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4.2 Desalination of seawater

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SUMMARY: *Drinking water production by desalination of seawater has become increasingly important in recent years and reached a world-wide total of about 19 million m³ per day in 2001. The main technical processes are MSF-distillation (market share of 66%) and Reverse Osmosis (22%) with facilities ranging from fully automated containers to industrial plants that produce water for both the public and private sector. As desalination capacities continue to grow, the concern for environmental impacts of this activity is also increasing. Besides the emission of combustion gases that can be attributed to the high energy demand of desalination plants, major impacts may result from the waste discharges into the sea.*

To produce drinking water from seawater – the only inexhaustible resource – has long been a dream of mankind. However, the amount of energy this requires is at least 1 kWh/m³ of drinking water. The real demand, however, is usually much higher and for »thermal desalination« can be up to 80 kWh of heat energy and up to 5 kWh of electrical energy. Larger facilities based on reverse osmosis demand at least 2.5 kWh/m³ and smaller facilities require more than 15 kWh/m³. Nevertheless, desalination of seawater has developed rapidly, and it is said to be one of the fastest growing industries. In 1999, the world-wide daily production amounted to approximately 15 million m³ and by the end of 2003 it had risen to 27.5 million m³ (WANGNICK 2004).

The following example serves to put these and other figures into perspective: The city of Hamburg (Northern Germany) for example provides approx. 325,000 m³ of drinking water for 1.725 million inhabitants (188 litres per inhabitant) per day. Kuwait, with 2 million inhabitants, produces almost 1.6 million m³ (600 litres per inhabitant) daily by seawater desalination only. In the world's largest facility, Al-Jubail on the Saudi–Arabian coast of the Arabian Gulf, daily production is 1.3 million m³. In Germany, there is only one location with a (partial) drinking water supply from seawater: On the island Helgoland, where 1,760 m³ of water are desalinated per day.

The following report describes the main techniques of seawater desalination, the costs, the development in time and geographical distribution of capacities as well as the effects on the marine ecosystem.

Desalination techniques

Any technique based on the vaporisation of seawater and condensation of vapour is considered a »thermal method«. Despite the above-mentioned high levels of energy consumption, more than 17 million m³ is produced according to the principle of multi-stage flash (MSF) distillation. 7.7 million m³ are desalinated by reverse osmosis (RO). A further approximately 3 million are produced by the processes of multi-effect distillation (MED) and vapour compression (VC).

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The thermal procedures limit the gain of drinking water from a certain amount of seawater, so that the salt concentration of the remaining concentrate (»brine«) is not higher than a factor of between 1.3 and 1.4 compared to the beginning of the process. A second common ground is the lower pressure over the heated seawater in order to make a vaporisation below the normal temperature of boiling possible, rather than to heat the seawater up to a higher temperature or to repeat the heating several times. A third common ground is the extensive use of counter-current heating or cooling. This means, thermal desalination has become the key example of energy saving.

Multi-stage flash distillation is the most frequently used variant, and in broad terms, works as follows: seawater is heated by means of steam to a temperature of at least 90 °C and flows into a vaporisation chamber where reduced pressure causes a very fast vaporisation of a certain amount of water. The steam is cooled by a counter-current of seawater which is thereby preheated. The remaining water flows into a second vaporisation chamber with even lower pressure. Again, a certain part is vaporised. This process is repeated up to 40 times, without adding additional heat to the seawater. The salt content of the seawater increases step by step and turns into brine. MSF facilities have existed since the 1950s. In general, they consist of several blocks with capacities between 5,000 and 65,000 m³/day each.

During the multi-effect distillation process, seawater is sprayed on heated evaporator surfaces in a thin film to achieve rapid vaporisation. Similar to MSF, there are several successive units (4–16), each having a lower pressure than the preceding one. The evaporator surfaces are heated by the steam produced in the preceding unit. This heightens the pressure and the steam condenses. MED facilities consist of several single blocks, each processing between 100 and 20,000 m³/day. The starting temperature of the seawater in this process can be 70 °C.

In the process of vapour compression, water vaporises under lowered pressure and the steam is condensed by an increase in pressure. Such facilities may even work without heating, just on the basis of pressure differences. Single blocks typically have capacities of 20–2,500 m³/day each.

VC facilities are usually compact and suited for low demands or remote locations (e.g. hotels).

The reverse osmosis process is used since the 1970s. It is based on synthetic membranes, which under pressure are permeable to water but not to salts. Since flow-rates and separation capacities are low, the membrane surfaces must be large. In general, spirally coiled membranes are used, which are placed in cylindrical containers and stacked on racks. This means that the RO process can be used to produce very small up to large volumes of freshwater. The seawater is pressurised to 80–100 bar, and part of the energy is retrieved when the relatively high residual pressure is lowered after the desalination process. The concentration factor of 1.4–1.5 is higher than in thermal desalination processes. The lower energy consumption of RO plants is advantageous and mainly attributed to the use of pressure rather than heat for separating water from salts. RO facilities exist, amongst others, as small, stand-alone, fully automated systems. They are used in many hotels and tourist resorts in semi-arid and arid regions. However, the fact that the membranes deteriorate over time and that the incoming seawater needs a more complex chemical pre-treatment than in thermal procedures is a disadvantage.

Of course, seawater desalination can also be driven by renewable energy sources, especially by electrical and mechanical energy produced by wind turbines for reverse osmosis (e.g. on Gran Canaria). So far, solar desalination plants have mainly pilot character, since they have high investment, repair and maintenance costs.

Costs and distribution

The costs of drinking water production are characterised by two opposite developments (Wangnick 2004). On the one hand, a rise in the costs of conventional water production is observed in many parts of the world due to overuse, contamination or salinisation of resources and because environmental damage is increasingly reflected in the cost. The cost has – depending on country, supply, demand and technology – risen to 1–1.5 US$/m^3. On the other hand, the cost of drinking water from desalination has decreased over time, in some places even below the cost of conventional water production. The reasons are technological development, the adaptation of facilities to local demand, the use of cheapest available energy sources (e.g. natural gas and refinery gas, which previously would have been burned off as waste), and finally the coupling of desalination plants to power plants, which allows the use of waste steam for desalination. The production costs of 0.88 US$/m^3 as reported for a large plant in the Arabian Gulf are broken down by Wangnick (2004) as follows (US$/m^3): staff 0.05, capital cost 0.28, electrical energy 0.08, thermal energy 0.44, and chemicals 0.03. These costs, however, do not reflect the real costs for the consumer, since drinking water in the Gulf states is either provided free or highly subsidised.

Desalination techniques suit a broad range of applications for municipalities, industry, tourism, military, trade and commerce. The use of desalination technology does not always imply water production on a large industrial scale. Facilities rather range from small-scale, stand-alone systems to heavy coastal industry.

Development in time and geographical distribution

In 1996 and 1997, the world-wide desalination capacity increased by 0.5 million m^3/day, respectively. In 1998, it increased by further 0.7 million and in 1999 by 0.9 million m^3/day. The largest rise ever was registered in the years 2000 and 2001 with 1.8 and 2 million m^3/day, respectively. At the end of 2001, the world-wide daily capacity amounted to 19 million m^3/day (Wangnick 2004).

The largest number of desalination plants is located in the Arabian Gulf with a total capacity of approximately 10 million m^3/day (see figure), which corresponds to 47% of the world-wide daily production. The main producers are the United Arab Emirates (25%), Saudi Arabia (11% Gulf, 13% Red Sea) and Kuwait (8%). In the Mediterranean region, approximately 2.6 million m^3/day (14%) are desalinated. Spain, with a share of 6% of the world-wide production, is ranking on fourth position. A third of Spain's capacity, however, is located on the Canary Islands. In contrast to the predominant thermal processes dominant in the Gulf states, 85% of Spain's production is by RO plants. The aforementioned countries, together with seven other states with shares of between 2–4% each, account for approximately 80% of the world-wide daily production. With the exception of the USA, these are located in the Arabian Gulf (Qatar, Bahrain, Iran) and in the Mediterranean (Libya, Italy, Israel) (see *Fig. 4.2-1*).

Effects on the marine ecosystem

All desalination plants produce, in addition to the actual product, large amounts of waste water. This is a salty concentrate (brine), which in general contains chemical residues from pre-treatment and also, as a result of corrosion, heavy metals and, to a certain extent, chemicals from the different cleaning stages. All these residues are typically discharged into the sea. Negative effects on the marine environment can occur especially when high desalination capacities coincide with sensitive ecosystems.

The physical and chemical properties of the brine depend on the desalination process and the operation of the plant in question. Normally, the brine from thermal plants is decreased in oxygen levels, but increased in salinity (salt

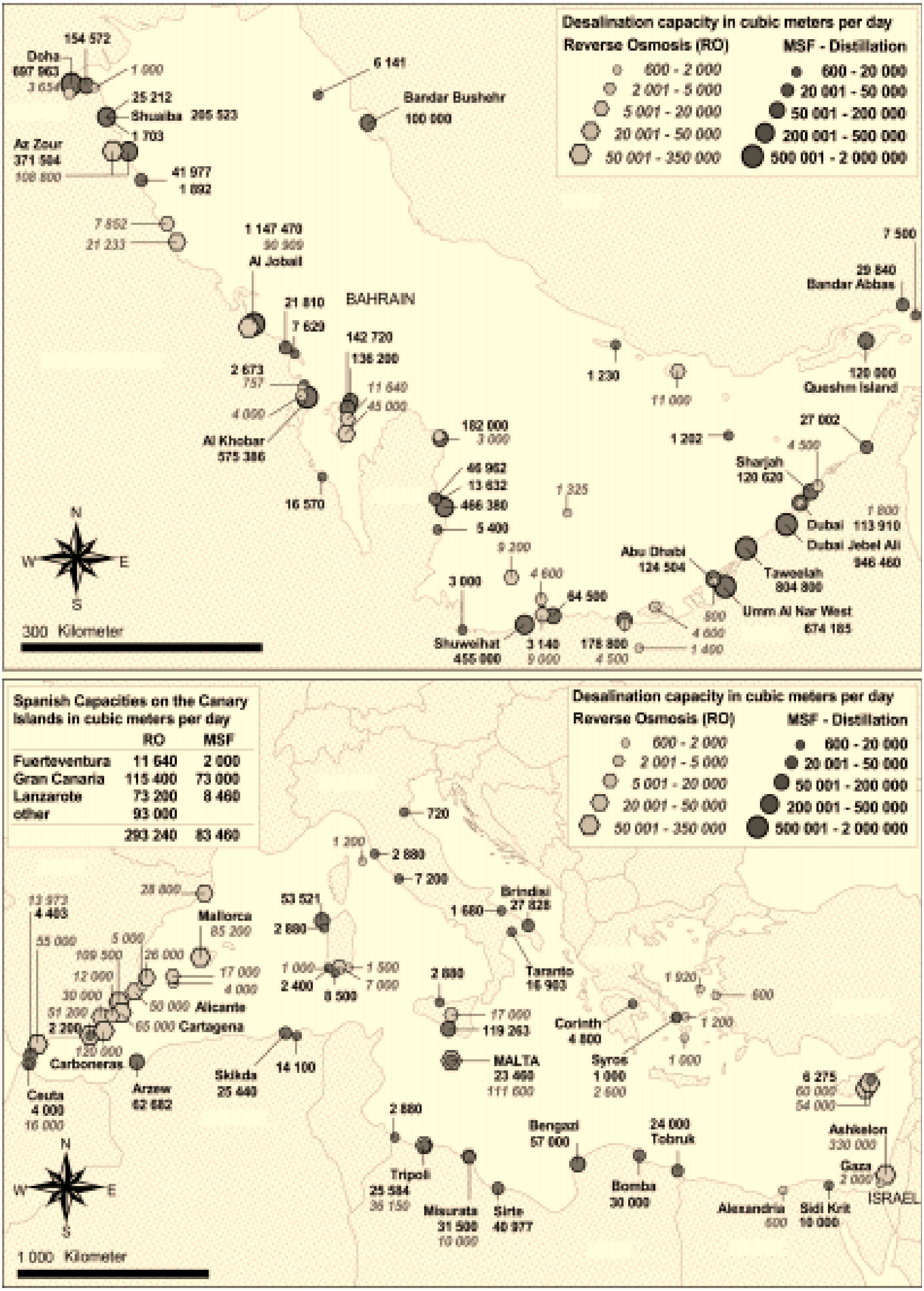

Fig. 4.2-1: Seawater desalination capacity of multi-stage flash (MSF) and reverse osmosis (RO) plants in the Arabian Golf (*above*) and the Mediterranean Sea (*below*). Raw data based on WANGNICK (2003).

content up to 50 g/litre) and temperature (by 5–15 °C). The latter two parameters determine the density of the desalination plant effluent, which is usually lower than ambient seawater density, i.e. the effluent »floats« on the surface following discharge. In addition to low concentrations of copper and nickel from the corrosion of heat exchanger surfaces, other chemical compounds in the discharge include residues of chlorine which is added for disinfection, halogenated organic by-products from chlorination, such as trihalomethanes, as well as so called »antiscalant« and »antifoaming« agents. The latter two are organic polymers, which are used to prevent scale deposits in pipes (e.g. polymaleic acid) and to reduce the formation of foam on the water surface (e.g. polyglycol blends). The cleaning of thermal plants is done by means of rinsing with acid dilutions (pH 2), to which corrosion inhibitors are added.

The brine from RO plants also shows decreased oxygen values. In contrast to the brine from thermal plants, salinity levels can reach up to 70 g/litre, whereas temperature values are not affected by the process. The brine has consequently a higher density than ambient seawater, and will quickly sink to the seafloor in shallow or unmixed coastal areas. Normally, chlorine is added to the inflowing water, but is removed again by adding a neutralising agent (sodium bisulfite) before the water reaches the RO membranes, which are sensitive to oxidation. Consequently, chlorine and halogenated hydrocarbons pollute the marine environment only to a very limited extent, if at all. Since the fine-pored membranes are also prone to clogging by suspended material, this is coagulated by iron- or aluminium chloride into larger particles, and subsequently removed from the feedwater by media filtration. The retained solid material is either discharged along with the brine to the sea, or can be transported to a landfill. Similar to thermal plants, »antiscalant« agents are used in RO plants, which are either phosphates (e.g. »Calgon«), organic polymers (e.g. polymaleic acid), or mineral acids (e.g. HCl). Since RO plants are built from materials that are very resistant to corrosion (synthetic material or stainless steel), heavy metals in the waste water are hardly a problem. The cleaning solutions for the membranes are either acidic (pH 2–3) for the removal of scale deposits, or alcaline (pH 11–12) for removal of biofilms. They may additionally contain detergents, oxidants, complexing agents and biocides in order to be more effective.

The emissions of chlorine and copper during normal operation of thermal plants are a major cause for concern. With chlorine concentrations of 200–500 µg/litre in the waste water, concentrations of about 30–50 µg/litre have been observed in the area surrounding the point of discharge. Even at these low concentrations, toxic effects on marine organisms are likely, since the high toxicity of chlorine has been proven in numerous studies. Normally, the copper concentrations in the brine discharge of thermal plants are between 15–100 µg/litre. In addition to possible toxic effects, an accumulation of the heavy metal in sediments and organisms has to be considered.

Despite low concentrations, the total discharge loads of chemicals can be immense due to the high volumes of brine discharges produced by desalination plants. Estimates of chemical loads can be derived from representative discharge concentrations and volumes. They amount to approximately 30 g copper and 2.25 kg chlorine per 1,000 m^3/day installed capacity (Höpner & Lattemann 2002). At a plant such as Al-Jubail in the Arabian Gulf, this amounts to about 2,850 kg chlorine and 34 kg copper per day (Lattemann & Höpner 2003). For the whole Gulf, these emissions amount to at least 18 t of chlorine and 240 kg of copper per day. As a result, desalination facilities, especially in marine areas with high capacities, are in addition to power plants and other large industrial plants, one of the main causes of marine pollution.

More facts about seawater desalination

A good reference source for statistical information is the global »inventory« of desalination facilities by Wangnick-Consulting (www.wangnick.com) (Wangnick 2004). A general introduction into the technology is given by Spiegler & El-Sayed (1994). The most elementary source of information is the »Desalination ABC« (Buros 2000). A book on the environmental effects of seawater desalination exists since 2003 (Lattemann & Höpner 2003). Other good sources of information are the International Desalination Association (IDA), located in the United States (www.idadesal.org), and the European Desalination Society (EDS), located in Italy (www.desline. com). The German Desalination Society (DME) was founded in 2003 and is located in Duisburg (www.dme-ev.de). Another international organisation that must be mentioned is the Middle East Desalination Research Centre (MEDRC) in Oman (www.medrc.org), which promotes research and development in water desalination technology and supporting fields ♦