A Desalination Guide for South African Municipal Engineers

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A DESALINATION GUIDE FOR SOUTH AFRICAN MUNICIPAL ENGINEERS

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FOREWORD

Water is probably the key element required to sustain social and economic growth in South Africa in future, as well as ensuring a sustainable environment. To date, vast sums of money have been spent on exploiting and transferring fresh surface water supplies to economic hubs and to the interior of the country through schemes such as the Tugela-Vaal, Lesotho Highlands Projects etc. Concurrently, many coastal cities such as the Metropolis of Cape Town as well as other smaller towns are gradually outgrowing the natural fresh water resources available to them. Further, the country as a whole is reaching the stage where the fresh water resources within its borders are nearly fully utilized and it is now becoming necessary to utilize and seek alternative sources of fresh water.

The past two decades has seen tremendous development and improvements in the use of membrane technology and the time is most opportune where treating saline water from the sea or from brackish boreholes has become a viable alternative to importing fresh water or impounding surface runoff (if it is available) and then treating it. Membrane technology is gaining greater popularity world wide and can now also be considered as one possible solution to water scarcity problems in South Africa.

This guideline sets out the aspects that municipal engineers and other planners need to consider when planning and designing a desalination plant as an alternative to a conventional water supply scheme.

It is hoped that the information provided here as simply as possible, but not so simply as to lose its technical value, will open avenues to obtaining the additional water needed for the sustenance of development in the country.

Lindiwe Hendricks

Minister of Water Affairs and Forestry

ABOUT THIS DESALINATION GUIDE

The literature available in the public domain (libraries and internet) encapsulates a vast collection of handbooks, journal publications, research reports and conference proceedings on desalination and water treatment. Some of them are presented in the list of references at the end of this document. Unfortunately, in the execution of daily tasks and responsibilities, most municipal engineers seldom have the time to evaluate and digest all this information to make it applicable to a specific municipality's water supply needs.

Therefore, the intention is certainly *not* to duplicate literature through in-depth investigative discussions on the numerous aspects of water treatment and desalination technology. Such an approach would dilute the focus, resulting in a ponderous document with limited additional benefit to the user.

Considering the above, the purpose of this Guide is to:

- provide a concise assessment of popular desalination technologies and related issues;
- provide applicable ***guidance*** in the process of evaluating potential augmentation of municipal water supply through desalination, specifically within the context of available ***South African saline water sources***. Such guidance is based on consideration of:
  - saline water source quality and location,
  - desalination technology and peripheral process selection,
  - operating and maintenance aspects,
  - environmental and socio-economic implications,
  - capital and operating cost estimates.

It is important to understand that the question "*How much does a desalination plant cost?*" is similar to the question "*How much does a motor car cost?*" Most people would agree that the latter question is virtually senseless, since the answers from different people could differ by an order of magnitude. In the same way, the cost of a desalination plant relates to so many specific parameters (*e.g*. geographic location, feed water quality, product water requirements, capacity, expected life of plant, standby requirements, manufacturing and design specifications, reliability, technical innovation, etc.) that, even for a specific well-defined tender, different vendors may quote prices that can easily differ by more than twenty per cent.

Therefore, a general approach to cost estimation, such as the one followed in this Guide, certainly does not have the objective to facilitate accurate costing, but rather ***to empower municipal engineers with conceptual knowledge related to their specific desalination needs***.

The Guide comprises three distinct parts, *viz*:

PART 1 EXECUTIVE GUIDE ON DESALINATION

PART 2 DESALINATION GUIDELINES AND PROCEDURES FOR PLANT SELECTION AND COSTING

APPENDICES

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A_{mem}	Total installed membrane area in desalination section	m^2
Alk	Alkalinity as mg/litre $CaCO_3$	mg/litre $CaCO_3$
B	Monthly capital cost repayment (cost of capital)	Rands/month
C_{Ba}	Concentration of barium in the feed	mg/litre
C_{Ca}	Concentration of calcium in the feed	mg/litre
C_{F}	Concentration of fluoride in the feed	mg/litre
C_{Fe}	Concentration of iron in the feed	mg/litre
$C_{\mathrm{SO_4}}$	Concentration of sulphate in the feed	mg/litre
C_{Sr}	Concentration of strontium in the feed	mg/litre
Cap	Total installed cost of plant (Capital cost)	Rands
$Cost_{\mathrm{mem}}$	Cost of desalination membrane per unit area	Rands/m^2
D	Unit cost of electricity	Rands/kWh
E_{desal}	Energy consumption at the desalination section	kW
E_{other}	Energy consumption at the rest of the plant (excluding desalination)	kW
E_{total}	Energy consumption of total plant (desalination + other)	kW
E_{specific}	Specific energy consumption per volume of product water	kW/m^3
n	Number of moles (else, number of months for capital redemption)	-
J	Salt rejection by a membrane system	-
K	Pre-treatment cost factor (K = 1 for one standard media filtration)	-
M_{cap}	Specific cost of capital redemption per volume desalinated water	Rands/m^3
M_{chem}	Specific cost of chemicals per volume desalinated water	Rands/m^3
M_{energy}	Specific cost of energy per volume desalinated water	Rands/m^3
M_{maint}	Specific cost of labour and maintenance / volume desalinated water	Rands/m^3

M_{mem}	Specific cost of membrane replacement / volume desalinated water	Rands/m^3
M_{tot}	Total specific unit production cost of desalinated water	Rands/m^3
P_{osm}	Osmotic pressure	bar
$P_{F(T)}$	Feed pressure to desalination section at certain temperature T	bar
Q_d	Daily production rate of a desalination plant	m^3/day
Q_{eff}	Hourly flow rate of total effluent from plant	m^3/h
Q_F	Hourly flow rate of feed to the desalination section	m^3/h
Q_h	Hourly design production rate of a desalination plant	m^3/h
$Q_{h(in)}$	Hourly feed rate to the pre-treatment plant (raw feed to plant)	m^3/h
Q_p	Hourly flow rate of product (permeate) from desalination section	m^3/h
R_{o}	Gas constant (8.314)	J/(mol·$^{\text{o}}$C)
R	Recovery of water over a the desalination section (product/feed)	-
R_{BaSO_4}	Maximum recovery allowed before $BaSO_4$ scaling/fouling occurs	-
R_{CaCO_3}	Maximum recovery allowed before $CaCO_3$ scaling/fouling occurs	-
R_{CaSO_4}	Maximum recovery allowed before $CaSO_4$ scaling/fouling occurs	-
R_{Fe}	Maximum recovery allowed before Fe scaling/fouling occurs	-
R_{SiO_2}	Maximum recovery allowed before SiO_2 scaling/fouling occurs	-
R_{SrSO_4}	Maximum recovery allowed before $SrSO_4$ scaling/fouling occurs	-
r	Monthly interest rate	-
T	Temperature	$^{\text{o}}$C
SDI_{15}	Silt Density Index for a total filtration period of 15 minutes	-
TDS	Total dissolved solids	mg/litre
$(TDS)_C$	Total dissolved solids in the concentrate (brine)	mg/litre
$(TDS)_F$	Total dissolved solids in the feed water	mg/litre
$(TDS)_p$	Total dissolved solids in the product water (permeate)	mg/litre

V	Volume	m^3
y	Number of years before full membrane replacement	year

Greek symbols

α	Plant availability as fraction of 24-hour day	-
β	Fraction of raw feed water lost at pre-treatment (backwash, etc.)	-
χ	Overall concentration factor (TDS in concentrate per TDS feed)	-
ε	Flux through membranes per unit driving pressure	litre/($h \cdot m^2 \cdot bar$)
η	Average efficiency of feed and other pumps (not high pressure)	-
η_p	Efficiency of high pressure pumps	-
μ_r	Efficiency of energy recovery turbine	-
φ	Average water flux through reverse osmosis membranes	litre/($h \cdot m^2$)
φ_1	Average water flux through 1st pass membranes	litre/($h \cdot m^2$)
φ_2	Average water flux through 2nd pass membranes	litre/($h \cdot m^2$)

GLOSSARY

Acidity	The quantitative capacity of aqueous media to react with hydroxyl ions.
Alkaline scale	Scale that will dissolve under acidic conditions; usually composed of calcium carbonate and magnesium hydroxide.
Alkalinity	A measure of the ability of water to neutralize acids; the sum of titratable bases. Bicarbonate, carbonate, and hydroxides in natural or treated water are major contributors to alkalinity.
Alum	Aluminium sulphate, $Al_2(SO_4)_3 \bullet 18H_2O$.
Amorphous	Noncrystalline; lacking any regular cohesive structure.
Anion	The ion in an electrolytic solution that migrates to the anode. It carries a negative charge.
Anode	The positive electrode of an electrodialysis cell.
Antiscalant	A chemical that inhibits scale information.
Array	A series of installed pressure vessels with common feed water, product, and concentrate lines.
Autopsy	The dissection of a membrane element to investigate causes for unsatisfactory performance.
Backwash	The process of reversing the flow of water either across or through a medium or a membrane.
Bacteria	Any of a class of microscopic single-celled organisms that reproduce by fission or by spores. They are often symbiotic in humans, but sometimes pathogenic.
Bactericide	An agent capable of destroying bacteria.
Bacteriostat	A substance that inhibits bacterial growth and metabolism.
Bank	A grouping of modules and a high-pressure pump.
Biological deposits	Deposits of organisms or the products of their life processes.
Blinding	In depth surface filtration, a build-up of particulates on or within the filter, preventing fluid flow through the filter at normal pressures.

Boundary layer	A very thin layer adhering to a membrane facing the feed water or concentrate water stream.
Brackish water	Water having a total dissolved solids concentration ranging from 1,000 to 30,000 mg/L.
Brine	A concentrate stream containing total dissolved solids at a concentration greater than 36,000 mg/L.
Bundle	A collection of parallel filaments or fibres.
Cathode	The negative electrode of an electrodialysis cell.
Cation	A positively charged ion in solution that migrates to the cathode.
Cellulose	The carbohydrate that is the principal constituent of wood.
Cellulose acetate	A polymer used to make semi permeable membranes.
Chelating agent	A sequestering or completing agent that, in aqueous solution, renders a metallic ion inactive through the formation of an inner ring structure with the ion.
Chemical rejuvenation	Any of several in-place chemical cleaning methods to remove fouling and scaling or to recondition membranes.
CIP	Cleaning in place.
Composite membrane	A membrane obtained by precipitating a thin desalinating layer on a porous carrier membrane.
Concentrate	The membrane output stream that contains water rejected by the membrane. It is where feed water constituents are concentrated. It is also known as reject, retentate, or the residual stream.
Contaminant	Any foreign substances present that will adversely affect performance.
Control block	A group of permeators having common piping and control system.
Degasification	The process of removing dissolved gases from water
Demineralization	The process of removing minerals from water, usually through deonization, reverse osmosis, or distillation.
Double-pass RO system	A reverse osmosis system in which the permeate is further processed by a subsequent reverse osmosis system.

Duplex steel	A category of stainless steel that is a mixture of austhenitic (Chromium-nickel stainless class) and ferritic (plain chromium stainless category) structures. Duplex stainless steels are suitable for heat exchanges, desalination plants and other marine applications.
Electrodialysis	Dialysis conducted with the aid of an electromotive force applied to electrodes adjacent to both sides of the membrane.
Feedwater	Influent or source water into the membrane process.
Filtrate	The portion of the feed water that has passed through a filter.
Flat sheet membrane	A reverse osmosis membrane coated onto a fabric substrate
Flux of water	The rate of water flow across the membrane surface area.
Fouling	A reduction in water mass transfer by materials in the water, typically caused by silts and colloids.
Groundwater	Water confined in permeable sand layers between rock or clay; that part of the subsurface water that is in the saturated zone.
Hardness	The concentration in water of polyvalent cations, generally calcium and magnesium.
Infiltration	The movement of water into and through a soil.
Ion	An electrified portion of matter of atomic or molecular dimensions.
Ionic strength	A measure of the overall electrolytic potential of a solution.
Mass transfer coefficient	A coefficient quantifying material passage through a membrane.
Membrane	A highly engineered polymer film containing controlled distributions of pores. Membranes serve as a barrier permitting the passage of materials only up to a certain size, shape, or character. Membranes are used as a separation mechanism in water treatment, laboratory, and industrial applications. membrane compaction. *See* compaction.
Membrane configuration	The arrangement of individual elements (cartridges) in a membrane treatment process.
Membrane element	A single membrane unit or cartridge.

Membrane system	Several membrane trains in parallel.
Microfiltration (MF)	Filtration designed to remove particles and bacteria in the approximate range of 0.05 to 10 micrometers.
Module	A membrane element combined with the membrane element housing; a pressure vessel containing one or more membrane elements.
Nanofiltration (NF)	A crossflow membrane separation process that removes particles in the 300 to 1,000 molecular weight range, selected salts, and most organics.
NOM	Natural organic matter.
Noncarbonate hardness	Hardness caused by chlorides, sulphates, and nitrates of calcium and magnesium. Evaporation of waters containing these ions makes the water highly corrosive.
O & M	Operations and maintenance
Operating pressure	The pressure at which feed water enters a device.
Osmosis	The naturally occurring transport of water through a membrane from a solution of low salt content to a solution of high salt content in order to equalize salt concentrations.
Osmotic pressure	A measurement of the potential energy difference between solution on either side of a semi permeable membrane. The applied pressure must first overcome the osmotic pressure in the chemical solution for satisfactory reverse osmosis equipment performance.
Permeability	The capacity of a membrane to allow water or solutes to pass through.
Permeate stream	A membrane output stream that typically contains a desirable quantity of constituents and it is to be used as a product.
Permeator	A reverse osmosis production unit consisting of the membranes and pressure vessel.
Plant capacity	A plant’s volume production of permeate per unit time.
Pore	An opening in a membrane or filter matrix.
Porosity	The proportion usually stated as a percentage, of the total volume of material that consists of pore space or voids.

Post treatment	One or more processes that may be used on the product water, such as chlorination or neutralization. Post treatment of concentrate, such as pH adjustment, may also be required before disposal.
Precipitate	A substance separated from a solution by chemical or physical change as an insoluble amorphous or crystalline solid.
Pressure filtration	Filtration aided by imposing a pressure drop across an enclosed filter vessel.
Pressure vessel	Several membrane elements in series contained in a single tube.
Pre-treatment	The processes such as chlorination, clarification, coagulation, acidification, and degasification that may be used on the feed water to a membrane system to minimize algae growth, scaling, and corrosion.
Recovery	The ratio of the permeate flow to the feed flow, generally expressed as a percentage.
Reverse osmosis (RO)	The transport of water from a solution having a high salt concentration to one having a low salt concentration through a membrane by applying pressure to the solution having a high salt concentration. RO removes ionized salts, colloids, and organics down to 150 molecular weight. It may also be called hyper filtration.
Scaling	The precipitation of inorganic salts on the feed side of a membrane.
SDI	Silt Density index.
Solids rejection	The percentage of mass removed from the feed water.
Semipermeable membrane	A membrane that is permeable only by certain molecules or ions. For example, reverse osmosis membranes will allow water but not salt to pass.
Sequestering agent	An agent added to feed water to extend the limits of saturation of scaling substances. The agent ties up and inactivates certain metal ions.
Solubility	A measure of the maximum amount of a certain substance that can dissolve in a given amount of water at a given temperature.
Solute	Matter dissolved in a solvent, typically water.
Solution	A homogenous mixture of substances in which the molecules of the solute are uniformly distributed among the molecules of the solvent.

Solvent	A liquid medium that carries dissolved substances, or solutes, typically water.
Source water	Water that has not been treated on-site, including untreated water from wells, surface sources, the sea, or public water supplies.
Spiral-wound cartridge	The heart of a spiral-wound desalination device, consisting of the product tube, membrane leaves, feed channel spacers, antitelescoping devices, and brine seal.
Spiral-wound membrane	*See* flat sheet membrane
Stage	Pressure vessels installed in parallel. For example, it is common for a membrane array to have three stages, with four pressure vessels in the first stage, two in the second, and one in the third.
Sterilization	Destruction or removal of all viable organisms.
Supersaturation	A state in which the inorganic salts are in solution at a level such that the respective solubility product is exceeded.
Thrust collar	A plastic cylinder located between the last spiral-wound cartridge and end plate to support the last cartridge in a pressure vessel. It has the same diameter as the inside diameter of the pressure vessel.
TOC	Total organic carbon
Total dissolved solids (TDS)	The sum of all dissolved solids, volatile and nonvolatile.
Train	A membrane arrangement of multiple stages in series where the concentrate is typically used as feed to the subsequent stage.
Turbidity	Any undissolved materials in water, such as finely divided particles of sand or clay, reducing the penetration of light and causing the water to appear cloudy.
Ultrafiltration (UF)	A process using a semi permeable membrane under a hydraulic pressure gradient to separate components in a solution. The membrane pores allows passage of the solvent but will retain non-ionic components primarily on the basis of physical size.

PART 1

EXECUTIVE GUIDE ON DESALINATION

1 NEED FOR A GUIDE ON SEAWATER AND BRACKISH WATER DESALINATION IN SOUTH AFRICA

Municipalities need to develop Water Service Development Plans (WSDP's) as part of Integrated Development Plans (IDP's) as a first requirement in their budgetary process, and need to be made aware of what options are available to provide adequate water services. While 25 l/person/day has been set as the minimum basic water supply and while many consumers receive far in excess of this amount, there are areas of the country where enough fresh water of acceptable quality is not available for household use. However, in many areas adequate quantities of saline water may be or are readily available. This is especially the case for coastal cities and towns.

The cost of treating water is a fraction of the total cost of making water available to the consumer. This, together with the fact that membrane desalination technology is becoming more affordable, makes the overall water tariff less dependent on the cost of desalination. In other words, desalination may in many cases become a viable option to supply fresh water for domestic purposes. Therefore, DWAF identified a need to provide guidelines and procedures to select and evaluate suitable treatment options for the desalinating of seawater from both the Indian and Atlantic oceans, or brackish water from boreholes.

The specific objectives of the project were to identify the technologies that can currently be commercially implemented in South Africa to treat saline water to drinking water standards, to identify typical pre-treatment requirements, and to identify the most common technical, operating and environmental problems experienced in the selection and use of these technologies. An important aspect was also to provide estimates for capital and operating costs, as would be required to successfully bring the water to the accepted standards for potable and domestic use. Of particular importance for the South African application was to identify the level of skills required for daily operation of the desalination plants, the level of skills required to provide technical back-up and advice, and to identify and advise on the competencies, training needs and capacity building required at operator and management levels. Lastly, the relevant local environmental legislation governing desalination were also identified.

2 IMPORTANT PRIMARY CONSIDERATIONS

This Guide provides information on desalination and estimation guidelines with the understanding that such information shall be utilised within context and with due consideration and understanding of the following important aspects:

- **Saline water source, energy source and process selection**.
  Compared to conventional municipal water treatment, desalination processes are energy intensive. No assessment of a desalination process is complete without proper understanding of the energy requirements and the available sources and cost of energy (*e.g*. residual steam, spent heat, electricity, etc.). The source of energy, the required plant capacity and the feed water quality play major roles in the selection of the most appropriate desalination process.

- **Fouling, scale formation and plant availability**.
  Water (H_2O in its pure form) contains dissolved gases, dissolved and suspended inorganic solids, dissolved and suspended organic matter and suspended micro-organisms. During the desalination process, the concentration of these components can effect various forms of scale formation and other inhibitive contamination of the desalination equipment.

  Continuous scaling and/or fouling can be one of the most crippling side-effects of desalination processes. A well-designed desalination plant always incorporates a well-designed and appropriate pre-treatment system to minimise fouling.

  A thorough knowledge of the feed water chemistry and related seasonal variations is essential.

- **Disposal of concentrate and environmental considerations**.
  At first consideration, one often tends to ignore the fact that the concentrate (which can be several times more saline than the feed - depending on the application) needs to be disposed of in an *appropriate* and *environmentally friendly* manner. However, quite often this unavoidable consequence of the desalination process can contribute to a major portion of the overall project cost.

- **Physical location of plant and cost of distribution**.
  Augmentation of municipal water by desalination requires a sensible tie-in into established municipal water supply networks. The selection of an optimum location for a desalination plant in relation to its feed source and its tie-in point can sometimes be less clear-cut than expected. Incorrect positioning can contribute to significant additional capital and operating costs.

- **Manufacturing specifications and plant life**.
  Incorrect selection of materials of construction and inferior equipment can have serious adverse effects on both the maintenance costs and general operability and availability of the plant. Therefore, clear and unambiguous definitions of the minimum required plant life and construction specifications are essential to avoid plant failure and consequent overhaul after a few years of operation.

3 DESALINATION TECHNOLOGIES APPROPRIATE FOR SOUTH AFRICAN CONDITIONS

In order to provide some fundamental background, various desalination technologies, divided into either distillation or membrane processes, are discussed in Part 2 of the Guide.

Thermal distillation systems account for the majority of the world's *seawater* desalination capacity, while membrane-based reverse osmosis systems (newer technology than distillation) are rapidly gaining ground. Distillation systems are more energy intensive (up to four times more) than reverse osmosis systems, but require less pre-treatment of the water and are therefore generally considered to be more robust. However, most distillation plants are located in the Middle East where low cost energy is available and where these plants run in combination with electrical power stations (using low-pressure steam, discharged from the turbines, as energy source).

In the *South African context*, thermal desalination processes would normally *not* be considered for desalination of brackish or sea water, *unless* sufficient waste heat or low cost fuels are available (*e.g*. in combination with nuclear power generation). Until recently, the upper capacity limit for reverse osmosis (RO) desalination of sea water was considered to be around 100 000 m^3/day, while plants with larger capacities were always based on distillation. However, the *Ashkelon* desalination plant in Israel, one of the most recent additions to large-scale seawater desalination plants, has a production capacity of 330 000 m^3/day and is, despite its “large” capacity, a RO plant. Therefore, considering the relatively low cost of electricity in South Africa and the typical capacity requirements of potential South African desalination plants, reverse osmosis would almost always be the process of choice. This statement is supported by the following facts:

- A detailed costing study by Namwater for a desalination plant at Swakopmund indicated that RO would be less expensive.
- After an in-depth assessment, Perth (Australia) is progressing with the design of a sea water RO plant.
- Sydney (Australia) is considering RO as their method of choice for desalination.
- The new, large (330 megalitre/day) desalination plant in Ashkelon (Israel) utilizes RO.
- Several other RO plants with capacities around or above 100 megalitre/day have recently been constructed in the UAE, Singapore and elsewhere.
- Existing sea water and brackish water desalination plants in South Africa and Botswana that provide water for municipal use are all RO plants. Appendix I provides a list of all the desalination plants in operation in South Africa.

Therefore, apart from describing the fundamental principles of operation for evaporation/distillation plants, no effort will be made to provide relevant step-wise costing rules. Distillation experts should be contacted in (rare) cases where the municipal engineer is of the opinion that thermal desalination could be applicable.

For small capacity plants (a few m^3/h or less) alternative technologies (such as solar desalination) may in some cases be considered, but the reader is specifically referred to the WRC report TT 221/04 by Goldie and Sanderson (2004) in this regard.

This Guide only provides rules for cost estimation of ***reverse osmosis*** desalination plants.

4 GUIDELINES AND PROCEDURES FOR PROCESS SELECTION AND COSTING

The rules and procedures outlined in Part 2 are based on experience and information from the literature. The main steps and guidelines are summarized in the Figure ES.1 and are described in detail, with the use of examples for illustration, in Section 5 of Part 2:

Determine:	Consider:	Refer to Part 2:
Treatment technology required (desalinantion vs conventional). Required plant capacity and the needs of the community.	- Available water resource. - Sources of available saline water. - Economic standing of community. - Required availability of plant. - Hours per day of operation. - Seasonal variation of needs.	Section 5.1
Quality of available saline water.	- TDS and minimum temperature. - Individual inorganic components. - Organic content. - Microbial content.	Section 5.2 & Appendix A
Maximum water recovery possible during desalination.	- Concentration factor. - Scaling potential of salts in the presence of anti-scalants. - Maximum system pressure allowed.	Section 5.2.2
Required membrane area and desalination feed pressure.	- Temperature and osmotic pressure. - Type of membrane and application. - One or two passes through membranes. - Selected flux through membranes.	Section 5.3
Pre-treatment and post-treatment requirements.	- Feed requirements to pre-treatment. - Potential for membrane fouling. - Potential for scale-formation. - Need to maximise recovery. - Potential blending of product.	Section 5.4 Section 6 Section 7
Energy requirement of the plant.	- Power requirement of high pressure pumps. - Presence of energy recovery system. - Pre-treatment and other systems.	Section 5.5
Discharge of concentrate and CIP effluent. Other environmental impacts.	- Dilution and distribution if discharged to sea. - Potential evaporation ponds. - Sensitive environmental aspects.	Section 5.6 Section 8 Section 9
Installed capital cost.	- Desalination section. - Pre-treatment section. - Intake, outfall and post-treatment. - Environmental assessments and other contractual items.	Section 5.7.1
Unit cost of desalinated water.	- Capital redemption. - Energy. - Membrane replacement. - Chemicals and consumables. - Labour and maintenance.	Section 5.7.7

Figure ES.1: Process selection and costing

5 SOUTH AFRICAN SALINE WATER SOURCES

5.1 Sea water

South Africa with its extremely long coastline has an almost infinite water resource available to the coastal towns and cities of the country, albeit of a highly saline nature. Three sea water zones with potentially different water qualities are identified and briefly discussed below.

- **East Coast**

  The East Coast of South Africa can be described as the area between East London up to the Mozambique border. All marine systems in this region are dominated by the Agulhas current, which brings warm, nutrient-poor water from the tropics to the east coast. The region can be subdivided into a tropical coast (north of Port Edwards) and a subtropical coast.

- **South Coast**

  The coastal region between East London and Cape Agulhas, referred to as the South Coast, acts as a transitional zone between the warm east coast waters and the cold west coast waters, with no clear boundaries. Boundary conditions might shift 100km in either way, depending on prevailing atmospheric conditions.

- **West Coast**

  The West Coast is generally referred to as the region between Cape Agulhas and the mouth of the Orange River. Sea water quality in this region can be rather variable and special care should be taken when assessing water supply in areas such as False Bay, St Helena Bay and the Saldanha Bay / Langebaan system.

  Due to the north-bound flow of the Benguela current from the Antarctic, the West Coast water is normally very cold and associated with low dissolved oxygen levels. Prevailing wind conditions frequently result in an up-welling of cold, nutrient-rich bottom water into the warmer surface water, triggering the associated red-tide phenomenon and the potential presence of H_2S in the water. The low water temperature demands higher operating pressures and lower membrane fluxes, while the high concentrations of nutrients and potential compounds such as H_2S cause the pre-treatment to be demanding. Therefore, desalination of West Coast water would normally be more expensive than at the East Coast.

5.2 Groundwater

Saline or brackish groundwater provides for a second alternative source of water. The specific desalination technology required will, as in the case of sea water, depend on the quality of the available groundwater. The groundwater exploitation potential map (Figure D 1), together with the groundwater quality (Figure D 2), both in Appendix D, provides a good estimate of the probability that groundwater of a specific quality (TDS in mg/l) can be found in an area and if the resource can be considered as a potential alternative water resource. However the presence of specific compounds, such as iron, manganese, fluorides and nitrates, will require special attention.

6 COMPARATIVE COST ESTIMATES FOR DESALINATION IN SOUTH AFRICA

Table ES.1 and Table ES.2 summarises cost estimates that were developed by applying the rules provided in Part 2, Section 5 of the Guide, while considering the typical characteristics and quality of saline water predominantly found in certain areas of South Africa. No attempt is made to provide cost estimates for all potential options and innovations (be it low-cost or expensive).

More detailed costs and description of conditions and assumptions as applied in these rules are provided in Part 2, Section 5 Furthermore, important notes on inclusions and exclusions are provided at the end of these tables.

Table ES.1: Cost estimates for brackish water RO desalination plants

BRACKISH WATER RO DESALINATION PLANTS							
Plant and Raw Water Type	**Capacity**	**Feed-water TDS (mg/l)**	**Feed-water Temp (°C)**	**Order of Magnitude Capital Cost (R million)**	**Operating and Maintenance Cost (R/kl)**	**Capital Redemption (R/kl)**	**Unit Production Cost (R/kl)**
Low TDS Standard Pretreatment	15 m^3/h	2 000	17	1,43	2,80	2,50	5,30
Low TDS Full Lime Pretreatment		2 000	17	2,07	4,90	3,60	8,50
High TDS Standard Pretreatment		12 000	17	1,43	3,10	2,50	5,60
High TDS Full Lime Pretreatment		12 000	17	2,27	5,50	3,90	9,40
Low TDS Standard Pretreatment	1,6 Mℓ/d	2 000	17	6,22	1,60	1,40	2,90
Low TDS Full Lime Pretreatment		2 000	17	9,18	3,30	2,00	5,30
High TDS Standard Pretreatment		12 000	17	6,22	1,90	1,40	3,30
High TDS Full Lime Pretreatment		12 000	17	9,85	3,70	2,20	5,90
Low TDS Standard Pretreatment	5,0 Mℓ/d	2 000	17	16,1	1,30	1,10	2,40
Low TDS Full Lime Pretreatment		2 000	17	23,4	2,80	1,60	4,40
High TDS Standard Pretreatment		12 000	17	16,1	1,60	1,10	2,70
High TDS Full Lime Pretreatment		12 000	17	24,5	3,20	1,70	4,90

Table ES.2: Cost estimates for seawater RO desalination plants

SEAWATER RO DESALINATION PLANTS							
Plant and Raw Water Type	**Capacity (Ml/d)**	**Feed-water TDS (mg/l)**	**Feed-water Temp (^{o}C)**	**Order of Magnitude Capital Cost (R million)**	**Operating and Maintenance Cost (R/kl)**	**Capital Redemption (R/kl)**	**Unit Production Cost (R/kl)**
West Coast	5	36 000	9	63	4,00	4,40	8,30
	50	36 000	9	530	3,30	3,70	7,00
South Coast	5	36 000	16	46	3,30	3,20	6,50
	50	36 000	16	394	2,80	2,80	5,60
East Coast	5	36 000	21	40	3,00	2,80	5,80
	50	36 000	21	338	2,60	2,40	5,00

Notes applicable to Table ES.1 and Table ES.2:

- For “low” TDS (ca 2 000 mg/l) brackish water desalination, a recovery of 60 % (conservative) is used for standard pre-treatment, and 85% recovery when using lime pre-treatment.

- For “high” TDS (ca 12 000 mg/l) brackish water desalination, a recovery of 60 % (conservative) is used for standard pre-treatment, and 75% recovery when using lime pre-treatment.

- Plant life is assumed to be 25 years. Therefore, capital redemption is estimated for 25 years at an annual interest rate of 12%.

- Capital cost estimates are complete installed costs, including all process, civil, mechanical, electrical and control works, but excluding the following:
    - *Large* product storage reservoirs and subsequent municipal distribution systems. These are considered to be part of any water treatment system and cannot be directly attributed to the cost of a desalination plant.
    - Access roads outside the equipment area, as well as laboratories and administration offices.
    - Electricity generation or installation of power supply lines over long distances.
    - Potential expropriation of land and/or existing infrastructure.
    - Full-blown lined evaporation ponds for brackish water RO systems (note that such ponds may effect a drastic increase in the total capital cost).
    - Potential development of boreholes.

- Note that operation and maintenance costs can vary drastically from site to site. For example, small plants at remote locations (relatively far removed from their managerial centres or municipalities) may have operating costs much higher than the “typical” values stated above.

7 COMPARISON OF DESALINATION PLANT OPERATIONAL COSTS AND COST STUCTURE WITH CONVENTIONAL TREATMENT PLANTS

The operational cost breakdown of an existing desalination plant in South Africa, and cost figures obtained from the costing guidelines, were compared with operational costs of a number of conventional treatment plants in the country. The results are presented in Table ES.3. The costs used in the comparisons vary significantly due to the different methods used by the authorities to reflect all the different cost aspects in the production cost. It was not always possible to ring fence the same criteria for all the treatment plants used.

Table ES.3: Typical water production costs for desalination plants and conventional water treatment plants

Treatment System		**Water production cost (R/kl)**	**Notes**
Conventional water treatment	Amatola Water *(For 14 water treatment plants)*	3.39	Cost includes purchase of raw water.
	Rand Water *(For 6 large water treatment plants, treating a total of 5 260 Ml/d)*	2.53	Conventional water treatment plants. Cost includes purchase of raw water.
	City of Cape Town *(various plants)*	1.05 – 1.25	Including raw water cost which includes the new Berg Water project and excludes bulk management and conveyance.
	Midvaal *(250 Ml/d treatment plant)*	2.52	Treatment plant includes ozonation and dissolved air flotation for treating eutrophied water. Cost includes R 1.52/kl for purchase of raw water, excluding capital redemption (2004).
	Withoogte *(72 Ml/d treatment plant)*	1.04	Conventional water treatment plant. Cost includes purchase of raw water. Only small portion of capital redemption remains.
Desalination plants	Bitterfontein *(12 m^3/h RO groundwater desalination plant)*	7.81	Relative high cost for management functions and transport due to remote location of the RO plant.
	Boesmansriviermond *(45 m^3/h RO seawater desalination plant)*	2.26	Cost includes electricity, labour, membrane replacement (every 5 years) and pump maintenance, but excludes capital redemption.
	Costing model *(15 m^3/h RO groundwater desalination plant)*	5.30 – 9.40	Range is for low TDS (2 000 mg/l)(lower cost) and high TDS (12 000 mg/l)(higher cost)
	Costing model *(5 Ml/d RO groundwater desalination plant)*	2.40 – 4.90	Range is for low TDS (2 000 mg/l)(lower cost) and high TDS (12 000 mg/l)(higher cost)
	Costing model *(5 Ml/d RO* ***seawater*** *desalination plant)*	5.80 – 8.30	Range is for East Coast water (lowest cost), South Coast water and West Coast water (highest cost)

8 PRE-TREATMENT METHODS

Pre-treatment to desalination processes forms an important and integral part of desalination installations, and is often a major cost consideration in the selection of desalination as a water treatment alternative. This holds true especially for seawater desalination, and in particular for West Coast seawater in South Africa.

A variety of pre-treatment methods may have to be employed to ensure that optimal desalination plant performance is achieved. These processes may be needed for one or more of the following: particulate and fine material removal; suspended solids removal; organics removal; biofouling prevention; control of biological activity (disinfection as well as dechlorination if chlorine is used); prevention of scaling and inorganic precipitation, including metals removal and removal of other elements such as sulphur and silica.

Pre-treatment processes may be relatively simple in the case of good quality groundwater, sometimes requiring only cartridge filtration and possible dosing of anti-scalants. For poor quality feed water, extensive chemical treatment (such as lime softening) may be required to maximise recovery, although most engineers would attempt to avoid such complication in the design. For seawater, pre-treatment normally requires extensive pre-filtration, which may consist of two-stage sand filtration (media filtration) with pre-flocculation, or even media filtration in combination with ultra-filtration.

For prevention of biofouling or control of biological activity, or for oxidation of metals such as iron, an oxidation step may be needed. Chlorination and ozonation are among oxidation processes that can be employed.

More detailed information on pre-treatment requirements and methods can be found in Part 2, Section 6 of the Guide.

9 POST-TREATMENT OF DESALINATED WATER

Post-treatment of desalinated water has two objectives, *viz.* stabilisation and final disinfection. Like most conventional water treatment plants, disinfection entails the dosing of a disinfectant (usually chlorine) to prevent biological growth in subsequent municipal reservoirs and distribution systems. Since organic matter and microbial organisms are removed by the desalination process, chlorine requirements are relatively low.

Depending on the plant design, the desalinated product water may have a TDS well below 30 mg/litre, containing negligible concentrations of calcium, magnesium and carbonate. Such water is corrosive and needs to be stabilised before final distribution. Loewenthal *et al* (1986) compiled an excellent monograph to explain the principles of stabilisation, indicating that a positive $CaCO_3$ precipitation potential (preferably above 3) is required. The principles have been incorporated into a software package on CD, Stasoft4, (WRC, 2000) which simplified the calculations considerably. Suffice to say that stabilised water, fit for municipal and potable use, typically has a pH between 8 and 8.5, contains approximately 20 mg/litre Ca and has an alkalinity above 50 mg/litre.

Single-pass sea water RO plants typically produce permeates with TDS in the order of 300 mg/litre which, if blended in with larger volumes of other municipal water, may only require minimal post-treatment such as pH adjustment by lime addition. However, a fully desalinated product that is used as single source of municipal water supply needs better post treatment, entailing pH adjustment with CO_2 and dissolution of lime, or limestone (usually via limestone filters). In some cases (only smaller plants) calcium chloride, sodium bicarbonate and sodium carbonate are dosed to produce the required levels of $CaCO_3$ in the water. More information can be found in Part 2, Section 5.4.2.

10 MANAGEMENT OF RESIDUALS (BRINE DISPOSAL)

During the desalination process, it is inevitable that waste streams are generated, which must be managed in a suitable way. The treatment and disposal of these residuals, within the legal environmental framework, may result in significant costs for the water service provider.

The most important and largest waste stream from any desalination plant is the brine (or concentrated salt) stream that is produced during the separation process. The brine stream contains high concentrations of salts and other concentrated impurities that may be found in the feed water, and which must be disposed of in a safe and acceptable way. Depending on the composition of the brine and the location of the site, additional treatment may be required before disposal.

> The character of the brine that is produced will be affected by feed water quality, pre-treatment processes, desalination processes, water recovery and post-treatment and concentrate blending.

The most common brine disposal options are ocean disposal, surface water discharge, sewer discharge, deep-well injection (not applied in South Africa at present), evaporation ponds, land application and co-disposal with wastewater treatment plant effluent or power plant cooling water.

Section 8 in Part 2 of the Guide provides an overview of the different methods of brine disposal and brine treatment, as well as emerging methods for minimisation of salt concentrates. Environmental considerations on brine disposal are discussed in Part 2, Section 9, and are summarised in Section 11.

11 ENVIRONMENTAL CONSIDERATIONS

When considering desalination as an alternative option to conventional water supply, it is important to carefully take into account all the environmental costs associated with the development and operation of desalination plants. The following legislation and permit requirements are applicable:

- The National Environmental Management Act (Act 107/98, NEMA)

  NEMA promotes sustainable development and regulates the procedures and steps to be taken when a development is considered for approval. It specifically promotes the cooperation between different role players and cooperative governance.

In this regard, it prescribes cooperation between government departments, such as the Department of Water Affairs and Forestry (DWAF), the Department of Environmental Affairs and Tourism and the relevant local authority. In specific instances, institutions such as Nature Conservation Boards will also need to be consulted.

- Environmental Conservation Act (Act 73/89, ECA)

  ECA, through regulation 1182, prescribes specific requirements for specific actions that might have a detrimental impact on the environment. These actions are listed in schedule one of the regulations and include "construction or upgrade of all structures below the high-water mark of the sea" and "schemes for the abstraction or utilisation of ground or surface water for bulk supply purposes".

  Regulation 1182 contains all the relevant steps to be taken for the required environmental impact assessment. It is extremely important to note that the involvement of interested and affected parties forms an integral part of this process.

- National Water Act (Act 36 of 1998, NWA) and Water Services Act (Act 108 of 1997, WSA).

  These two acts regulate the water industry and deal primarily with the management structures and the licensing procedures required before water can be abstracted from a source.

  Depending on the method of abstraction in the case of seawater desalination, it might be a requirement to apply for a licence or permit to abstract water. Beach wells as a possible abstraction method will almost always involve the abstraction of groundwater resources, which are regulated by the NWA. General authorisations granted by DWAF are only applicable up to 750 m inland from the high tide level and an application for a permit to abstract water needs to be lodged by the relevant local authority.

  In the case of the abstraction of groundwater, the permit or licensing procedure is well described and is compulsory through the WSA.

- General authorisations and permits

  During the construction phase of specific seawater desalination plants, a permit is required from the relevant Nature Conservation Board for access to beaches and the removal of specific plant species in dune areas.

  The concentrated wastewater generated from a desalination plant contains high concentrations of salt and particulate matter, which have the potential to impact negatively on the receiving environment. In the case of reverse osmosis plants, filter backwash water (or sludge) and CIP chemicals need to be disposed of, apart from the concentrated brine. Thermal desalination plants, driven by auxiliary boilers, also discharge fumes (CO_2, NO_X, and SO_X) and cooling water blow-down with associated heat into the environment.

12 SKILLS REQUIRED FOR OPERATION AND MAINTENANCE OF DESALINATION PLANTS

12.1 Operating

The operation of a desalination plant can be performed under contract, but it is preferable that the plant is operated by personnel of the water service provider (municipality or water board). Operating a desalination plant is not necessarily more difficult than operating a conventional water treatment plant, but a lack of adequate control measures during the operational phase, can be very costly in terms of membrane life expectancy and therefore operational cost. The maintenance cost for desalination is normally also slightly higher than that of conventional treatment plants due to the higher pressure pumps and membrane cleaning processes required.

Perhaps the most important aspect of the operation of any desalination plant is the availability of accurate data on which decisions regarding the operational aspects can be based. If a specific plant is operated by an external company, then the water service authority must have adequate access to all the relevant data.

The day to day operations of desalination plants do not require any special formal qualified staff. However, plant operators should be well-trained and capable of acquiring the skills necessary to perform daily operations of the plant and to report any deviations from normal operating parameters. Chemical cleaning of membranes needs to be performed under the control and guidance of a knowledgeable supervisor or technician.

It is advisable that at least one staff member of the water service provider has an adequate understanding and knowledge of membrane treatment processes. This would require some form of training in membrane treatment, albeit short courses or as part of formal training. This staff member would either be a technician, technologist or an engineer (depending on the size of the plant).

12.2 Maintenance

Sufficient funds and labour must be available to do preventative maintenance. A good preventative maintenance program will document the schedule and work plan for each maintenance function. This schedule serves as the basis for estimation of labour requirements for specific maintenance functions.

To determine trade and manhour requirements for each preventative maintenance function, the function should be broken down into tasks. Such tasks may then be analysed further to determine specific skills and man-hours required for each specific maintenance function.

It is important to use trained and experienced individuals to perform maintenance. At larger service providers, individuals who are specialised in each trade will in all likelihood be available to do the required maintenance. If not, it is advisable to contract specialised maintenance work, such as electrical control panel repair or generator maintenance out to private contractors. Full dependence on contractors for maintenance tasks needs to be minimised where possible. However, due to cost implications it might be the most appropriate option, specifically for smaller communities.

12.3 Technical support

Technical support for desalination plants is necessary to ensure that any deviations from normal operating regimes are addressed rapidly and effectively, so that service delivery (volume of water produced and quality of product water) is not compromised. The support would normally comprise rapid response to call-outs, trouble shooting and corrective action to normalize the situation. It would also include action plans to rapidly identify/forecast similar problems in future and communicating this to the municipal engineer.

Technical support can be provided by any of the following:

- membrane plant supplier
- contracted external company
- competent municipal technician.

The latter would again be the option of choice, but additional support by the membrane supplier would be strongly recommended.

12.4 Levels of responsibility

Considering the above, the levels of responsibility are as follows:

- plant operators (process controllers)
- supervisor (technician; technologist)
- municipal engineer

12.5 Qualifications

The following qualifications are recommended:

12.5.1 Operating personnel

- Plant Operators

  Grade 12 and in-service training on the desalination plant (NQF 4 equivalent)

- Supervisor

  Qualification in Water Treatment and short course on membrane treatment (B.Tech equivalent)

12.5.2 Maintenance personnel

In-service training by membrane suppliers during commissioning process.

12.5.3 Technical support personnel

Qualification in Water Treatment and short course on membrane treatment. In-service training by membrane suppliers during commissioning process.

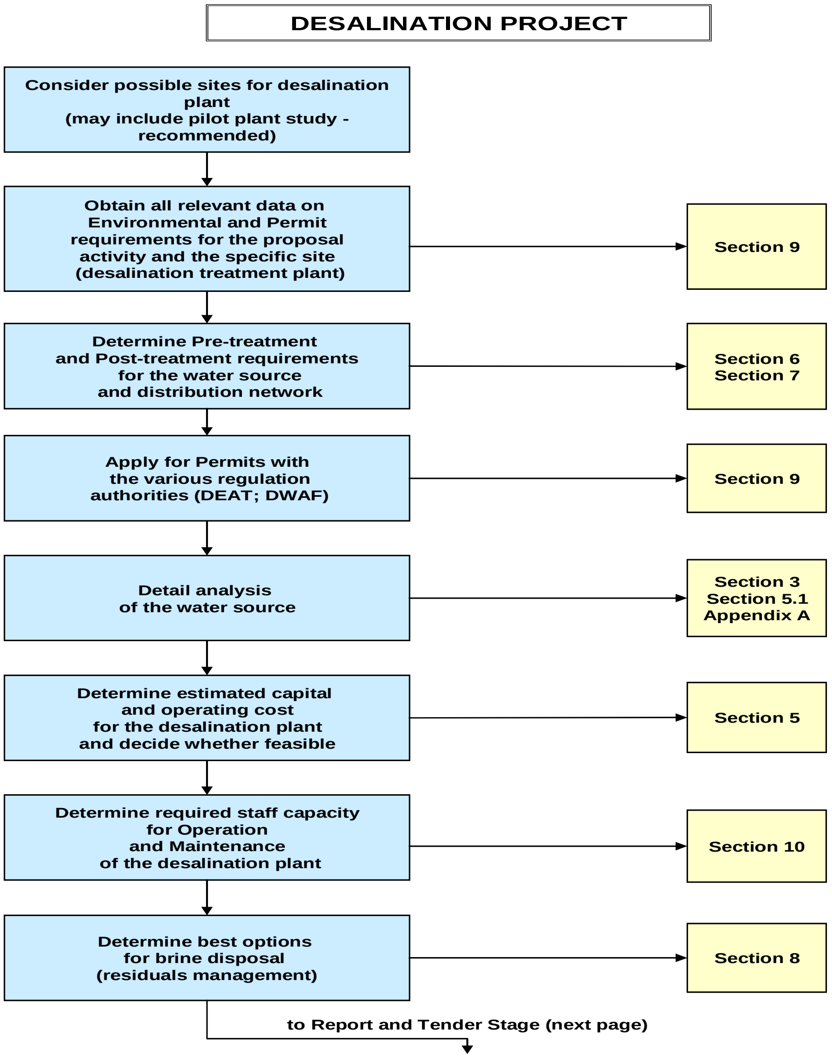
12.6 Training requirements

Existing plant operators (process controllers) at municipal treatment plants can be trained to operate desalination plants. The operators should at least have a Grade 12 school qualification and should receive in-service training on the operation of desalination plants during the commissioning of such plants.

Additional short courses for plant operators and supervisors on operation of membrane based desalination plants would be beneficial.

13 FLOW DIAGRAM FOR STEPS TO BE FOLLOWED WHEN UNDERTAKING A DESALINATION PROJECT.

The flow diagram in **Figure ES.2** presents the main steps to be followed when performing an engineering feasibility study on desalination of a water source as prospective water supply option, with reference to the relevant sections in Part 2 of the Guide.



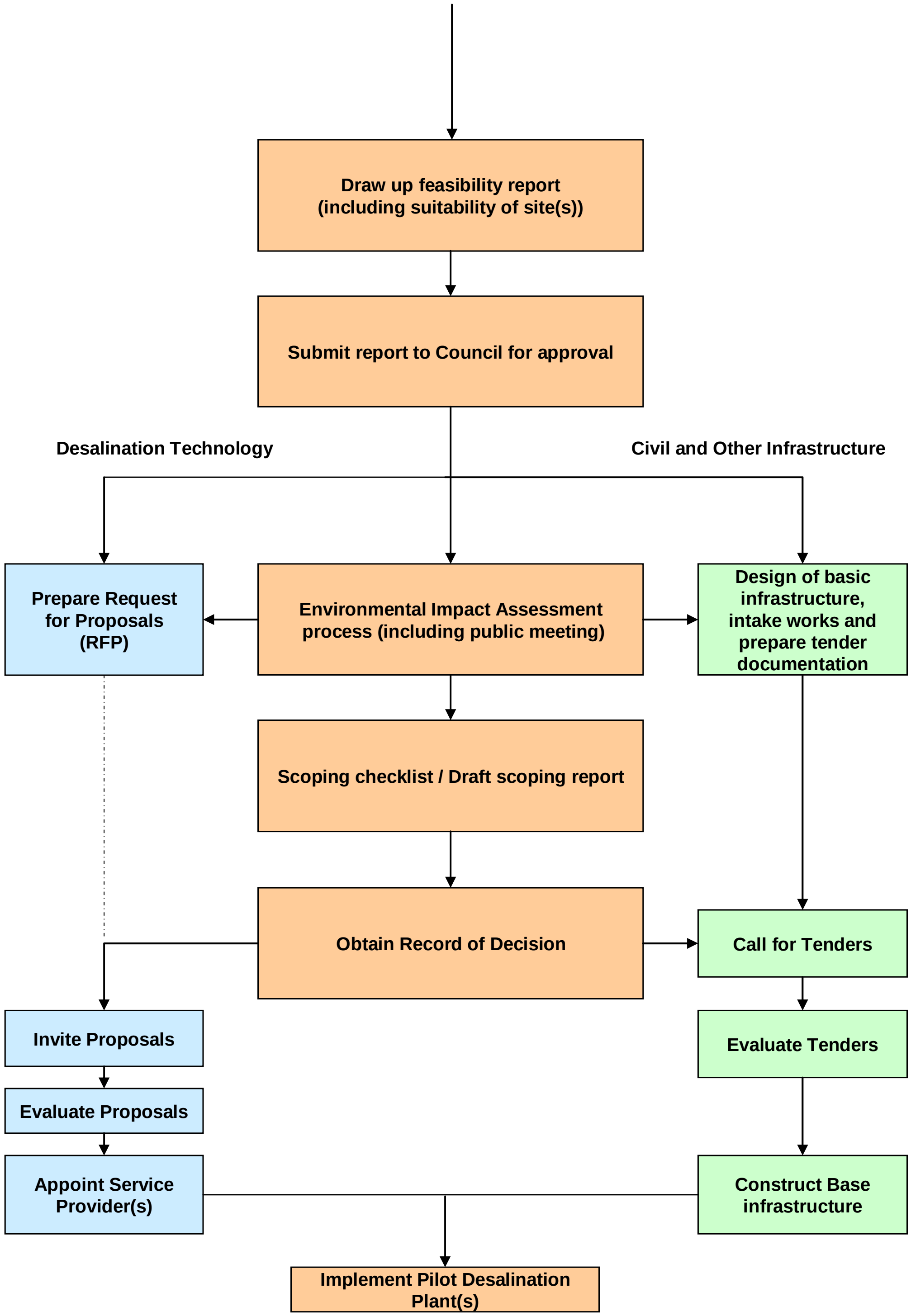


Figure ES.2: Decision making flow diagram

PART 2

DESALINATION GUIDELINES AND PROCEDURES FOR PLANT SELECTION AND COSTING

1 INTRODUCTION

1.1 Background

South Africa is a country with unevenly distributed water resources and large climatic differences. In general terms South Africa can be classified as an arid or semi-arid region with 21% of the country receiving less than 200 mm/year, while 44% receives between 200 and 500 mm/year. The average rainfall for South Africa is only about 450 mm/year, which is significantly lower than the world average of 860 mm/year. The National Water Resource Strategy estimates the total available yield from resources in South Africa at approximately 13 227 million m^3/a, while the requirements for the year 2000 already stood at 12 871 million m^3/a. (DWAF, 2004)

South Africa is already sharing water resources with neighbouring counties like Namibia and Lesotho and large inter-basin transfers already form part of the National Water Resource Strategy. The extent of these transfers is shown in Figure 1.1.

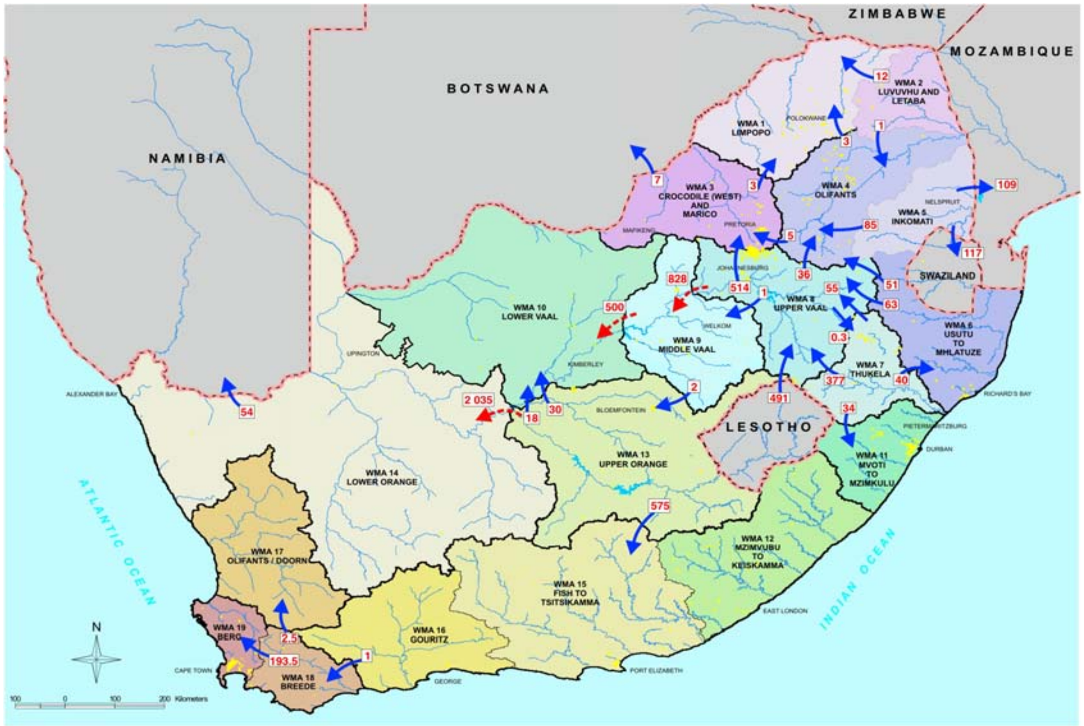


Figure 1.1: Inter basin and border transfers (DWAF, 2004)

Only about 8.2% of the total available yield for SA is available as good quality ground water. Due to the hard rock nature of the geology in SA, very few large scale well fields exist, with mainly the rural areas the prime users of groundwater resources. South Africa, as a developing country and as the cornerstone for developments in Africa, will need to plan its water resources rather carefully to sustain the required growth rate. Figure 1.2 presents the current situation regarding available water resources in SA and clearly shows the small role groundwater is at present playing in the water supply chain.

However, for a large fraction of the rural population, this is often their sole source of drinking water.

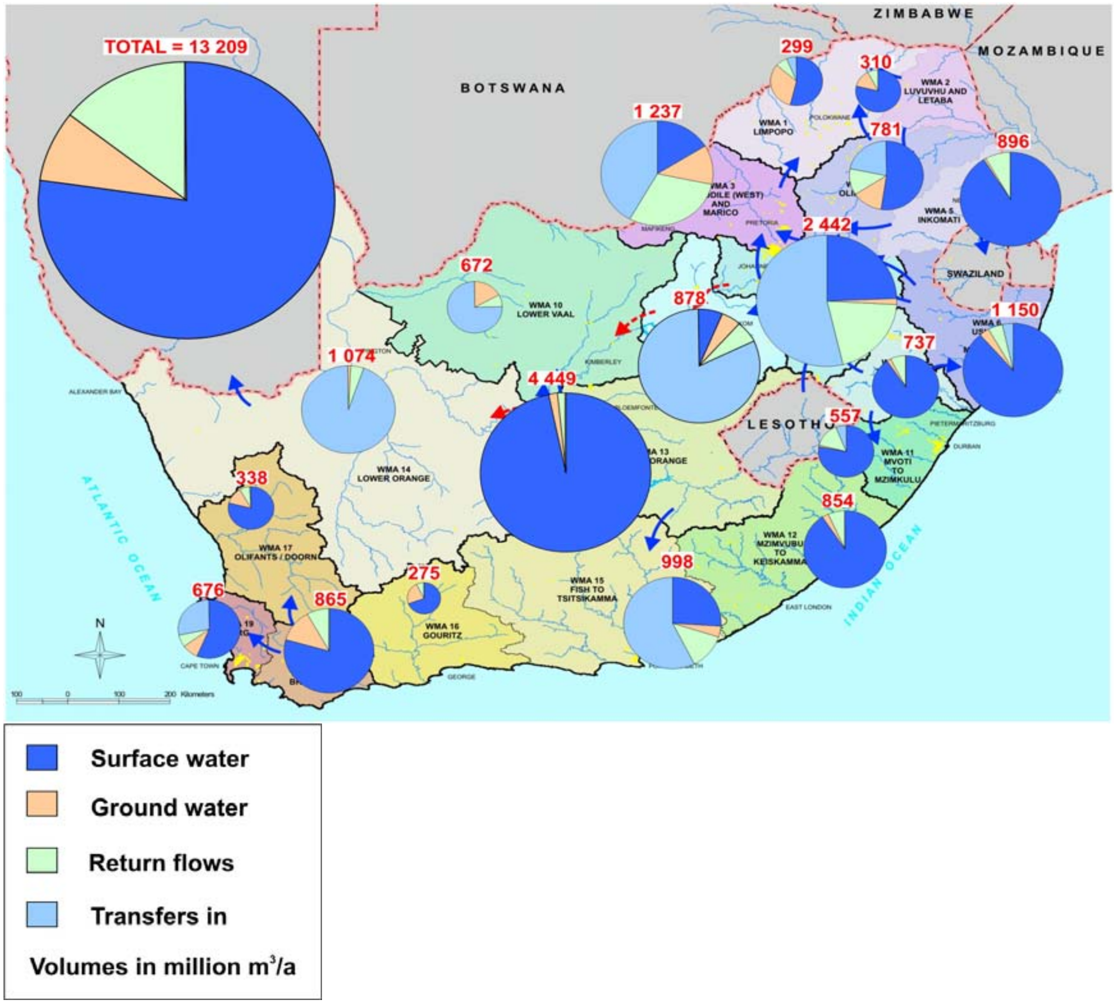


Figure 1.2: Available water resources in South Africa (DWAF, 2004)

By comparing the regional distribution of available water resources against the predicted increase in demand, Figure 1.3 clearly shows that SA is running out of its available resources at an alarming rate in certain areas and is already in a deficit in specific regions. The Department of Water Affairs and Forestry (DWAF) predicts that the water resources in SA will only be sufficient at the present rate of consumption until 2020. Such estimates are made within the framework of the available technologies and certainly do not portray a favourable situation for SA.

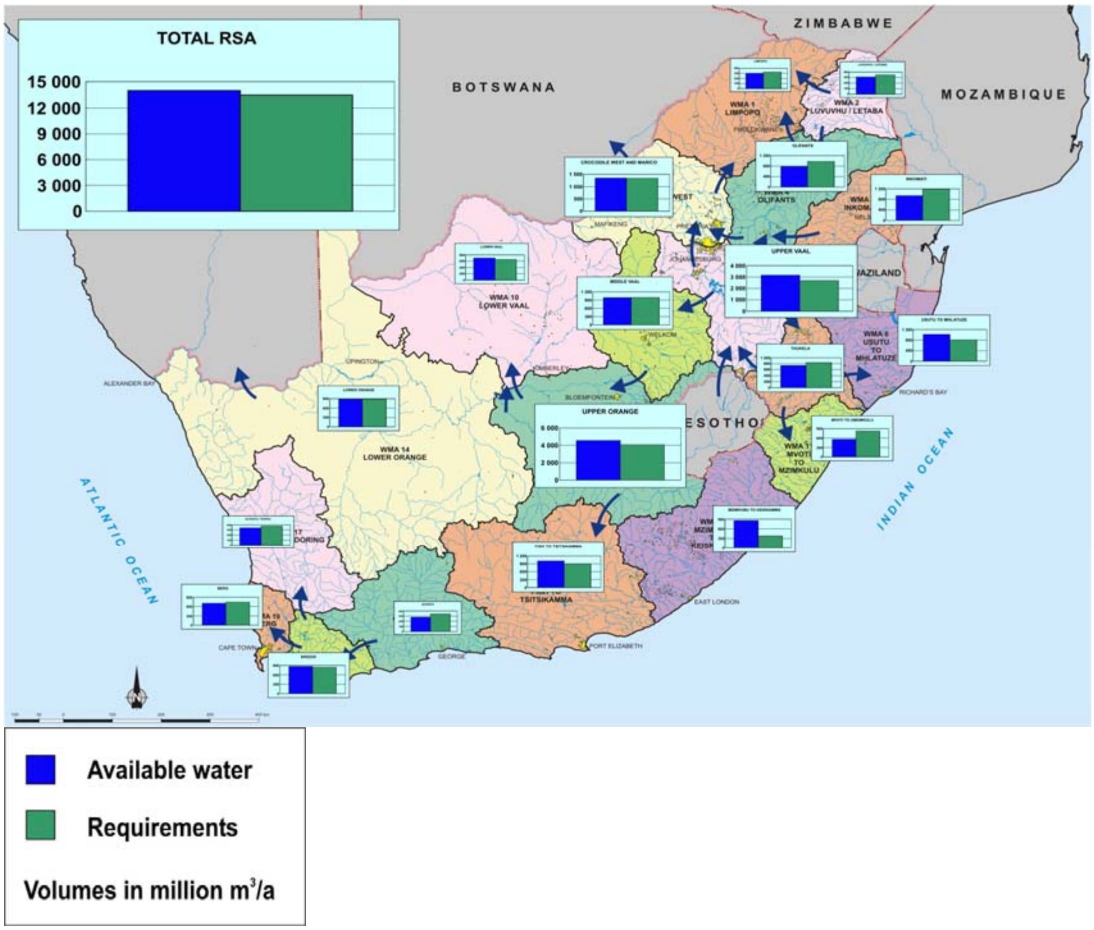


Figure 1.3: Regional comparison between available and required water resources for South Africa (DWAF, 2004)

Desalination is relatively expensive if compared with conventional treatment processes. Until fairly recently, very little of the groundwater available in South Africa was considered as an economically viable resource due to unacceptably high salinity levels and the resultant need for desalination. For the same reason, desalinated seawater is reluctantly considered as an alternative water source. However, desalination is becoming more affordable as related technologies improve and as the cost of surface water increases due to increasing shortages. Therefore, the objective of this Guide is to provide useful information and methods whereby the municipal planner can evaluate desalination of ground water or sea water, in the correct context, as an option to augment current municipal water supplies.

1.2 Important primary considerations

This Guide provides general information and estimation guidelines on desalination with the understanding that such information shall be utilised within context and with due consideration and understanding of the following important aspects:

- **Saline water source, energy source and process selection**.

  Compared to conventional municipal water treatment, desalination processes are energy intensive. No assessment of a desalination process is complete without proper understanding of the energy requirements and the available sources and cost of energy (e.g. residual steam, spent heat, electricity, etc.). The source of energy, the required plant capacity and the feed water quality play major roles in the selection of the most appropriate desalination process.

- **Fouling, scale formation and plant availability**.

  Water (H_2O in its pure form) contains dissolved gases, dissolved and suspended inorganic solids, dissolved and suspended organic matter and suspended micro-organisms. During the desalination process, the concentration of these components can effect various forms of scale formation and other inhibitive contamination of the desalination equipment. Continuous scaling and/or fouling can be one of the most crippling side-effects of desalination processes. A well-designed desalination plant always incorporates a well-designed and appropriate pre-treatment system to minimise fouling. A thorough knowledge of the feed water chemistry and related seasonal variations is essential.

- **Disposal of concentrate and environmental considerations**.

  At first consideration, one often tends to ignore the fact that the concentrate (which can be several times more saline than the feed - depending on the application) needs to be disposed of in an appropriate and environmentally friendly manner. However, quite often this unavoidable consequence of the desalination process contributes to a major portion of the overall project cost.

- **Physical location of plant and cost of distribution**.

  Augmentation of municipal water by desalination requires a sensible tie-in into established municipal water supply networks. The selection of an optimum location for a desalination plant in relation to its feed source and its tie-in point can sometimes be less clear-cut than expected. Incorrect positioning and potential expropriation of land can contribute to significant additional capital and operating costs.

- **Manufacturing specifications and plant life**.

  Incorrect selection of materials of construction and inferior equipment can have serious adverse effects on both the maintenance costs and general operability and availability of the plant. Therefore, clear and unambiguous definitions of the minimum required plant life and construction specifications are essential to avoid plant failure and consequent overhaul after a few years of operation.

2 THE CONCEPT OF DESALINATION

For the purpose of this Guide, and in the general sense of the word, *desalination* is considered to be a process whereby the concentrations of both multi-valent *and* mono-valent ions in saline water can be reduced to levels that are acceptable for potable use. In practice, dissolved salts and other matter are concentrated in a portion of the feed water (the *brine*, or *concentrate*) to render the remaining portion of the feed water (the *desalinated product*) less saline. Desalination seldomly implies a complete removal of dissolved salts.

In order to provide some fundamental background, various desalination technologies are discussed in Section 4. However, it is not the intention of this Guide to pursue each technology in detail.

Thermal distillation systems account for the majority of the world's *seawater* desalination capacity, while membrane-based reverse osmosis systems (newer technology than distillation) are rapidly gaining ground. Distillation systems are more energy intensive than reverse osmosis systems, but require less pre-treatment of the water and are therefore generally considered to be more robust. However, most distillation plants are located in the Middle East where low cost energy is available and where these plants run in combination with electrical power stations. El-Nashar (2001) and Balaban (1991c, ed) provide useful information.

In the *South African context*, thermal desalination processes would normally *not* be considered for desalination of brackish or sea water, *unless* sufficient waste heat or low cost fuels are available (*e.g*. in combination with nuclear power generation). Until recently, the upper capacity limit for reverse osmosis (RO) desalination of sea water was considered to be around 100 000 m^3/day, while plants with larger capacities were always based on distillation. However, the *Ashkelon* desalination plant in Israel, one of the most recent additions to large-scale seawater desalination plants, has a maximum production capacity of 330 000 m^3/day and is, despite its "large" capacity, an RO plant (Einav, 2003).

Against this background, this Guide provides rules for cost estimation of ***reverse osmosis*** (RO) desalination plants.

3 TYPICAL WATER SOURCES AS FEED TO DESALINATION PLANTS

3.1 Saline water sources in general

Most natural in-land surface water sources, such as rivers, dams and lakes usually contain water with TDS levels well below 1000 mg/litre. Some surface water sources are affected by high salinity levels, often as a result of industrial and domestic activities. Industrial effluents can literally contain any type of pollutant and related desalination investigations are highly case specific. Therefore, although it may in some cases be an important and large source of saline water, discussions on the treatment and desalination of such effluents fall outside the scope of this Guide.

Grey water and outfall from municipal sewerage plants (secondary and tertiary effluents) can certainly be considered as a useful source of water and the public should be educated to accept this "alternative" method of water supply (Al-Jayyousi, 2004). The Goreangab reclamation plant in Namibia is a good example where such effluent is treated and recycled for municipal use (without desalination). The TDS of treated sewerage is usually below 1000 mg/litre and desalination is not necessarily required. However, the membrane barrier (in the case of reverse osmosis) is considered to be a reliable second-stage protection against pathogen break-through and membrane desalination thereby offers an important added benefit. It should be noted that there are several plants in operation in the world where treated sewerage is recycled via double membrane systems (ultra-filtration and reverse osmosis), but this is considered to be a specific case of desalination worth handling in a separate, dedicated document.

To this end, while acknowledging the fact that industrial and municipal effluents are potentially useful secondary sources of water, further discussions will only focus on two main categories of saline water sources, *viz*.

- sea water;
- brackish borehole and well water.

3.1.1 Sea water

The TDS of sea water varies according to geographic location. For example, the TDS of the Baltic Sea is less than 20 000 mg/litre, while sea water in the Middle East can reach TDS levels around 50 000 mg/litre. The *typical* TDS of Atlantic Ocean and Indian Ocean water is 36 000 mg/litre and 34 000 mg/litre respectively. The internationally agreed definition of so-called "standard sea water" is given by Heitmann (ed. 1990), in Table 3.1.

Table 3.1: "Standard" sea water - main constituents (mg/litre)

Sodium, Na^+	10 561
Magnesium, Mg^{2+}	1 272
Calcium, Ca^{2+}	400
Potassium, K^+	380
Chloride, Cl^-	18 980
Sulphate, SO_4^{2-}	2 649
Bicarbonate, HCO_3^{2-}	142
Bromide, Br^-	65
Other solids	34
TDS	34 483
Density (20 ^{O}C)	1.0243 s.g.

Depending on coastal conditions and sea currents, marine life activity, the presence of estuaries and large river deltas, human activities and effluent outfalls, tanker and freight liner traffic, etc. the presence of colloidal, organic and biological components in coastal water can differ significantly between any two intake points. Even at the same intake point, seasonal variations in water quality can be notable.

One important aspect worth mentioning is the so-called red tide phenomenon, mostly occurring around the temperate middle latitudes. Red tides are naturally occurring population explosions, called blooms, of reddish-brown phytoplankton (microscopic algae) in the sea, resulting in the presence of many millions of cells per litre of water. The corresponding depletion of oxygen and release of neurotoxins into the water can result in the death of marine life. The anaerobic conditions can also be accompanied by the release of H_2S into the water. H_2S is a poisonous gas that readily dissolves in water and is formed under anaerobic conditions when sulphate-reducing bacteria convert organic carbon to CO_2 while reducing the SO_4 anions in the water to H_2S.

Therefore, apart from the fact that the salt concentration in sea water is high (~3.5%), the presence of varying concentrations of a wide range of impurities in sea water makes the pre-treatment to desalination more tricky than most borehole-water applications. Moreover, the high salt content of sea water and the humid atmosphere at the coast support conditions that are ideal for rapid corrosion of many materials of construction.

3.1.2 Brackish groundwater

Underground water from various sources has, depending on geo-hydrological conditions and geographic location, highly variable TDS concentrations. Some boreholes may contain super saline water with TDS close to that of sea water. However, the TDS levels of groundwater in South Africa are usually much lower than that of sea water - usually well below 15 000 mg/litre. The time-related decay of dissolved organic substances at high underground pressures often results in the presence of dissolved carbon dioxide in borehole waters. Such water also quite often contains relatively high concentrations of dissolved iron and manganese, but it is rather easy to remove these by appropriate pre-treatment prior to desalination.

Although the desalination requirements for borehole waters are case-specific, microbial life and suspended colloidal clays are usually low in unpolluted borehole water. Therefore, the fouling of desalination systems that treat borehole water can normally be controlled quite easily. Suffice to say that, *as long as inorganic scaling can be prevented* and turbidity and undesirable metals removed by effective pre-treatment, the desalination of most borehole waters usually does not pose insurmountable technical problems.

3.2 South African saline water sources and related geo-hydrology

3.2.1 Sea water

South Africa with its extremely long coastline has an almost infinite water resource available to the coastal towns and cities of the country, albeit of a highly saline nature. Three sea water zones with potentially different water qualities are identified and briefly discussed below (also see Table 3.2 and Table 3.3):

- **East Coast**

  The East Coast of South Africa can be described as the area between East London up to the Mozambique border. All marine systems in this region are dominated by the Agulhas current, which brings warm, nutrient-poor water from the tropics to the east coast. The region can be subdivided into a tropical coast (north of Port Edward) and a subtropical coast.

- **South Coast**

  The coastal region between East London and Cape Agulhas, referred to as the South Coast, acts as a transitional zone between the warm east coast waters and the cold west coast waters, with no clear boundaries.

Boundary conditions might shift 100 km in either way, depending on prevailing atmospheric conditions.

- **West Coast**

The West Coast is generally referred to as the region between Cape Agulhas and the mouth of the Orange River. Sea water quality in this region can be rather variable and special care should be taken when assessing water supply in areas such as False Bay, St Helena Bay and the Saldanha Bay / Langebaan system.

Due to the north-bound flow of the Benguela current from the Antarctic, the West Coast water is normally very cold and associated with low dissolved oxygen levels.

Prevailing wind conditions frequently result in an up-welling of cold, nutrient-rich bottom water into the warmer surface water, triggering the associated red-tide phenomenon and the potential presence of H_2S in the water.

A typical analysis of West Coast water (near Cape Town) is provided in Table 3.4.

Table 3.2: Typical temperature of South African sea water

Coastal Region	Temperature (^{O}C)	Comments
East	21 – 25	Only small seasonal variations at depths, while surface water temperatures may vary by $9^{O}C$.
South	16 – 21	-
West	9 – 14	Temperature depends on wind-induced up-welling. Surface water temperature can rise to $16^{O}C$ after sufficient warming by the sun.

Table 3.3: Typical salinity of South African seawater

Coastal Region	TDS (mg/litre)	Comments
East	>35 000	Higher than West Coast TDS due to higher evaporation. Large river systems like the Zambezi and Limpopo can reduce the TDS significantly.
South	35 000 – 35 400	Highest TDS in summer when evaporation is high.
West	34 700 – 35 400	The TDS at the Langebaan Lagoon can be as high as 37 000 mg/litre due to high evaporation losses.

Table 3.4: Analysis of typical sea water near Cape Town (CSIR, 2001)

Potassium (as K mg/litre)	393
Sodium (as Na mg/litre)	10 957
Calcium (as Ca mg/litre)	406
Magnesium (as Mg mg/litre)	1 312
Sulphate (as SO_4 mg/litre)	2 757
Chloride (as Cl mg/litre)	19 677
Alkalinity (as $CaCO_3$ mg/litre)	117
Fluoride (as F mg/litre)	1.1
Cyanide (as CN mg/litre)	<0.05
Dissolved Organic Carbon (mg/litre)	<1
Conductivity (µS/cm) @ 25°C	51 000
pH (Lab)	8.1
Total Dissolved Solids (Calc) (mg/litre)	35 644
Total Dissolved Solids (180°C) (mg/litre)	35 900
Hardness (as $CaCO_3$ mg/litre)	6 417
CATIONS (meq/litre)	614.87
ANIONS (meq/litre)	614.82
Suspended Solids (mg/litre) (No. 1 filter)	3.7
Suspended Solids (mg/litre) (0.45 µm)	1.5
Turbidity (NTU)	6.5

The pH of the sea water at all three coastal zones is slightly alkaline, between 8.1 and 8.3, and in equilibrium with the atmospheric CO_2 levels.

Note that, although the TDS levels of the seawater from the three zones are rather similar, the suspended solids content and presence of microbial life and other organic matter may vary significantly, not only between the three major zones, but also inside a specific zone, depending on sea currents and other local factors. For example, turbidity readings (NTU) of water samples taken at seven different locations along the Namibian coast in the late 1990's varied between 0.5 and 7.3, while fats and oils were reported as being between 2.2 and 4.8 mg/kg.

3.2.2 Groundwater

Saline or brackish groundwater provides for a second alternative source of water. The specific desalination technology required will, as in the case of sea water, depend on the quality of the available groundwater. The groundwater harvesting potential map (Figure D 2) and the exploitation potential map (Figure D 1) provides a good estimate of the probability that groundwater of a specific quality (TDS in mg/l) can be found in an area and if the resource can be considered as a potential alternative water resource. Some of the quality parameters that might influence the desalination process include the following:

- Chloride
- Sulphate
- Calcium
- Magnesium
- Sodium

- Nitrates
- Alkalinity
- Total Dissolved Solids (TDS)

These parameters have all been evaluated in the National Groundwater Quality Assessment (WRC K5/841) and the relevant maps are attached in Appendix D. Of specific interest is the TDS (mg/l) shown in Figure D 1: and the associated salinity in Figure D 3.

4 POPULAR DESALTING PROCESSES

4.1 Desalination versus demineralisation

Although the words desalination and *demineralisation* in principle imply the same concept, *i.e*. “removal” of dissolved salts from water, they have different meanings in their application.

The term “*demineralisation*” is normally applied to processes where the TDS of the *feed* water is well inside the potable range and usually less than ~200 mg/litre. With demineralisation, the focus is on producing high quality water with TDS very often below 1 mg/litre. Conductivity readings become more reliable than TDS measurements at such low concentrations and the pharmaceutical, electronics and high-pressure boiler industry typically require water with conductivity <0.10 μS/cm. Ion exchange is, for example, a popular demineralisation technique, due to its ability to produce such pure water. However, conventional ion exchange requires periodic regeneration of resins with chemicals such as sulphuric acid and caustic. The higher the TDS of the feed water, the higher the chemical consumption of the process, so that ion exchange becomes non-viable at the higher TDS levels that require desalination for production of potable water.

The term “*desalination*” is applied to processes where the TDS of the *feed* water is higher than that tolerated for potable purposes and usually well above 500 mg/litre. With desalination, the focus is on producing water with TDS acceptable for general potable or industrial use.

Quite often, (especially for industrial applications) desalination and demineralisation are used in combination to produce high-purity water from highly saline feed water.

4.2 Popular desalination technologies

Considering the fact that ion exchange is mostly considered to be a demineralisation technique rather than a desalination technique, its application as a primary desalination method will not be considered further. However, ion exchange technology can be applied in various forms and may even be utilised as a pre-treatment step for membrane desalination (for removal of hardness, or trapping of organics). Therefore, any further discussions on conventional ion exchange will only focus on its potential application as a pre-treatment method.

Against this background, the *most popular* desalination techniques can broadly be categorised into two main groups, *viz*:

- Distillation (evaporation & condensation) processes

- MSF: Multi-stage flash distillation
  - MED: Multi-effect distillation
  - VC: Vapour compression distillation
- Membrane-based processes
  - RO: Reverse Osmosis (pressure driven)
  - NF: Nano-filtration (pressure driven; partial desalination)
  - EDR: Electro-dialysis Reversal (electro-potentially driven)

The above grouping is *not* complete and excludes methods such as:

- freezing,
- capacitive deionisation,
- solar desalination (also distillation), etc.

However, the focus of this Guide is on well-proven processes with full-scale reference plants in operation. Of the above, RO, MSF and VC dominate the desalination industry, with RO becoming the method of choice due to its *relatively* good energy efficiency.

More detailed descriptions and discussions on these technologies can be found in the literature, such as by Aly and El-Fiqi (2003a,b), Bahar *et al* (2004), Drablos (2004), Porteous (ed. 1983), Heitmann (ed. 1990), Mussati *et al* (2001), Watson *et al* (2003) and Cerci *et al* (2003).

More information on specialised desalination and water re-use methods are provided by Al-Jayyousi (2004), Al-Mutaz (2003), Aybar (2004), Al-Shammari (2004), Bar (2004), Bouhelal *et al* (2004), Cohen *et al* (2001), Gotor *et al* (2003), Misra and Kupitz (2004), Mohsen (2004), Szacsvay and Posnansky (2001) and Zejli (2004) to name a few examples.

In concept, the following process steps (Figure 4.1) are usually encountered in a complete desalination plant. Depending on the selected technology and the source of saline water, some of the process inputs, or effluents, may be omitted.

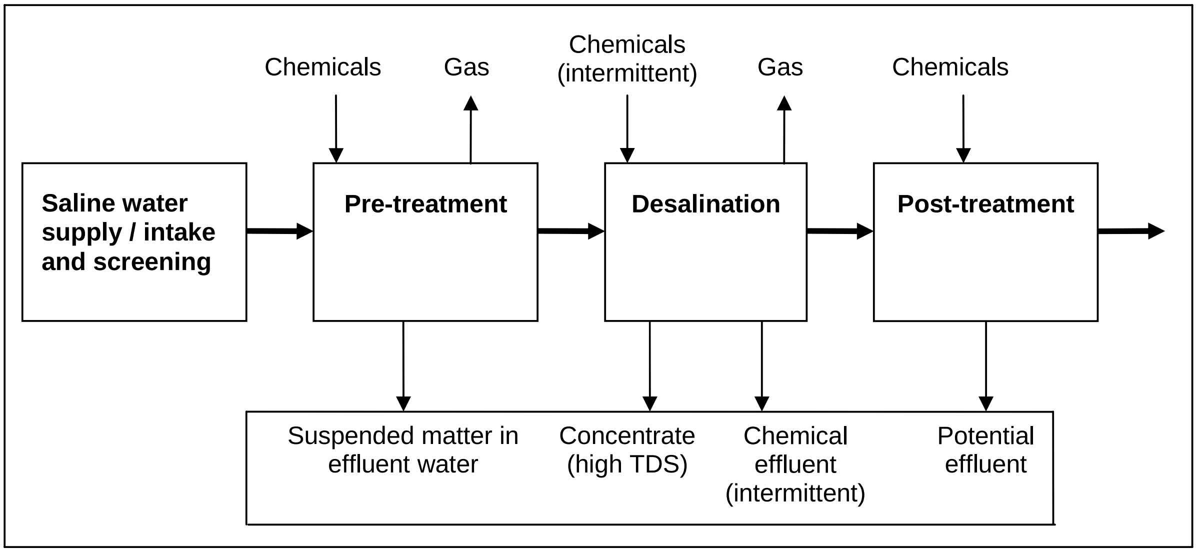


Figure 4.1: Typical process flow of a complete desalination plant

4.3 Distillation processes

4.3.1 Multi-effect distillation (MED)

In an MED plant, the sea water enters the "first effect" and is raised to the boiling point after being preheated in tubes. The sea water is either sprayed or otherwise distributed onto the surface of evaporator tubes in a thin film to promote rapid boiling and evaporation. The tubes are heated by steam from a boiler (or any other heating source), which is condensed on the opposite side of the tubes. The condensate from the boiler steam is recycled to the boiler for reuse. MED, like the MSF process, takes place in a series of evaporator vessels (effects) each operating at a slightly lower ambient pressure than the previous. Since water boils at lower temperatures as the pressure decreases, the water vapour of the first effect serves as a heating medium for the second effect, and so on. This permits the sea water feed to undergo multiple boiling without supplying additional heat after the first effect.

Various design types are available, including horizontal tube (low or high temperature), vertical tube (low or high temperature) and stacked vertical tube designs.

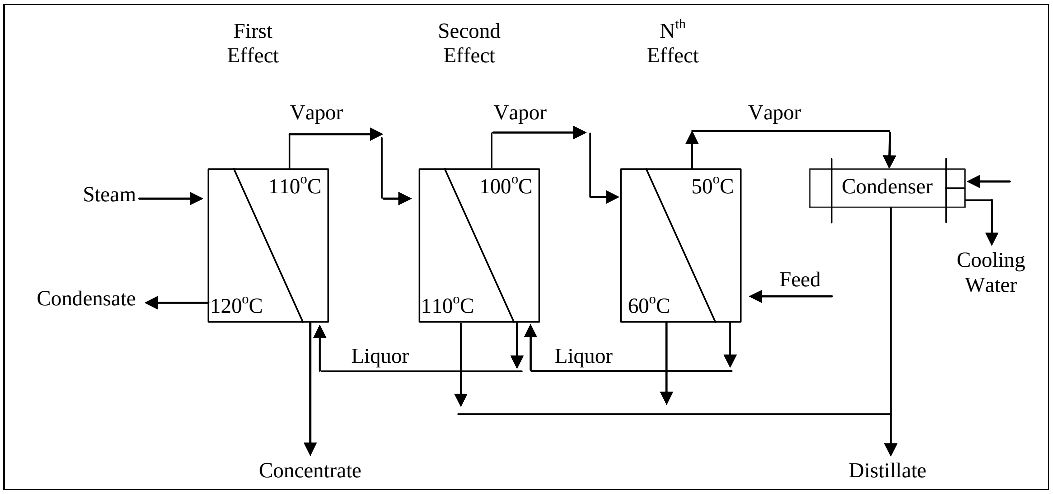


Figure 4.2: Typical multi-effect distillation unit.

4.3.2 Multi-stage flash (MSF)

In the MSF process, saline feed water is heated in a so-called brine heater. The water is *not* allowed to boil, thus reducing the risk of scale formation. This heating is generally performed by condensing steam on a bank of tubes that passes through the vessel which in turn heats the saline water. The heated water (at boiling point, under pressure) then flows into another vessel (a stage) where the ambient pressure is sufficiently low to cause an immediate phase change of a portion of the water, almost exploding or *flashing* into steam. Generally, only a small percentage of the water is converted to steam, depending on the pressure maintained in this stage, since flashing will continue only until the remaining water cools (by furnishing the heat of vaporization) to the boiling point at the prevailing pressure.

By using a series of stages set at increasingly lower pressures, the feed water passes from one stage to another to boil (flash) repeatedly without adding more heat. An MSF plant can typically contain anywhere from 4 to 50 stages.

The steam generated by flashing is converted to fresh water by being condensed on tubes of heat exchangers that run through the upper section of each stage. The tubes are cooled by the incoming feed water going to the brine heater. This, in turn, warms up the saline feed water, so that the amount of external thermal energy needed in the brine heater is reduced. Unlike the MED process, the MSF process generates and condenses its vapour in the same effect (stage).

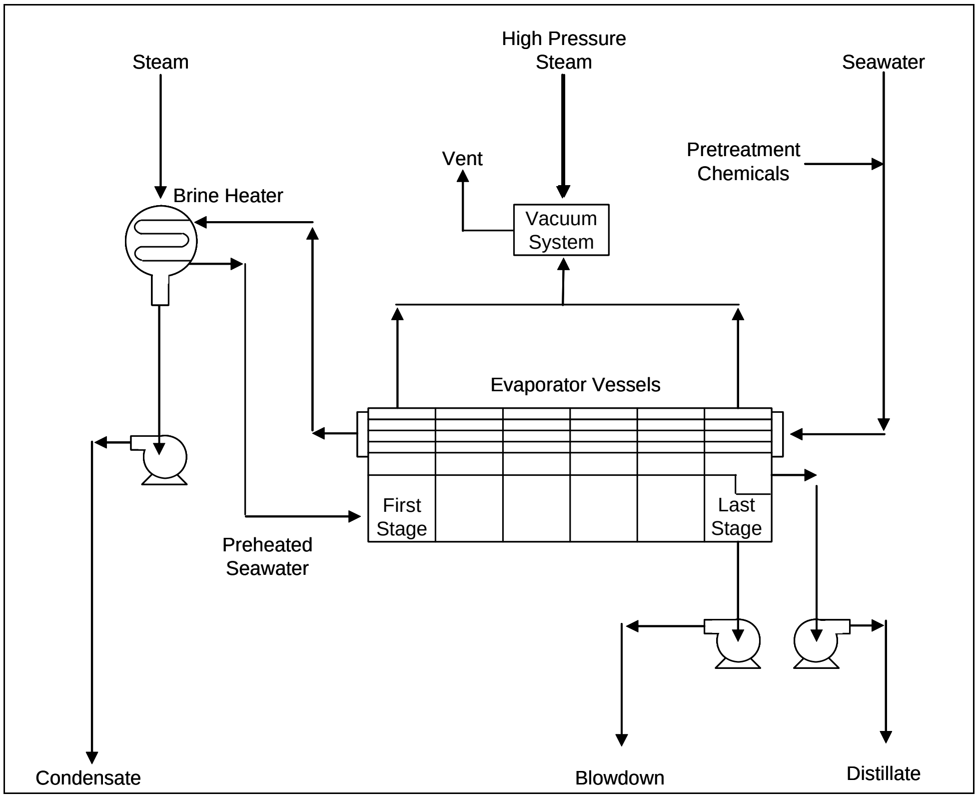


Figure 4.3: Typical once-through MSF distillation unit

4.3.3 *Vapour compression (VC)*

The vapour compression (VC) distillation process is generally used for small- and medium-size (up to 30 megaliters per day) distillation units. The heat for evaporating the water comes from the compression of vapour rather than the direct exchange of heat from steam produced in a boiler. The plants which use this process are generally designed to take advantage of the principle of reducing the boiling point temperature by reducing the pressure. Two primary methods are used to condense vapour so as to produce enough heat to evaporate incoming saline water, *viz*. a mechanical compressor (MVC) or a steam jet (TVC). The mechanical compressor is usually electrically driven, allowing the use of only electrical power to produce water by distillation. VC units have been built in a variety of configurations to promote the exchange of heat to evaporate the saline water. The compressor creates a vacuum in the vessel and then compresses the vapour taken from the vessel and condenses it inside of a tube bundle also in the same vessel. Saline water is sprayed on the outside of the heated tube bundle where it boils and partially evaporates, producing more fresh water.

With the TVC unit, also called a thermo-compressor, a venturi orifice at the steam jet creates and extracts water vapour from the main vessel, creating a lower ambient pressure in the main vessel. The steam jet compresses the extracted water vapour. This mixture is condensed on the tube walls to provide the thermal energy (heat of condensation) to evaporate the saline water being applied on the other side of the tube walls in the vessel.

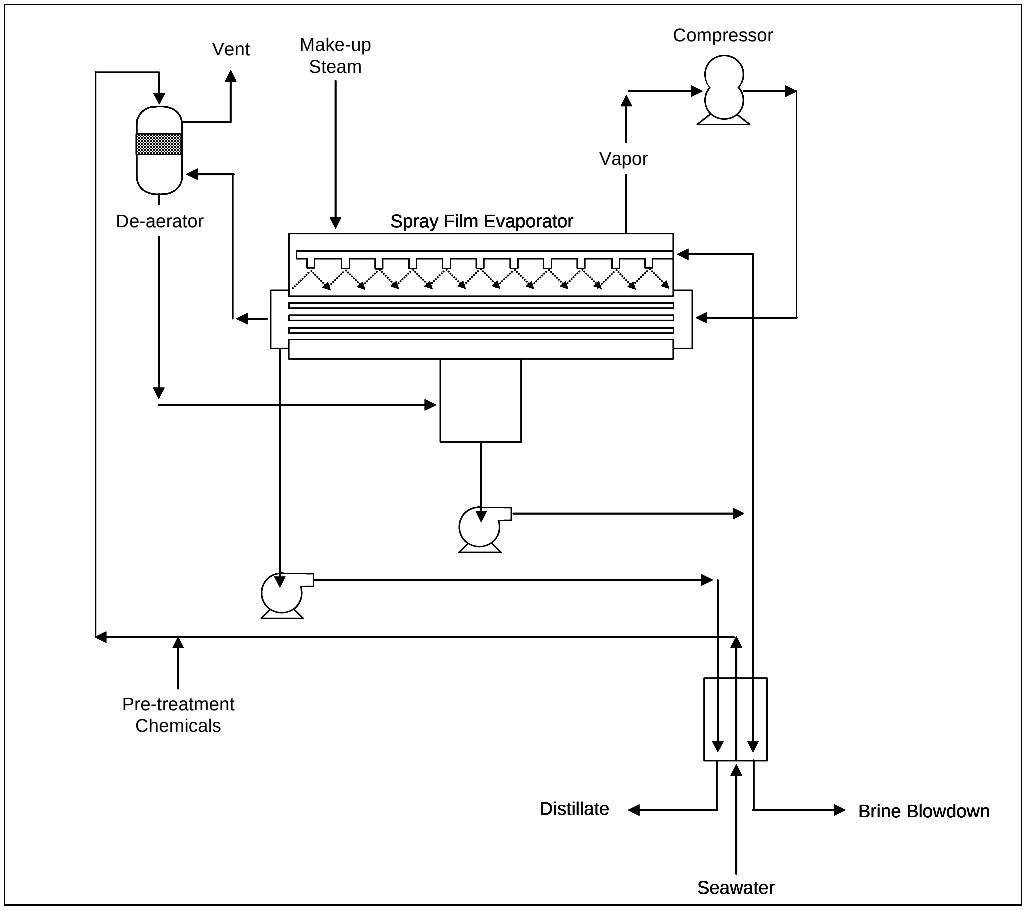


Figure 4.4: Typical MVC distillation unit

4.3.4 *Process parameters of distillation systems*

4.3.4.1 Energy demand

It has been shown (Cerci *et al*, 2003) that the theoretical minimum separation work required to desalinate specific saline water is independent of any hardware and is thus the same for all desalination processes. For example, the minimum work of separation of sea water (TDS of 35 000 mg/litre) at 15^{O}C is 1.874 kJ per kg (0.52 kWh/m^3) product water when 40% of the water is recovered while producing a product with TDS of 100 mg/litre. (1 kJ/kg ≡ 1/3.6 kWh/m^3 ≡ 0.278 kWh/m^3)

However, in practice, distillation plants consume far more energy, depending on the application and design, typically between 290 and 160 kJ per kg (81 and 44 kWh/m^3) product. It can nevertheless be argued that, by combining a distillation process with power production, the use of waste steam from the power plant turbine can reduce the effective distillation power demand to approximately 96 kJ/kg (27 kWh/m^3) (Porteous, ed. 1983). Also see Watson (2003) for more detail.

4.3.4.2 Scale control

Since distillation fundamentally implies a heat transfer process, the most basic engineering challenge is to optimise the economic transfer of large quantities of water, vapour and heat. Effective heat transfer requires clean transfer surfaces, so that scale formation (with a consequent reduction in heat transfer efficiency) is one of the most significant operational problems encountered in distillation plants. Three types of scale are most commonly encountered, *viz*. $CaSO_4$, $CaCO_3$ and $Mg(OH)_2$.

Of these three, $CaSO_4$ is perhaps the most difficult to control. Three different levels of crystal hydration are encountered, *viz*. the anhydrous, hemihydrate and dehydrate crystalline forms which have different solubilities at different temperatures. The solubility of especially the anhydrate ($CaSO_4$) and hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$) forms are inversely related to temperature. Therefore, scaling increases with increasing temperature, so that plants operating under vacuum at lower temperatures are less prone to scale formation. Each distillation process can operate at different maximum temperatures and concentrations and therefore the scale control mechanisms may differ.

$CaCO_3$ and $Mg(OH)_2$ are soft alkaline scales which can be removed more easily than $CaSO_4$ scale. Pre-treatment of the feed water through pH control and decarbonation can minimise related scaling. In addition to temperature and pH control, the dosing of chemical antiscalants such as polyphosphates and polymers are also commonly utilised to reduce scale formation.

Several modern-day distillation plants operate effectively by only dosing around 5 mg/litre of antiscalant.

4.3.4.3 Corrosion control

Distillation plants are potentially subject to severe corrosion. Amongst other, the pH, temperature, chloride concentration and dissolved oxygen content of the feed water, as well as the demineralised nature of the product water can influence corrosion.

Corrosion is controlled by proper selection of corrosion-resistant materials, as well as appropriate pre-treatment of the feed water.

4.3.4.4 Other pre-treatment of feed water

Modern-day distillation plants are relatively robust and only require course filtration or screening, typically below 500 μm. If the sea water intake is very shallow and high loads of solids are present in the water, then some form of decantation may be required.

This rather simplistic pre-treatment for distillation plants is perhaps their most prominent advantage in comparison with membrane desalination plants, which are more energy efficient but have stringent pre-treatment requirements.

Chlorination of the intake water (continuous and/or intermittent shock) is usually required to prevent the growth of marine life in the intake systems. The presence of chlorine in the seawater retained during a shutdown can also prevent the development of sulphate-reducing bacteria with production of undesirable H_2S.

4.3.4.5 Carry-over of saline water and product quality

It is a fundamental aspect of distillation process design to avoid carry-over of saline droplets into the condensate product. A high-quality product is obtained by proper demister design and (sometimes) the use of anti-foaming agents. Depending on the design, seawater distillation plants typically produce condensates (desalinated products) with TDS between 0.5 and 25 mg/litre.

4.4 Membrane processes

4.4.1 Reverse osmosis (RO) and nanofiltration (NF)

To the interested reader, Baker (2004) provides useful fundamental insight into membrane technology and its various applications. Both RO and NF are *pressure-driven* membrane processes. TDS and temperature are two of the most important feed water characteristics to consider in the design of these systems. The required feed pressure increases with increasing TDS and decreasing temperature.

Nanofiltration membranes are operated in a similar fashion than RO membranes. However, mono-valent ions (such as Na^+ and Cl^-) pass through these membranes with relative ease. Therefore, the NF process is typically used to soften water, *i.e*. removing hardness. It operates at lower pressures than RO systems, but produces relatively poor quality water compared to RO. Other membrane processes such as ultra-filtration (UF) and micro-filtration (MF) cannot be used for desalination, but can form part of the pre-treatment before desalination. For the purpose of this Guide, further discussions will focus on RO. Heitmann (1990, ed.), Latteman and Höpner (2003), Watson *et al* (2004) and Côte *et al* (2004) can typically be consulted for more detailed information. General practical experiences with RO are described by Abdel-Jawad *et al* (2001),

The process of osmosis is inherently related to a semi-permeable membrane, allowing selective migration of water (but almost no salts) from one side to the other. In other words, if a solution of salt water is placed on one side of a semi-permeable membrane and pure water is placed on the other side, then there is a natural tendency for water to diffuse through the membrane to the solute (saline) side until an equilibrium osmotic pressure is achieved.

By applying a pressure to the solute side, substantially greater than the osmotic pressure, then water diffuses (against the osmotic pressure) from the solute side to the pure water side. Hence, this pressure-driven process is called *Reverse Osmosis* (RO).

The osmotic pressure of dilute solutions obeys a relationship similar to the ideal gas law, i.e:

$P_{\text{osm}} = \frac{nR_0T}{V}$, where $\frac{n}{V}$ is the molarity of the solution.

A good rule of thumb is that every 1000 mg/litre of dissolved salt (TDS) generates an osmotic pressure of approximately 0.76 bar.

The mechanism of separation by reverse osmosis is not fully understood. However, current thinking suggests that molecular diffusion *through* minute physical pores in the membrane, as well as from one bonding site to another *within* the membrane, contribute to the overall process. To achieve this, theory has it that the chemical nature of the membrane should be such that it will absorb and pass water preferentially to dissolved salts at the solid-liquid interface, a process which may occur by weak chemical bonding of the water to the membrane surface, or by dissolution of the water within the membrane structure.

Industrial RO membrane elements are typically configured in the following forms:

- Spiral
- Tubular
- Capillary
- flat sheet

The spiral RO membrane element (cartridge) is by far the most popular option for large scale desalination of saline water. Full-scale cylindrical elements are typically 200 mm in diameter and 1016 mm long and contain spirally wrapped membrane sheets with a total surface area typically between 32m^2 and 38 m^2, depending on the design. Up to seven of these cartridges can be installed in series in a single pressure vessel. Several of these pressure vessels are again installed in parallel in a series-taper configuration (as indicated by the example in Figure 4.5) to ensure optimum flow of water across (and through) the full membrane area.

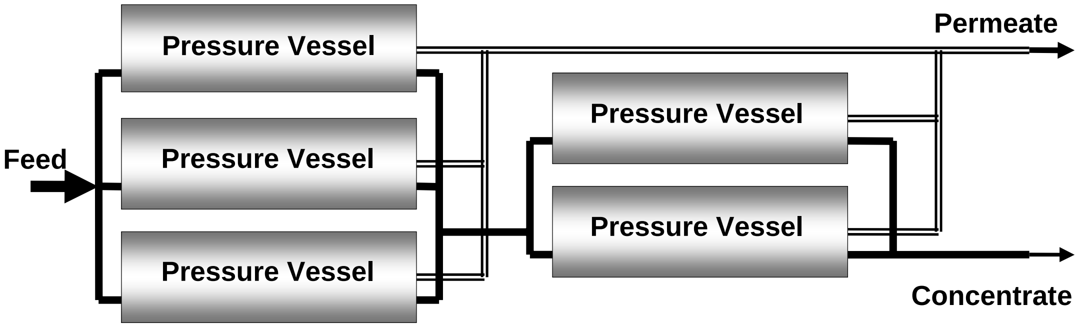


Figure 4.5: A typical taper configuration with five pressure vessels, each pressure vessel again containing several spiral wound membrane elements.

The most commonly used semi-permeable membrane material is either cellulose acetate or poly-amide, with poly-amide being far more popular due to its ability to withstand a broader range of operating and cleaning conditions (higher and lower pH and higher temperature than cellulose acetate). Poly-amide membranes also have a better ability to reject salt at lower pressures than the cellulose acetate membranes. However, cellulose acetate membranes can tolerate low concentrations of chlorine and also tend to be more resistant to organic fouling than the poly-amide material.

Most poly-amide membranes can tolerate temperatures up to $45^{O}C$ and can operate at a pH between 2 and 11.

4.4.1.1 *Water recovery and salt rejection*

The water recovery is defined as the fraction of the feed water that passes through the membrane and ends up as desalinated *permeate*. The salt in the feed water is progressively concentrated in the remaining water until it leaves the system as the final *concentrate* (or brine). In loose terms, the concentration factor is mathematically defined as the inverse of the remaining fraction of feed water in the final concentrate. (Refer to Section 5.2 for more detail). The concentration factor indicates how many times the salt concentration of the final concentrate is higher than that of the feed water. For example, at 75% recovery, the concentration factor is 4, but at 95% recovery it is 20. Since, the concentration factor increases rapidly and drastically above 85% recovery, few plants are operated at 90% recovery or higher.

Seawater RO plants are typically operated at or below 50% recovery (concentration factor of 2), while most brackish water RO plants tend to run at higher recoveries, typically between 65% and 85%.

The reverse osmosis process is not perfect, so that a small portion of the salt in the feed water ends up in the desalinated product (permeate). The salinity of the permeate depends on the relative rates of water and salt transport through the RO membrane.

The flow of water through the membrane (flux) increases with pressure, while the migration of salt through the membrane only increases with an increase in the concentration difference across the membrane. Therefore, since salt flow through the membrane is not pressure dependent, an increased feed pressure will only increase the transport rate of water (or flux), thus reducing the TDS of the permeate.

RO membranes will typically “reject” between 96% and 99% of the salt in the feed water, depending on the operating pressure, the type and quality of the membrane, etc. These salts are thus concentrated in the remaining water, increasing the osmotic pressure. Apart from the scaling potential of the water, the osmotic pressure of the concentrate may limit the recovery of water. At present, the design of most commercial RO membrane elements is such that they cannot operate at pressures above 80 bar.

4.4.1.2 *Energy demand*

The power consumption of industrial reverse osmosis plants depends, amongst other, on the TDS of the feed water, the water temperature and the water recovery. It ranges between 2 and 15 kJ per kg permeate, with the higher values being typical for seawater desalination. Although this is significantly better than for distillation plants, it is still much higher than the theoretical minimum work of separation (1,874 kJ per kg or 0,52 kWh/m^3) calculated by Cerci *et al* (2003) for sea water (with TDS of 35 000 mg/litre at 15^{O}C, with 40% recovery and a product TDS of 100 mg/litre).

4.4.1.3 *Scale control*

Various salts may precipitate during the reverse osmosis process if super-saturated concentrations are reached. These may include:

- Calcium salts such as $CaSO_4$, $CaCO_3$ and CaF_2
- Barium sulphate ($BaSO_4$) and strontium sulphate ($SrSO_4$)
- Oxides and/or hydroxides of certain metals, such as Fe, Mn and Al
- Silicates in polymeric form, or as Ca-Mg-silicates, etc.

The maximum allowed recovery of water by an RO plant is therefore limited by the water chemistry and the scaling potential of the water. Chemical scale inhibitors are commonly used to reduce scale formation and thus increase the maximum water recovery. Various products are available on the market, but care should be taken to select the most appropriate product for a specific feed water. For example, some anti-scalants are specifically designed for inhibition of iron (Fe) precipitates, but may have no effect on silica (SiO_2).

The likelihood of $CaCO_3$ precipitation is pH dependent and $CaCO_3$ scale can thus easily be prevented by the dosing of acid, typically reducing the pH of the feed water to around 6.

4.4.1.4 *Other pre-treatment of feed water*

The prevention of membrane fouling is perhaps *the* most important aspect to consider during the early stages of plant design. Apart from the above-mentioned scale formation by inorganic salts, fouling by fine colloidal material, dissolved organic matter and microbial organisms must be minimised.

As for distillation systems, chlorination of the intake water (continuous and/or intermittent shock) is usually required to prevent the growth of microbial species in the intake systems, or to prevent the development of sulphate-reducing bacteria with production of undesirable H_2S during no-flow situations (e.g. during shutdown). However, poly-amide membranes are *not* chlorine resistant, so that dechlorination is required before the feed water makes contact with the membranes. A reducing agent, such as sodium meta-bisulphite (SMBS), is typically used for dechlorination.

Other general pre-treatment methods for prevention of membrane fouling are discussed in Section 6.

4.4.1.5 Corrosion

Since the reverse osmosis process is performed at ambient temperature, corrosion is less problematic than with distillation plants. ***However, water with a high TDS and high chloride concentrations (such as sea water) can be highly corrosive at ambient temperatures and the selection of appropriate corrosion-resistant materials for a specific application remains an important consideration during design.*** For example, ordinary 316 stainless steel is not sufficient for sea water and duplex steel would typically be used for equipment in direct contact with such water.

4.4.2 Electrodialysis (ED) and electrodialysis reversal (EDR)

Commercially, electrodialysis (ED) is an older process than reverse osmosis. It uses a direct electric current to transfer ions through a membrane that possesses fixed ion groups chemically bound to the membrane structure (ion exchange functionality groups). A cation permeable membrane allows cations to pass through, but no anions. Similarly, anion permeable membranes only allow anions to pass, but no cations. By combining cationic and anionic membranes in repeating fashion, ions of opposite charge migrate in different directions through one set of membranes and combine in a concentrate stream between two membranes of opposing charge. By regularly reversing the polarity of the electric current (EDR), the concentrated layers that have formed against the membranes in the concentrate compartments are dissipated, thus reducing the tendency for scaling. More information is provided by Baker (2004).

It should be noted that, contrary to RO, salts (ions) predominantly travel through EDR membranes, and not water. This means that the EDR process does not remove colloidal, non-ionized matter, or bacteria from the water, which may be considered as notable disadvantages when compared to RO. ED membranes also have the tendency to foul when rather low concentrations of metal ions (e.g. Fe or Mn) are present in the feed water. Furthermore, EDR is not economical when the TDS of the feed water is above 10 000 mg/litre (Watson *et al*, 2003). Even below this TDS, RO is currently by far the process of choice for desalination of brackish water in South Africa and world wide. Therefore, no further discussions will be focussed on EDR.

5 GUIDELINES AND PROCEDURES FOR PROCESS SELECTION AND COSTING

The rules and procedures outlined below are based on the authors' experience and other useful information from the literature. They guide the reader to systematically answer specific questions and are supported by more detailed information provided in the Appendices. If a more critical assessment is required, the reader is referred to the literature, amongst other Andrianne (2002), Ashour and Ghurbal (2004), Avlontis *et al* (2003), Hafez (2002), Lokiec and Kronenberg (2003), Meerganz von Medeazza (2004), Sommariva *et al* (2002) and Watson *et al* (2003).

5.1 Step 1: Determine the desalination capacity requirements

A proper assessment of consumption behaviour requires sufficient and effective flow measurement and recording of a community's water use, together with consumption by its industries. Furthermore, it is well-known that the per capita water consumption of households increases in accordance with the living standards of the relevant population. Only after due consideration of these factors, coupled with a good understanding of the variation in supply from existing available fresh water sources, can the municipal engineer define the capacity requirement of an applicable desalination plant.

5.1.1 *Hourly production rate of plant*

Define the daily desalinated water production requirement as Q_d (m^3/day).

Define the plant availability, α, as a fraction of a 24-hour day in which the plant is required to operate at full capacity. The remaining fraction relates to potential trips, down-time for emergency maintenance, planned daily down-time, etc. If the plant is operated 24 hours per day, then availability, α, may typically be between 0.90 and 0.95, depending on the robustness of design, duty-standby philosophy, etc. However, in some cases (typically small communities) one may choose to run the plant only for 12 hours per day, in which case α would be equal to or less than 0.5.

The actual hourly production rate required for a desalination plant is:

$$Q_h = \frac{Q_d}{24 \cdot \alpha} \qquad \frac{\mathrm{m}^3}{\mathrm{h}}$$

[Equation 1]

5.1.2 *Example*

By thorough assessment of water demand profiles of a community and its industries, the daily production of desalinated water is estimated as 4000 m^3/day. It is assumed that the plant will be operated 24 hour per day, and that 7% down-time may be allowed (i.e. availability must be 0.93). Therefore:

$$Q_h = \frac{Q_d}{\alpha} = \frac{4000}{24 \cdot 0.93} = 179.2 \qquad \frac{\mathrm{m}^3}{\mathrm{h}}$$

5.2 Step 2: Identify the available saline water quality and desalination recovery

Appendix A provides fundamental insight into water quality measurements and definitions. The water recovery, R, of a desalination plant is defined as the volumetric fraction of feed water that is converted to non-saline product water (permeate), while the remaining fraction (1-R) of water is discharged as concentrate, containing almost all the salt from the feed water.

In order to prevent scale-formation on the RO membranes by precipitation of inorganic salts, the recovery should be maintained below a certain critical value. At this critical recovery, the first salt crystals would appear in the concentrate (potentially forming scale on membranes) due to super-saturation.

The intention is not to dwell on detailed discussions related to solubility products of various salts. Since anti-scalants, commonly dosed into the feed water of desalination plants, modify the crystal formation and morphology of various salts, the most logical approach is to provide guidelines related to the typical maximum salt concentrations allowed *in the presence of such anti-scalants*. From these concentrations, the maximum potential water recovery of the plant may be predicted.

The following broad guidelines could be applied if no water analyses are available:

- For desalination of *standard* sea water: $0.3 < R < 0.5$ (typically 0.40)
- For desalination of borehole water: $0.6 < R < 0.9$ (typically 0.75)

5.2.1 Concentration Factor and Related Parameters

As explained above, recovery is defined as:

$$R = \frac{Q_P}{Q_F}$$

[Equation 2]

The salt rejection of a membrane plant is defined as:

$$J = 1 - \frac{(TDS)_P}{(TDS)_F}$$

[Equation 3]

The overall concentration factor, χ, represents the ratio of salt content of the concentrate $(TDS)_C$ to the salt content of the feed $(TDS)_F$ and it can easily be shown that:

$$\chi = \frac{(TDS)_C}{(TDS)_F} = \frac{1 + R \cdot J - R}{1 - R}$$

[Equation 4]

However, since the salt rejection on an RO plant is usually above 0.97 (97%), calculation of the concentration factor is commonly simplified to:

$$\chi \approx \frac{1}{1-R}$$

[Equation 5]

5.2.2 *Maximum recovery*

To estimate the maximum possible water recovery over a desalination plant (without scale formation), the likelihood of precipitation of specific salts in the concentrate should be evaluated. The following paragraphs provide simple *rule-of-thumb guidelines* that may be used as first approach to estimate recovery limitations set by the chemistry of the raw feed water *in the presence of an anti-scalant*.

Various anti-scalants are available on the market for various types of scale prevention. However, an anti-scalant that effectively prevents Fe related fouling, for example, may not necessarily be effective for silica or $CaSO_4$. Therefore, the following rules are not at all comprehensive, albeit useful. Anti-scalant vendors or knowledgeable consultants should be contacted if more accurate and specific assessments are required.

5.2.2.1 *Calcium salts*

If it is found that the recovery is severely limited by potential precipitation of a calcium salt, then one of the following pre-treatment techniques may be applied (at additional cost, of course) to reduce the feed concentration of Ca:

- Chemical softening (with lime and/or soda-ash)

  This technique requires the installation of lime and/or soda-ash silos with make-up systems, acid dosing systems, flocculant dosing systems, a clarifier with peripherals, sludge disposal systems (e.g. filter press and cake disposal, or sludge to ponds) and filtration equipment (typically media filters).

  The installation of such equipment will notably increase the capital cost of the total plant, while also complicating its operation. However, one must consider the increased cost against the alternative where much lower RO recoveries would require larger feed flow rates and produce larger volumes of concentrate, which would again need to be disposed of according to environmental regulations.

  Lime softening can also reduce the concentration of metal ions such as Fe and Mn, as well as silica.

- Softening by ion exchange (with strong cation resins in the sodium form)

  This technique can be applied where relatively low concentrations of Ca and Mg need to be removed in order to maximise recovery. It will also remove other multi-valent cations such as Fe, Mn, Ba and Sr. However, rapid fouling of the resin may occur in the presence of high Fe concentrations. As a result of the exchange process, the sodium concentration of the feed water will increase.

The process requires the installation of ion exchange columns, brine (NaCl) make-up, storage and regeneration systems and most importantly, disposal facilities for highly saline regeneration effluents.

The following calcium salts may typically limit recovery (unless Ca is removed by softening):

- Calcium carbonate (calcite)

  $CaCO_3$ (calcite) is one of the most common salts that can precipitate during desalination. Luckily, its formation can easily be controlled by downward adjustment of the pH of the feed water. At a feed pH of 7, the maximum recovery possible *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

  $$R_{\mathrm{CaCO_3}} \approx 1 - \frac{\sqrt{Alk \cdot C_{\mathrm{Ca}}}}{2000}$$

  [Equation 6]

  with Alk being the feed alkalinity in mg/litre $CaCO_3$ and C_{Ca} being the *feed* Ca concentration in mg/litre. For further discussions, bear in mind that a decrease in feed pH would increase the maximum possible recovery.

- Calcium sulphate (gypsum)

  Unlike calcite, the formation of $CaSO_4$ (and its hydrated forms) is *not* dependent on pH. Therefore, without softening, the formation of $CaSO_4$ can only be prevented by limiting the concentration factor or, to a lesser extent, the feed temperature. The maximum possible recovery *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

  $$R_{\mathrm{CaSO_4}} \approx 1 - \frac{\sqrt{C_{\mathrm{SO_4}} \cdot C_{\mathrm{Ca}}}}{2500}$$

  [Equation 7]

  with $C_{\mathrm{SO_4}}$ and C_{Ca} being the concentration, in mg/litre, of SO_4 and Ca in the *feed* respectively.

- Calcium fluoride

  Similar to calcium sulphate, the formation of CaF_2 can only be prevented by limiting the concentration *factor*, unless calcium is removed by softening. The maximum possible recovery *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

  $$R_{\mathrm{CaF_2}} \approx 1 - \frac{\left[\left(C_{\mathrm{F}}\right)^2 \cdot C_{\mathrm{Ca}}\right]^{0.33}}{40}$$

  [Equation 8]

with C_F and C_Ca being the concentration, in mg/litre, of F and Ca in the *feed* respectively.

5.2.2.2 Silicates (SiO_2 and various forms of Ca-Mg-silicates)

Silica may polymerise, or precipitate in combination with calcium and magnesium when concentrated. The maximum possible recovery *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

$$R_{\text{SiO}_2} \approx 1 - \frac{C_{\text{SiO}_2}}{200}$$

[Equation 9]

with C_{SiO_2} being the concentration, in mg/litre, of SiO_2 in the feed. Note that a silica-specific anti-scalant is required to achieve this recovery and threshold-inhibitors that primarily focus on the prevention of gypsum formation may be *far less* effective than suggested in Equation 9.

If the recovery is severely limited by the presence of silica, then lime softening may be considered as a suitable pre-treatment technique.

5.2.2.3 Oxides and hydroxides of iron, manganese and aluminium

In general, one would like to keep the concentrations of Fe, Mn and Al below 1.0 mg/litre *in the concentrate*. However, some anti-scalants are specifically designed to inhibit Fe fouling, in which case the Fe content of the concentrate may be allowed to reach between 3 and 4 mg/litre, although such high levels are generally not recommended. The maximum possible recovery *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

$$R_\text{Fe} \approx 1 - \frac{C_\text{Fe}}{3}$$

[Equation 10]

with C_Fe being the concentration, in mg/litre, of Fe in the *feed*.

Fe and Mn are typically found in borehole waters and can be removed during pre-treatment by oxidation and precipitation/filtration, or by a more expensive softening process.

5.2.2.4 Salts with barium and strontium

Barium sulphate has a low solubility and the maximum possible recovery *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

$$R_{\text{BaSO}_4} \approx 1 - \frac{\sqrt{C_{\text{SO}_4} \cdot C_\text{Ba}}}{30}$$

[Equation 11]

with $C_{\mathrm{SO_4}}$ and C_{Ba} being the concentration, in mg/litre, of SO_4 and Ba in the *feed* respectively.

For strontium sulphate, the maximum possible recovery *in the presence of an appropriate anti-scalant* may typically be estimated as follows:

$$R_{\mathrm{SrSO_4}} \approx 1 - \frac{\sqrt{C_{\mathrm{SO_4}} \cdot C_{\mathrm{Sr}}}}{400}$$

[Equation 12]

with $C_{\mathrm{SO_4}}$ and C_{Sr} being the concentration, in mg/litre, of SO_4 and Sr in the *feed* respectively.

5.2.3 *Example*

Saline feed water with an alkalinity of 250 mg/litre $CaCO_3$ contains 400 mg/litre Ca, 1200 mg/litre SO_4, 0.2 mg/litre Fe and 10 mg/litre SiO_2. The pH is approximately 7.8.

$$R_{\mathrm{CaCO_3}} \approx 1 - \frac{\sqrt{Alk \cdot C_{\mathrm{Ca}}}}{2000} = 1 - \frac{\sqrt{250 \cdot 400}}{2000} = 0.84 \quad \text{(assuming that the pH is adjusted to 7)}$$

$$R_{\mathrm{CaSO_4}} \approx 1 - \frac{\sqrt{C_{\mathrm{SO_4}} \cdot C_{\mathrm{Ca}}}}{2500} = 1 - \frac{\sqrt{1200 \cdot 400}}{2500} = 0.72$$

$$R_{\mathrm{SiO_2}} \approx 1 - \frac{C_{\mathrm{SiO_2}}}{200} = 1 - \frac{10}{200} = 0.95$$

$$R_{\mathrm{Fe}} \approx 1 - \frac{C_{\mathrm{Fe}}}{3} = 1 - \frac{0.2}{3} = 0.93$$

Therefore, the limiting component is $CaSO_4$, which will start to precipitate when the recovery is approximately 72% *in the presence of an appropriate anti-scalant*. In other words, the plant should be operated at recoveries below 72% (typically 65% - 70%), while an appropriate anti-scalant is dosed and while the pH is adjusted to around 7. If higher recoveries are required (e.g. up to 85%), then chemical softening would be required as part of pre-treatment.

5.3 ***Step 3: Estimate the total membrane area and the required feed pressure***

5.3.1 *Flux and membrane area*

In this approach, the estimation of membrane area is considered to be an important parameter, since it is used as the basis for cost prediction of the desalination systems (see Section 5.7). The argument is that the prominent effects of TDS, temperature and even fouling potential of the feed water are reflected in the membrane area (via an appropriate and educated selection of flux).

Once the hourly feed flow rate, Q_h, has been determined (as per Step 1), then one only needs to specify an average flux through the membranes to calculate the total required membrane area. In some cases, especially with seawater desalination, two membrane stages (double pass) are utilised to produce a high quality permeate. The total membrane area can therefore be estimated as follows:

$$A_{\text{mem}} \approx \left(\frac{1000 \cdot Q_h}{\varphi_1} \right) + z \cdot \left(\frac{1000 \cdot Q_h}{\varphi_2} \right) \quad (\text{m}^2)$$

[Equation 13]

where φ_1 and φ_2 are the average fluxes (in litre/hour per m^2) through the first and second pass membranes respectively and Q_h is the hourly production rate of desalinated water. The selection factor, z, equals one for a double-pass system, or zero for a single-pass system.

The required feed pressure increases with an increase in flux. Furthermore, membrane fouling tends to worsen with an increase in flux. The following guidelines apply:

- Desalination of sea water: 9 litre/(m^2.h) < φ < 18 litre/(m^2.h)
- Desalination of borehole water: 18 litre/(m^2.h) < φ < 30 litre/(m^2.h)

When desalinating cold, West Coast sea water, one would tend to design the plant for a flux of around 10 litre/(m^2.h) to prevent over-pressure. For warmer Indian Ocean sea water, an average flux around 17 litre/(m^2.h) might be more appropriate.

The TDS, fouling characteristics and temperature of different borehole waters can differ radically, thus having a significant influence on the selected flux. However, in the absence of more detailed design information, an average flux of around 22 litre/(m^2.h) is a good starting point for borehole water.

5.3.2 *Desalination feed pressure*

The desalination feed pressure - coupled with flow rate - determines the major portion of the energy demand of the plant (see Section 5.5). The pressure output required by high-pressure feed pumps is determined by the following factors:

- Temperature

  Higher pressures are required at lower temperatures, due to an increase in viscosity of the water.

- Osmotic pressure (TDS-related)

  An increased osmotic pressure requires higher feed pressures. Osmotic pressure can be estimated as: $0.00076 \cdot (TDS)$ bar (with *TDS* in mg/litre).

- Flux through the membrane (φ)

  Higher feed pressures are required to drive higher fluxes. Higher fluxes increase the risk of membrane fouling.

- Membrane type and its flux per driving pressure (ε)

  This parameter is membrane-specific and is constantly improved by membrane manufactures. The following rough guidelines apply:

$1 < \varepsilon \text{ litre/(m}^2 \cdot \text{h} \cdot \text{bar)} < 5$

with high-rejection seawater RO membranes typically at 1 and low rejection brackish water RO membranes typically between 4 and 5.

- System pressure losses (between feed pump and concentrate)

  The final layout of plant and membrane configuration will determine the hydraulic pressure drop between the feed pump and the concentrate outlet (before pressure relief). For the purpose of this guide, it is assumed to be 5 bar.

  Considering the above, the typical feed pressure at a given temperature, $P_{F(T)}$, can be *estimated* as follows:

$$P_{F(T)} \approx \frac{0.00076 \cdot (TDS)_F}{1-R} + \left(\frac{\varphi}{\varepsilon} + 5\right) \cdot 1.034^{(25-T)} \quad \text{bar}$$

[Equation 14]

Note that current membrane designs do *not* allow operating pressures above 80 bar. In fact, one would tend to run the plant well below this pressure (closer to 70 bar) to allow for potential variations related to fouling and other process changes.

When a double-pass membrane system is installed, then the feed pressure for the second stage is calculated on the same basis, allowing for high recovery (85%-90%) through brackish water membranes, while the feed TDS to this second pass is approximately 1% of the raw feed TDS to the first pass.

5.3.3 Example - sea water

West Coast sea water with a TDS of 36 000 mg/litre and a temperature of 11 ^{O}C is desalinated in an RO plant at a recovery of 40% to produce 2500 m^3/h of desalinated water. A double-pass system is installed to produce a high-quality permeate.

Select a first pass membrane flux, φ_1, of 10 litre/(m^2.h).
Select a second pass membrane flux, φ_2, of 28 litre/(m^2.h).
Select a first-pass membrane flux per driving pressure, ε_1, of 1.0 litre/(m^2.h.bar)
Select a second-pass membrane flux per driving pressure, ε_2, of 4.5 litre/(m^2.h.bar)

$$A_{\text{mem}} = A_{\text{mem}} \approx \left(\frac{1000 \cdot Q_h}{\varphi_1}\right) + z \cdot \left(\frac{1000 \cdot Q_h}{\varphi_2}\right)$$

$$= \frac{1000 \cdot 2500}{10} + \frac{1 \cdot 1000 \cdot 2500}{28} = \underline{\underline{339\ 286\ \ \text{m}^2}}$$

$$P_{F(11^{\text{o}}\text{C})} \approx \frac{0.00076 \cdot (TDS)_F}{1-R} + \left(\frac{\varphi}{\varepsilon} + 5\right) \cdot 1.034^{(25-T)}$$

$$= \frac{0.00076 \cdot 36000}{1-0.4} + \left(\frac{10}{1} + 5\right) \cdot 1.034^{(25-11)}$$

$$= \underline{\underline{70\ \ \text{bar}}} \quad \text{(to first pass membranes)}$$

$$P_{F(11^{\text{o}}\text{C})} \approx \frac{0.00076 \cdot 360}{1-0.9} + \left(\frac{28}{4.5} + 5\right) \cdot 1.034^{(25-11)}$$

$$= \underline{\underline{21\ \ \text{bar}}} \quad \text{(to second pass membranes)}$$

Note that, to prevent over-pressure on the first pass, a rather low flux has to be selected to compensate for the low water temperature.

5.3.4 Example - brackish borehole water

Borehole water with a TDS of 3500 mg/litre and a temperature of 20 ^{O}C is desalinated in an RO plant at a recovery of 78% to produce 100 m^3/h of desalinated water.

Select a membrane flux, φ, of 22 litre/(m^2.h).
Select a membrane flux per driving pressure, ε, of 4.5 litre/(m^2.h.bar).

$$A_{\text{mem}} = A_{\text{mem}} \approx \left(\frac{1000 \cdot Q_h}{\varphi_1}\right) = \frac{1000 \cdot 100}{22} = \underline{\underline{4\ 545\ \ \text{m}^2}}$$

$$P_{F(20^{\text{o}}\text{C})} \approx \frac{0.00076 \cdot (TDS)_F}{1-R} + \left(\frac{\varphi}{\varepsilon} + 5\right) \cdot 1.034^{(25-T)}$$

$$= \frac{0.00076 \cdot 3500}{1-0.78} + \left(\frac{22}{4.5} + 5\right) \cdot 1.034^{(25-20)}$$

$$= \underline{\underline{24\ \ \text{bar}}}$$

5.4 Step 4: Define the pre-treatment and post-treatment requirements

5.4.1 *Pre-treatment capacity*

Section 0 provides background information on typical pre-treatment processes and it is thus assumed that the reader is sufficiently informed to make some educated assumptions regarding the appropriate pre-treatment requirements for a specific application.

With due consideration of the water chemistry, while considering the recovery guidelines stipulated in Section 5.2.2, the pre-treatment process is selected such that the overall cost of operation of the desalination plant (including capital redemption) is minimised. Parameters such as the turbidity, organic content and microbial content of the feed water do not influence recovery in a direct way, but most certainly affects membrane fouling. Therefore, as a general rule, the pre-treatment process must at least reduce the Silt Density Index (see Appendix A) to below 3 and minimise the organic and microbial content.

Virtually all spiral-wound membrane plants at least have polishing cartridge filtration as pre-treatment to “protect” the membranes. As soon as notable quantities of suspended matter need to be removed, then media filtration, micro-filtration or ultra-filtration (or a combination of these) are utilised, often aided by the dosing of coagulant and/or flocculants.

In principle, the hourly feed capacity of the pre-treatment plant, $Q_{h(in)}$, is determined by three factors, viz. the required desalination capacity, the water recovery at the desalination plant and the water losses at the pre-treatment plant (due to backwash, etc.). Therefore:

$$Q_{h(in)} = \frac{Q_h}{R \cdot (1-\beta)} \qquad \frac{\mathrm{m}^3}{\mathrm{h}}$$

[Equation 15]

where R is the desalination recovery and β is the fraction feed water lost at the pre-treatment plant (typically between 3% and 15%, depending on the process).

This intake flow rate, together with the selected technology, serves as basis for the cost prediction of the pre-treatment system (see Section 5.7).

5.4.2 *Post-treatment*

In all cases, disinfection of the water is required before distribution for potable use (usually by dosing chlorine).

Furthermore, fully desalinated water is corrosive and needs to be stabilised before distribution. The actual TDS and pH of the desalinated product depends on the desalination process. For example, when sea water is desalinated with RO, then a *single* membrane stage will produce a permeate TDS that is typically still above 300 mg/litre. In a distillation process, however, the condensate has a TDS well below 10 mg/litre, rendering it highly corrosive. Quite often, especially on smaller RO plants, only quasi-stabilisation is performed, *i.e*. the pH is adjusted to between 8.4 and 8.9 by dosing lime while the final product water may still have a negative $CaCO_3$ precipitation potential. If this water is blended in with other potable water, no further stabilisation may be required.

Proper stabilisation (especially for distillation condensates) requires manipulation of the $CaCO_3$ precipitation potential to approximately +3 mg/litre, usually by CO_2 dissolution, subsequent dissolution of limestone and final pH adjustment with caustic soda.

In other words, the post treatment may only consist of simple chemical dosing systems, or it may include CO_2 absorbers and limestone filters, depending on the process and application requirements.

The capacity requirement for post-treatment is similar to the desalination production capacity, Q_h

5.4.3 Example

A sea water desalination plant produces 2500 m^3/h of desalinated water while being operated at a recovery (R) of 45%. The pre-treatment process includes flocculation/coagulation, dual media filtration and final ultra-filtration. It is estimated that water losses (backwash, etc.) at the two filtration stages are approximately 5% and 10% of the intake volume respectively (therefore $\beta = 0.15$).

$$Q_{h(in)} = \frac{Q_h}{R \cdot (1-\beta)} = \frac{2500}{0.45 \cdot (1-0.15)} = 6536 \quad \frac{\text{m}^3}{\text{h}}$$

The post-treatment flow rate ≈ 2500 m^3/h.

5.5 Step 5: Estimate the energy consumption of the plant

5.5.1 Energy consumption of the membrane desalination section

RO plants that operate at high pressures and relatively low recoveries (such as for seawater desalination) usually will have energy recovery units installed to recover energy from the high-pressure concentrate stream. These recovery units typically operate at efficiencies between 85% and 90%.

Considering the recovery, R, (Equation 2) and the desalination feed pressure, $P_{F(T)}$, (Equation 14) one can now easily *estimate* the energy consumption of the desalination unit itself, as follows:

$$E_{\text{desal}} \approx \left[\frac{Q_h \cdot P_{F(T)}}{36 \cdot R \cdot \eta_p}\right] - s \cdot \left[\frac{Q_h \cdot \left(P_{F(T)} - 5\right) \cdot (1-R)}{36 \cdot R \cdot \eta_r}\right] \quad \text{kW}$$

[Equation 16]

where Q_h is in m^3/h, $P_{F(T)}$ is in bar, η_p is the pump efficiency (typically around 0.75) and η_r is the efficiency of the energy recovery unit (if installed). The selection parameter, s, is either 1 or 0. If an energy recovery unit is installed, then s = 1. If no recovery unit is installed, which is usually the case for brackish water RO plants that run at relatively high recoveries and low pressures, then s = 0.

Note that Equation 16 estimates the energy consumption for a single-pass membrane system. For a double-pass system (such as for some seawater plants) the same equation should again be applied to the second pass and then the total desalination energy consumption would be the sum of the two passes.

5.5.2 *Other energy requirements and total energy requirement*

Apart from driving the high-pressure pumps, which feed the desalination units, energy may also be required to:

- feed the pre-treatment systems, typically at pressures between 2 and 6 bar(g), depending on the application and design-layout,
- feed post-treatment filters (if any),
- intermittently backwash filtration systems (if any) and CIP of RO units,
- provide power for lighting, control systems, dosing systems, maintenance, etc.

Since exact plant designs are not investigated here, the best way of *estimating* the total *additional* energy requirement may typically be as follows:

$$E_{\text{other}} \approx \frac{Q_{h(in)} \cdot P_{in}}{36 \cdot \eta} \quad \text{kW}$$

[Equation 17]

where P_{in} (again in bar) is a slight over-estimate of the sum of the feed pressures required to drive the various intake and pre-treatment systems.

The total power requirement for the plant then simply is:

$$E_{\text{total}} = E_{\text{desal}} + E_{\text{other}} \quad \text{kW}$$

[Equation 18]

The specific energy requirement per volume of product water produced is then:

$$E_{\text{specific}} = \frac{E_{\text{total}}}{Q_h} \quad \frac{\text{kWh}}{\text{m}^3}$$

[Equation 19]

5.5.3 *Example - seawater desalination*

A sea water RO plant at the East Coast produces 180 m^3/h of desalinated water, while the high pressure feed pumps to the desalination unit operate at a pressure, $P_{F(T)}$, of 70 bar and the water recovery, R, over the RO unit is 45%. These pumps operate at an efficiency of 71%. Furthermore, an energy recovery system is installed, which operate at 89% efficiency. The intake feed flow rate, $Q_{h(in)}$, is calculated by Equation 15 to be 450 m^3/h and the sum of feed pressures, P_{in}, is selected as 5.5 bar.

$$
\begin{aligned}
E_{\text{desal}} &\approx \left[\frac{Q_h \cdot P_{F(T)}}{36 \cdot R \cdot \eta_p}\right] - s \cdot \left[\frac{Q_h \cdot \left(P_{F(T)} - 5\right) \cdot (1 - R)}{36 \cdot R \cdot \eta_r}\right] \\
&= \left[\frac{180 \cdot 70}{36 \cdot 0.45 \cdot 0.71}\right] - 1 \cdot \left[\frac{180 \cdot (70 - 5) \cdot (1 - 0.45)}{36 \cdot 0.45 \cdot 0.89}\right] \\
&= \underline{\underline{649\ \text{kW}}}
\end{aligned}
$$

$$E_{\text{other}} \approx \frac{Q_{h(in)} \cdot P_{in}}{36 \cdot \eta_p} = \frac{450 \cdot 5.5}{36 \cdot 0.71} = \underline{\underline{97\ \text{kW}}}$$

$$E_{\text{total}} = E_{\text{desal}} + E_{\text{other}} = 649 + 97 = \underline{\underline{746\ \text{kW}}}$$

$$E_{\text{specific}} = \frac{E_{\text{total}}}{Q_h} = \frac{746}{180} = \underline{\underline{4.14\ \frac{\text{kWh}}{\text{m}^3}}}$$

5.5.4 *Example - brackish water desalination*

A brackish water RO plant in the Karoo produces 50 m^3/h of desalinated water, while the high pressure feed pumps to the desalination unit operate at a pressure, $P_{F(T)}$, of 20 bar and the water recovery, R, over the RO unit is 75%. These pumps operate at an efficiency of 77%. No energy recovery system is installed. The intake feed flow rate, $Q_{h(in)}$, is calculated (by Equation 15) as 70 m^3/h and the sum of feed pressures, P_{in}, is selected as 2.5 bar.

$$
\begin{aligned}
E_{\text{desal}} &\approx \left[\frac{Q_h \cdot P_{F(T)}}{36 \cdot R \cdot \eta_p}\right] - s \cdot \left[\frac{Q_h \cdot \left(P_{F(T)} - 5\right) \cdot (1 - R)}{36 \cdot R \cdot \eta_r}\right] \\
&= \left[\frac{50 \cdot 20}{36 \cdot 0.75 \cdot 0.77}\right] - 0 \\
&= \underline{\underline{48\ \text{kW}}}
\end{aligned}
$$

$$E_{\text{other}} \approx \frac{Q_{h(in)} \cdot P_{in}}{36 \cdot \eta_p} = \frac{70 \cdot 2.5}{36 \cdot 0.77} = \underline{\underline{6.3\ \text{kW}}}$$

$$E_{\text{total}} = E_{\text{desal}} + E_{\text{other}} = 48 + 6.3 = \underline{\underline{54.3\ \text{kW}}}$$

$$E_{\text{specific}} = \frac{E_{\text{total}}}{Q_h} = \frac{54.3}{50} = 1.1\ \frac{\text{kWh}}{\text{m}^3}$$

5.6 Step 6: Consider discharge of residuals and environmental impacts

Section 9, provides some insight into the various environmental aspects that should be considered during conceptual design of an RO plant.

5.6.1 Discharge of concentrate

Perhaps one of the most significant aspects to take into consideration is the fact that the saline concentrate from an RO plant needs to be disposed of in an appropriate manner, either into lined evaporation ponds when far from the sea, or back into the sea in an appropriately distributed way to ensure rapid dilution.

The total effluent volume to be discharged from the plant is:

$$Q_{\text{eff}} \approx (Q_{in} - Q_h) = \frac{Q_h}{R \cdot (1-\beta)} - \frac{Q_d}{24 \cdot \alpha} \qquad \frac{\text{m}^3}{\text{h}}$$

[Equation 20]

and the maximum possible TDS of this concentrate is:

$$(TDS)_C \approx \frac{(TDS)_F}{1-R}$$

[Equation 21]

5.6.1.1 Discharge to ponds

The capital cost of an evaporation pond (cost of land and cost of construction) can have a significant effect on the total capital cost of a desalination plant. Therefore, it is usually necessary to assess methods of pre-treatment whereby recovery, R, can be maximised to ensure a minimum Q_{eff} (as per Equation 20).

Typical cost estimates for properly designed, lined evaporation ponds are considered in Appendix F.

5.6.1.2 Discharge to sea

When considering discharge of concentrates to the sea, environmental investigations should at least take the behaviour of sea currents and localised sensitive sea life into consideration. Special care should be taken when deciding on methods of management, dilution and discharge of potentially hazardous CIP chemicals. Discharge costs would mainly be related to the cost of an appropriate pipeline, which could in reality be several kilometres long, depending on the location of the plant and discharge philosophy.

5.6.2 Environmental impact studies, mitigation, licensing and contracts

Costs related to environmental assessments, mitigation and licensing will depend on the location and capacity of the desalination plant. It is to be expected that a large seawater desalination plant constructed near sensitive coastal reserves will require significantly more attention than a small brackish water plant in the Karoo and related environmental assessments and licensing negotiations may require many man-hours by several parties concerned.

5.7 Step 7: Estimate costs

After due consideration of the main parameters that may influence design and cost, as highlighted in the previous sections, *order-of-magnitude* cost estimates can be performed by applying the simple principles summarised below.

5.7.1 Capital cost

5.7.1.1 Installed cost of desalination section

For *order-of-magnitude costing*, the installed capital cost for the desalination section (including mechanical, civil and electrical works) may be related to the installed membrane area. ***The argument is that the total membrane area does to a large extent determine the mechanical and civil footprint of the installed desalination equipment.*** Furthermore, the selected flux (flow through membrane) is normally lower at lower temperatures and higher TDS, which implies a larger selected membrane area under such conditions. In other words, the variation in costs of high-pressure pumps and piping at different feed pressures would in a sense be compensated for if the same ratio of (plant cost) / (membrane area) is applied for installations with similar production capacities at different pressures.

The total installed membrane area, $\boldsymbol{A}_{\mathbf{mem}}$, can be estimated by applying the guidelines in Section 5.3. For double-pass RO systems, such as for some seawater plants, the combined area (both passes) should be calculated, bearing in mind that the second-pass membranes will be operated at a *much* higher flux than the first-pass membranes.

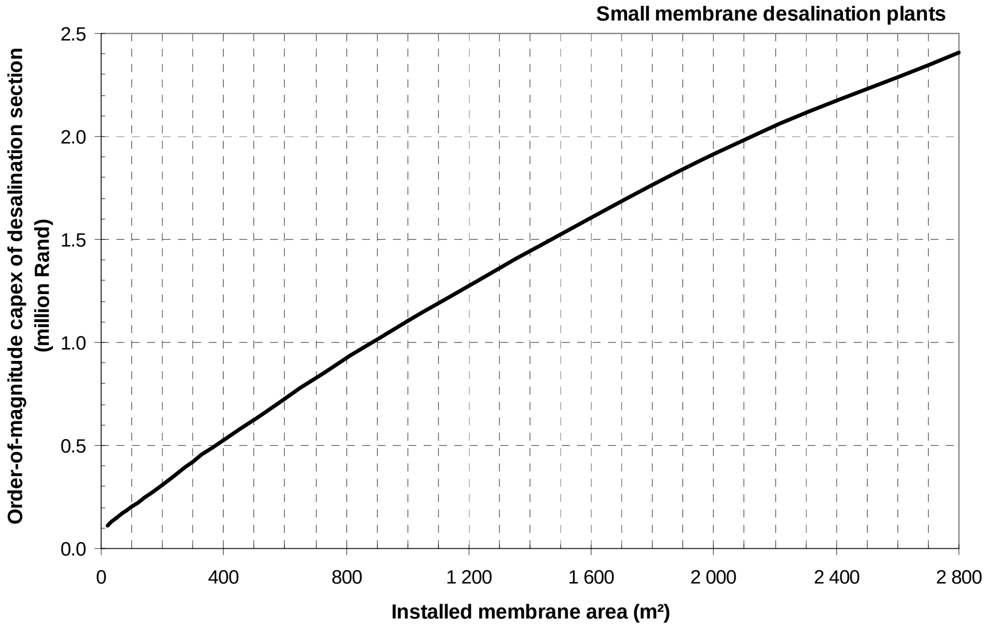


Figure 5.1: Order-of-magnitude cost of the desalination section - small plants

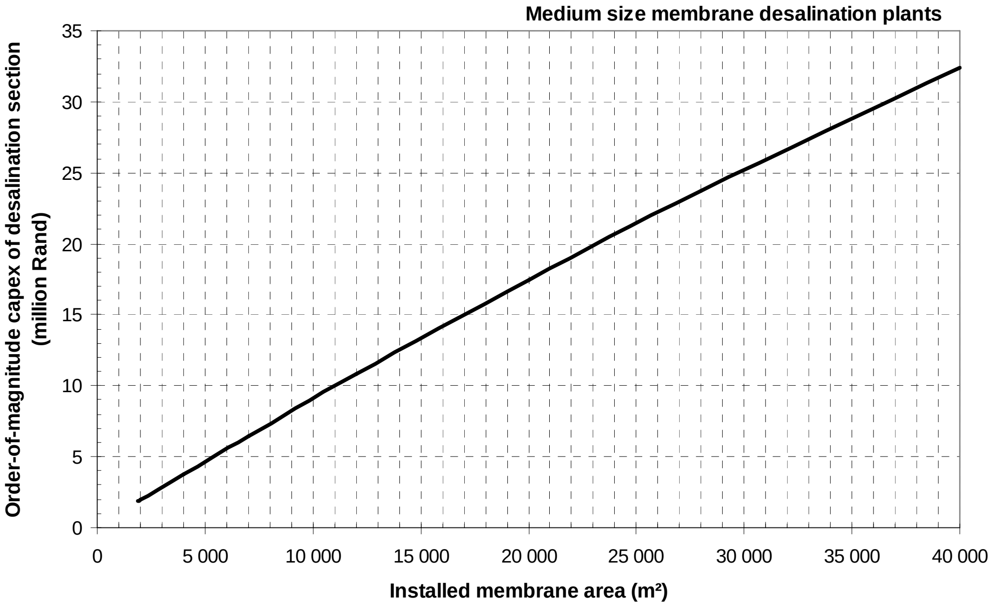


Figure 5.2: Order-of-magnitude installed cost of the desalination section - medium size plants

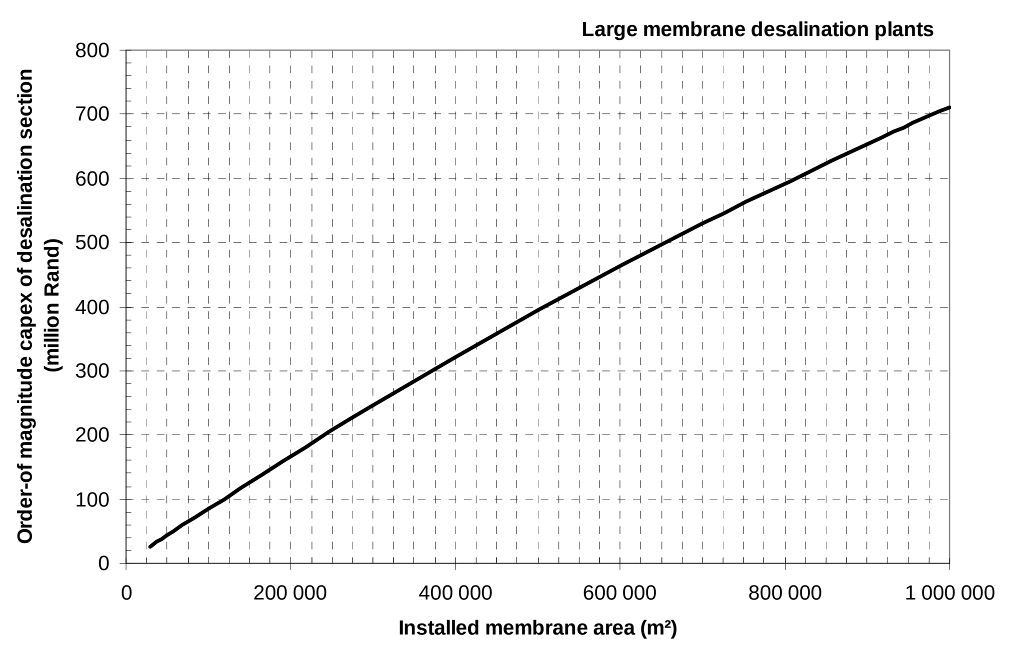


Figure 5.3: Order-of-magnitude installed cost of the desalination section - larger plants

5.7.1.2 *Installed cost of complete pre-treatment system*

The size of the pre-treatment equipment is largely determined by the hourly feed flow rate to the plant. Furthermore, the nature of the pre-treatment process itself (type of equipment and operation) plays a prominent role in the cost of the plant.

For *order-of-magnitude* costing, an approach is followed whereby the total installed cost of a typical, well-equipped *single-stage* fine media sand filtration system (complete with all mechanical, civil and electrical works, including chemical dosing and peripherals) is related to the feed flow rate of raw water, $Q_{h(in)}$, into the plant (as explained in Section 5.4.1). Figure 5.4 and Figure 5.5 provide appropriate correlations.

It is furthermore necessary to make provision for pre-treatment systems that may include a primary (rougher) media filtration stage, membrane-based ultra-filtration systems, lime softening systems, etc. Therefore, for the purpose of this guide, let K be the price obtained from Figure 5.4 or Figure 5.5, then apply the following factors to *estimate* costs for other systems:

- For coarse media filtration at high down-flow rate, as is typically used at some seawater RO plants where two-stage media filtration is applied: $\sim 0.7 \cdot K$
- For a membrane-based ultra-filtration system with conservative flux: $\sim 1.5 \cdot K$
- For a complete lime softening system (lime and soda-ash storage, make-up and dosing systems, flocculation, clarifier, sludge disposal, etc.): $\sim 1.7 \cdot K$

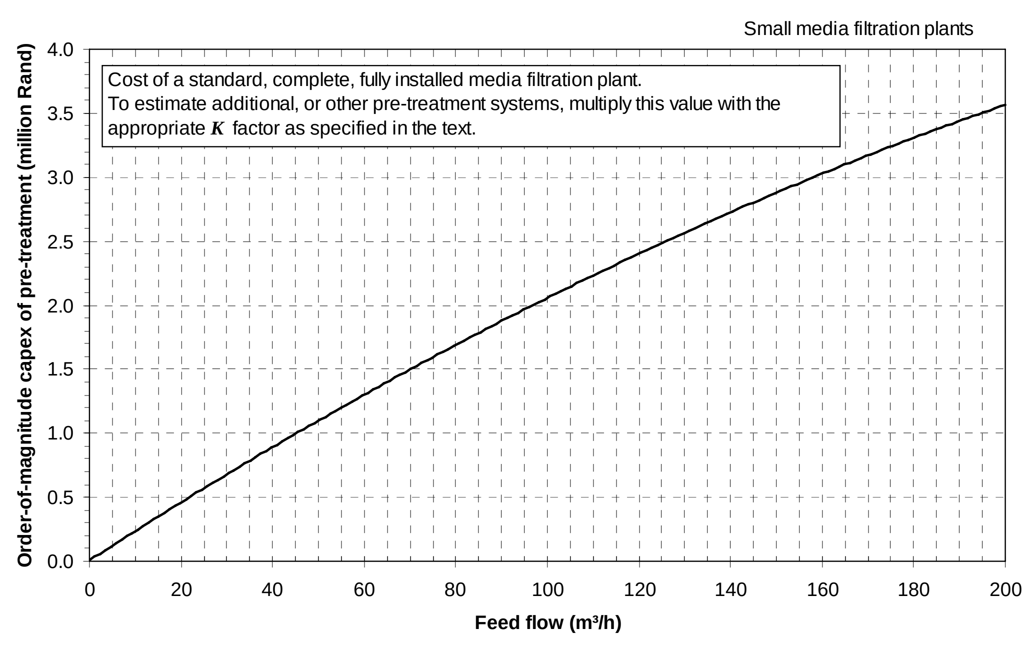


Figure 5.4: Order-of-magnitude installed cost of pre-treatment plant - small to medium size

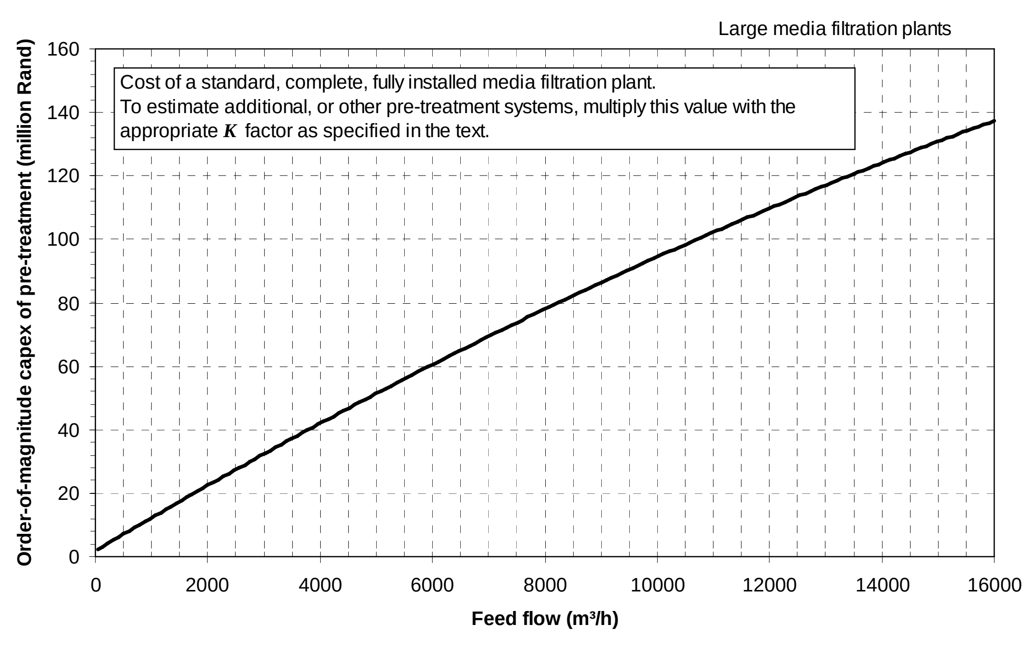


Figure 5.5: Order-of-magnitude installed cost of pre-treatment plant - medium to large size

5.7.1.3 Cost of intake, outfall and post-treatment

No attempt will be made here to cater for the potential variations in pipe length of intake and discharge systems, the type of intake system, or the nature of design. Suffice to say that, depending on plant size and design, the intake, outfall and post-treatment systems for ***seawater plants*** can typically be:

~ 15% to 30% of the combined pre-treatment and desalination plant costs.

For ***inland brackish water plants***, the cost of intake, outfall and post-treatment (*excluding* development of boreholes and potential construction of evaporation ponds) may be:

~ 2% to 10% of the combined pre-treatment and desalination plant costs.

Note that, when the concentrate has to be discharged into evaporation ponds, the cost of well-designed lined ponds may easily contribute to more than 50% of the combined pre-treatment and desalination plant costs.

Appendix F provides relevant information in this regard, confirming the fact that rainfall and rate of evaporation can influence the size (and thus cost) of the pond in a significant way. When ponds are required, it is wise to maximise recovery over the desalination unit (by proper pre-treatment) to minimise the concentrate flow rate and thus the required rate of evaporation.

5.7.1.4 Cost of environmental assessments and contractual items

Depending on the size and location of the plant, environmental studies, mitigation, licensing and other contractual costs may typically range between:

~ 0.05% and 5% of the total contract value.

5.7.1.5 Example - estimation of total capital cost of plant

Brackish water with a TDS of 5000 mg/litre and a minimum temperature of 18 ^{O}C needs to be desalinated to provide 3000 m^3/day of potable water. The plant will be operated 24 hours per day and provision should be made for 90% plant availability. Determine the energy consumption and the total installed capital cost of the plant, following Steps 1 to 7 as described above.

<u>Step 1:</u>

Determine the design product flow rate from Equation 1.

$$Q_h = \frac{Q_d}{\alpha} = \frac{3000}{24 \cdot 0.9} = 138.9 \quad \frac{\text{m}^3}{\text{h}}$$

<u>Step 2:</u>

Specify the water recovery by applying the information in Section 5.2.2, considering potential scale formation of various inorganic salts. For the purpose of this example, assume that this exercise leads to the specification of a 75% recovery of water (R = 0.75).

<u>Step 3:</u>

No second-pass membrane system is installed and an average flux of 23 litre/(m^{2}h) is assumed. Estimate the total membrane area from Equation 13.

$$A_{\text{mem}} \approx \left(\frac{1000 \cdot Q_h}{\varphi_1}\right) + z \cdot \left(\frac{1000 \cdot Q_h}{\varphi_2}\right)$$
$$= \frac{1000 \cdot 138.9}{23} = 6039 \ \text{ m}^2$$

Assume a membrane-specific flux per driving pressure (ε) of 4.5 and calculate the feed pressure delivered by the high pressure pump from Equation 14.

$$P_{F(T)} \approx \frac{0.00076 \cdot (TDS)_F}{1-R} + \left(\frac{\varphi}{\varepsilon} + 5\right) \cdot 1.034^{(25-T)}$$
$$= \frac{0.00076 \cdot 5000}{1-0.75} + \left(\frac{23}{4.5} + 5\right) \cdot 1.034^{(25-18)} = 28 \ \text{ bar}$$

<u>Step 4:</u>

Assume a well-designed, complete media filtration system with chemical dosing systems as pre-treatment. Assume that 5% of the feed water is consumed for backwash and purging (i.e. $\beta = 0.05$), then calculate the design feed flow rate from Equation 15.

$$Q_{h(in)} = \frac{Q_h}{R \cdot (1-\beta)} = \frac{138.9}{0.75 \cdot (1-0.05)} = 194.9 \quad \frac{\text{m}^3}{\text{h}}$$

Step 5:

Assume that no energy recovery system is installed and that the high pressure pumps operates at an efficiency of 78%. Estimate the energy consumption at the desalination section from Equation 16.

$$E_{\text{desal}} \approx \left[\frac{Q_h \cdot P_{F(T)}}{36 \cdot R \cdot \eta_p}\right] - s \cdot \left[\frac{Q_h \cdot \left(P_{F(T)} - 5\right) \cdot (1-R)}{36 \cdot R \cdot \eta_r}\right]$$

$$= \frac{138.9 \cdot 28}{36 \cdot 0.75 \cdot 0.78} = 184.7 \quad \text{kW}$$

Having assumed a single pre-treatment stage (standard media filtration), the sum of the feed pressures (P_{in}) is assumed to be around 3 bar. Now estimate the total additional energy requirements of the plant from Equation 17.

$$E_{\text{other}} \approx \frac{Q_{h(in)} \cdot P_{in}}{36 \cdot \eta} = \frac{194.9 \cdot 3}{36 \cdot 0.78} = 20.8 \quad \text{kW}$$

Therefore, from Equation 18, the total power requirement of the plant is:

$$E_{\text{total}} = E_{\text{desal}} + E_{\text{other}} = 184.7 + 20.8 = 205.5 \quad \text{kW}$$

According to Equation 19, the specific energy requirement per volume *product* water is:

$$E_{\text{specific}} = \frac{E_{\text{total}}}{Q_h} = \frac{205.5}{138.9} = 1.48 \quad \frac{\text{kWh}}{\text{m}^3}$$

Step 6:

Consider the various environmental issues related to disposal of the concentrate. If an existing evaporation pond (or discharge to sea) is not available, bear in mind that the construction of a properly lined pond can contribute to a *very* significant portion of the total installed cost. Use Equation 20 to estimate the effluent volumes to be evaporated:

$Q_{\text{eff}} \approx \left(Q_{h(in)} - Q_h\right) = 194.9 - 138.9 = 56 \quad \frac{\text{m}^3}{\text{h}}$ (to pond or other acceptable point of discharge)

Step 7:

From Figure 5.2, read off the installed cost of the desalination section as approximately R6 million (at a total membrane area of 6039 m^2).

From Figure 5.4, read off the installed cost of a standard pre-treatment plant as approximately R3.5 million (at a feed flow rate of 194.9 m^3/h). Since the pre-treatment section is assumed to consist of a standard media filtration system, the pre-treatment cost factor is 1 and the total installed cost for the pre-treatment plant remains R3.5 million.

Make provision for an additional 5% costs for intake and outfall systems, as well as post-treatment facilities. Therefore, the total installed cost, excluding environmental assessments and contractual items amounts to:

$$(6+3.5)\cdot 1.05 = 9.98 \text{ million Rand}$$

Note that the above price <u>excludes</u> the construction of evaporation ponds. Assume that another 1% is spent on assessments and contractual items, then the total installed cost of the plant (<u>excluding</u> evaporation ponds) is estimated at:

$$9.98\cdot 1.01 \approx \underline{\underline{10 \text{ million Rand}}}$$

Considering the information in Appendix F, the construction of a properly lined evaporation pond can double the overall project cost to approximately 20 million Rand.

5.7.2 Unit production cost of desalinated water

5.7.2.1 Cost of capital redemption

$$B = \frac{Cap\cdot r\cdot (1+r)^n}{(1+r)^n - 1} \quad \frac{\text{Rand}}{\text{month}}$$

[Equation 22]

with B being the monthly capital cost repayment, Cap the total contract cost at start-up, r the *monthly* interest rate and n the period of full redemption in *months*.

This implies that the specific cost of redemption, M_{cap}, can be estimated as:

$$M_{\text{cap}} \approx \frac{B}{30\cdot Q_d} \quad \frac{\text{Rand}}{\text{m}^3}$$

[Equation 23]

5.7.2.2 Cost of energy

The specific energy requirement is calculated according to the guidelines in Section 5.5. By assuming an appropriate cost of electricity per kWh, the specific cost of electricity is simply estimated as:

$$M_{\text{energy}} \approx D\cdot E_{\text{specific}} \quad \frac{\text{Rand}}{\text{m}^3}$$

[Equation 24]

where D is the unit cost of electricity in Rands/kWh.

5.7.2.3 *Cost of RO membrane replacement*

The total installed membrane area is easily estimated by Equation 13. Due to their higher operating pressures and better salt rejections, seawater desalination membranes are more expensive than standard brackish water membranes. The actual cost of membranes depends on the manufacturer, the area per element, rejection rating, pressure rating, etc. Membrane prices also depend on the quantity of elements ordered, so that any specific indication of cost may in a sense be misleading. For the purpose of this guide, the following cost estimates will apply (depending on the R/$ exchange rate):

- Brackish water spiral wound RO membranes: $Cost_m$ ~15.0 US$/m^2 (105 Rands/m^2)
- Seawater spiral wound RO membrane: $Cost_m$~16.5 US$/m^2 (115 Rands/m^2)

The intention is always to minimise the frequency of replacement of membranes. In practice, full replacement may typically happen after 3 to 6 years, depending on the nature of fouling and degradation experienced on a specific plant.

The specific cost of membrane replacement can be estimated as:

$$M_{\text{mem}} \approx \frac{Cost_{\text{m}} \cdot A_{\text{mem}}}{y \cdot Q_d \cdot 365} \quad \frac{\text{Rand}}{\text{m}^3}$$

[Equation 25]

where y is the number of years before full replacement (typically 3 to 6).

5.7.2.4 *Cost of chemicals and consumables*

The cost of chemicals and consumables may differ radically from plant to plant, depending on the level of pre-treatment. Some brackish water plants may sometimes only require dosing of anti-scalant. In the case of seawater desalination, acid, coagulant, flocculant, chlorine, SMBS and anti-scalant may be required for pre-treatment, together with limestone and chlorine for post-treatment. Pre-treatment processes where lime softening are required, could easily have specific chemical and *consumable costs* well above R1.00/m^3 product water. It is normally true that,

$$\frac{\text{R } 0.2}{\text{m}^3} < M_{\text{chem}} < \frac{\text{R } 2.0}{\text{m}^3}$$

and one could, for the sake of simplicity, assume the following:

- Brackish water RO plants with some pH adjustment, disinfection, anti-scalant dosing and reasonable post-treatment :
  $M_{\text{chem}} \approx 0.3$ Rand/m^3
- Seawater RO plants with typical chlorination, acid dosing, coagulant dosing, dechlorination, anti-scalant dosing and acceptable post-treatment :
  $M_{\text{chem}} \approx 0.5$ Rand/m^3

- Brackish water RO plants with full lime softening (lime + soda-ash), acid dosing, chlorination, dechlorination, anti-scalant dosing and reasonable post-treatment:

  $M_{\text{chem}} \approx 1.60$ Rand/m^3

5.7.2.5 *Cost of labour and maintenance*

On plants of reasonable size, *i.e*. more than 2000 m^3/day capacity, the cost of labour and maintenance may typically be *estimated* as equivalent to 5% of the total capital cost per year. For smaller plants this value increases significantly, so that:

$$M_{\text{maint}} \approx \frac{z \cdot Cap}{365 \cdot Q_d} \quad \frac{\text{Rand}}{\text{m}^3}$$

where z typically varies between 0.15 (around 50 m^3/day capacity) and 0.05 (above 2000 m^3/day capacity).

Be aware of the fact that small plants that are located in remote areas (far from convenient service centres) may have rather high specific labour and maintenance costs (in R/m^3). The Bitterfontein plant in South Africa is a good example.

5.7.2.6 *Total unit cost of water*

The total specific cost of desalinated water is:

$$M_{\text{tot}} = M_{\text{cap}} + M_{\text{energy}} + M_{\text{mem}} + M_{\text{chem}} + M_{\text{maint}} \quad \frac{\text{Rand}}{\text{m}^3}$$

5.7.2.7 Example

A sea water desalination plant produces 15 000 m^3/day (Q_d) of desalinated, potable water. The installed capital cost of the plant (Cap) is estimated at R110 million. The following parameters are selected or estimated:

- Period of full capital redemption: $n = 25$ years
- Annual interest rate (bond): $r = 13\%$
- Total installed membrane area: $A_{\text{mem}} = 67\,500\ \text{m}^2$
- Membrane cost per area: $Cost_{\text{m}} = 115\ \text{R/m}^2$
- Frequency of full membrane replacement: $y = 3.5$ years
- Specific energy consumption of plant:
  $E_{\text{specific}} = 4$ kWh per m^3 product
- Labour and maintenance factor:
  $z \approx 0.05$ (5% of capital/year)

$$Cap = \frac{B \cdot r \cdot (1+r)^n}{(1+r)^n - 1} = \frac{110\,000\,000 \cdot \left(\frac{0.13}{12}\right) \cdot (1+0.13)^{(12 \cdot 25)}}{\left(1+\frac{0.13}{12}\right)^{(12 \cdot 25)} - 1} = \text{R } 1\,240\,619 \text{ per month}$$

$$M_{\text{cap}} \approx \frac{Cap}{30 \cdot Q_d} = \frac{1240619}{30 \cdot 15000} = 2.76 \quad \frac{\text{Rand}}{\text{m}^3}$$

$$M_{\text{energy}} \approx D \cdot E_{\text{specific}} = 0.3 \cdot 4 = 1.20 \quad \frac{\text{Rand}}{\text{m}^3}$$

$$M_{\text{mem}} \approx \frac{Cost_{\text{m}} \cdot A_{\text{mem}}}{y \cdot Q_d \cdot 365} = \frac{115 \cdot 67500}{3.5 \cdot 15000 \cdot 365} = 0.41 \quad \frac{\text{Rand}}{\text{m}^3}$$

$$M_{\text{chem}} \approx 0.50 \quad \frac{\text{Rand}}{\text{m}^3} \quad \text{(typical for sea water RO plant)}$$

$$M_{\text{maint}} \approx \frac{z \cdot Cap}{365 \cdot Q_d} = \frac{0.05 \cdot 110\,000\,000}{365 \cdot 15\,000} = 1.00 \quad \frac{\text{Rand}}{\text{m}^3}$$

$$M_{\text{tot}} = 2.76 + 1.20 + 0.41 + 0.50 + 1.00 = \underline{\underline{5.87 \quad \frac{\text{Rand}}{\text{m}^3}}}$$

5.7.3 Cost inclusions and exclusions

The simple estimation methods above do not specifically consider the following:

- *Large* product storage reservoirs and subsequent distribution systems. These are considered to be part of any water treatment system and cannot be directly attributed to the cost of a desalination plant.
- *Large* intermediate storage reservoirs.
  These are usually not necessary, but may be required in some designs.
- Access roads outside the equipment area, as well as laboratories and administration offices.
- Electricity generation or installation of power supply lines over long distances.
- Potential expropriation of land.
- Construction of double-lined evaporation ponds.
- Development of wellfields.

6 PRE-TREATMENT METHODS

6.1 Pre-treatment to distillation processes

Pre-treatment to distillation processes are significantly less complex than for membrane processes and are often limited to chlorination, screening and dosing of antiscalant (see discussions in Section 4.3.4.4).

6.2 Pre-treatment to RO, NF and EDR

6.2.1 Prevention of membrane fouling

An accumulation of one or more foreign substances on the surface of a membrane will result in a loss of flux. Higher operating pressures will then be required to maintain water production and quality. Membrane fouling generally occurs by one of the following mechanisms:

- precipitation of inorganic salts (scaling) due to super-saturation
- deposition of silt or other suspended solids
- interaction of organics with the membrane
- biological fouling caused by excessive microbial growth

The objective of proper pre-treatment is therefore to prevent membrane fouling, as discussed below.

6.2.1.1 Suspended solids removal

Pre-treatment normally includes at least some cartridge filtration to remove residual fine suspended matter from the feed water. However, quite often, the concentrations of suspended matter in the feed water are too high to rely on cartridge filtration only. Therefore, pre-filtration, and, if necessary, the use of chemical pre-treatment and clarification may be required to assist in removal of suspended solids.

Membrane manufacturers usually specify one or more of the following guidelines for suspended solids:

- turbidity less than 0.2 NTU (<0.1 preferred)
- zeta potential of more than –30 Mv
- maximum silt density index (SDI) of 3 to 5

Pre-treatment methods include (AWWA M46):

- Chemical Treatment (coagulation and flocculation)

    - Aluminium sulphate or alum ($Al_2(SO_4)_3$)
      Minimum solubility is achieved at pH 5.7 to 7.8. Must allow sufficient time for complete precipitation or aluminium salts may deposit on the membrane.

    - Ferrous sulphate ($FeSO_4$)
      Oxidation to ferric form of iron is required to be effective. Optimal pH is >8.4

    - Ferric sulphate ($Fe_2(SO_4)_3$)
      Works best at high pH.

    - Ferric chloride ($FeCl_3$)
      Works best at pH 4.5 to 7.0. This chemical is widely used.

    - Cationic polyelectrolytes
      Will interact with antiscalants. Can irreversibly foul many spiral-wound membranes.

    - Anionic and nonionic polyelectrolytes
      Will not interact with antiscalants. May foul certain membranes. Consult manufacturer. Generally less effective than cationics as coagulants-flocculants.

- Clarification

  After chemical treatment, clarification may be required if high solids loadings are produced (for low solids loadings, direct filtration may be employed). Clarification is normally achieved in gravity solids-separation processes such as sedimentation (downward movement of solids) or dissolved air flotation (DAF)(upward movement of solids).

- *Rapid* sand *filtration*

  Coagulants are generally required to achieve acceptable SDI reduction, most typically through in-line coagulation. Limited turbidity levels can be accommodated.

- *Cartridge* filtration

  A variety of in-line cartridges are commercially available, and are widely used as part of pre-treatment for any membrane treatment processes. The filtration elements are generally not expensive and are replaced frequently to protect downstream equipment and membranes. Filtration down to 5µm is typically required.

- *Precoat filtration*

  Also relatively expensive and not popular. Precoat media must be added to replace losses in backwash step. Does not remove dissolved organics.

- *Microfiltration*

  Operates at low pressures and requires periodic chemical cleaning and frequent backwashing. Removes particulates but no dissolved organics. Cost may be comparable to coagulation-flocculation-clarification and direct filtration for small systems.

- *Ultrafiltration*

  Relatively expensive, but effective. Frequent backflushing and periodic cleaning are required. Operate at slightly higher pressures than microfilters. Removes higher molecular-weight organics (>100 000 molecular mass) in addition to particulates.

6.2.1.2 Organics removal

Natural organic material (NOM) consists mainly of humic and fulvic acids in solution, some of which exhibit colloidal properties (larger molecules) with the remainder in true solution (smaller molecules). This material will therefore cause fouling of RO membranes if not removed upstream by some form of pre-treatment. Large quantities of NOM (the organic material may be quantified either by colour or UV254 measurement) will result in rapid fouling of RO membranes.

The organic material cannot be removed effectively by fine filtration such as media filtration or microfiltration on its own because of the small size of a large portion of the organic molecules. Chemical treatment such as coagulation is therefore required to destabilise the charged particles and render it amenable to flocculation and subsequent removal of flocs by sedimentation and/or filtration.

Even ultrafiltration will only achieve around 60 – 80% removal of NOM, which is not sufficient to protect the RO membranes against rapid fouling. Nanofiltration will normally achieve sufficient NOM removal, but may prove to be too costly. Activated carbon may be used in combination with ultrafiltration, but will require pilot plant studies. Another possible option is oxidation with ozone, followed by biological filtration (biologically enhanced filtration) or activated carbon..

6.2.1.3 Biofouling prevention (AWWA M46)

Control of biological fouling is essential if a membrane system is to perform at design levels on a consistent basis. The wet interior of a membrane module or permeator is an ideal place for certain micro-organisms to grow. Once established on the membrane, microbes can adhere to the polymer tenaciously. More harmful than the organisms themselves is the biofilm they secrete. This biofilm uniformly covers the membrane, causing deterioration in flux and salt rejection (SR). Fortunately, the population of micro-organisms in most brackish ground-water sources is small enough that pre-treatment for biological fouling is not required, provided the membrane system is used on a fairly continuous basis.

One of the best steps toward elimination of biological fouling is to minimise events where membrane sections are out of operation. Any membrane that is allowed to be out of service for more than a day or two should be flushed with pre-treated water on a daily basis to prevent a tolerably small bacteria population from growing to an intolerable level. If the system is to be out of service for extended periods of time, it is necessary to flush the membranes with permeate and add a sanitizer recommended by the manufacturer. Formaldehyde and sodium bisulfite solution are effective in preventing microbes from proliferating in the membrane modules during storage, but formaldehyde has carcinogenic properties and its use is not recommended. The chemical gluderaldehyde is increasingly being used as a biocide during membrane storage.

Surface waters are more likely to need some type of pre-treatment to prevent biofouling. For the most highly contaminated waters, continuous chlorination (and de-chlorination) just before the water enters the membrane system) would be required. For less severe problems, periodic shock treatments with high chlorine doses may be the only treatment required to maintain an acceptable bacteria count. Table 6.1 summarizes current methods used to control biological fouling in membrane systems.

Table 6.1: Chemicals used to control biofouling in membrane systems (AWWA M46)

Treatment	**Comments**
Iodine	Dechlorination required for polyamide membranes
Copper sulfate	Effective for algae. Generally limited to seawater systems.
Chloramines	Some polyamide membranes not affected, but these chemicals are not as efficient as other disinfectants. Long contact time may be required.
Shock treatment	**Comments**
Sodium bisulfite	Minimum dose of 500 mg/l for at least 30 minutes. Time between treatments depends on bacteria counts. Will not affect most membranes
Iodine	Effective, but life of polyamide membrane will be shortened. Maximum dose is 15 mg/l.
Hydrogen peroxide	Same as for iodine. Presence of metals on membrane surface should be minimized during use.

The disinfectant most widely used is still chlorine, although other alternatives are also being investigated (ozone). If chlorine is used to prevent biofouling on the membranes, care should be taken to remove the residual chlorine before coming into contact with certain types of membrane material (see below).

6.2.1.4 Dechlorination

Care must be taken to remove residual free chlorine if the membrane is of a polyamide composition or to adjust the source water pH for cellulose acetate membranes.

Although polyamide membranes are not particularly pH sensitive, all varieties of these membranes are to some extent intolerant of chlorine and certain other oxidizing agents. Adding sodium metabisulfite (SMBS) to the source water in excess of what is required to reduce the chlorine should protect polyamide membranes form chlorine attack. For the most susceptible polyamide compositions, chlorine should be totally avoided as a part of pre-treatment.

6.2.2 Prevention of scaling

The solubility of salts in water varies widely. Certain salts have very high solubilities, while others have low solubilities. The characteristics of low solubility are often used to separate such a compound from the water by precipitating it as an insoluble precipitate. When the concentration of ions of such a sparingly soluble salt is increased beyond a certain point in solution the salt will start to precipitate. In the case of RO treatment the compounds with low solubilities in the feed water can precipitate when water is removed, and the salt will precipitate on the membrane surface. Measures then need to be taken to prevent this scaling on the membrane, because it will have a major effect on flux through the membrane.

Calcium carbonate scaling is usually controlled by addition of sulphuric acid to convert any carbonate to the bicarbonate or carbonic acid form. However, in many cases sulphates may be the limiting salt and addition of sulphuric acid will aggravate the problem. Commercially available chemical antiscalants can be used to prevent scaling by complexing the metal ions to prevent precipitation. Manufacturers of these compounds can provide information on required dosages for a given recovery, water quality and membrane.

Table 6.2 lists the main species that can form scaling on the surface of RO membranes, and the preventative measures that are required to prevent such scaling. The water recovery over an RO plant must always be limited to concentration levels where precipitation will not occur (after taking the effect of anti-scalants and pre-treatment into consideration).

Table 6.2: Scale-forming compounds on membrane surfaces (AWWA M46)

Species	**Prevention Method**
Calcium carbonate, $CaCO_3$	Threshold inhibitor / Mineral acid
Calcium sulfate, $CaSO_4$	Threshold inhibitor / Soften
Barium sulfate, $BaSO_4$	Threshold inhibitor / Soften (if SO_4 can be removed)
Strontium sulfate, $SrSO_4$	Threshold inhibitor / Soften (if SO_4 can be removed)
Calcium fluoride, CaF_2	Threshold inhibitor / Soften
Silica, SiO_2	Inhibitor / Co-precipitate during softening
Ferric hydroxide, $Fe(OH)_3$	Precipitation and filtration / Soften
Aluminium hydroxide, $Al(OH)_3$	Precipitation and filtration
Sulfur, S	Exclude air and other oxidants

6.2.3 Metals removal

If removal is needed to meet operating guidelines under the manufacturer's warranty, iron is usually removed by oxidation followed by filtration.

- Manganese greensand filtration is a convenient way of doing both in one step.
- Care should be taken to prevent excess oxidant, such as potassium permanganate, form contacting membranes.
- Air oxidation or chlorine addition followed by filtering through appropriate filter media is another option, provided the same precautions are taken to minimize residual iron as when used as a coagulant-flocculant.
- Feedwater with a free chlorine residual should not contact thin-film composite membranes.
- For source water with high ferrous and low ferric iron levels, precipitates can be held in suspension by lowering the pH to 6.0 or less and adding dispersants and chelants.
- Microfiltration and ultrafiltration (UF) have also been effectively used to remove undissolved iron, and iron dispersants are now included with polymeric scale inhibitors.

Iron fouling may also occur by deposition of corrosion products from mild steel or cast-iron pipe in the system. Such fouling is generally found in older, often smaller, systems where existing materials have not been replaced. Proper selection of construction materials is the best insurance against this type of iron fouling.

6.2.4 Removal of other elements

6.2.4.1 Sulphur

Many groundwaters contain hydrogen sulphide, which can be oxidized to elemental sulphur if air or other oxidants are introduced into the membrane system. If such an air leak occurs before the final filters, a certain portion of the colloidal sulphur may be caught by the filters and membrane damage can be minimized. However, a significant proportion of the colloidal sulphur is smaller than the 5- to 25-micron effective retention size of the filters and will pass through to the membrane elements.

It is especially important to ensure that air is not allowed to enter the module from the reject or product side of the system on shutdown. If it does, colloidal sulphur fouling, which is difficult to remove by cleaning, will be inevitable. No chemical pre-treatment can prevent colloidal sulphur fouling; good system design is the best prevention.

6.2.4.2 Silica

Silica is another example of a substance that, if its solubility is exceeded, can form an amorphous, inorganic deposit on a membrane. Because silica is a polymer rather than having a crystalline ionic lattice, threshold scale inhibitors (antiscalants) have not been effective in stabilizing supersaturated silica solutions. Specialised inhibitors are available on the market, but their success is limited. Silica can be removed by co-precipitation during expensive lime softening. Alternatively, the only choice is to limit recovery.

6.2.5 Summary of pre-treatment methods

The pre-treatment methods are summarised in Table 6.3.

Table 6.3: Summary of membrane pre-treatment methods

PRETREATMENT METHODS	APPLICATION, LIMITATIONS AND CRITICAL ASPECTS
Fine Residual Material Removal	
Cartridge filtration	A variety of in-line cartridges are commercially available, and are widely used as part of pre-treatment for any membrane treatment processes. The filtration elements are generally not expensive and are replaced frequently to protect downstream equipment and membranes

Suspended Solids Removal	
Chemical treatment	
Clarification	Solids-separation is achieved by sedimentation or dissolved air flotation (DAF)
Rapid sand filtration	Coagulants are generally required to achieve acceptable SDI reduction, most typically through in-line coagulation. Can handle limited turbidity levels.
Precoat filtration	Also relatively expensive. Precoat media must be added to replace losses in backwash step. Does not remove dissolved organics.
Cartridge filtration	See above
Microfiltration	Operates at low pressures and requires periodic chemical cleaning and frequent backwashing. Removes particulates but no dissolved organics. Cost may be comparable to coagulation-flocculation-clarification and direct filtration for small systems.
Ultrafiltration	Relatively expensive. Frequent backflushing and periodic cleaning are required. Operate at slightly higher pressures than microfilters. Removes higher molecular-weight organics (>100 kD) in addition to particulates.
Organics Removal	
Chemical treatment followed by clarification and filtration	Widely used, but requires efficient control of dosages, especially when raw water quality may vary considerably
Ozonation followed by biological filtration.	Research undertaken for further development of this process. Ozonation is expensive.
Activated carbon	
Biofouling Prevention	
Use of oxidants, of which chlorination is the most commonly used. Other oxidants are listed in Table 6.1	If the system is to be out of service for extended periods of time, it is necessary to flush the membranes with permeate and add a sanitizer recommended by the manufacturer. For the most highly contaminated waters, continuous chlorination is necessary for membranes that can tolerate free chlorine. For less severe problems, periodic shock treatment with high chlorine doses may be the only treatment required to maintain an acceptable bacterial count.
Control of Biological Activity	
Chlorination and other oxidants (Section 6.2.1.3)	If chlorine is used to control biological activity in the feedwater to the membranes, care should be taken to remove the residual chlorine before coming into contact with certain types of membrane material
Prevention of Scaling	
Dosing of appropriate acids or antiscalants	Manufacturers of antiscalants have computer programs available to calculate dosages for a given recovery, water quality and membrane.

Metals removal	
Oxidation and filtration	Iron and manganese may cause serious fouling of membranes. When using oxidants, care should be taken not to let the oxidant come in contact with the membranes.
Microfiltration and ultrafiltration	Microfiltration and ultrafiltration may present effective filtration alternatives.
Removal of other elements	
Sulphur – oxidation and filtration	Air should *not* be allowed to enter the module from the reject or product side of the system on shutdown. If it does, colloidal sulphur fouling, which is difficult to remove by cleaning, will be inevitable. No chemical pretreatment can prevent colloidal sulphur fouling; good system design is the best prevention.
Silica	Specialised antiscalants are available to inhibit silica precipitation, but with limited success. Apart from recovery control, expensive lime softening may be used.

A wealth of relevant information is available from the literature. A few examples include Tchobanoglous *et al* (2003), Ben Ahmed *et al* (2004), Benzaoui and Bouabdallah (2004), Bonnelye *et al* (2004), Coopmans and Schwarz (2004), Wilfa and Schierach (2001) and Tlili *et al* (2003),

7 POST-TREATMENT OF DESALINATED WATER

Post-treatment of desalinated water has two objectives, *viz.* stabilisation and final disinfection. Like most conventional water treatment plants, disinfection entails the dosing of a disinfectant (usually chlorine) to prevent biological growth in subsequent municipal reservoirs and distribution systems. Since organic matter and microbes are removed by the desalination process, chlorine requirements are relatively low.

By studying the monograph by Loewenthal *et al* (1986) and the useful presentation by Delion *et al* (2004), it is relatively easy to understand why and how post-treatment is performed to stabilise the water.

Depending on the plant design, the desalinated product water may have a TDS well below 30 mg/litre and, more importantly, may contain negligible concentrations of calcium, magnesium and carbonate. Such water is corrosive and needs to be stabilised before final distribution. A positive $CaCO_3$ precipitation potential (preferably around 3) is required. Stabilised water, fit for municipal and potable use, typically has a pH between 8 and 8.5, contains approximately 20 mg/litre Ca and has an alkalinity above 50 mg/litre. High concentrations of chlorides and/or sulphates must also be prevented to minimise corrosion potential.

Single-pass seawater RO plants typically produce permeates with TDS in the order of 300 mg/litre which, if blended in with larger volumes of other municipal water, may only require minimal post-treatment such as pH adjustment by lime addition

However, a fully desalinated product that is used as single source of municipal water supply, requires better post treatment, entailing one of the following treatment methods:

- $CO_2 + Ca(OH)_2$ (lowest operating cost; most difficult to operate)
- $CO_2 + CaCO_3 + Na_2CO_3$ (best water quality; easy to operate; expensive)
- $CaCl_2 + NaHCO_3 + Na_2CO_3$ (worst water quality; lowest capital cost)

Propery controlled dosing of hydrated lime ($Ca(OH)_2$) as proposed in the first method is usually a relatively laborious operation. Limestone ($CaCO_3$) filters are usually installed when the second option is used. The third method adds Cl^- and Na^+ ions back into the water, again increasing the risk of corrosion (it is therefore usually applied only at smaller operations).

8 MANAGEMENT OF RESIDUALS

During the desalination process, it is inevitable that waste streams are generated which must be managed in a suitable way. ***The treatment and disposal of desalination residuals can be a major cost and environmental consideration for the water service provider.*** Latteman and Höpner (2003), Einav and Lokiec (2003), Mickley (2004) and Sommariva *et al* (2004) provide useful information on the topic.

8.1 Brine disposal (also referred to as concentrate management)

The most important and largest waste stream from any desalination plant is the brine, or concentrated salt stream that is produced during the separation process.

The brine stream contains high concentrations of salts and other concentrated impurities that may be found in the feed water, and which must be disposed of in a safe and acceptable way. Depending on the composition of the brine and the location of the site, treatment may be required before disposal. Normally, the brine streams from seawater RO plants are returned to the sea in a well-managed (sometimes diluted and distributed) fashion.

For large inland brackish water RO plants, the solution is not so simple and evaporation ponds or other methods of disposal may be required. In such cases, the water recovery should be maximised to minimise the volumetric disposal requirements.

The character of the brine that is produced will be affected by the following factors:

- feed water quality
- pre-treatment processes
- desalination process
- water recovery
- post-treatment and concentrate blending

The amount by which the salts and other constituents in the feed water can be concentrated during the desalination process can be substantial at high recoveries, as shown in Table 8.1.

Table 8.1: Concentration factors for different recovery ratios

Recovery (%)	**Concentration Factor**
50 – 75	2 – 4
75 – 80	4 – 5
80 – 90	5 – 10
90 – 95	10 – 20
95 – 99	20 – 100
99 – 99,9	100 – 1 000

8.1.1 Brine treatment and disposal options

A number of alternatives exist for the disposal of brine, and the choice of which to use is influenced by environmental considerations (legislation; permits by regulating authorities), location of the desalination plant, and cost. The most generally used treatment and disposal options are the following [Schutte & Schoeman (2005]:

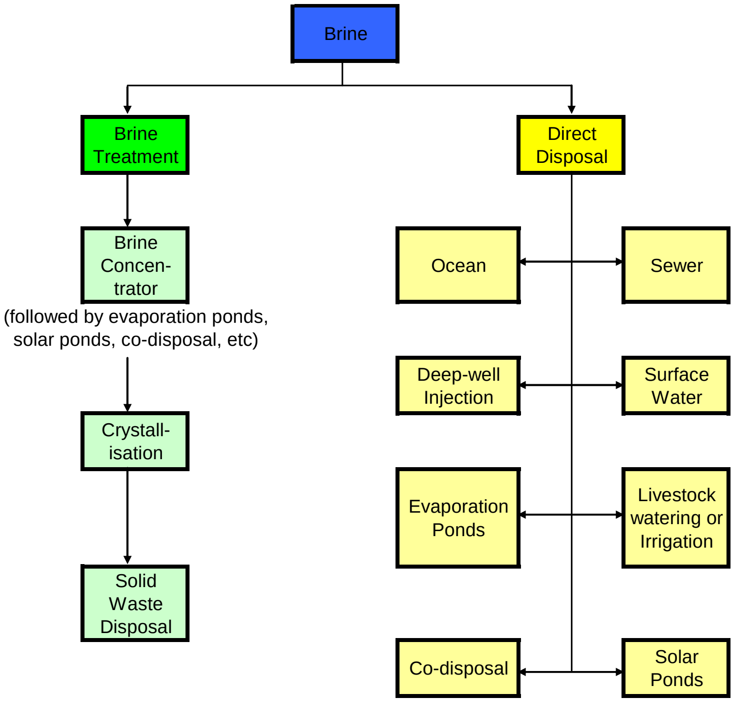


Figure 8.1: General treatment and disposal options

8.1.1.1 *Direct disposal options*

- Ocean disposal
  For seawater or brackish water desalination, brine disposal in off-shore turbulent zone (to ensure mixing) may be acceptable. The cost involved may be reasonable, and consists mainly of capital cost of the pipeline and diffusers, and pumping costs as operating expenditure. A permit from the relevant authorities will be required for this activity.

- Surface water discharge
  Disposal to a large receiving body of surface water (*e.g*. river, ocean, lagoon) that will not be adversely affected by the concentrate. This activity will also require a permit.

- Sewer discharge
  Discharging concentrate into the collection system of a wastewater treatment facility. This activity will require agreement with the municipality. Generally, this would only be an option where small volumes of brine are concerned (*e.g.* from small desalination plants).

- Deep well injection
  Injecting concentrate into an acceptable underground aquifer using a disposal well. This is practised widely in some overseas countries, notably the USA, but have not been applied in South Africa to date, presumably because of the potential pollution of groundwater.

- Evaporation ponds
  Solar evaporation, generally limited to small flows and areas of arid climate (with high evaporation rates and low rainfall) and inexpensive land. This is essentially a zero-liquid discharge process. Because of potential pollution of the groundwater, ponds must be lined, which has a significant cost implication. Evaporation ponds also require a permit or license from the relevant authorities.

- Land application
  Disposal to percolation ponds or use as irrigation water.

- Livestock watering or irrigation
  This may be feasible for low TDS brines (generated during desalination of brackish waters by low rejection membranes, and/or at low recovery rates). Irrigation may be feasible on salt-tolerant plants.

- Co-disposal
  Blending and disposal with wastewater treatment plant effluent or power plant cooling water, into ash dams or ashing systems for dust suppression. Potential pollution due to leaching may exist.

8.1.1.2 *Treatment options*

- Brine concentrator
  Thermal process used to concentrate brines (see Zero liquid discharge below). High recovery rates can be achieved (90 – 96%) to produce very high TDS brines. Distillate and by-product recovery can be achieved. Final disposal is in the form of a solid waste or slurry. Technologically, this is a good option for brine concentration, but has high capital and operating costs, and requires very efficient operational control.

- Zero liquid discharge (ZLD) or near-ZLD
  Thermal evaporation, concentration or crystallization into solid salts (e.g., thermal evaporators, crystallizers, spray dryers). Again, these options are capital intensive, with high operating costs.

8.1.2 *Emerging methods for concentrate minimization (Ahuja & Howe, 2005)(Sthi,et al,2005)*

- Hybrid primary RO – Physical/Chemical treatment – Secondary RO

  Concentrate from primary RO chemically treated to remove cations of concern (Ca, Mg, other sparingly soluble ions) via chemical precipitation, followed by media filtration, followed by secondary RO. Combined recovery could be potentially 95% or greater.

- Hybrid primary RO – Biological Reduction – Secondary RO

  Concentrate from primary RO biologically treated to remove anions of concern (sulphate, carbonate) via biological reduction, air stripping, followed by thickening and filtration, followed by secondary RO. Combined recovery could be potentially 95% or greater.

- High-efficiency RO (HERO^{TM})

  Ion exchange softening pre-treatment and high pH (~11) RO operation to inhibit scaling. Reported recovery around 95%.

- Slurry precipitation and recycle RO (SPARRO)

  Introduce seed crystals to precipitate and remove scaling compounds in a controlled fashion. To date, this has only been evaluated on high sulphate mining water (WRC, 2005)

8.1.3 *Emerging methods for brine treatment (Sthi,et al, 2005)*

- Dew-vaporization

  Air used as carrier-gas to evaporate water using waste/solar/fuel energy. Dew forms pure condensate at atmospheric pressure.

- Salt solidification and sequestration

  Lowering of crystallization temperature with addition of polymers. Use of solids in construction materials or other possible applications.

- Wind aided intensified evaporation (WAIV)

  Using wind energy to evaporate wetted surfaces that are packed in high-density footprint. Concentrate sprayed over vertical transport surfaces. Evaporation surfaces can consist of woven nettings.

- Re-use

  Beneficial re-use in brackish or salt marsh wetlands; discharge for re-use by another facility (e.g. concentrate can be used as cooling or process water).

- Freeze Concentration

  Portion of saltwater is frozen to form ice crystals that are separated from brine to produce pure water, rinsing removes adhering salt.

- Aquaculture

  Concentrate beneficially used for sustaining fish that live in high salinity waters.

8.2 Disposal of cleaning chemicals

Spent chemicals that are used in the CIP and other cleaning processes also have to be disposed of in an acceptable manner. The method of disposal will depend on the types of chemicals used in the cleaning and rinsing processes, and on the volumes that needs to be disposed of.

If the spent chemical streams do not contain any hazardous or toxic substances, the streams can be disposed of to the environment or sewer, but will require formal permits and permission from the regulating authorities and/or municipality involved.

Should the chemical waste streams contain hazardous materials, the effluent must be contained in a suitable way and disposed of to a hazardous waste site.

9 ENVIRONMENTAL CONSIDERATIONS

When considering desalination as an alternative option to conventional water supply, it is important to carefully consider all the potential environmental costs associated with the development and operation of desalination plants. Such considerations should primarily focus on the effluent generated and its environmental impact, both in short- and long-term. Many impact parameters are site-specific, which require that environmental studies be carried out on a case-by-case basis.

More general factors that might influence the environment are discussed in section 8.2 for both brackish water and seawater desalination. However, one should firstly take note of the following relevant legislation and permit requirements:

9.1 Legislation and permit requirements

- The National Environmental Management Act (Act 107/98, NEMA)

NEMA promotes sustainable development and regulates the procedures and steps to be taken when a development is considered for approval. It specifically promotes the cooperation between different role players and cooperative governance.

In this regard, it prescribes cooperation between government departments, such as the Department of Water Affairs and Forestry (DWAF), the Department of Environmental Affairs and Tourism and the relevant local authority. In specific instances, institutions such as Nature Conservation Boards will also need to be consulted

- Environmental Conservation Act (Act 73/89, ECA)

ECA, through regulation 1182, prescribes specific requirements for specific actions that might have a detrimental impact on the environment. These actions are listed in schedule one of the regulations and include "construction or upgrade of all structures below the high-water mark of the sea" and "schemes for the abstraction or utilisation of ground or surface water for bulk supply purposes".

Regulation 1182 contains all the relevant steps to be taken for the required environmental impact assessment. It is extremely important to note that the involvement of interested and affected parties forms an integral part of this process.

- National Water Act (Act 36 of 1998, NWA) and Water Services Act (Act 108 of 1997, WSA).

These two acts regulate the water industry and deal primarily with the management structures and the licensing procedures required before water can be abstracted from a source.

Depending on the method of abstraction in the case of seawater desalination, it might be a requirement to apply for a licence or permit to abstract water. Beach wells as a possible abstraction method will almost always involve the abstraction of groundwater resources, which are regulated by the NWA. General authorisation granted by DWAF is only applicable up to 750 m inland from the high tide level and an application for a permit needs to be lodged by the relevant LA.

In the case of the abstraction of groundwater, the permit or licensing procedure is well described and is compulsory through the WSA.

- General authorisations and permits

During the construction phase of specific seawater desalination plants, a permit is required from the relevant Nature Conservation Board for access onto beaches and the removal of specific plant species in dune areas.

The concentrated brine wastewater generated from desalination plants comprise of numerous components which have the potential to cause wide ranging negative impacts into the receiving environments. The waste brine produced by the desalination plants includes salts, cooling water, particulate matter, emissions and heat. Several components present in the brine at high concentrations are sodium, calcium, magnesium, copper, nitrates, phosphorus, total dissolved solids (TDS), and fluoride. In the case of reverse osmosis (RO) based-plants, besides the concentrated brine, backwash sludges are discharged. Thermal desalination plants driven by auxiliary boilers are responsible for discharging fumes (CO_2, NO_X, and SO_X), and heat into the environment.

During the cleaning processes of desalination plants and pre-treatment of feed-water, a variety of chemicals may be used. These may include: chlorine, sulphuric acid, sodium meta-bisulphite, lime powder, citric acid, ammonia and sodium hydroxide, just to mention a few. The brine and the feed water have conductivity values ranging from a few μS/m to tens of thousand μS/m.

Irrespective of the point of effluent disposal (surface or sub-surface soils, or ocean), highly concentrated effluents could pose serious environmental threats if inadequately managed.

The Environmental Impact Assessment procedure prescribed in the Environmental Conservation Act, which is a precondition to construction of a desalination facility, implies the generation of a *detailed* list of possible environmental impacts. The list below is not at all complete, but provides useful guidelines.

9.2 Desalination of brackish water

- Construction aspects

  The typical environmental problems associated with the drilling of a borehole, include damage caused by access roads, construction of buildings and the disposal of builders rubble, the disposal of slimes from the developing process of a specific borehole, the provision of services such as electricity, water and sanitation supply to the desalination site.

  When testing new boreholes, huge volumes of water (depending on the scale of the project) are normally abstracted over a very short period of time. Appropriate steps need to be taken to ensure that erosion does not occur and planning for the disposal of this water needs to be done in advance.

- Reserve determination and over-exploitation

  Proposed abstraction might have a significant impact on existing groundwater developments, which may be situated significant distances from the proposed site. The dependence of sensitive areas such as lagoons, marshlands and fountains needs to be evaluated with due caution. In this respect it is necessary to calculate the reserves of the specific resource (as prescribed in the National Water Act), allowing for existing environmental and human needs. This can be a time consuming exercise and needs to be planned carefully.

  Unchecked and continuous abstraction of brackish water can cause over-exploitation of a groundwater resource, thus lowering the groundwater levels, which may in turn destabilize the ecosystem. Precautionary measures such as continuous measurement of ground water levels should be undertaken and documented, while also monitoring any changes to the ecosystem.

- Visual impact

  Industrial constructions can have negative visual impacts, which should be limited to a minimum. Proper planning of the plant and architectural input can greatly help to soften the visual impact, as can be seen on the photo of the Bitterfontein desalination plant (Figure 9.1).

Figure 9.1: Bitterfontein desalination plant

- Disposal of brine

  Poor management of brine disposal may result in one or more of the following negative impacts:

  - Making the soils saline due to high sodium absorption ratio (SAR), hence interfering with proper soil drainage.
  - Harming vegetation that is sensitive to salt content variations.
  - Accumulation of salts in the substrata.
  - Pollution of the underlying groundwater.
  - Damage of biological systems that come into contact with high concentrate brine. Unique biological systems are site-specific and impacts can only be determined on a case-by-case basis.
  - Pollution of surface water sources such as dams and lakes. This mainly occurs through storm water from the desalination plant.

  Brine should normally be disposed of through the use of evaporation ponds. Depending on the effluent volumes and the rate of evaporation in the specific area, large areas may be required to dispose of the brine. Lining of these ponds is recommended to minimise the pollution risk to groundwater resources. Ponds are generally used on a rotation bases and need to be cleaned regularly. Disposal of salt concentrate from these ponds needs to be treated as hazardous waste.

  Commercial harvesting of the salts may be possible, but will depend on the size of the desalination system. Small scale projects normally do not justify this procedure.

- Noise

  On reverse osmosis desalination plants, noise may emanate from high pressure pumps, energy recovery turbines and compressors. Depending on the plant location in relation to noise sensitive areas, special attention should be paid to these aspects while adhering to the regulations of the relevant local authority. Noise problems may be addressed either by installing the desalination plant away from densely populated areas, or (more preferably) by adopting appropriate technologies to reduce noise levels.

- Chemical pollution

  Feed water to a desalination plant requires pre-treatment and the addition of chemicals. Antiscalants (e.g. polycarbonic acids and polyphosphates) and biocides (e.g. chlorine and hypochlorite) may be added into the feed water for antiscaling and antifouling purposes. Chemicals are also used to clean the membranes on an intermittent basis. These chemicals can all have a negative impact on the environment if not managed properly.

9.3 Desalination of sea water

- Construction aspects

  Seawater desalination poses unique problems due to the fact that construction normally takes place close to beaches, or directly in the sea. The environmental issues related to the construction of a direct sea intake depend on the size of the proposed intake system and whether existing structures such as harbours or jetties are used.

  Beaches are normally ecological sensitive areas and special care needs to be taken not to put aspects such as breeding areas for seabirds at risk. Access onto beaches is also regulated and special permission needs to be obtained.

  Environmental issues as a result of the provision of services like roads and sanitation during construction also need to be monitored closely.

- Visual impacts

  As is the case for brackish RO plants, good planning and architectural input can minimise the visual impact of the desalination facilities. If applicable, specific attention needs to be given to the abstraction pipeline and the pipeline conveying brine back into the sea. Bear in mind that such piping is exposed to extreme climatic conditions and the associated wave action can cause serious damage to additional equipment installed to prevent visual exposure.

- Noise pollution

  Seawater reverse osmosis plants can generate fairly high noise levels if not well-designed. These plants operate at higher pressures than brackish water plants and related pumps and turbines are often more noisy. Preventative measures are the same as for brackish water plants.

- Disposal of brine

  The brine from seawater RO plants typically contains 1.7 times more salt than the incoming sea water. The preferred option for the disposal of the brine from a seawater desalination plant is to take the brine directly back into the sea. Although site-specific conditions like the wave action and the relevant sea currents play an important role, the brine normally disperses fairly quickly with relative little environmental impact. However, the brine is, as a result of its concentration, denser than seawater and tends to sink to the bottom, where it can impact on the marine environment. Special care needs to be taken when cleaning chemicals are disposed of together with the brine.

  The disposal of brine in the dune areas adjacent to the surf zone is not recommended. The vegetation in dune areas is normally extremely sensitive to the salinity levels. The pictures below clearly show how a badly planned disposal site causes the deterioration of vegetation. The visual impact discussed before, can clearly be seen in Figure 9.2.

Figure 9.2: Impact of undesirable brine disposal

- Chemical pollution

  The same problems occur as described for brackish water plants. In addition, for plant parts coming into direct contact with seawater, corrosion cannot be entirely prevented. Therefore, heavy metals may be present in the brine concentrate discharged into the marine environment.

  Table 9.1 lists possible environment impacts that might occur due to the interaction of these chemicals and the receiving seawater environment.

Table 9.1: Impact of chemicals on different environmental aspects

Environmental aspects	Chemicals present	Environmental impacts
Corrosion products	Iron, copper, nickel, zinc, and other heavy metals	Can cause toxicity to biological systems if present in excessive concentrations. Copper is the most predominant heavy metal. The toxicity effect is a function of biological organisms present, their nature and the environment and its conditions.
Antiscaling additives	Polycarbonic, polyphosphates	May cause eutrophication of the sea through formation of algal blooms and macro algae. Since the sea water is extracted from the same area, this could lead to increased biofouling, increased content in organic matter, and increased need of antifoulants. The net effect is severe deterioration of the environmental quality.
Antifouling additives	Chlorine, Hypochlorite	Causes sterilisation effect in organisms through chlorination and metabolism processes. Converts bromide and iodide organic seawater constituents into bromine and iodine though the halogenation process. These chain reactions may result in the formation of compounds with carcinogenic and mutagenic properties.
Antifoaming additives	Alcylated polyglycols, fatty acids, fatty acid esters.	Since antifoulants are detergents, they cause adverse effects on organisms, mainly through interruptions of the intercellular membrane system. Note that the full extent of their environmental impacts is unknown. Therefore, it is imperative to invoke precautionary principles when dealing with them.
Cleaning processes	Acids e.g. sulphuric acid.	Owing to the high concentrations of acid required during the acid wash cycle, the pH of the receiving environment is highly variable and mostly extremely low. In that respect, care should be taken as this can cause considerable damage to the organisms before the acidified seawater is neutralized.

Although an attempt was made to classify the different environmental aspects linked to different feed water sources, there are other environmental issues that need to be considered in a broader context, like energy consumption.

Desalination is an energy-intensive process as energy accounts for 20-30% of the total operational costs of a given plant. Therefore, overall consideration of the desalination process should factor in an increased usage of energy by the relevant municipality. This implies that desalination plants play a role in posing both direct and indirect environmental damage stemming from increased production of electricity (air-pollution, coal-dust pollution, etc.) as well as thermal pollution owing to heat releases from such plants. Alternative energy sources for the desalination plants should be explored, with bias towards those with reduced greenhouse gas (e.g. carbon dioxide) generation.

Table G 1 in Appendix G summarises the main environmental impacts that the different desalination techniques might have on the environment and the sensitivity of each technique on these impacts.

10 OPERATION AND MAINTENANCE ASPECTS

10.1 Introduction

Operation of desalination plants require constant monitoring of operating parameters and water quality. There are several different operating parameters that should be monitored to determine overall plant performance. The most common parameters for monitoring are pressure drop, flux, conductivity and water quality. Supervisors and engineers on new plants should also be informed about experiences at other older plants, thus ensuring that evident operational mistakes are avoided. Apart from standard textbooks, useful reading includes Burashid and Hussain (2004), Darton and Buckley (2001), Ebrahim *at al* (2001), Hafsi *et al* (2004), Kersham (2001), Liberman (2001), Marangou and Savvides (2001) and Tsiourtis (2001).

Effective maintenance of the plant is equally necessary to ensure trouble-free operation and plant performance that will achieve the treated water quality goals.

10.2 Monitoring

10.2.1 Introduction

Each unit operation in a membrane treatment plant should be monitored for function. Typical flow processes in the plant should include pre-treatment processes, acid or antiscalant addition, membrane filtration, aeration, and post-treatment (disinfection and corrosion control). Flow, pressure, and applicable water quality are general monitoring parameters that are applicable to each unit operation in a membrane process. Recording the performance of a desalination plant should begin immediately during start-up and continue during operation. A start-up report should include a complete plant description, pretreatment unit performance, membrane performance, and post treatment performance [Schutte & Schoeman (2005)]

10.2.1.1 Start-up report

- Complete plant descriptions can include a flow diagram, equipment and instrumentation literature provided by engineers and manufacturers, instrumentation literature and operating manuals, and material lists. The plant description should show water source, all pre-treatment unit operations, membrane array configuration, and all post treatment unit operations.

- Actual initial performance of pre-treatment and membrane sections should be monitored. The pre-treatment unit operations typically include pre-treatment and acid and/or antiscalant additions, which are described by SDI or some other fouling index, pH, flow and pressure.

- All gauges and meters should be calibrated based on manufacturers' recommendations as to method. The expected process performance can be used to check gauges and meters. Flow gauges can also be checked by mass balances around stages or pressure vessels. Pressure gauges and conductivity meters can be checked by comparison to similar readings before and after the desired gauge or meter.

10.2.1.2 *Operating report*

Operating reports must also be kept as part of the monitoring exercise. The operating data describe the performance of the membrane systems. They must be collected routinely during the life of the plant. This data, along with periodic water analyses, provide the necessary input for the evaluation of the plant's performance. The information includes:

- Flows (product and brine of each stage)
- Pressures (feed, product, and brine of each stage and permeator brine sample port)
- Temperature (feed after RO pump or product)
- pH (feed, product and brine)
- Conductivities (TDS) of each stage and each permeator (feed, product, and brine)
- SDI of feed after microfiltration
- Unusual incidents (upsets in pH, SDI, and pressure, shutdowns, etc.)
- Calibration of all gauges and meters

Complete water analysis of the feed, permeate, and concentrate streams for the plant and the raw water should be obtained at start-up, quarterly, and as required by regulation thereafter. Changes in conductivity can be correlated to TDS and possibly to other major ions. Partial water analyses of the feed, product and brine for each stage should be obtained once a month and should include TDS, chloride, and conductivity. The chloride content and conductivity should be obtained twice a week. Conductivity can be monitored continuously throughout the process.

Records must be kept of the operating characteristics of the pre-treatment equipment. Chemical consumption and performance must be recorded. Pre-treatment operating data should include at least the following:

- SDI before and after acid addition once per day
- Inlet and outlet pressure of microfilters twice a day
- Acid and other chemical consumption once per day
- Discharge pressure of feed pumps twice per day
- Calibration of all gauges and meters no less than once every three months

Maintenance records on the plant must also be kept. They provide further information about the performance of the permeators and the mechanical equipment in the plant and need to include at least all aspects listed in section 10.2.1.3.

10.2.1.3 Maintenance report

- Routine maintenance
- Mechanical failures
- Permeator replacements
- Cleanings (cleaning agents and conditions used)
- Chemical post treatments (type and conditions used)
- Frequency of changing 5-µm filters
- Calibration of all gauges and meters

10.2.2 Process monitoring

System monitoring is essential to prevent fouling and scaling and to identify a problem early when it may easily be reversed. Table 10.1 lists typical monitoring parameters, tests, frequency of testing, and limiting conditions.

Table 10.1: Monitoring parameters for reverse osmosis systems (from AWWA M46)

Parameter	Measurement	Frequency
Pretreatment monitoring:		
Feedwater particulates (monitoring fouling potential)	Turbidity, NTU Silt density index, SDI Conductivity, mS/m	*Frequency depends on whether feed water is surface water or groundwater, and whether plant operation is 24h/day or 8h/day*
Feedwater dissolved substances (monitoring scaling potential)	Alkalinity, barium, calcium, pH, strontium sulphate	
Particle counts and size distribution	Particle counter	
Membrane unit monitoring:		
Flow	Feedwater, permeate, concentrate	Continuously, on stream
	Percent recovery	Continuously, on stream
	Normalized permeate flow	Daily, graphed weekly
	Pressure drop	Daily, graphed weekly
Salt concentration (conductivity)	Feedwater, permeate, concentrate	Continuously, on stream
	Percent salt rejection	Daily, graphed weekly
	Permeate from each pressure vessel	Monthly
Temperature	Feedwater	Continuously, on stream
Pressure drop, normalized permeate flow (see above)	Feedwater, permeate, concentrate, interstage	Continuously, on stream
Biological monitoring:		
Chlorine dosage	Feedwater	1-3x/day
Bacterial counts	Feedwater, permeate, concentrate	2-4x/year
Instrumentation calibration:		
Flows, pressures, conductivities, turbidities, other	Feedwater, permeate, concentrate	1-4x/year
System balance check	Flows and conductivities	Weekly

10.2.3 Biological monitoring

Fouling of noncellulosic RO and NF membrane systems by bacteria is a constant threat because most noncellulosic membranes do not tolerate continuous additions of an oxidizing biocide, typically chlorine, in the feed water. Bacterial growth is minimized by operating the system at design flow rates and by maintaining proper pre-treatment chemical feeds. The shear force imparted by the feed water stream of an operating system limits bacterial growth. When a system is shut down, however, bacterial biofilm formation may increase. Within 24 to 48 hours of non-operation, bacteria multiply and produce substances around their bodies that effectively adhere to the membrane system. In addition, seawater RO systems can be adversely affected by micro-organisms, such as algae, if pre-treatment systems fail to operate properly.

If the RO or NF unit must be shut down, it should be flushed with permeate or feed water at least once a day to limit bacterial growth. Flushing or operating the system every 8 hours, if possible, is recommended. A biocide should be added to the system if the system will be shut down for two or more days.

10.3 Controls

Membrane desalination plants are operated with control based on the monitoring of flow, pressure, conductivity, temperature, pH, liquid level. Specific chemical analyses, and lapsed time indicators. The comments here are only with regard to the pre-treatment and membrane arrays.

- Flow is monitored for control of water production in arrays and may be controlled automatically.

- Pressure is monitored for control of water production in arrays and may be controlled manually or automatically by regulating pump operation and valve settings through a computer system. Pressure is typically increased or decreased to increase or decrease production in each stage.

- Temperature is monitored for protection of pumps and membranes, with complete plant or array shutdown from on-off temperature control.

- The pH can be monitored and controlled automatically by feedback control. Monitoring is essential if acid is used to control scaling. Automatic monitoring will cause a shutdown or an alarm will be activated if a set range is violated.

- Liquid levels are monitored and controlled by on-off proportional controllers in chemical feed systems for membrane plants.

- Specific chemical analyses such as conductivity or turbidity may be monitored automatically by feedback or manually to ensure membrane, pressure vessel, and array integrity.

- Lapsed-time meters are recorded continuously for plant analyses and maintenance. Actual time of operation is essential for accurate evaluation of plant-performance.

10.4 Chemical cleaning

If membrane systems become fouled or scaled, the fouling or scaling material has to be removed by chemical cleaning. Chemical cleaning will accomplish the following:

- dissolve and remove inorganic scales
- flush out particulate material
- break down bacterial slimes
- eliminate bacteria

Chemical cleaning agents fall into the following categories:

- enzymes to break down bacterial slimes
- detergents and surfactants to resuspend particulate material and dissolve organic material
- biocides to kill bacteria
- chelators to remove scale
- acids to dissolve inorganics
- caustics to dissolve organic substances and silica

Membrane manufacturers recommend certain cleaners, and membrane chemical cleaning vendors sell proprietary chemical cleaners. Only those chemicals that have been approved in writing by the membrane manufacturer should be used in the membrane system. The membrane manufacturer's guidelines must always be followed for types of cleaning chemicals, solution temperature, pH, and other parameters. Table 10.2 shows the suitable chemical cleaning methods for different types of problems.

Table 10.2: Chemical cleaning approaches for different problems

Problem	Chemical Cleaner
Inorganic scale	Acid (low pH) Chelator
Silt or dirt	Caustic (high pH) Chelator Detergent
Biofouling	Caustic (high pH) Enzyme Detergent Chelator Biocide

10.5 Rejuvenation and sterilisation [Schutte & Schoeman (2005)]

10.5.1 Rejuvenation

Rejuvenation is the enhancement of salt-rejection characteristics by the application of chemical treatments to the surface of semi-permeable membranes. During the life of RO membranes, degradation of performance will be experienced. Cleaning treatment generally has varying degrees of success. In some cases, a noticeable loss of salt rejection will have occurred, which may be due surface defects, abrasion damage, chemical attacks (cleaning compounds, oxidants) and/or hydrolysis. To restore the lost salt-rejection characteristics, rejuvenation chemicals should be tried.

Membrane rejuvenation typically increases salt rejection to at least 94 percent. The keys to successful application of these products are (1) to thoroughly clean the RO membrane and (2) to follow carefully the instructions supplied by both membrane manufacturers and chemical suppliers. These procedures will not work when either physical damage of the membrane is great or the O-rings are damaged. When salt rejection is below 75 percent, successful rejuvenation is unlikely; if below 45 percent, rejuvenation treatment is completely ineffective.

10.5.2 Sterilisation

Sterilisation is a necessary process in the maintenance of RO systems.

Several procedures are available to sterilize RO membranes and systems. Hydrogen peroxide (0.25 percent wt), sodium bisulfate/glycerine (0.2 to 1 percent/16 to 20 percent wt), sodium bisulfate (0.5 to 1 percent), formaldehyde (0.25 to 1 percent) and copper sulfate (0.1 to 0.5 ppm) have all been successfully used as disinfectants. For storage purposes, formaldehyde, sodium bisulfite and the sodium bisulfite/glycerine solutions have been proved effective and membrane compatible.

Sterilizing agents may pose a health hazard and a serious disposal concern. Consult with suppliers to determine whether the sterilizing agents can be neutralized before disposal.

10.6 Mechanical integrity

The performance of any RO or NF system is determined by monitoring the quality and quantity of permeate produced by each train in the system. When one or more factors are outside projected values, the problem should be investigated and corrective action taken as soon as possible. If the problem is left unchecked, permeate water quality may deteriorate, and the loss in performance may become irreversible. Probing is a method of checking the mechanical integrity of the membrane.

10.7 Staffing

10.7.1 Human resource inputs required

10.7.1.1 Operating

Operation of a desalination plant can be performed under contract, but it is preferable that the plant is operated by personnel of the water supply authority (municipality or water board).

Operation of desalination plants does not require specially skilled personnel. However, plant operators should be well-trained and capable of acquiring the skills necessary to perform daily operation of the plant and to report any deviations from normal operating parameters (see section 10.11). Chemical cleaning should be performed under supervision of a qualified technician or trained supervisor.

It is advisable that at least one staff member of the water supply authority has an adequate understanding and knowledge of membrane treatment processes. This would require some form of training in membrane treatment, albeit short courses or as part of formal training. This staff member would be a technician, technologist or engineer.

10.7.1.2 *Maintenance*

Sufficient funds and labour must be available to do preventative maintenance. A good preventative maintenance program will document the schedule and work plan for each maintenance function. This schedule serves as the basis for estimation of labour requirements for specific maintenance functions.

To determine trade and manhour requirements for each preventative maintenance function, the function should be broken down into tasks. Such tasks may then be analysed further to determine specific skills and man-hours required for each specific maintenance function..

It is important to use trained and experienced individuals to perform maintenance. At larger service providers, individuals who are specialised in each trade will in all likelihood be available to do the required maintenance. If not, it is advisable to contract specialised maintenance work, such as electrical control panel repair or generator maintenance out to private contractors. Full dependence on contractors for maintenance tasks needs to be minimised where possible. However, due to cost implications it might be the most appropriate option, specifically for smaller communities.

10.7.1.3 *Technical support*

Technical support for desalination plants is necessary to ensure that any deviations from normal operating regimes are addressed rapidly and effectively, so that service delivery (volume of water produced and quality of product water) is not compromised. The support would normally comprise rapid response to call-outs, trouble shooting and corrective action to normalize the situation. It would also include action plans to rapidly identify/forecast similar problems in future, and communicating this to the municipal engineer.

Technical support can be provided by any of the following:
- membrane plant supplier
- contracted external company
- competent municipal technician.

The latter would again be the option of choice, but additional support by the membrane supplier would be strongly recommended.

10.7.1.4 *Levels of operation*

From the above, the levels of operation of a desalination plant are as follows:

- plant operators (process controllers)
- supervisor (technician; technologist)
- municipal engineer

10.7.2 Qualifications

The following are recommended qualifications for operation of a desalination plant:

- Operating Personnel
  - Plant Operators:
    Grade 12 and in-service training on the desalination plant (NQF 4 equivalent)
  - Supervisor:
    Qualification in Water Treatment and short course on membrane treatment (B.Tech equivalent)
- Maintenance Personnel
  - In-service training by membrane suppliers during commissioning process.
- Technical Support Personnel
  - Qualification in Water Treatment and short course on membrane treatment. In-service training by membrane suppliers during commissioning process.

10.7.3 Training requirements

Existing plant operators (process controllers) at municipal treatment plants can be trained to operate desalination plants. The operators should at least have a Grade 12 school qualification and should receive in-service training on the operation of desalination plants during the commissioning of the plants.

Additional short courses for plant operators and supervisors on operation of membrane based desalination plants would be beneficial.

10.8 Operating manuals

It is imperative that a detailed operating manual be made available during the commissioning of the desalination plant. The consulting engineer is responsible for ensuring that a set of operating manuals is provided to the client prior to or during commissioning, and that the manual contains all information required for the trouble-free operation of the plant. The operating manual should include the following:

- overall description of the desalination plant (with flow diagrams)
- treatment philosophy
- description of pre-treatment processes
- description of desalination system (membranes)
- description of post-treatment processes
- description of residuals management procedures
- design criteria
- start-up procedures
- normal operating procedures (day-to-day)
- cleaning procedures (chemical cleaning)
- shut-down procedures
- process control and quality control procedures (monitoring)
- trouble-shooting
- summary of technical specifications
- safety aspects
- glossary/index

Information on membrane systems is of particular importance and must be provided by the membrane supplier.

During commissioning, designated operating personnel and supervisors should receive training on the operation of the desalination plant, using the *Operating Manual* as the basis of the training. The municipal engineer should ensure that his operating personnel are fully and completely conversant with the operation of the plant before handing over of the plant takes place.

10.9 Operation and maintenance schedules

A detailed Operation and Maintenance Schedule should be drawn up for the desalination plant, including any pre-treatment, post-treatment and residuals handling facilities.

An example of the format of such a schedule is given in Table 10.3.

Table 10.3: Example of maintenance schedule

Aspect	Tasks required	Daily required	Weekly required	Monthly required	Bi-Annually required	Annually required	Continuously
Pumps							
Instrumentation							
Membrane modules							

10.10 Maintenance programs

The maintenance of equipment and machinery at a works can be carried out in several ways. These can be classified as routine preventative or planned maintenance, breakdown maintenance, and as an example of a structured approach or Reliability Centred Maintenance (RCM).

Budget for Maintenance

Budgeting for maintenance will require that sufficient funding is available for the following:

- Preventative Maintenance – Operating Budget
  Labour (staff time, person hours)
  Parts and supplies
  Equipment

- Emergency Maintenance – Operations Reserve Account
  Labour (overtime)
  Materials
  Replacement equipment
  Contractors

- Equipment Replacement
  Evaluation and design
  Labour
  Equipment cost

10.11 System troubleshooting

Troubleshooting is required when RO system performance changes at unanticipated levels, for example, when one or more of the following occurs:

- Normalized production changes by 15 percent.
- Normalized salt passage changes by 50 percent.
- Corrected differential pressure (d/p) changes by 15 percent.

Troubleshooting an RO system that is not meeting performance expectations consists of the following steps:

- Verify instrument operation.
- Review operating data.
- Evaluate potential mechanical and chemical problems.
- Compare current feed-water analysis with design criteria.
- Identify foulants.

10.12 Safety

Safety is a fundamental responsibility for all personnel in a water treatment plant, and therefore also at any desalination plant. Industry goals include zero accidents and total compliance with all regulatory statutes. To achieve these goals, water treatment personnel involved in membrane processes need the following training and knowledge (AWWA M46):

- a hazard review of all operating steps with appropriate follow-up audits
- operating instructions, including design criteria and prints, posted where they are easily accessible to all personnel
- training for operation, maintenance, and supervisory staff on an ongoing basis
- appropriate tools and clothing
- a thorough understanding of and compliance with Occupational Safety regulations
- a facility evacuation plan, with adequate fire protection and fire-fighting equipment

APPENDICES

APPENDIX A:

BASIC WATER CHEMISTRY

A1. BASIC WATER CHEMISTRY AND THE NEED FOR DESALINATION

When investigating the merits of desalination as a potential method to augment municipal water supplies, one should be familiar with common terminologies related to the characterisation and chemistry of water. Various reference handbooks such as Tchobanoglous & Schroeder (1985), Tchobanoglous *et al* (2003), Droste (1997) and Nazaroff & Alvarez-Cohen (2001) - to name a few - could be consulted for elaborate descriptions and explanations of such terminology. For clarity, some of the most important concepts and definitions are briefly discussed below.

A1.1. Physical characteristics of water

- Turbidity, measured in nephelometric turbidity units (**NTU**).

  The NTU-reading is a measure of the light-transmitting properties (clarity) of water and is an *indirect* indicator of the presence of suspended and colloidal matter in water.

- Total solids, commonly reported in mg/litre (**TS**).

  The TS is determined by weighing the remaining dry residue after evaporation and drying of a water sample at a temperature between $103^{O}C$ and $105^{O}C$.

- Total suspended solids, commonly reported in mg/litre (**TSS**, or simply **SS**).

  The TSS is that portion of the TS that is retained on a filter with a specified pore size (usually a glass fibre filter with nominal pore size of 1.58 μm), measured after being dried at $105^{O}C$. The TSS test is somewhat arbitrary, since nominal filter pore sizes varying from 0.45 μm and 2.0 μm have been used for TSS measurements.

- Total dissolved solids, commonly reported in mg/litre (**TDS**)

  $TDS = TS - TSS$. In other words, TDS represents the solids that pass through the filter and that are then weighed after evaporation and drying at the specified temperature. It is *important to note* that the TDS measurement encapsulates both truly dissolved solids and *colloidal* solids. Colloids are typically in the size range between 0.001 μm and 1 μm.

- Silt density index (**SDI**)

  This method makes it possible to measure the content of finely suspended and some colloidal matter in a liquid by filtration of a 500 ml sample through a 0.45μm filter at a constant measuring pressure of 2 bar. By measuring the filtration time for consecutive 500 ml samples (filtration initiated after set periods of time) the SDI can be calculated according to a specific formula. Due to the nature of the formula, the maximum possible value for the SDI_{15} is 6.7. The higher the SDI value, the more colloidal matter is contained in the sample. As a loose rule of thumb, the SDI_{15} of feed water to a reverse osmosis desalination plant must be less than 3 (and preferably much lower) to ensure successful operation without rapid fouling.

A1.2. Organic matter in water

The nature of organic matter in water can be highly diverse, ranging from natural compounds, such as proteins, carbohydrates and lipids, to synthetic compounds such as surfactants, pesticides, solvents and trihalomethanes. A number of different analytical methods have been developed over the years to determine the organic content of water and waste water. The following typical methods are used to measure *aggregate* organic matter comprising a number of organic constituents.

- BOD_5 (5-day biochemical oxygen demand; mg/litre O_2)

  This test involves the measurement of the dissolved oxygen consumed by micro-organisms during the biochemical oxidation of the organic matter in the sample over a period of five days. This test has several limitations, the most important one being the fact that the 5-day period may or may not correspond to the point where all soluble organic matter present has been consumed.

- COD (chemical oxygen demand; mg/litre O_2)

  The oxygen equivalent of the organic matter in water is measured by oxidation of the organic matter with a strong oxidising agent (potassium dichromate) under acidic conditions. The consumption of dichromate is, after appropriate mathematical conversion, reported in terms of the equivalent oxygen required to oxidise the organic matter to CO_2. The COD test is popular and useful, but does not differentiate between biologically oxidisable and inert organic matter. Certain inorganic components (e.g. chloride) can interfere with the test.

- TOC (total organic carbon; mg/litre TOC)

  After removal of inorganic carbon (by acidification and aeration), the amount of carbon dioxide released during evaporation and catalytic oxidation of the organic carbon in the sample is measured with an infrared analyser.

Although very useful indicators, these aggregate organic analyses do not identify the specific molecular composition of the organic constituents present in the water. Therefore, reliable prediction of their effect on a potential desalination process is not possible. If necessary, individual organic compounds should be identified and measured by sophisticated analytical instruments such as GC, HPLC, GCMS, etc.

A1.3. Microbial life in water (biological character of water)

Apart from their well-known potential impact on human health, micro-organisms may also affect the taste, odour, corrosive nature and bio-fouling nature of water. Without further elaboration, such organisms can be classified (Metcalf & Eddy; 2003) as:

- obligate intracellular parasites (viruses);
- procaryotic cells (blue-green algae, bacteria and archaea);

- eucaryotic cells (protozoa, green algae, fungi/yeast, rotifers, etc.)

The chart in Appendix B indicates the typical sizes of these organisms.

A notable feature of micro-organisms is their ability to form resistant forms that strongly resist disinfecting chemicals and heat, thus being able to remain dormant in water for extended periods. The ability of micro-organisms to effect corrosion and bio-fouling can severely influence the design and operation of a desalination plant.

A1.4. Dissolved inorganic matter

The need for desalination is generally based on the presence of dissolved inorganic solids in water, as typically represented by a TDS measurement. The TDS of most potable waters typically varies between 50 mg/litre and 500 mg/litre and desalination becomes essential when the TDS exceeds 1000 mg/litre. However, poor taste of water and/or unacceptably high concentrations of a single chemical component may force a need for desalination at TDS levels well below 1000 mg/litre.

A quick estimation of the TDS can be performed by measuring the conductivity of the water at $25^{O}C$. The TDS (in mg/litre) is typically equivalent to between 0.55xConductivity and 0.7xConductivity, where the conductivity is recorded in μS/cm.

The most prominent dissolved inorganic components in water include:

- Cationic
    - Calcium (Ca^{2+}; divalent component of hardness)
    - Hydronium (H_3O^+ ; monovalent dissociation cation directly related to **pH**)
    - Magnesium (Mg^{2+}; divalent component of hardness)
    - Potassium (K^+; monovalent)
    - Sodium (Na^+; monovalent)
    - Other cationic components include, amongst other, iron, manganese, zinc, aluminium, copper, barium, strontium, boron, ammonia, etc. The concentration of these secondary cations is *usually* low compared to the others above, so that their contribution to TDS is usually relatively small. However, their presence can have a significant effect on pre-treatment requirements and the performance of desalination equipment.
- Anionic
    - Bicarbonate (HCO_3^- ; monovalent component of alkalinity)
    - Carbonate (CO_3^{2-} ; divalent component of alkalinity)
    - Chloride (Cl^-; monovalent mineral acid)
    - Hydroxide (OH^-; monovalent dissociation anion related to pH and alkalinity)
    - Nitrate (NO_3^- ; monovalent mineral acid)
    - Sulphate (SO_4^{2-} ; divalent mineral acid)

  - Other secondary anionic components include, amongst other, fluoride, nitrite, phosphates, sulphide, sulphite, bromide and cyanide. Again, these secondary components *usually* do not contribute significantly to TDS, but some of them may influence the final design in a very significant way.

- Non-ionic

  The soluble forms of silica, usually expressed as SiO_2, is generally considered to be non-ionic or very weakly anionic. Silica on its own, or in combination with other elements, can cause severe scaling problems in desalination equipment.

The accuracy and acceptability of an inorganic water analysis should be verified by checking the *electro-neutrality* of the analysis via a cation-anion balance. When comparing the sum of cation equivalents with the sum of anion equivalents, a significant difference would indicate either incorrect analysis, or an incomplete analysis.

In order to further characterise the dissociation and association of dissolved ions in water, the following parameters are frequently determined:

- Alkalinity (commonly reported in mg/litre $CaCO_3$)

  $\text{Alkalinity} = \left[HCO_3^-\right] + \left[CO_3^{2-}\right] + \left[OH^-\right]$ in mg/litre $CaCO_3$. The alkalinity is determined by acid titration and is therefore a measure of the water's ability to neutralise acid. When the pH, temperature and TDS of the water are known, the concentration of dissolved CO_2 (H_2CO_3) can also be calculated from the alkalinity value.

- Total Hardness (commonly reported in mg/litre $CaCO_3$)

  $\text{Total Hardness} = \sum\left[\text{mulivalent cations}\right]$ in mg/litre $CaCO_3$. The total hardness (often just called hardness) is largely determined by the concentrations of dissolved calcium and magnesium and is a good indicator of the scale-forming capacity of the water.

Appendix A summarises the SABS guidelines for acceptable concentrations of only the most prominent inorganic components in potable water. However, by *only* considering the dissolved inorganic salt content of water, an engineer could potentially design a plant that is prone to severe fouling and is non-functional.

Suffice to say that, although the need for desalination is largely based on the concentration of inorganic salts in water (TDS), the presence of fine suspended solids, dissolved organic matter and microbial life forms in water vastly complicates the water chemistry and should not be ignored during assessment of desalination requirements.

APPENDIX B:

QUALITY GUIDELINES FOR POTABLE WATER

QUALITY GUIDELINES FOR POTABLE WATER (SELECTED INORGANIC COMPONENTS)

(Extracts from SANS 241 of 2005)

Table B 1: **Quality guidelines for potable water**

Determinand	Unit	Class I (recommended operational limit)	Class II (max. allowable for limited duration)	Class II water consumption period, max
Aluminium as Al	µg/L	< 300	300 - 500	1 year
Ammonia as N	mg/L	< 1,0	1,0 – 2,0	No limit
Boron as B	mg/L	*		-
Bromide as Br	mg/L	**		-
Calcium as Ca	mg/L	< 150	150 - 300	7 years
Copper as Cu	µg/L	< 1 000	1 000 – 2 000	1 year
Chloride as Cl-	mg/L	< 200	200 - 600	7 years
Fluoride as F-	mg/L	< 1,0	1,0 – 1,5	1 year
Iron as Fe	µg/L	< 200	200 – 2 000	7 years
Magnesium as Mg	mg/L	< 70	70 -100	7 years
Manganese as Mn	µg/L	< 100	100 – 1 000	7 years
Nitrate + Nitrite as N	mg/L	< 10	10 - 20	7 years
Potassium as K	mg/L	< 50	50 - 100	7 years
Sodium as Na	mg/L	< 200	200 - 400	7 years
Sulphate as SO4=	mg/L	< 400	400 - 600	7 years
Zinc as Zn	mg/L	< 5,0	5,0 - 10	1 year

* WHO provisional guideline for Boron: 0.5 mg/litre as B
** Rand Water guideline for Bromide: 1.0 mg/litre as Br

APPENDIX C:

PARTICLE SIZES IN WATER TREATMENT

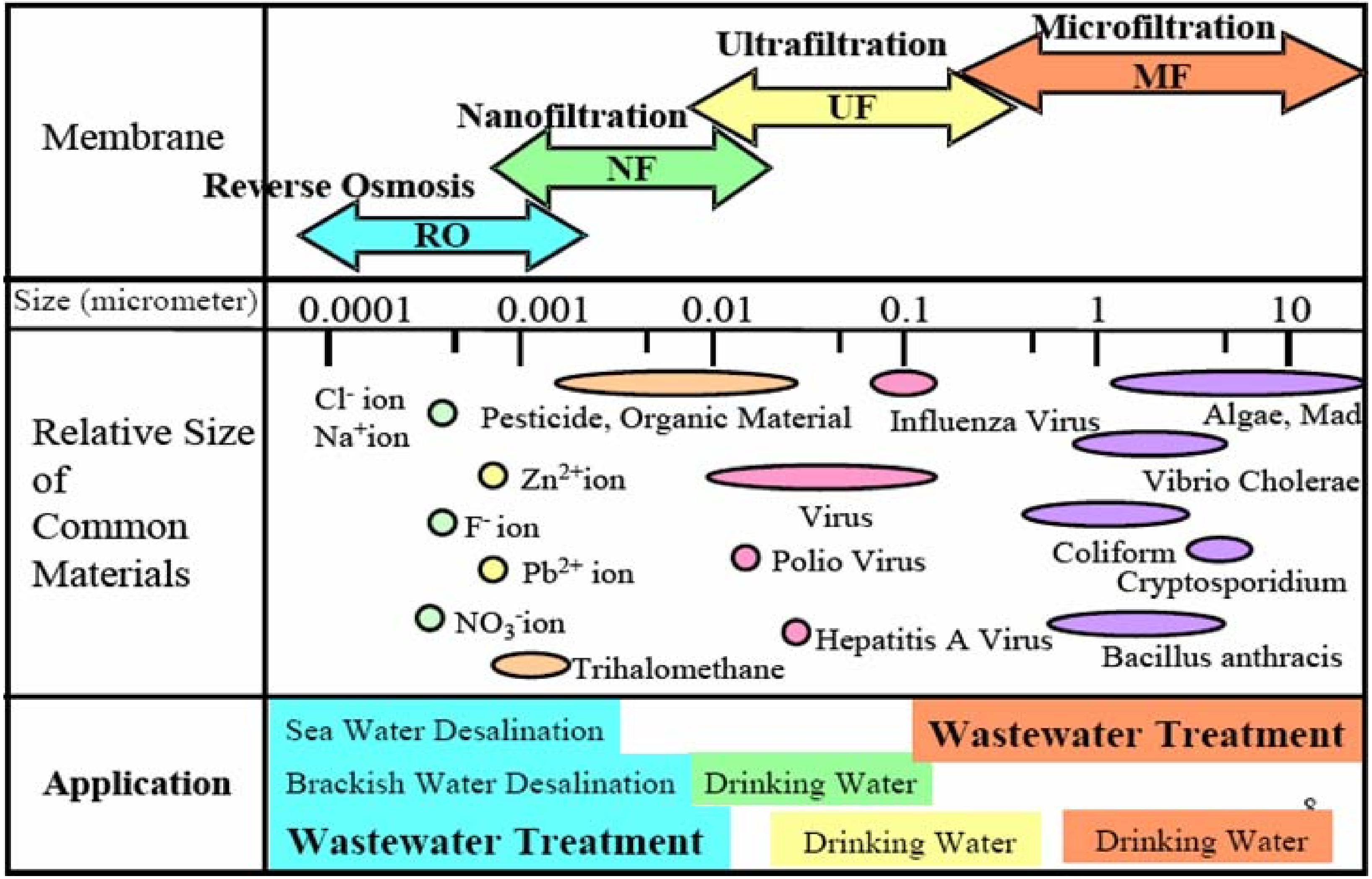


Figure C 1: Order of magnitude indication of particle size in water treatment

APPENDIX D:

GROUNDWATER QUALITY MAPS FOR SOUTH AFRICA

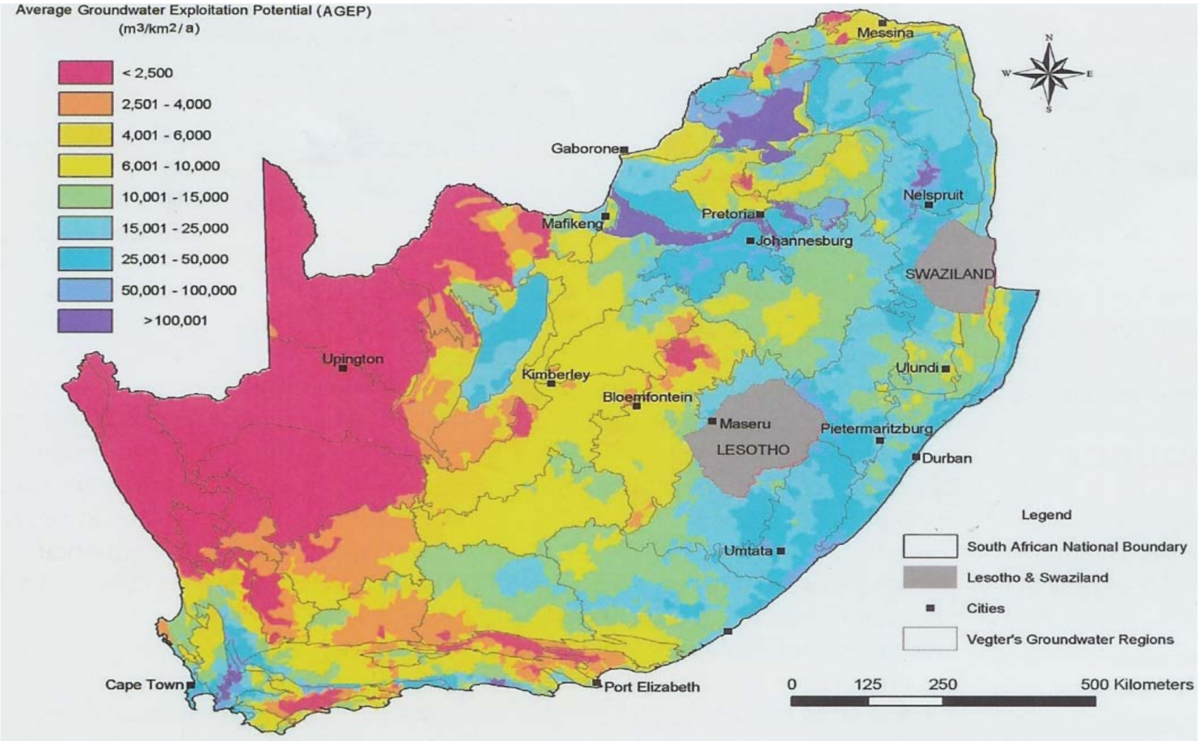
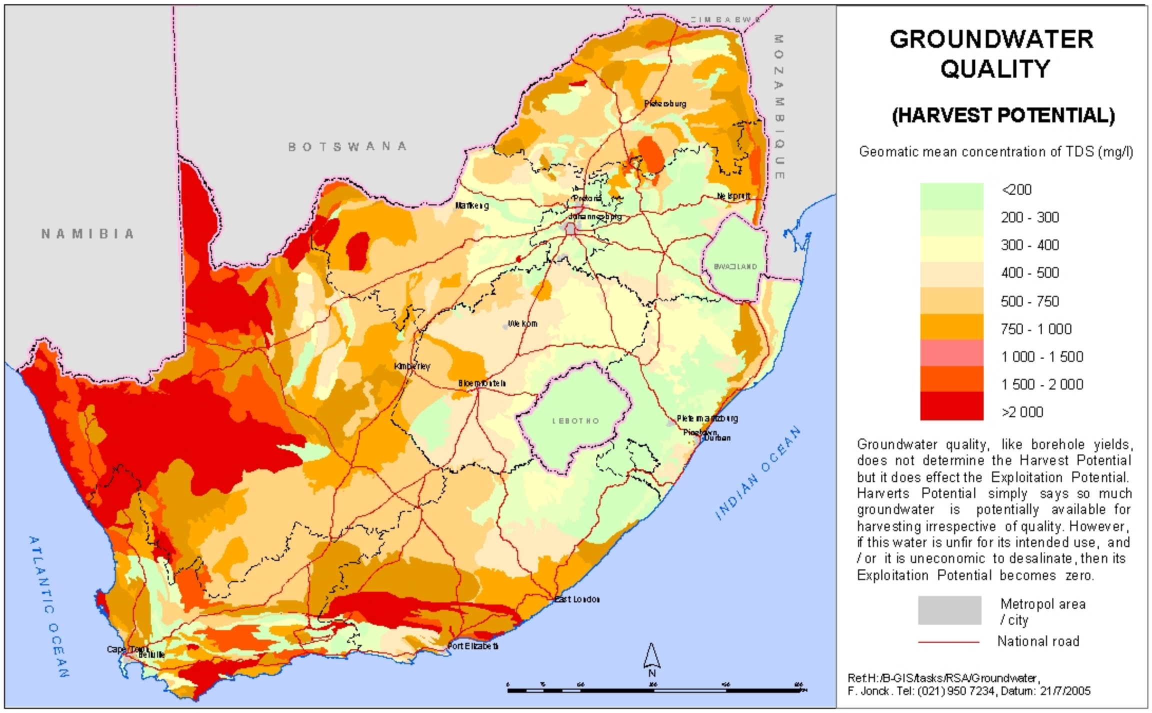


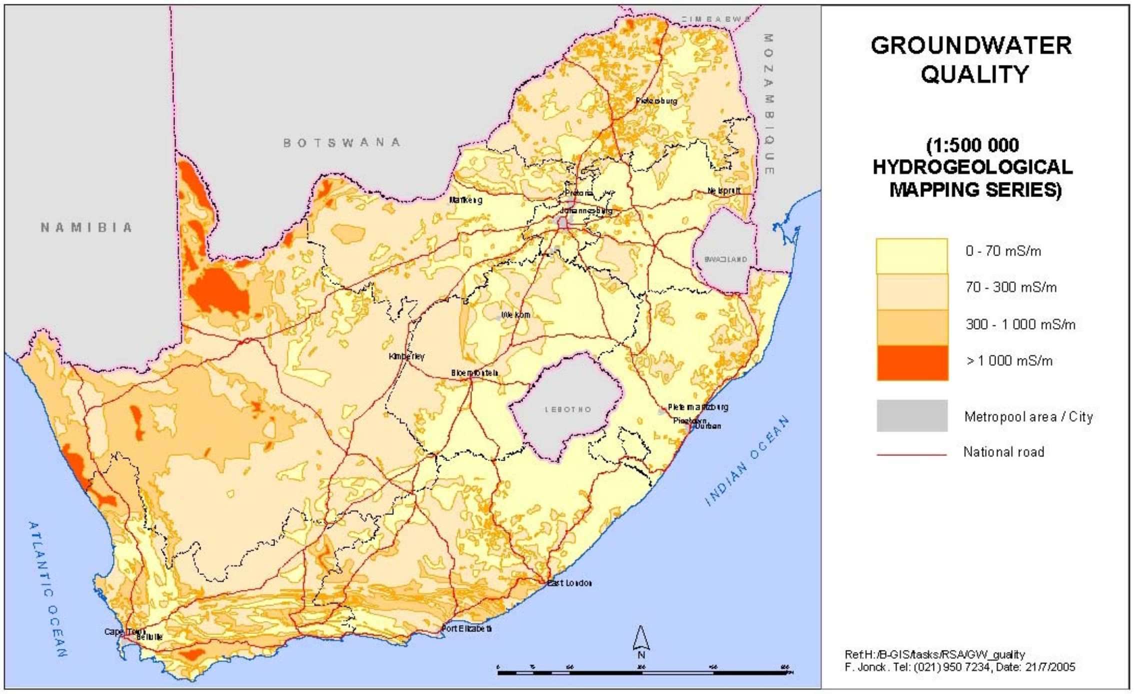
Figure D 1: Groundwater exploitation potential



Groundwater quality, like borehole yields, does not determine the Harvest Potential but it does effect the Exploitation Potential. Harverts Potential simply says so much groundwater is potentially available for harvesting irrespective of quality. However, if this water is unfir for its intended use, and / or it is uneconomic to desalinate, then its Exploitation Potential becomes zero.

Ref:H:/B-GIS/tasks/RSA/Groundwater,
F. Jonck. Tel: (021) 950 7234, Datum: 21/7/2005

Figure D 2: Groundwater quality: TDS



Ref:H:/B-GIS/tasks/RSA/GW_quality
F. Jonck. Tel: (021) 950 7234, Date: 21/7/2005

Figure D 3: Groundwater quality: Conductivity

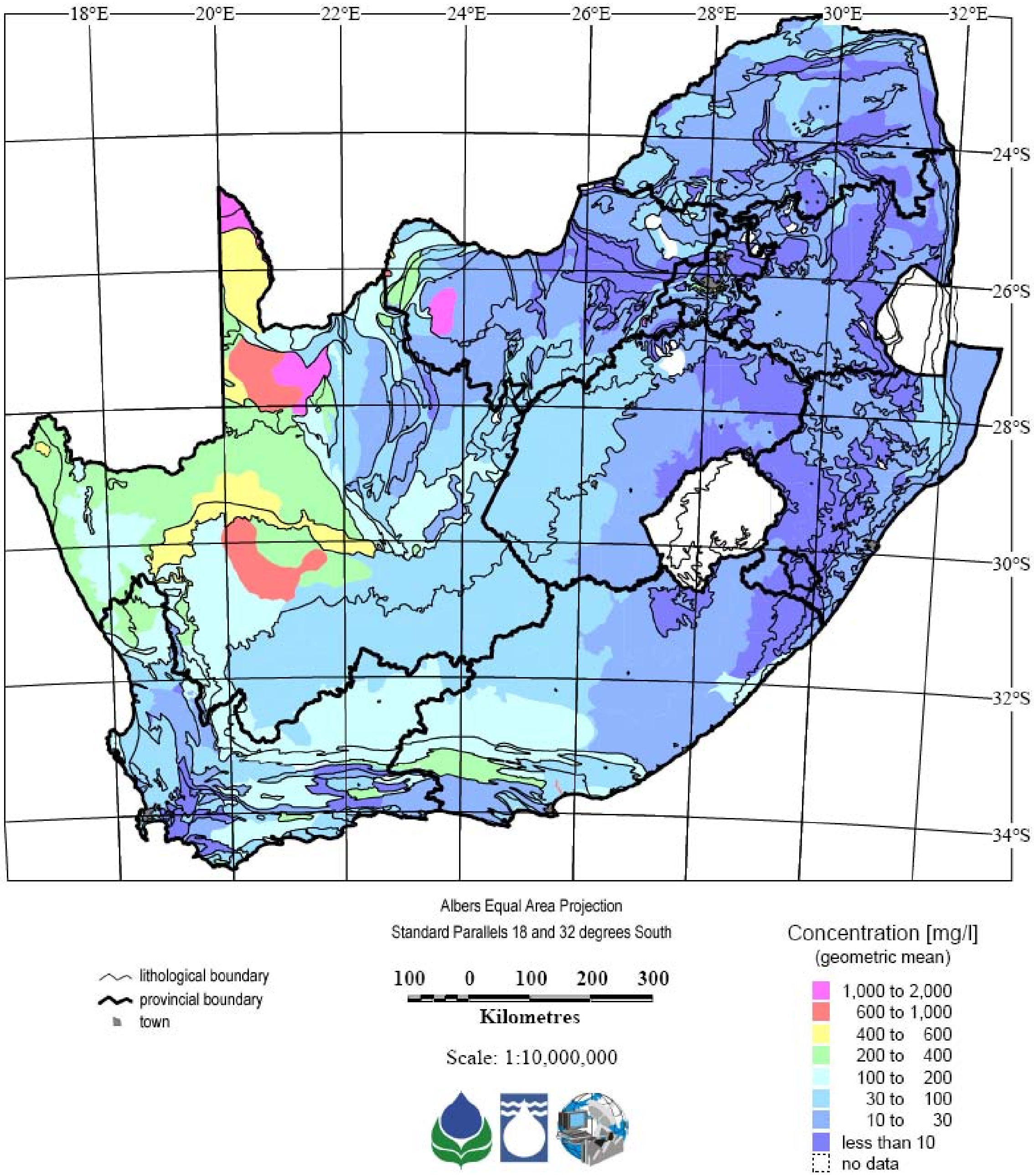


Figure D 4: Groundwater quality: Sulphate

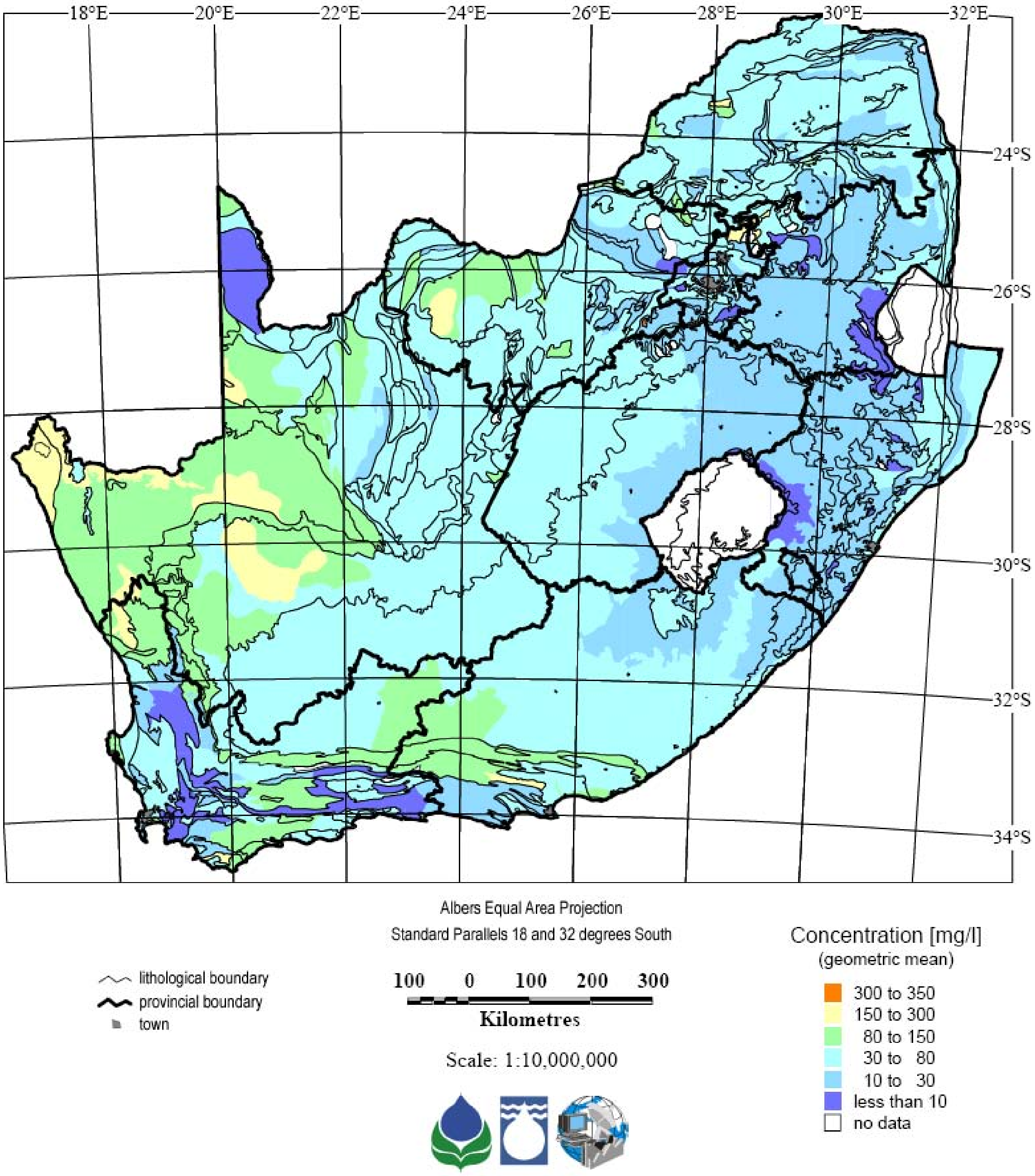


Figure D 5: Groundwater quality: Calcium

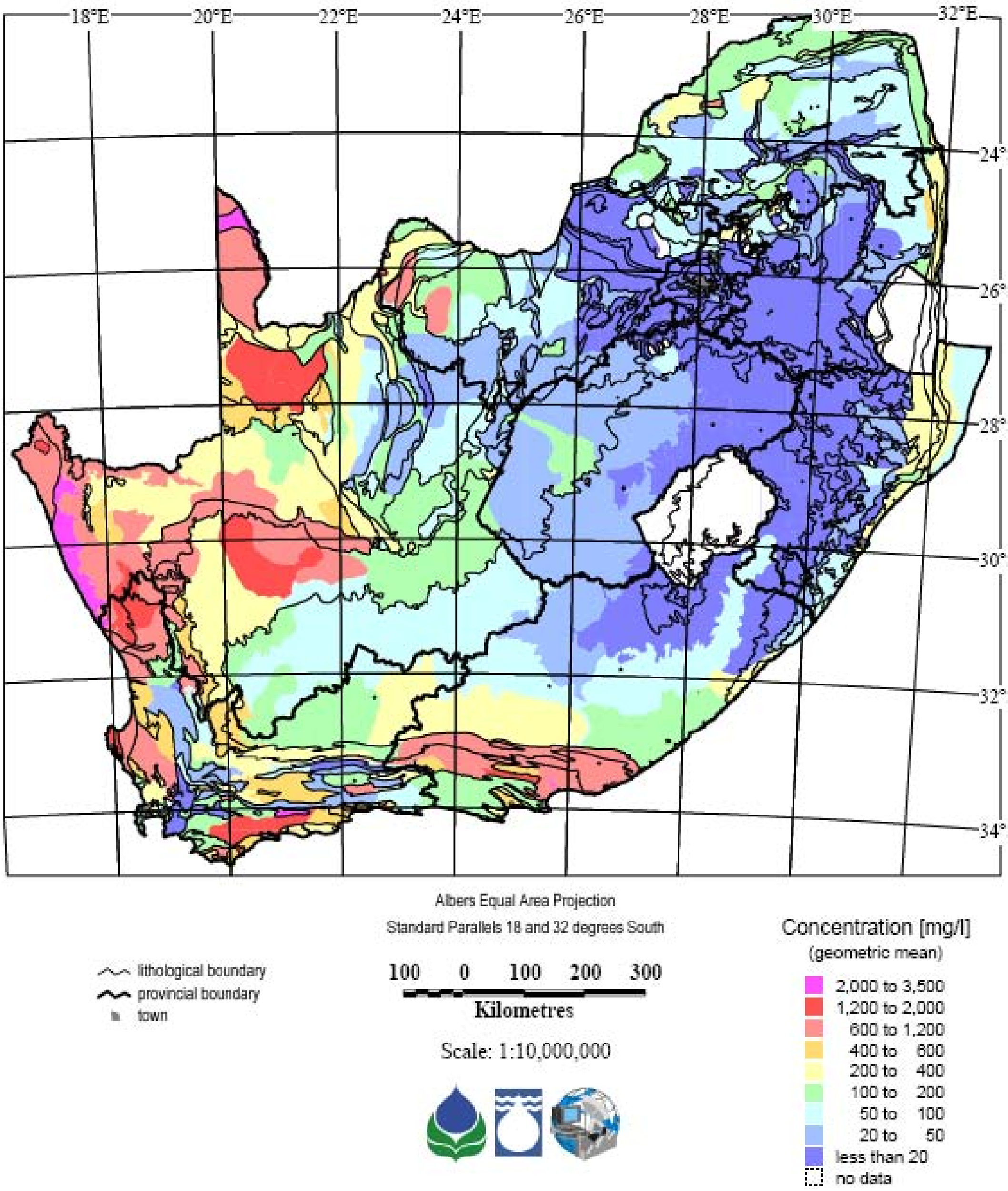


Figure D 6: Groundwater quality: Chloride

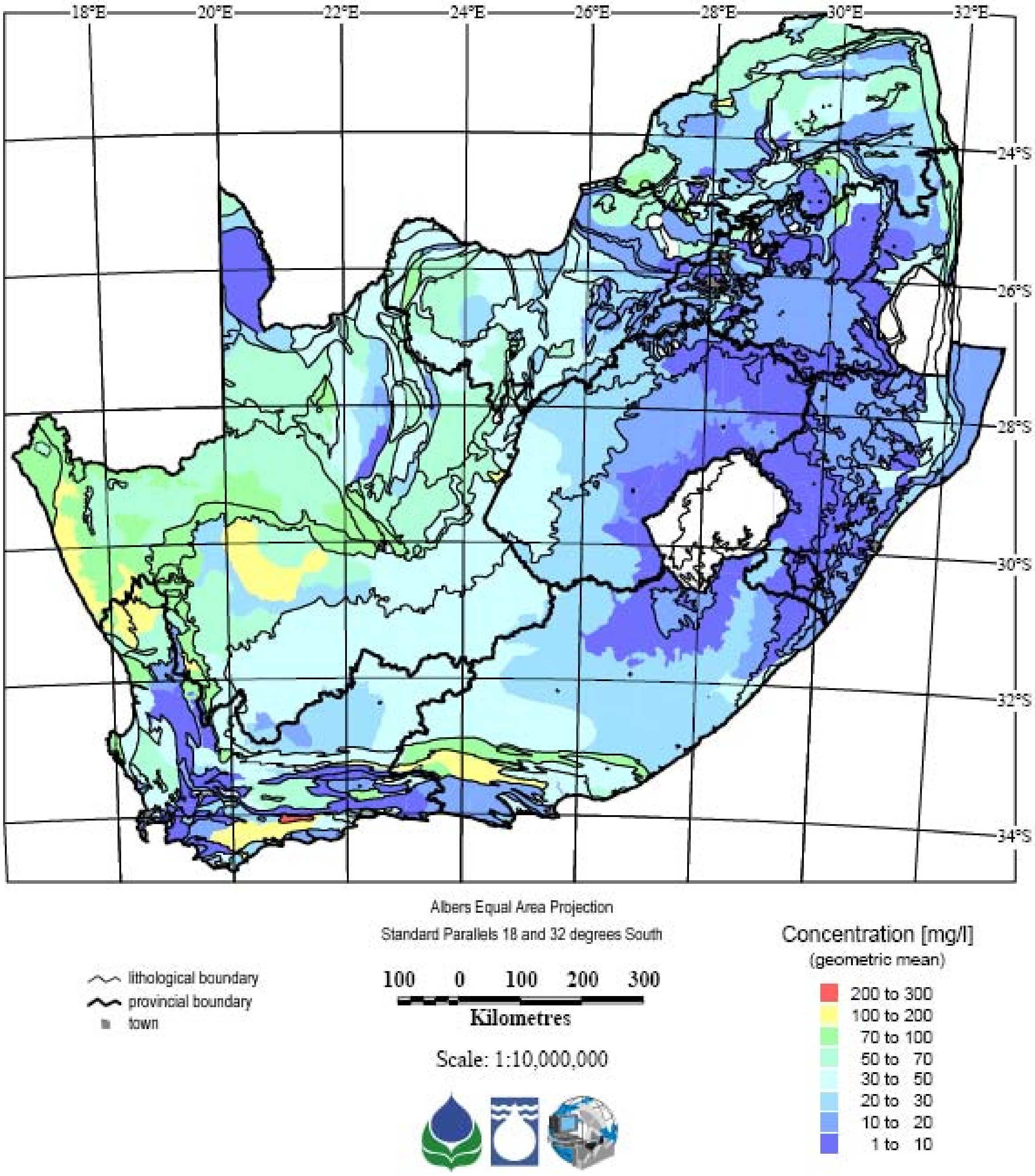


Figure D 7: Groundwater quality: Magnesium

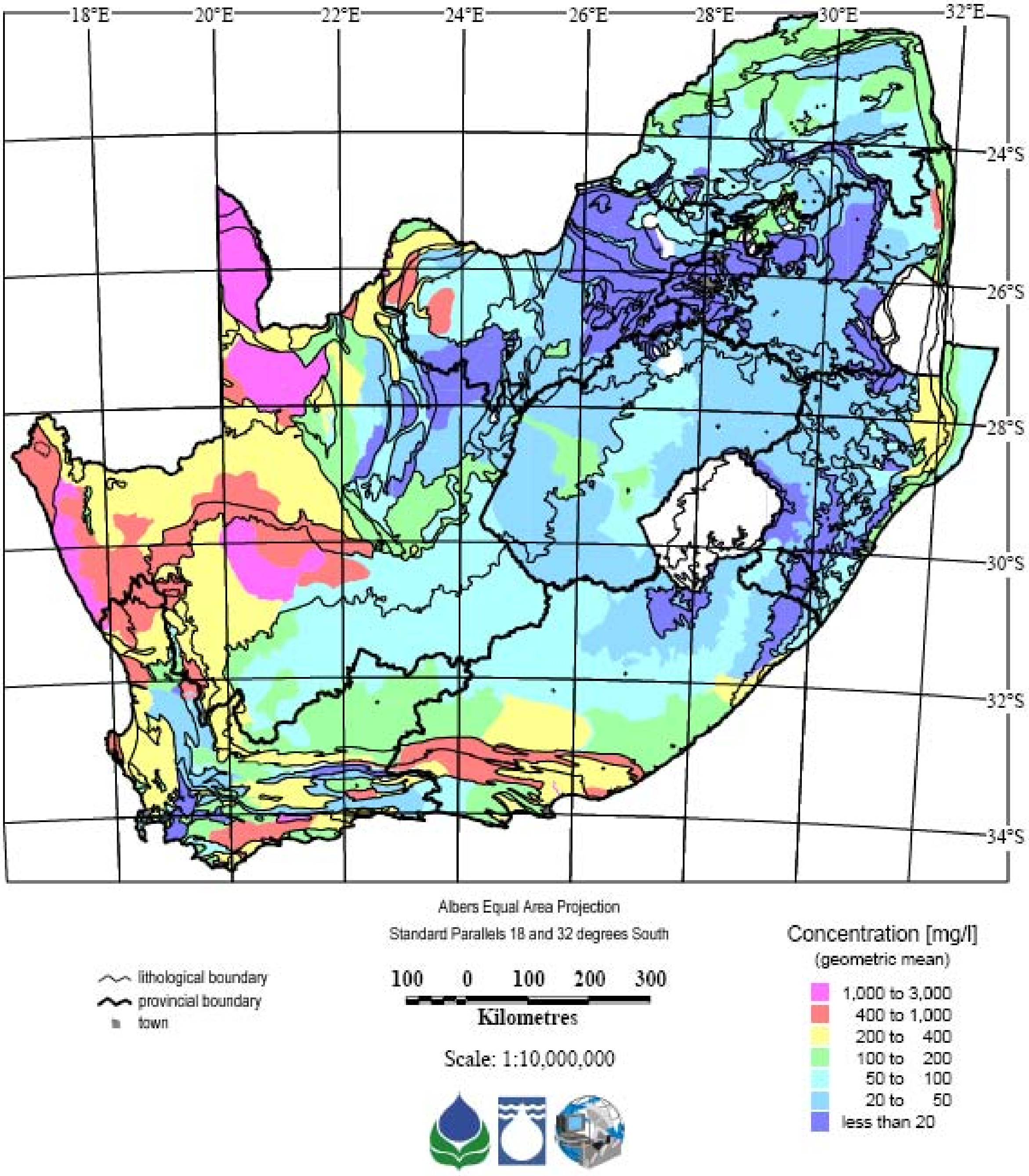


Figure D 8: Groundwater quality: Sodium

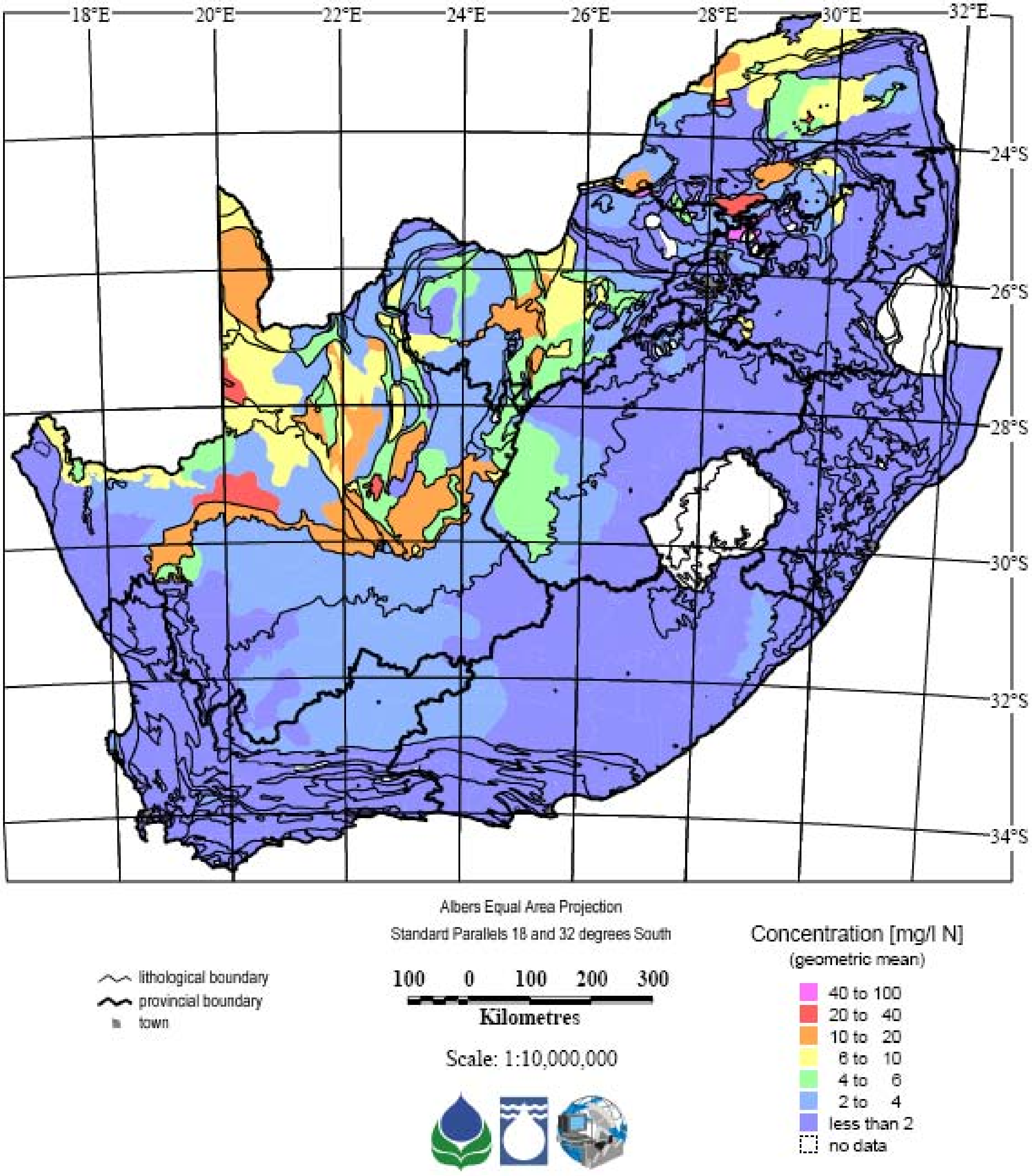


Figure D 9: Groundwater quality: Nitrates

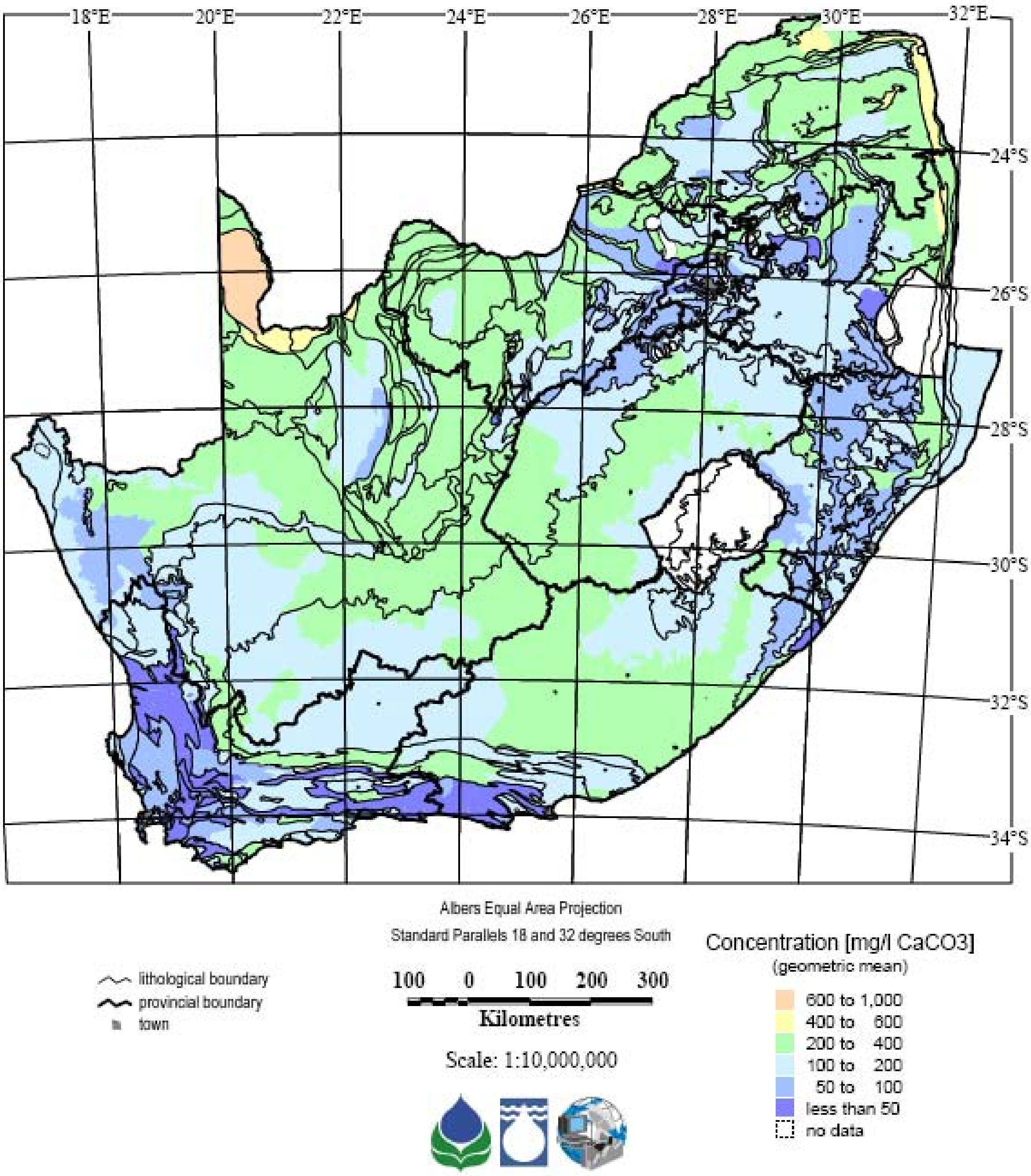


Figure D 10: Groundwater quality: Alkalinity

APPENDIX E:

COSTING TABLES FOR SOUTH AFRICAN SEAWATER AND BRACKISH WATER DESALINATION

SEAWATER DESALINATION

Table E 1: Seawater RO plants with single membrane pass

	Units	Notes	West coast		South coast		East coast	
			Small	Large	Small	Large	Small	Large
Daily capacity (permeate production)	ML / day		5 000	50 000	5 000	50 000	5 000	50 000
Typical design production rate	m³ / h	1	231	2 315	231	2 315	231	2 315
Feed TDS	mg / litre		36 000	36 000	36 000	36 000	36 000	36 000
Feed water temperature	°C		9	9	16	16	21	21
Water recovery over desalination section	%	2	40	40	42	42	45	45
Number of membrane passes	-	3	1	1	1	1	1	1
Energy recovery system installed	-	4	1	1	1	1	1	1
Complexity cost factor for pre-treatment	-	5	3.2	3.2	2.2	2.2	2.0	2.0
Capital expenditure (±35%)	Rands	6; 7	62 633 200	529 866 900	45 988 700	394 237 400	39 552 600	338 457 000
Operation and maintenance costs	R / m³	8	3.93	3.32	3.26	2.83	2.99	2.62
Capital redemption	R / m³	9	4.40	3.72	3.23	2.77	2.78	2.38
Unit cost of produced water	R / m³	10	8.32	7.04	6.49	5.59	5.77	4.99

Notes

1: Depends, amongst other, on the number of hours that the plant is operated per day. At small communities, this may be less than 12 hours per day. Most large plants operate 24 hours per day.
2: Depends on water chemistry and maximum pressure allowed for the specific selected membrane system.
3: Two passes are installed if low-TDS permeate is required from a seawater RO plant.
4: Standard for seawater RO plants, where pressures are high and recoveries low.
5: Highly dependent on a specific plant's feed water quality. A factor of 1 implies a single, complete, well-designed media filtration system.
6: Excluding large storage reservoirs and municipal distribution systems, access roads outside the plant area, power supply lines outside battery limits and (for BWRO) lined evaporation ponds.
7: Indicative cost with October 2005 as baseline for exchange rate and inflation. Note that well-built, lined concentrate evaporation ponds may easily increase the price by more than 50%.
8: Including energy, chemicals, membranes, consumables, maintenance and labour. Labour is plant specific and may vary drastically from site to site, depending on the use of existing labour.
9: Based on 25-year redemption period and 12% interest.
10: Including capital redemption, but excluding final cost of distribution and other municipal overheads.

SEAWATER DESALINATION

	Units	Notes	West coast		South coast		East coast	
			Small	Large	Small	Large	Small	Large
Daily capacity (permeate production)	ML / day		5 000	50 000	5 000	50 000	5 000	50 000
Typical design production rate	m³ / h	1	231	2 315	231	2 315	231	2 315
Feed TDS	mg / litre		36 000	36 000	36 000	36 000	36 000	36 000
Feed water temperature	°C		9	9	16	16	21	21
Water recovery over desalination section	%	2	40	40	42	42	45	45
Number of membrane passes	-	3	2	2	2	2	2	2
Energy recovery system installed	-	4	1	1	1	1	1	1
Complexity cost factor for pre-treatment	-	5	3.2	3.2	2.2	2.2	2.0	2.0
Capital expenditure (±35%)	Rands	6; 7	71 594 400	609 632 000	54 965 400	475 557 800	48 540 400	420 888 400
Operation and maintenance costs	R / m³	8	4.57	3.89	3.87	3.36	3.57	3.13
Capital redemption	R / m³	9	5.03	4.28	3.86	3.34	3.41	2.96
Unit cost of produced water	R / m³	10	9.60	8.17	7.72	6.70	6.98	6.09

Table E 2: Seawater RO plants with full double membrane pass

BRACKISH WATER DESALINATION

Table E 3: 200 ML/day brackish water RO plant at 15h per day operation

	Units	Notes	Low TDS	Low TDS	Low TDS	High TDS	High TDS	High TDS
			Low R	High R	High R	Low R	High R	High R
			Standard pre-treat	Standard pre-treat	Full lime pre-treat	Standard pre-treat	Standard pre-treat	Full lime pre-treat
Daily capacity	ML / day		200	200	200	200	200	200
Typical design flow	m³ / h	1	15	15	15	15	15	15
Feed TDS	mg / litre		2 000	2 000	2 000	12 000	12 000	12 000
Feed water temperature	°C		17	17	17	17	17	17
Water recovery over desalination section	%	2	60	85	85	60	75	75
Number of membrane passes	-	3	1	1	1	1	1	1
Energy recovery system installed	-	4	0	0	0	0	0	0
Complexity cost factor for pre-treatment	-	5	1.0	1.0	2.7	1.0	1.0	2.7
Capital expenditure (±35%)	Rands	6; 7	1 428 800	1 233 800	2 066 600	1 428 800	1 296 600	2 236 200
Operation and maintenance costs	R / m³	8	2.76	2.47	4.91	3.05	2.92	5.50
Capital redemption	R / m³	9	2.51	2.17	3.63	2.51	2.28	3.93
Unit cost of produced water	R / m³	10	5.27	4.64	8.54	5.56	5.19	9.43

Table E 4: 1600 ML/day brackish water RO plant at 24h per day operation

	Units	Notes	Low TDS	Low TDS	Low TDS	High TDS	High TDS	High TDS
			Low R	High R	High R	Low R	Medium R	Medium R
			Standard pre-treat	Standard pre-treat	Full lime pre-treat	Standard pre-treat	Standard pre-treat	Full lime pre-treat
Daily capacity	ML / day		1 600	1 600	1 600	1 600	1 600	1 600
Typical design flow	m³ / h	1	74	74	74	74	74	74
Feed TDS	mg / litre		2 000	2 000	2 000	12 000	12 000	12 000
Feed water temperature	°C		17	17	17	17	17	17
Water recovery over desalination section	%	2	60	85	85	60	75	75
Number of membrane passes	-	3	1	1	1	1	1	1
Energy recovery system installed	-	4	0	0	0	0	0	0
Complexity cost factor for pre-treatment	-	5	1.0	1.0	2.7	1.0	1.0	2.7
Capital expenditure (±35%)	Rands	6; 7	6 218 800	5 470 600	9 175 500	6 218 800	5 720 100	9 849 100
Operation and maintenance costs	R / m³	8	1.58	1.45	3.26	1.87	1.85	3.71
Capital redemption	R / m³	9	1.36	1.20	2.01	1.36	1.26	2.16
Unit cost of produced water	R / m³	10	2.94	2.65	5.28	3.24	3.10	5.88

Note: Low, medium and high R refer to water recovery

BRACKISH WATER DESALINATION

Table E 5: 6000 ML/day brackish water RO plant at 24h per day operation

	Units	Notes	Low TDS	Low TDS	Low TDS	High TDS	High TDS	High TDS
			Low R	High R	High R	Low R	Medium R	Medium R
			Standard pre-treat	Standard pre-treat	Full lime pre-treat	Standard pre-treat	Standard pre-treat	Full lime pre-treat
Daily capacity	ML / day		5 000	5 000	5 000	5 000	5 000	5 000
Typical design flow	m³ / h	1	225	225	225	225	225	225
Feed TDS	mg / litre		2 000	2 000	2 000	12 000	12 000	12 000
Feed water temperature	°C		17	17	17	17	17	17
Water recovery over desalination section	%	2	60	85	85	60	75	75
Number of membrane passes	-	3	1	1	1	1	1	1
Energy recovery system installed	-	4	0	0	0	0	0	0
Complexity cost factor for pre-treatment	-	5	1.0	1.0	2.7	1.0	1.0	2.7
Capital expenditure (±35%)	Rands	6; 7	16 113 500	14 823 000	23 383 600	16 113 500	15 236 300	24 499 400
Operation and maintenance costs	R / m³	8	1.25	1.19	2.77	1.55	1.56	3.17
Capital redemption	R / m³	9	1.13	1.04	1.64	1.13	1.07	1.72
Unit cost of produced water	R / m³	10	2.39	2.23	4.41	2.68	2.63	4.89

Note: Low, medium and high R refer to water recovery

APPENDIX F:

EVAPORATION PONDS

EVAPORATION PONDS

Many factors can influence the cost of the evaporation ponds required to allow for the disposal of the brine from a desalination plant. Aspects such as rainfall, evaporation, availability of appropriate dam building materials, location, topography and geology all can play important roles. The basic design principles adopted for compilation of the relevant cost curve include the following aspects:

- The area required for the evaporation of the brine received was based on net evaporation, using annual average rainfall and evaporation figures. No pan evaporation factors were used.
- Calculations were based on a cut to fill exercise.
- Calculations for the winter rainfall areas provide the most critical retention period to allow for the storage of brine from the wet winter months with very little evaporation to the drier summer months. A pond depth of approximately 1 meter provides for adequate storage. As the net evaporation decreases, the pond depth is also decreased to reduce storage. However, the depth of excavation for the pond is not allowed to be less than 400 mm from a practical point of view, although this provides for a retention time of almost 12 months in areas with low net evaporation.
- All evaporation ponds are lined to avoid leakage.
- All ponds are considered to be square and consist of 2 ponds to allow for maintenance and cleaning.
- The unit cost for the lining was accepted as R 45-00 /m^2, while the cut to fill cost were based on a rate of R 35/m^3, based on 2005 values.

Figure F 1 serves to provide a guideline as a first estimate to the possible costs for a well designed evaporation pond, based on annual net evaporation losses and the daily brine flow rate expected. These costs are considered to be conservative and can be reduced based on knowledge of the specific site and local weather situations.

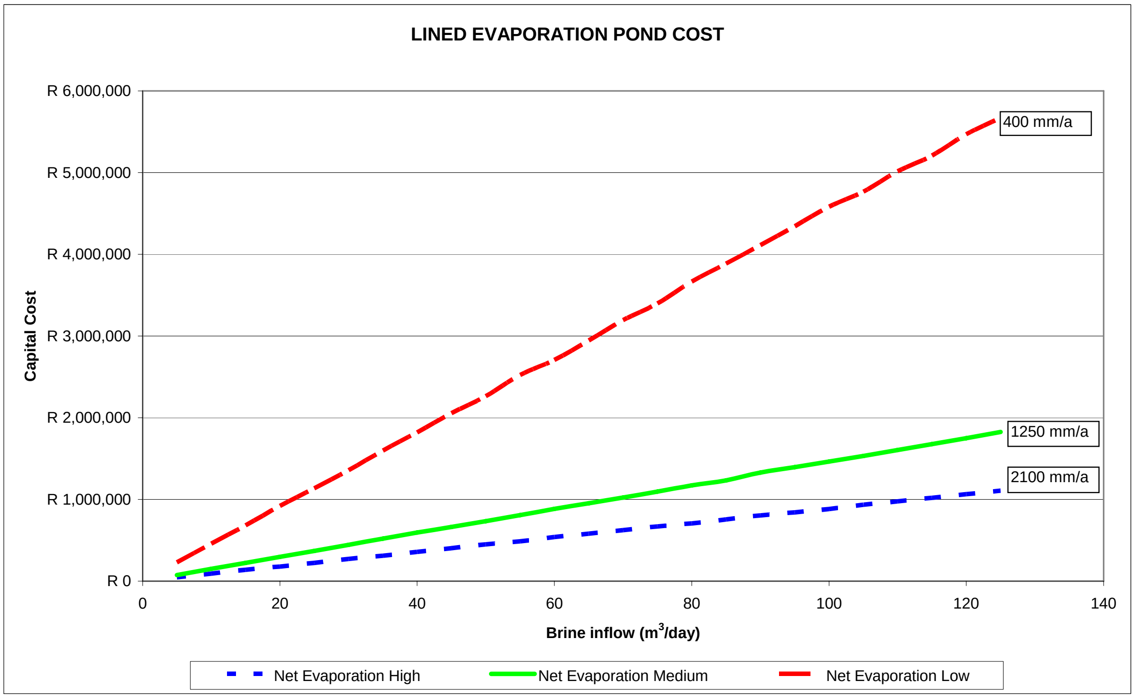


Figure F 1: Cost estimates for lined evaporation ponds (2005)

APPENDIX G:

ENVIRONMENTAL IMPACTS

Table G 1: Potential environmental impacts of various desalination processes

Desalination Technology	ENVIRONMENTAL IMPACT						
	Noise	Heat	Brine	Visual	Gas	Cleaning Solvents	Energy
MSF	🟨	🟥	🟥	🟨	🟨	🟥	🟥
MED	🟨	🟥	🟥	🟨	🟨	🟥	🟥
VC	🟨	🟥	🟥	🟨	🟨	🟥	🟥
RO	🟥	🟩	🟥	🟨	🟩	🟥	🟥
NF/UF	🟩	🟩	🟥	🟨	🟩	🟥	🟥
EDR	🟩	🟩	🟥	🟨	🟨	🟥	🟥
Solar Distillation	🟩	🟩	🟥	🟨	🟩	🟨	🟩

Notes: All Brackwater desalination options will have a risk of over exploitation of the water resources

Environmental aspects only refer to operational aspects. Construction will have a number of different possible environmental risks.

High Risk 🟥
Low Risk 🟨
No Risk 🟩

APPENDIX H:

MEMBRANE TECHNOLOGY COMPANIES

Table H 1: A selection of membrane technology companies (2006)

ASW Engineering P.O. Box 814, Randburg 2125 Tel: 011 793-1330 Fax: 011 793-4829 Cell: E-Mail: ken@asw.co.za Contact: Mr. Ken Meiring	**Biwater** P.O. Box 71942 Bryanston 2021 Tel: 011 549-7600 Fax: 011 463 8404 E-Mail: hardus@biwater.co.za Contact: Mr. Hardus Hattingh Position: Commercial Manager	**CH Chemicals (Pty) Ltd.** P.O. Box 13012 Mowbray 7705 Tel: 011 876 6738 Fax: 011 255 2938 Cell: 082 888 1344 E-Mail: hschade@chcgroup.co.za Contact: Mr. Hein Schade Position: Business Manager Separation Div.
Consolidated Water Conditioning P.O. Box 455 Germiston 1400 Tel: 011 828 0103 Fax: 011 828 9699 Cell: E-Mail: colin@cwc.co.za Contact: Mr. C W Brown Position: Managing Director	**Degremont (Pty) Ltd** P.O. Box 896 Sunninghill 2157 Tel: 011 807-1983 Fax: 011 807-4118 Cell: 083 274 3243 E-Mail: george.van.der.merwe@degremont.co.za Contact: Mr. George van der Merwe Position: Engineering/Project Execution Manager	**Explochem Water Treatment (Pty) Ltd** P O Box 400 Ferndale 2160 Tel : 011 888-3926 Fax : 011 888-3942 E-Mail : maniec@explochem.co.za Contact : Mr Manie Coopmans Position : Managing Director
FiltRSA Membrane Technologies (Pty) Ltd P O Box 3135 P O Matieland 7602. Tel : 021 808 3178 Fax : 021 808 3913 Cell : 082 801 6150 (Ed Jacobs) E-Mail : epj@sun.ac.za Contact : Prof Ed Jacobs Position : Operations Manager	**GE Water Technology** P.O. Box 800 Wendywood 2144 Tel: 011 237 0025 Fax: 011 314 0121 Cell: 083 380 4081 E-Mail: graham.heath@gesm.ge.com Contact: Mr. Graham Heath Position: Country Technical Manager	**Grahamtek Systems (Pty) Ltd** P O Box 3112 Somerset West 7129 Tel : 021 853 0699 Fax : 021 853 0692 Cell: 083 703 3930 E-Mail : neil@grahamtek.com Contact : Mr Neil Bezuidenhout Position : Director
Keyplan (Pty) Ltd P.O. Box 430 Kelvin 2054 Tel: 011 444 8120 Fax: 011 444 8014 Cell: 083 444 9006 E-Mail: info@keyplan.co.za Contact: Mr. Ralph Jones Position: Managing Director	**Pall South Africa** P.O. Box 3584 Halfway House 1685 Tel: 011 266 2300 Fax: 011 315 3243 Cell: 082 783 0802 E-Mail: jakes_jacobs@pall.com Contact: Mr Jakes Jacobs Position: Engineering Manager	**Paterson-Candy** P.O. Box 308 Northriding 2162 Tel: 011 704 5372 Fax: 011 704 5373 Cell: E-Mail: azihc@bv.co.za Contact: Mr Cletus Azih Position: Operations Director
Proxa (Pty) Ltd 1 Gimnasium Street, Paarl PO Box 43, Paarl, 7622 Tel: 021-872 0089 Fax: 021-872 7299 Cell: 083 321 2819 E-mail: wimpie@proxa.co.za Contact: Mr Wimpie van der Merwe Position: Managing Director	**Quality Filtration Systems (Pty) Ltd** PO Box 212 Somerset West 7129 Tel: 021 883 3534 Fax: 021 883 3469 Mobile: 083 269 5441 E-mail: qfs@iafrica.com Contact: Herman Smit Position: Director	**VWS Envig (Pty) Ltd** P.O. Box 7240 Noorder-Paarl 7623 Tel: 021 871 1877 Fax: 021 872 2664 Cell: 083 650 4277 E-Mail: bernardc@envig.co.za Contact: Mr. Bernard Cannon Position: Managing Director

APPENDIX I:

DESALINATION PLANTS IN SOUTH AFRICA

LIST OF SOME EXISTING DRINKING WATER DESALINATION PLANTS IN SOUTH AFRICA

The table below presents information on a selection of existing desalination plants in South Africa which are owned by a water supply authority (e.g. local authorities). It excludes privately owned desalination plants, such as may be found on farming estates, etc.

Desalination Plant	Owner/ Water Supply Authority	Capacity (m^3/h)	Number of persons supplied	Raw water TDS (mg/l)	Plant age (years)
Bitterfontein	West Coast District Municipality	12 (currently being upgraded to 38)	5 000	5 000	13
Robben Island	Cape Metropolitan Council	20			8
Bushman’s River Mouth	Albany Water Board	71	20 000	35 000	8
Rietpoort	West Coast District Municipality	1,8	1 000	2 500	
Kheis	Kamiesberg Municipality	1,6	450	5 000 – 15 000	6
Lepelfontein	Kamiesberg Municipality	1,6	370	5 000 – 15 000	6
Klipfontein	Kamiesberg Municipality	1,6	469	5 000 – 15 000	6
Spoegrivier	Kamiesberg Municipality	1,6	457	5 000 – 15 000	6
Soebatsfontein	Kamiesberg Municipality	1,6	241	5 000 – 15 000	6

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