polymer materials, multiport diffuser
Unless NF membranes are not resistant against fouling and scaling, NF pretreatment probably has no environmental, but only operational benefits, and is ruled out.

Sponge ball cleaning is a cost-efficient pretreatment technique according to experiences in several MSF plants and can replace chlorine addition which has been rated the most critical pollutant in MSF effluents. Therefore, it is a highly recommended technique.

Antiscalants cannot be avoided with the available methods. Therefore, the use of green antiscalants or agents with good biodegradability is recommended in order to avoid the risk of accumulation, especially in regions with high desalination capacities.

Duplex steels are recommended to be used for MSF plants and should particularly replace the copper-nickel heat transfer elements in order to eliminate copper discharges. Duplex steel has excellent corrosion resistance and is preferred to titanium and conventional stainless steel due to the lower raw material costs.

Polymers may be a future material for heat exchange tubes. They have the lowest costs and the best corrosion resistance of all materials and provide adequate conductance in a thin tube design. But as operational problems remain and appropriate polymers are still in an experimental stage, they cannot yet be recommended for application.

Multiport diffuser should definitely be installed as they reduce the impact of thermal pollution which was classified as critical. Additional cost-efficient measures to decrease brine concentrations before or after discharge into the sea should be considered, e.g. discharge design optimisation, pre-dilution, etc.

Consequently, the recommended mitigation technologies for MSF plants, under ecological and economical aspects, are:

1. Sponge ball cleaning
2. Green antiscalants
3. Duplex stainless steels, particularly in exchange for Cu-Ni
4. Multiport diffuser, dilution enhancement

By means of this combination of technologies, all critical MSF pollutants can be reduced or avoided without major cost increases:

- chlorine (very critical) and THM (critical) can be avoided
- antiscalants (critical) can be slightly reduced
- residual antiscalants are replaced by harmless alternatives
- copper discharge (critical) is avoided
- impact area of temperature (critical), salinity (less critical) and other residual pollutants is restricted
MSF and RO plants account for the highest share in global seawater desalination capacity. It was shown that the effluents of these plants have a variety of physical properties and chemical constituents which can be harmful for the marine environment. The impact intensity depends on the pollutant concentrations and loads as well as on the sensitivity of the respective coastal ecosystem. After consideration of toxicity, degradability and typical dosages, a ranking was developed which reflects the potential harmfulness of pollutants in desalination effluents. Chlorine, antiscalants and copper discharge as well as increased temperatures were classified as most critical in MSF effluents. For RO effluents, the high salinity, antiscalants and the membrane cleaning solutions containing several dangerous substances were identified to be the most critical pollutants. Reduction of these should have the highest priority for mitigation measures. The case study of the Sur RO plant in Oman documents the lethal impacts of saline effluents on a coral reef and underlines the high sensitivity of a range of ecosystems to brine discharges. Therefore, environmental impact assessment studies should be carried out for each desalination project in order to minimise adverse environmental effects.

The public opinion about desalination and its possible environmental impacts depends on the focused countries. In MENA countries, where desalination has an important share in fresh water supply, no studies or any other evidence of major concerns or opposition against desalination plants were found. Sea and coastal pollution is mentioned as important environmental issue by the majority of respondents in a relevant survey, but the possible origins of sea pollution were not questioned. The absence of concerns regarding desalination might be due to the lack of knowledge, the low number of detailed opinion polls or the high importance of the desalination industry for MENA countries. The opinion in Western countries is more controversial. Whereas the majority of people generally are in favour of desalination plants, the local approval rates drop when specific projects are envisaged. In these cases environmental and cost concerns are most often raised and strong opposition against projects in the United States and Australia evolved.

One reason for the differing public opinions is related to the socio-economic benefits of desalination. Seawater desalination contributes to economic and population growth and enables better fresh water supply in many of the water-scarce MENA countries. Western countries still have enough alternative sources in order to meet the fresh water demand and the growth effects of desalination are not necessarily wanted, as the Californian example has shown. The benefits of desalination, however, still are a privilege for richer countries. Even if
calculations have shown that desalination can be more cost-efficient than the overuse of natural resources, the high capital and energy costs of desalination are a major obstacle for the extensive application in poor and low income countries.

Precise regulations for brine discharges in particular do not exist or are not exactly formulated in legislations. The LBS protocol for the Mediterranean and the EC water framework directive only give qualitative guidelines. California and Australia define discharge limits and mixing zone requirements on an ad-hoc basis and an EIA study is carried out for each specific desalination project. As far as the official documents can tell, MENA countries like Saudi-Arabia and Oman have some relevant regulations for desalination. But the described discharge limits for pollutants are too high in order to restrict the typical concentrations in desalination effluents and a couple of important pollutants are missing. A comprehensive regulatory coordination of desalination activities at the Arabian Gulf does not exist. Thus, it must be concluded that current regulations are not capable of reducing the marine impacts of desalination plants at the Arabian Gulf.

Instead of regulatory incentives, it was shown that operational and financial incentives exist to reduce marine impacts. The most important result of this work is that efficient technologies exist to reduce the environmental impacts of desalination effluents and that these technologies are not necessarily more costly than conventional systems. UF pretreatment and sponge ball systems provide more efficient pretreatment, better process control and enable to remove or reduce many of the chemicals used in conventional MSF and RO plants. Sub-seabed intakes can be an equally efficient and ecologically beneficial pretreatment alternative, if the costs are properly assessed. Indispensable antiscalants can be replaced by more biocompatible alternatives. Copper pollution can be avoided by installing less costly duplex steels in MSF plants. The impact area of brine discharges is reduced by installing multiport diffusers and by optimising the discharge design.

The combination of these measures enables to avoid or reduce the impact of all critical pollutants and has similar costs as conventional systems. The cost balance would even be better if all environmental costs were included in the calculation. Usually, only capital and operational costs are considered for investment decisions. A decision support model was developed which describes a possible way of incorporating environmental costs and impacts of desalination plants into the investment decision. By establishing more stringent discharge regulations and by setting penalties for non-compliance, the operators could be forced to include environmental costs into their calculations and the incentives for the proposed environmental investments would rise.

With regard to the predicted increase of worldwide seawater desalination capacities it can be concluded that important technologies are available to manage the upcoming boom of activities in a environmentally friendly and sustainable way and to improve the reputation of the desalination industry in the public. Therefore, it must be ensured that old paradigms are broken and that the recommended technologies are considered and applied in new plants. Besides the inherent cost and operational intensives of the technologies, smart regulatory incentives can help to achieve this goal.
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Appendix
Appendix A  Water depth and sensitive coastal ecosystems of the Arabian Gulf (Höpner et al., 2008)

Appendix B  Estimated chlorine discharges of MSF plants and total daily chlorine discharge into the Arabian Gulf (Höpner et al., 2008)
Appendix C  Estimated antiscalant discharges of desalination plants and total daily antiscalant discharge into the Arabian Gulf (Höpner et al., 2008)

Appendix D  Estimated copper discharges of MSF plants and total daily copper discharge into the Arabian Gulf (Höpner et al., 2008)