INVESTIGATION INTO THE COST AND OPERATION OF SOUTHERN AFRICAN DESALINATION AND WATER REUSE PLANTS

Volume I:
Overview of Desalination and Water Reuse

KN Turner, K Naidoo, JG Theron, J Broodryk

WATER
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INVESTIGATION INTO THE COST AND OPERATION OF SOUTHERN AFRICAN DESALINATION AND WATER REUSE PLANTS

Volume I: Overview of Desalination and Water Reuse

Report to the
Water Research Commission

by

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The report forms part of a series of three reports. The other reports in the series are:

Volume II: Current Status of Desalination and Water Reuse in South Africa **(WRC Report no. TT 637/15)**
Volume III: Best Practices on Cost and Operational Aspects of Desalination and Water Reuse Plants **(WRC Report no. TT 638/15)**.

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EXECUTIVE SUMMARY

The aim of this project was to capture real operational and maintenance data (including associated costs) of selected desalination and water reuse plants, as well as to establish a first-order knowledge base for these types of projects in the augmentation of water supply in a Southern African context. The selected plants are:

No.	Plant	Type of Plant
1	Mossel Bay 15 Mℓ/d SWRO plant	Desalination – direct potable
2	Sedgefield 1.5 Mℓ/d SWRO plant	Desalination – direct potable
3	Albany Coast 1.8 Mℓ/d SWRO plant	Desalination – direct potable
4	Beaufort West 2.1 Mℓ/d reclamation plant	Reuse – direct potable
5	Windhoek 21 Mℓ/d Goreangab reclamation plant	Reuse – direct potable
6	George 10 Mℓ/d UF plant (full capacity tested as 8.5 Mℓ)	Reuse – indirect potable
7	Mossel Bay 5 Mℓ/d UF/RO plant	Reuse – direct industrial

This report (Volume I) provides background and insight into desalination and water re-use. A literature review on desalination and water reuse is presented to place these processes into context and provide an understanding of current state-of-the-art, including how these relate to the technology used at the selected plants.

Volume II follows with a report on the current status of desalination and water reuse in Southern Africa.

Volume III presents descriptions of the selected plants and their main processes, as well as summaries of the capital costs and O&M costs. The report then provides unit costs and comparisons with the other plants, and finally presents summaries of lessons learnt and best practices in desalination and water reuse.

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ACRONYMS & ABBREVIATIONS

ACIP	Accelerated Community Infrastructure Programme
ACWB	Albany Coast Water Board
AOP	Advanced Oxidation Processes
BAC	Biological Activated Carbon
BEE	Black Economic Empowerment
CAPEX	Capital Expenditure
CEB	Chemical Enhanced Backwash
CEC	Contaminant of emerging concern
CIP	Cleaning in Place
CMA	Catchment Management Agencies
CoGTA	Ministry for Cooperative Governance and Traditional Affairs
CPI	Consumer Price Inflation
DAF	Dissolved Air Flotation
DOC	Dissolved Organic Carbon
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation (formerly DWA)
ED	Electrodialysis
EDC	Endocrine Disrupting Compounds
EDR	Electrodialysis Reversal
EIA	Environmental Impact Assessment
ERD	Energy Recovery Device
GAC	Granular Activated Carbon
GDP	Gross Domestic Product
GWWTP	Gammams Wastewater Treatment Plant
HACCP	Hazard Analysis and Critical Control Points
HDD	Horizontal Directional Drilling
IPS	Institute of Polymer Science (University of Stellenbosch)
IRR	Internal Rate of Return
MED	Multi-effect distillation
MFMA	Municipal Finance Management Act
MIG	Municipal Infrastructure Grant
MISA	Municipal Infrastructure Support Agent
MOD	Manipulated Osmosis Desalination
MSA	Municipal Systems Act
MSF	Multi-stage-flash
MWIG	Municipal Water Infrastructure Grant
NACQ	Nominal Annual Compounded Quarterly
NF	Nanofiltration
NGO	Non-Governmental Organization
NGWRP	New Goreangab Water Reclamation Plant
NMBM	Nelson Mandela Bay Municipality
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
OHS	Occupational Health and Safety
OPEX	Operating Expenditure
PAC	Powdered Activated Carbon
PFMA	Public Finance Management Act
PPP	Public Private Partnerships
PSA	Pressurised Swing Adsorption

PST	Primary Settling Tank
RBIG	Regional Bulk Infrastructure Grant
REUSECOST	WRC Water Reuse Costing Model
RHIG	Rural Households Infrastructure Grant
RO	Reverse osmosis
RWU	Regional Water Utilities
SCADA	Supervisory Control and Data Acquisition
SHEQ	Safety, Health, Environmental and Quality
SLA	Service Level Agreement
SST	Secondary Settling Tank
SWRO	Seawater Reverse osmosis
TBMs	Tunnel Boring Machines
TCTA	Trans-Caledon Tunnel Authority
TDS	Total Dissolved Solids
TMP	Transmembrane pressure
TOC	Total Organic Carbon
TOU	Time of Use
TRO	Tubular Reverse Osmosis
TSS	Total Suspended Solids
UAE	United Arab Emirates
UF	Ultrafiltration
USA	United States of America
USDG	Urban Settlements Development Grant
UV	Ultra-violet
VCD	Vacuum Compression Distillation
VFD	Vacuum Freeze Distillation
WABAG	Proprietary technology from VA TECH WABAG Ltd
WHO	World Health Organisation
WINGOC	Windhoek Goreangab Operating Company Ltd
WRC	Water Research Commission of South Africa
WRP	Water Reclamation Plant
WSA	Water Services Authority
WSOS	Water Services Operating Subsidy
WSP	Water Service Provider / Water Safety Plan
WWTP	Wastewater Treatment Plant
WWTW	Wastewater Treatment Work

UNITS OF MEASURE

µm	micrometre
µS/cm	microsiemens per metre
bar(g)	bar gauge pressure
kPa(g)	kiloPascal gauge pressure
kVA	kilovolt ampere
kWh	kiloWatt hour
m^3/h	cubic meter per hour
mg/ℓ	milligram per litre
mS/m	millisiemens/meter
NTU	Nephelometric Turbidity Units
ppm	parts per million

CHEMICAL FORMULAS

$CaCl_2$	Calcium Chloride
$CaCO_3$	Calcium Carbonate (Lime)
Cl_2	Chlorine gas
CO_2	Carbon Dioxide
$FeCl_3$	Ferric Chloride
H_2O_2	Hydrogen Peroxide
H_2SO_4	Hydrogen Sulphate (Sulphuric acid)
$KMnO_4$	Potassium Permanganate
N_2	Nitrogen gas
$NaClO$	Sodium Hypochlorite (bleach)
Na_2CO_3	Sodium Carbonate (Soda Ash)
$NaOH$	Sodium Hydroxide (Caustic Soda)
$Na_2S_2O_5$	Sodium Metabisulphite (also referred to SMBS)
O_3	Ozone

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

South Africa is generally a water scarce country and water could become the limiting factor in sustaining social and economic development in the region in the future. The problem has historically been addressed by exploiting and transferring fresh surface water supplies to economic hubs and the interior of the country through schemes such as the Tugela-Vaal and the Lesotho Highlands projects. However many coastal cities, particularly in the Western and Eastern Cape, as well as KwaZulu-Natal are gradually outgrowing the natural fresh water resources available to them. The country as a whole is reaching the stage where the fresh water resources within its boundaries are nearly fully utilised and it has become necessary to investigate and exploit alternative sources of "new water" to augment existing supplies.

This state of affairs is addressed in the Department of Water and Sanitation’s (formerly Department of Water Affairs) National Desalination Strategy and the Draft National Strategy for Water Reuse (DWA, 2011), which highlight the need to consider desalination and reuse in future water supply schemes.

During the last three decades tremendous development and improvements in the use of membrane technology, both internationally and locally (Lipsett, 2012), have taken place. This allowed the technology to gain popularity in desalination (Than, 2011) and advanced water reclamation schemes (Wintgen et al., 2005) as a means of providing an alternate water resource.

Desalination by reverse osmosis is now considered as playing a considerable role in the future supply of water in South Africa by the general water community (Holman, 2010), as well as at ministerial level (Davis, 2010). To this end, a literature review was conducted on the topic of reuse and desalination to put the treatment approach and technology into context and provide an understanding of current state-of-the-art treatment processes and configurations and how these relate to the technology used at the plants investigated under this research project.

This report concentrates on seawater desalination by reverse osmosis at coastal locations. Although the inland desalination of brackish water sources (e.g. ground or surface water) is also of importance, the desalination plants included in this investigation relate to the production of potable water from seawater.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To evaluate and report on the various costs (capital and operating) of the desalination and reuse plants as a function of the quantity of water produced, as well as the various technologies used with focus on the progression from non-potable to potable desalination and reuse.
2. To report on the technical, as well as operational and maintenance challenges experienced in operating the desalination and reuse plants with reference to project implementation issues.
3. To provide concise Best Operating Practices to maximise production of desalinated and reclaimed water while at the same time ensuring the sustainability of the technology in terms of cost minimisation.
4. To provide a concise report on the various institutional models which can be used to finance and operate desalination plants with a view to minimising risk to the end-user.

1.3 SCOPE AND LIMITATIONS

This report (**Volume I**) covers the initial task, which was to conduct a literature search on the topic of water reuse and desalination to put the process into context and provide an understanding of current state-of-the-art treatment processes and configurations, including how these relate to the technology used at the identified plants. During this period the researcher also made contact with the various collaborating parties to establish communication and flow of information, access specialised knowledge on the subject and determine what additional aspects they would like to see being addressed in the project.

Also available is **Volume II**, where the current status of desalination and water reuse in South Africa is reviewed, as well as **Volume III**, which details the selected desalination and water reuse plants in South Africa, including plant and process configurations, various product end uses, as well as a number of contractors and equipment suppliers. Each plant location and situation has different advantages and challenges to be evaluated for making the best decisions for implementation. Around 2009/10, the Southern and Eastern Cape regions of South Africa experienced the worst drought in known history, and to prevent the risk of complete water supply failure a number of desalination and water reuse projects were undertaken.

Data for the desalination plants at Knysna and Plettenberg Bay is also readily available, and so these plants may be used as comparisons and to provide supplementary data. There has been increasing pressure in recent years on surface water supply to meet the growth in water demand. Water reuse and desalination are now being considered as options both on a local/regional level in the Integrated Development Plans of city councils and municipalities, as well as in national strategies by the Department of Water and Sanitation. The Southern Cape has almost exhausted its terrestrial water resources, particularly as a result of the drought. Furthermore, other parts of the Western Cape, Eastern Cape and KwaZulu-Natal are fast approaching the limits of the terrestrial water resources.

Without adequate freshwater resources, municipalities will have to consider desalination and water reuse to gain access to alternative, as yet less exploited water sources. Without sufficient water, economic growth is likely to stall, resulting in a decline in socioeconomic conditions. In addition to this, health standards are likely to decline. A substantial amount of literature exists in the public domain with respect to cost and water quality aspects for desalination and reuse plants. However, none of these provide real information on cost and water quality obtained from actual plants constructed in South Africa. This research project enhances the knowledge on the subject within the South African water community and will provide information relevant to the South African situation and context. This project entails gathering of cost, operational and other data associated with local (South African) desalination and water reuse plants that have been implemented recently and are planned for implementation in the near future.

The information gathered during the project will be of beneficial use to municipal engineers and the water community as a whole to define real costs for desalination and reuse. This may be used for more effective future planning and comparison of different water supply options.

For reasons of practicality and availability of useable and relevant information, the battery limits for the project were the seven existing desalination plants under investigation, namely:

No.	Plant	Type of Plant
1	Mossel Bay 15 Mℓ/d SWRO plant	Desalination – direct potable
2	Sedgefield 1.5 Mℓ/d SWRO plant	Desalination – direct potable
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CHAPTER 2: OVERVIEW OF DESALINATION & WATER REUSE

2.1 INTRODUCTION

Roughly 70% of the earth's surface is covered by water, of which 3% is fresh water and the remaining 97% saltwater in the oceans. In addition most of the fresh water is locked up in glaciers and icecaps as shown in Figure 2.1. Of the available fresh water, only roughly 0.3% is considered renewable, i.e. precipitation that occurs over land and is easily available for human use.

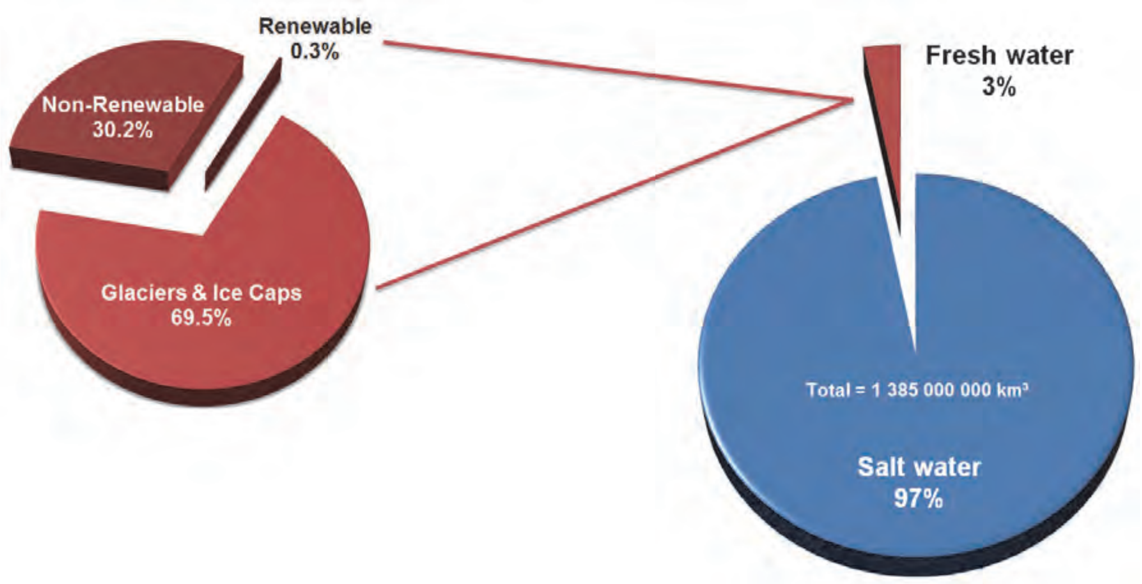


Figure 2.1: Distribution of the World's Water

The renewable fresh water therefore is a small amount, visually illustrated by a sphere with a diameter of 60 km, in relation to the total water sphere that is 1 400 km in diameter. Shown in Figure 2.2, the 60 km sphere of renewable fresh water would be scarcely visible in the image.

The ever-growing world population and adverse climate changes place an increasing strain on suitable water sources, especially in existing water-challenged areas. Another problem is uneven distribution, as many countries have sufficient water, but in the wrong place.

This situation is expressed in the accompanying water scarcity projection chart (IWMI, 2000).

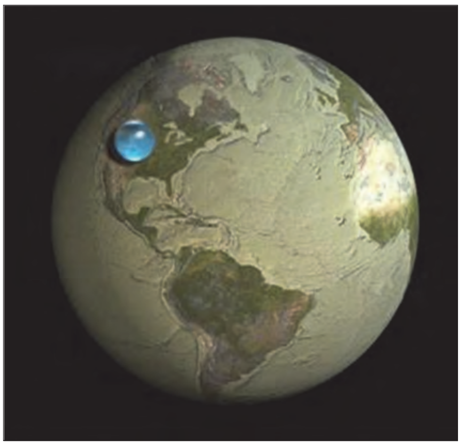


Figure 2.2: Total Water Sphere

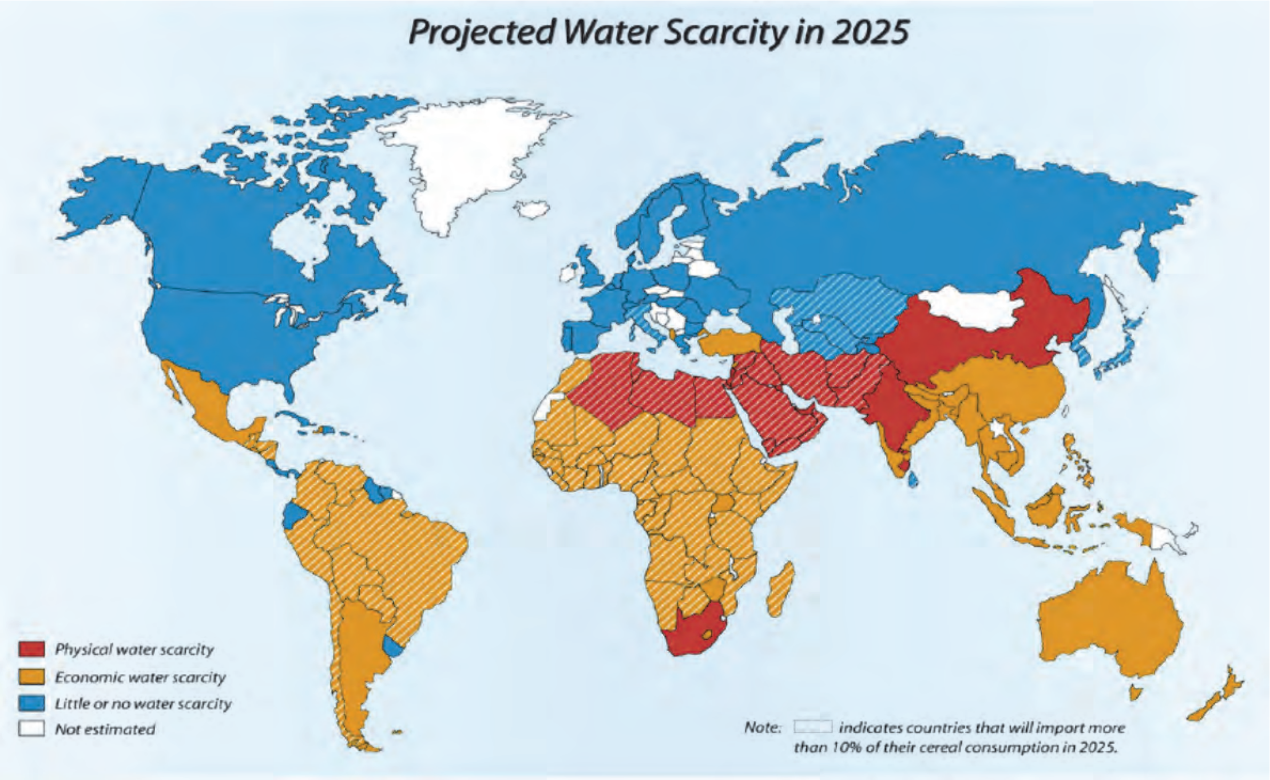


Figure 2.3: Projected Water Scarcity in 2025

Producing potable water from some of the 99.7% fraction of salt and non-renewable water is the challenge for desalination and reuse. To do this the relevant technology must be able to provide solutions for places that need, and will need, water most on a cost-effective and reliable basis.

As pointed out above the increasing water scarcity will challenge the human population more and more in the future. With water being a finite resource the obvious approach to counter this is to focus on efficient use and conservation. Ultimately a number of approaches will be necessary to curb the growing water problem, e.g. implementing policies for water conservation and reuse, slowing population growth and tapping into non-traditional sources to augment fresh water supplies. From a traditional perspective the most practical way of increasing the water supply is to build new dams and to harvest the available renewable water supply more effectively. However, with most resources already being close to fully exploited, the only other alternative to grow the water supply is to create “new” or “produced’ water. This is the objective of desalination and reuse.

From a global perspective desalination and reuse are likely to have a relatively small impact on the total fresh water supply. On a local basis, however desalination and reuse could play a significant role due to the “locality” aspect associated with the supply and use of water mentioned in the previous section.

2.2 DESALINATION OVERVIEW

Desalination refers to processes that reduce the salinity of the water fed to a particular treatment process. All naturally occurring waters contain dissolved substances which contribute to their varying salinities.

The three basic approaches to separate salt from water are by thermal means, physical separation or chemical process.

Thermal means relate to distillation processes where the saline water is boiled to effect a phase change in order to drive off pure water vapour from the salt solution. The main commercial thermal (distillation) processes are multi-stage-flash (MSF) and multi-effect distillation (MED) techniques. Another thermal method refers to the separation of salt from water by freezing of the feedwater, thereby separating fresh water from the saline solution.

A secondary approach is physical separation of the dissolved salts from the saline solution. This is generally done with a membrane, which can be considered to act as an extremely fine “sieve”. The two main membrane processes used for desalination are reverse osmosis (RO) and electrodialysis (ED).

Lastly chemical approaches to desalination include physical-chemical processes, such as ion exchange (IX), liquid-liquid extraction and precipitation. Chemical processes are generally too expensive to apply to the production of fresh water as standalone processes. Ion exchange, on the other hand, is widely used for softening or the production of highly demineralised water for industrial applications (e.g. boiler feedwater preparation).

Desalination processes are applied to saline feedwater to typically convert a portion of the feed stream into a product stream of reduced salinity. A simplistic view is that all desalination processes split the saline feed stream into a stream of desalinated (fresh) water and a concentrated (brine) stream by utilising energy. Normally the desalinated stream constitutes the product with the brine being the waste stream, as illustrated in the accompanying schematic.

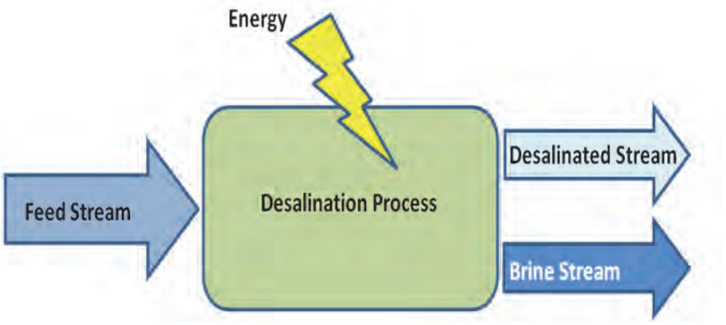


Figure 2.4: Desalination process energy

The energy used by the desalination process can take the form of heat (e.g. thermal desalination), pressure (e.g. membrane desalination) or electricity (e.g. electrodialysis), as shown in Figure 2.4.

The main groups of desalination processes are thermal processes and membrane processes. In saline feedwaters, two main categories can be distinguished, viz. seawater and brackish water.

This report will focus on pressure-driven membrane processes, in particular the reverse osmosis (RO) process as applied to the desalination of seawater. The other desalination approaches are further detailed in Appendix A.

2.2.1 Historical Timeline of Desalination

The concept of desalination for the removal of salts from sea water using primitive methods of distillation is not new and has been applied for thousands of years (Fox, 2012). However, methods applied to desalinate water, were not only limited to the need for recovery of fresh water but also for the need of salt which was a precious commodity. The concept of desalination relates to Greek, as well as 17th century Japanese sailors that used earthenware pots to boil seawater, and bamboo tubes to collect condensed fresh water from the steam. The Romans are reported to have used clay filters to trap salt. There are also biblical references as well as historical accounts from ancient Egyptian, Phoenician and Greek writings, mentioning the purification of brackish water.

The need to supply freshwater to remote locations, such as naval ships resulted in the development of methods to replenish freshwater supplies and this led to the issuing of the first desalination patent in 1852 (GWI, 2012). Some key developments and turning points in recent desalination history are summarised below (adapted from various sources, namely DEPI, 2013 and GWI, 2012).

Table 2.1: Summary of Desalination History

Date	Event
320 BC	First written record of saline water desalination, by Aristotle
1684	Shipboard desalination, UK. "An experiment to produce fresh water out of salt"
1791	First technical report of the desalination process written by Thomas Jefferson (US Secretary of State)
1940s	Mobile and ship based desalination units used extensively by military forces in WWII
1955	Smith from the CSIR laid the foundation for ED theory, later used internationally. Installed ED treatment system at the FS Gold Mines this year
1955	Development of the MSF process
1958	Office of Saline Water, USA established to research and develop desalination technologies
1959	First large scale MED installation, Netherlands Antilles
1961	Development of the first asymmetric, commercially useful RO membrane by Loeb and Sourirajan
1963	First hollow fibre RO membrane produced (DuPont)
1972	First locally produced South African tubular RO, by Bakke Industries, Paarl (later Envig) with WRC funding.
1972	Thin film composite RO membrane developed by Cadotte
1974	First single pass SWRO plant, Bermuda (Polymetrics)
1978	Largest thermal desalination plant capacity ever built, Al-Jubail Phase 2 MSF (908 000 m^3/d)
1980	Entropie's first commercial MED unit, France
1980s	Desalination becomes commercially accepted, widely used and successful, as well as more affordable
1990s	Dramatic increase and improvement in reverse osmosis technology as energy use and costs decrease. Large scale plants constructed across the Middle East, Mediterranean and America
2005	Largest membrane desalination plant ever constructed at Ashkelon, Israel SWRO (330 000 m^3/d)
2006/12	Large SWRO plants constructed, e.g. Melbourne (600 000 m^3/d), Hadera (462 000 m^3/d), Sydney (500 000 m^3/d), Adelaide (275 000 m^3/d)

2.2.2 Current Desalination Technologies

As mentioned before desalination technologies may be divided into the main categories of:

- Thermal processes (e.g. multi stage flash and multiple effect distillation)
- Chemical processes (e.g. ion exchange and precipitation processes)
- Physical processes (e.g. membrane and ion exchange processes)

The salinity of the feedwater is defined according to the total dissolved solids (TDS) concentration, typically expressed in milligrams per litre (mg/ℓ). Feedwater is typically categorised as follows:

- Seawater: 15 000 to 50 000 mg/ℓ TDS
- Brackish water: 1 500 to 15 000 mg/ℓ TDS
- Surface water: 500 to 3 000 mg/ℓ TDS
- Pure water: less than 500 mg/ℓ TDS

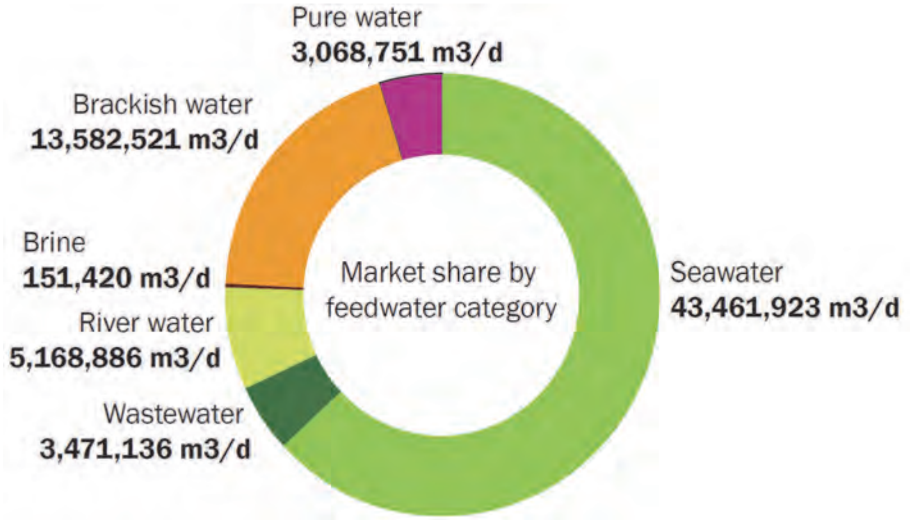


Figure 2.5: Desalination Market by Feedwater Category (GWI, 2011)

A breakdown of the desalination market by feedwater category is shown in Figure 2.5. It follows that the existing emphasis is on the desalination of seawater, followed by the treatment of brackish water and wastewater (which may be considered to include reuse).

2.2.3 Reverse osmosis

Reverse osmosis is the desalination technology of choice in South Africa at present. RO is a pressure driven membrane process with the required energy being provided by high pressure pumps. Pure water is pushed through the semi-permeable membrane by reversing the natural osmotic process (hence the term ‘reverse osmosis’). The membrane allows the passage of water, but not dissolved salts. Please refer to Figure 2.6 for a schematic representation of the process. The pressure required must be higher than the osmotic pressure of the saline feedwater. Therefore the required energy depends on the salinity of the feed since higher salinity implies higher osmotic pressure. The net driving force is the difference in applied pressure and osmotic pressure of the saline feed. The use of reverse osmosis in desalination applications was pioneered in the 1960s as a result of the development of a useful reverse osmosis membrane by Loeb and Sourirajan (Loeb, 1981).

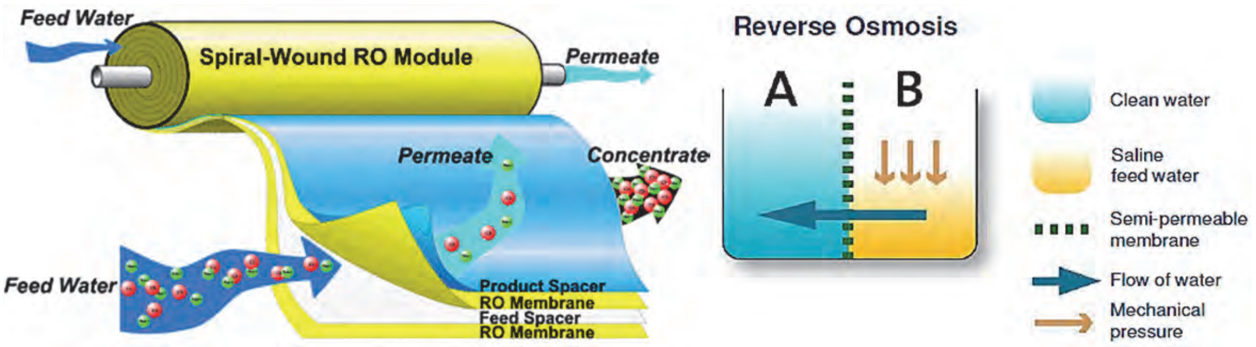


Figure 2.6: Membrane Desalination Schematic representation of RO process

Since commercialisation in the 1970s there has been a tremendous improvement in membrane efficiency and quality, resulting in a dramatic fall in the cost of desalination using RO. The primary difference between seawater and brackish water is the salt content, which has a direct effect on the operating pressure, energy requirement and water recovery (portion of feedwater that is converted to product water).

2.2.4 Geography of desalination

Desalination is currently used by countries that have an extreme need for fresh water, have sufficient financial capability to fund it and have access to energy required to produce it.

The Middle East holds the top spot for desalinated water, due to large facilities installed in several countries, including Saudi Arabia, the United Arab Emirates, and Israel. Other large producers of desalinated water are: Spain, the United States, Algeria, China, India and Australia. The technology is expected to spread increasingly, particularly in the United States, Libya, China, and India.

This is reflected in the desalination market rankings of the top 15 countries with respect to expenditure as illustrated in Table 2.2 (GWI, 2010).

In the United States, the largest desalination plant is located in Tampa Bay, Florida, though it has a very small output compared to most facilities in the Middle East. Other states that are developing plans for large desalination plants include California and Texas. The United States need for desalination plants is not as severe as many other countries, but as the population continues to explode in dry, coastal areas, the need increases.

Table 2.2: Top 15 desalination markets, 2010 to 2013

Position		Country	Capital Expenditure
1	(2)*	Saudi Arabia	$5 159 m
2	(7)*	USA	$4 419 m
3	(3)*	Australia	$3 237 m
4	(16)*	Israel	$2 503 m
5	(13)*	Kuwait	$2 480 m
6	(15)*	Libya	$2 443 m
7	(1)*	UAE	$2 198 m
8	(5)*	China	$1 517 m
9	(9)*	India	$1 293 m
10	(21)*	Chile	$1 200 m
11	(17)*	Caribbean	$1 069 m
12	(29)*	Morocco	$926 m
13	(4)*	Spain	$861 m
14	(11)*	Oman	$785 m
15	(20)*	Iran	$709 m

*The position in brackets represents the country’s market rank during 2008/09

The worldwide emphasis on the desalination of seawater by RO is also illustrated by the annual contracted capacity compared to brackish RO and thermal technologies as shown in Figure 2.7.

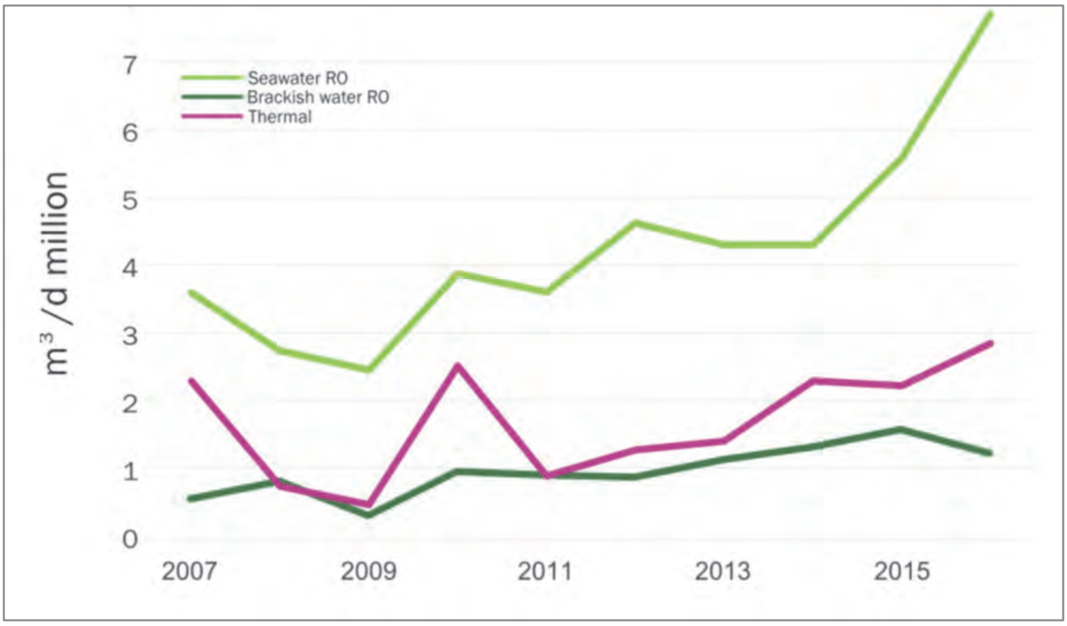


Figure 2.7: Thermal versus membrane technology by annual contracted capacity (GWI, 2011)

2.2.5 Basic aspects of seawater desalination by reverse osmosis

The following points summarise some key technical fundamentals of seawater desalination by RO:

- The RO process for the desalination of seawater operates at approximately 40 to 50% recovery, i.e. 40 to 50% of the seawater feed is converted to product water. This means than more than twice the flow of product water required must be pumped from the ocean, and slightly more than the produced flow must be returned. As a result the piping and pumping costs for the seawater intake and the concentrate return are higher per length than the delivery cost of the final product water. The implication is that it is more economical to locate the desalination plant as close as possible to the ocean source.

- In the case of smaller plants (< 2 Mℓ/day) the seawater intake and concentrate return can be accommodated by beach wells. For larger capacities, however, open intake and brine outfall systems are preferred, both from a cost and implementation perspective. Beach wells offer the advantage that the raw water has been pre-filtered naturally, resulting in less additional pre-treatment that is required (depending on suitable soil conditions and absence of pollution ingress). Open intake systems imply that the pre-treatment of the raw water may need to make provision for the removal of elevated levels of suspended solids, turbidity, organics and even microbiological constituents, e.g. phytoplankton, algae, etc.

- Drawing from seawater in deeper open ocean levels, which are unaffected by inflows from land leads to more consistent salinity and lower suspended solids. This is ideal for larger plants, but ocean floor bathymetry, wave action and other considerations that have an effect on plant design need to be taken into account.

- Dispersion of the concentrate from the desalination plant to the sea can be done effectively in the case of open sea outfalls by using diffusers on the outlet pipeline. This, however needs a minimum depth of water (refer bathymetry) depending on the generated brine flows, local currents and other conditions. Dispersion of concentrate via beach wells needs to allow for flushing of the pipelines, as well as take into consideration the permeability of the sand and are only acceptable at lower flows.

- The cost of piping and pumping product water is also significant. It is, therefore, preferable to site the plant at a location where the ocean abstraction point and plant site are relatively close to the point where the water can be introduced into the water supply system. Furthermore, the height to which the product water must be lifted to reach the supply system affects the costs and energy use, so desalination plant sites that are close to areas where lower lifts are required, are preferred.

- The plants are also fairly energy intensive. To this end, it is important that to ensure that sufficient infrastructure for the supply of electricity is available. If not, then this infrastructure will have to be developed, which could have a direct bearing on the suitability of the proposed plant location from a cost and implementation perspective.

- In order to reduce the energy demand of the RO plant the hydraulic energy (as a result of high pressure) remaining in the concentrate stream should be recovered. This may be achieved by fitting the plant with an energy recovery device that reduces the net energy input required to pressurise the feedwater.

- The desalinated water produced (RO permeate) is essentially stripped of all alkalinity and hardness. This, together with an acidic pH makes the water corrosive and aggressive to metal pipe work. The need for remineralisation (i.e. adding back alkalinity and hardness) to reduce the corrosivity of the product water must be considered in relation to potential detrimental effects on the distribution network. The potential blending with other water supplies and the selection of the pipe construction material for conveying RO permeate will have a direct bearing on this aspect.

- Compatibility of the desalinated water with the terrestrial water quality to ensure corrosion and scaling is not excessive over all blending ratios and seasonal changes.

2.2.6 Site selection criteria for seawater desalination by reverse osmosis

The importance of site selection is a critical step in the implementation of seawater desalination plants. The reason for this is that the chosen site can affect a number of aspects to a large extent, e.g. design and operation of the plant, socio-economic and environmental impacts, public acceptance, cost and long-term success of the project.

Basic prerequisites for the construction and successful operation of desalination plants are:

- Suitable access to seawater feed (preferably at relatively constant salinity and quality).
- An acceptable and cost effective method of disposing the brine and waste streams.
- A reliable source of electricity.
- Proximity to a water distribution system to deliver water to the end user.

2.2.7 Suitable access to seawater feed

2.2.7.1 *Seawater intakes*

Seawater intakes for desalination plants can be divided into two broad categories:

- Direct intakes where seawater is drawn directly from the water column by means such as deep water intake structures, jetty mounted pumps or open channels; and

- Indirect intakes where seawater is drawn indirectly from the ocean by means such as beach wells (vertical bores) or seabed infiltration.

A schematic illustration of the categorisation of the various intake types is shown in Figure 2.8. By far the greatest number of intakes associated with large desalination plants are of the direct intake type, normally based on a velocity cap intake. Open channel intakes may be considered where sharing with a power station seawater intake is feasible.

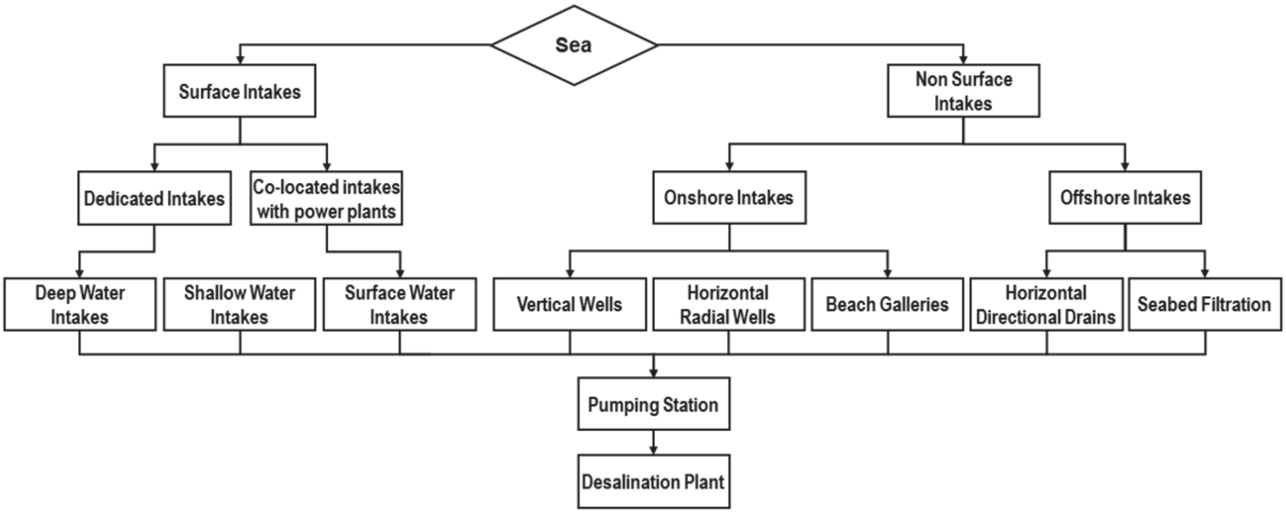


Figure 2.8: A schematic illustration of the categorisation of the various intake types

Intake Depth

The basic difference between the various types of direct intakes is the sea depth at which water is extracted. The depth can range from close to zero metres for open channels (or shoreline intakes), up to 15 m for common intakes and 20 to 35 m for deep water intakes.

Intake depth is important in determining the quality of the desalination plant feedwater for a number of reasons, including:

- **Level of organic matter:** As depth increases there is decreased light and therefore decreased algae quantity (due to the limited photosynthesis).

- **Level of Suspended Solids:** As the total water depth increases (i.e. further distance from shore) there is less turbulence hence there are less suspended solids due to wave action in the water column.

- **Risk of Accidental Pollution:** As depth increases the impact of potential accidental pollution (e.g. from tanker spills, etc.) reduces.

- **Water temperature impact:** As depth increases temperature decreases. Colder water results in better quality desalinated water; although colder water increases water viscosity, decreasing the permeate flux thus increasing the RO feed pressure and therefore energy consumption. Increased depth will generally provide a more stable water temperature, which is more important for plant operation.

- **Impact of low salinity discharges from local creeks, rivers:** As depth increases the risk of extracting low salinity fresh water is reduced, i.e. leads to greater stability of salinity, which is important for the desalination process.

Other factors that may influence the selection of intake depth are:

- **Bathymetry:** Large distances to deep water from the shoreline increase the length and cost of intake conduits making shallower solutions more economical.
- **Tidal conditions:** Large tidal ranges increase the length and cost of intake pipelines making shallower solutions more economical.
- **Geotechnical conditions:** Unfavourable tunnelling or dredging conditions will increase the cost of intake conduit construction making shallower solutions more economical.
- **Wave environment:** the underwater dynamic forces resulting from wave action decrease with water depth. Large waves increase the anchoring requirements for seabed structures making deeper solutions more economical.
- **Shipping activity:** Sufficient freeboard is required over the intake if it is exposed to shipping movements. This can result in deeper solutions. In some circumstances the intake is marked as a shipping exclusion zone and this constraint can be eliminated.
- **Sediment transport:** the higher the intake opening is above the seabed the less likelihood there is of the intake being blocked by sediment. The higher intake opening also means less likelihood of benthic marine species being impacted by the intake.

Conduits and shoreline crossings

The choice of marine conduit is dependent upon a number of factors including:

- **Geology:** consistency and depth of underlying rock and suitability of the ground conditions for tunnelling, drilling, dredging or trench excavation;
- **Weather:** suitability for the use of construction barges;
- **Tidal range and local currents:** suitability for the use of construction barges and equipment;
- **Wave environment:** suitability for the use of construction barges and underwater dynamic forces on pipe and backfill during and after construction
- **Materials:** availability of stone and rock for trench backfill;
- **Diameter, length, alignment and grade:** different approaches have different limits;
- **Environment:** sensitivity of local environment to sediment plumes and seabed disruption; Impact on shoreline, both during and at completion of construction;
- **Cost:** cost of construction.

Conduit construction options

There are a broad range of options that can be adopted for the intake and outfall conduits. The main categories are summarised as follows:

- Trenchless technologies:
  - **Option 1:** excavated tunnels using double-shield tunnel boring machines (TBMs) and lined using pre-cast steel fibre-reinforced concrete segments (Gold Coast, Sydney and Melbourne); and
  - **Option 2:** micro-tunnelling with pipe-jacking using plastic lined pre-cast pipe sections (Perth 2, Adelaide); and
  - **Option 3:** horizontal directional drilling (HDD);
- Pipelines trenched into the seabed (Perth 1 and Mossel Bay);
- Pipelines laid on top of the seabed and anchored in place by various means (Ashkelon, Mossel Bay and Gold Coast diffuser);
- Pipelines constructed on jetty structures.

These options can be used alone or in combination, e.g. tunnelling across the shoreline and wave zone, then trenched pipe to the intake and outfall locations can be used to ensure the shoreline is not disturbed.

Screening

The choice of screen configuration and size is dependent upon the following factors:

- **Marine life:** the type and size or marine life in the area and the risk of entrainment into the intake pipe;
- **Pumps:** the type of pumps proposed and the risk of pump fouling by entrained debris;
- **Pre-treatment:** the type of pre-treatment equipment proposed downstream and its ability to remove and handle solids of various sizes;
- **Cleaning:** the physical location of the screen and the ease of providing a method to clean or back flush the screen and dispose of solids;
- **Tidal range:** can influence the location of an active screen before or after the seawater pumps.

Pump stations

The choice of pump station configuration is dependent upon the following factors:

- **Conduit construction:** various pump station structures have synergies with different conduit construction methods;
- **Screening strategy:** pumps have varying ability to pass solids;
- **Efficiencies: different** styles of pumps have different efficiencies which effects energy costs, particularly at higher pumping pressures;
- **Back-flushing:** the need to reverse flows for back flushing of an infiltration intake;
- **Pump failure:** the need to provide standby pumps or to protect the pump motors from flooding;
- **Maintenance access:** the facilities available to remove pumps and motors.

The above aspects illustrate the complexities associated with the selection of a suitable location for a desalination plant, resulting in increased emphasis on intake (and outfall) design and economics. In fact, intake (and outfall) selection could be considered as the “fatal flaw issue” of new seawater desalination facilities (Pankratz, 2008).

2.2.8 Seawater quality

The seawater quality is the key external input which drives the process design (noting that it can be influenced by the location and type of inlet). Deeper or subsurface inlets can provide improved water quality, and thus reduce the need for pre-treatment prior to the RO system.

The intake selection is generally based on the plant location and should consider, amongst other things, seawater quality, environmental impacts, intake technology and costs. As such, the expected quality of seawater fed to the desalination plant can only be defined within a certain degree of accuracy once the following have been established:

- Location of the seawater abstraction point (e.g. depth, distance from shore, hydrodynamic conditions, seabed stability, sand transport, etc.).
- Preferred choice of intake type and arrangement (e.g. direct surface, indirect off-shore).
- Results from preliminary seawater sampling regime and review of relevant historical water quality data and potential diffuse and point pollution sources in the vicinity of the intake which may impact on source water quality.

Variations in seawater salinity and temperature are fundamental for RO process design with respect to the adopted configuration, recovery, membrane selection and required operating pressure to meet product water quality and plant availability targets.

Equally important for the design of the RO pre-treatment facilities and RO plant is the characterisation of seawater quality with respect to fouling parameters, such as turbidity, TOC and DOC, hydrocarbons, picophytoplankton, metals, nutrient status, as well as the possible occurrence of sulphur outbreaks, algal, jellyfish and seaweed blooms. These will have a direct bearing on the selection of the pre-treatment system (and hence cost) in order to achieve the desired RO feedwater quality (e.g. turbidity and SDI – DOE, 2010) and maintain the required plant availability.

2.2.9 Disposing (and treatment) of Brine and Waste Streams

The desalination plant will produce seawater concentrate, often referred to as brine, which is approximately twice the salinity of the ambient seawater and therefore of a higher density. This brine needs to be disposed of in the ocean in an environmentally acceptable and cost effective manner. Typically the following options are available:

- Pumped seawater dilution option consists of pumping additional seawater through the intake system and then diluting the brine with this additional seawater prior to brine disposal into the marine environment. This reduces the salinity and temperature difference between the background conditions and the discharge and assists with near field dilution. However, this substantially increases the required capacity of the inlet pump station, the inlet pipeline and the outlet pipeline.
- Shoreline discharge, in many areas of the world the concentrated brine is simply discharged back into the ocean at the shoreline with no attempt at dilution or diffusion. For small quantities of brine being discharged into an active surf zone this may be a viable option. However, if large quantities of brine are to be disposed of, it is almost certain that such a design would not gain environmental approval.

- Utilising outfall diffuser is the brine disposal method adopted by all the large seawater desalination plants in South Africa, Namibia, Australia and the world. The diffuser can be either configured as a piped diffuser or rosette style diffuser. The diffusers are generally located far enough offshore so that they are beyond the surf zone and in sufficient depth of water to effect adequate dilution.

2.2.10 Integration with Water Distribution System

Desalination plants generally operate as a base load facility with limited turn-down ratio. However, since they are generally configured in multiple, parallel trains they can be operated in steps by taking one or more trains off-line.

However, this would result in “stranded assets” if not fully utilised. Thus the integration into the water distribution system should be done so that the final staged flow can be accommodated on a continuous basis with the future demand curve for potable water determining the base load and increments.

Water quality aspects and considerations can play an even more important part in operational requirements when desalination plants are connected into existing systems for the following reasons:

- Water quality can be of a lesser or higher standard than the water to which it is being added.
- Pipe flow directions can end up being reversed, especially in relation to customers provided along the route if a separate rising main is not provided.
- Blending of water in a balancing reservoir could change in quality, depending on the ratio of desalinated water to the water provided at the point of mixing.

As such, the integration of the product water with the distribution system is an important aspect in the implementation of a desalination plant.

2.2.11 Electricity Source

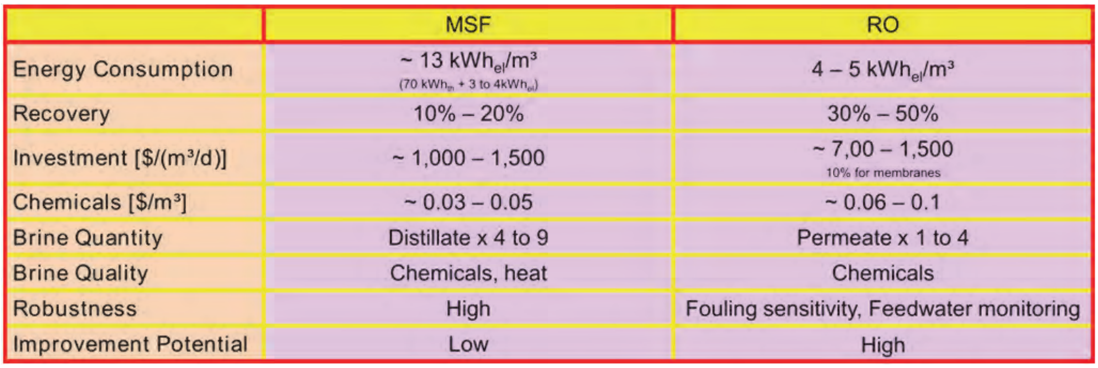
Essentially modern SWRO plants conservatively require about 150-200 kW of power per Mℓ/day of water produced. Other factors may play a role here such as plant elevation (requiring more power for feedwater supply) and the product water pumping system static and dynamic head. The use of energy recovery devices (ERD) serves to minimise the energy consumption on the RO portion of the plant.

It is generally accepted that the conventional power source for a desalination plant will come from the electrical power grid at competitive rates. Nevertheless, the implications of wind and solar energy should be considered as potential alternative power sources to meet the power requirement of the desalination plant.

2.2.12 Cost Aspects of Seawater Desalination by Reverse Osmosis

2.2.12.1 *Basic cost considerations*

The cost of producing drinking water by the desalination of seawater with reverse osmosis may be considered to be high, although RO is substantially less energy intensive than equivalent thermal processes. On the other hand, this must be balanced against the cost and far reaching implications of running out of water as a result of not meeting the water supply demand from conventional sources. To this end, desalination provides an alternative water source that is independent of rainfall and may be considered as “new” water.



	MSF	RO
Energy Consumption	~ 13 kWh_{el}/m^3 (70 kWh_{th} + 3 to 4kWh_{el})	4 – 5 kWh_{el}/m^3
Recovery	10% – 20%	30% – 50%
Investment [$/(m³/d)]	~ 1,000 – 1,500	~ 7,00 – 1,500 10% for membranes
Chemicals [$/m³]	~ 0.03 – 0.05	~ 0.06 – 0.1
Brine Quantity	Distillate x 4 to 9	Permeate x 1 to 4
Brine Quality	Chemicals, heat	Chemicals
Robustness	High	Fouling sensitivity, Feedwater monitoring
Improvement Potential	Low	High

Figure 2.9: Thermal vs. membrane comparison (Banat, 2007)

It must be kept in mind, however, that the basic RO plant itself is only a part of the total scheme. With known feedwater and target product water qualities the basic plants are relatively standard and consistent in price. However, the infrastructures in front of (intakes, pre-treatment, etc.) and after (waste discharge, product water pumping systems) the basic plant building block (membrane system) are major variables in determining the capital and operating costs of the selected solutions. Each location and situation has different advantages and challenges that need to be evaluated for making the best decisions for implementation from a holistic point of view. Although the individual cost category factors that contribute to the overall cost of the desalination scheme are largely the same for each project, their individual contributions may vary significantly from project to project thereby often resulting in large cost differences. The cost categories associated with SWRO desalination projects are shown below (WADC, 2011).

Figure 2.10: Cost categories contributing to SWRO projects (adapted from WADC, 2011)

2.2.12.2 *Selection of intake and discharge*

As illustrated before the variety of intake options and the associated construction aspects cover a wide range of possibilities. Besides being site and project specific the ultimate choice and configuration may also be affected by the legislative and environmental requirements of the country in which the plant is located. A comparison of selected aspects for various intake types is given in Table 2.3.

Table 2.3: Comparison of various seawater desalination intake types (WADC, 2011)

Intake Type	Relative Values			Reliability
	Cost (for equal capacity)	Intake Space Requirements	Pre-treatment Space Requirements	
Beach Wells	Low	High	Theoretically less	Variable based on subsurface lithology
Horizontal Directional-drilled	Medium	High	Theoretically less	Unknown
Radial Wells	Medium	High	Theoretically less	Unknown
Constructed seabed/infiltration gallery	High	Medium	Theoretically less	Unknown
Submerged open intake	Medium-low	Low	More	High
Surface: open intake	Low	Low	More	High
Co-located intake	Low	Low	More	High

Various methods for the disposal of the concentrate stream exist, e.g. open sea outfall, co-disposal with power plant or waste water treatment works outfall, deep well injection, evaporation ponds and zero liquid discharge arrangements. For coastal desalination plants however the open sea outfall arrangement is the most common.

The costs associated with intake and discharge arrangements vary widely due to many site-specific variables, in particular conveyance costs. Higher than normal cost trends for intake and discharge systems seen in recent large-scale Australian desalination projects are attributed to these plants being located in the vicinity of highly sensitive marine habitats requiring special environmental consideration.

There has been a downward trend in the costs and energy use of desalinated water due to the technological advances that have improved the efficiency of the RO process. Since its inception the electrical consumption of RO has been reduced by a factor of four due to more efficient membranes and energy recovery systems (Figure 2.11). Similarly, the cost of desalination by RO has reduced substantially due to more advanced production techniques and increased production rates of membranes and the maturation of the technology. Due to the increasing scarcity of surface water and subsequent higher cost of its augmentation, the cost of desalination has become competitive in many instances.

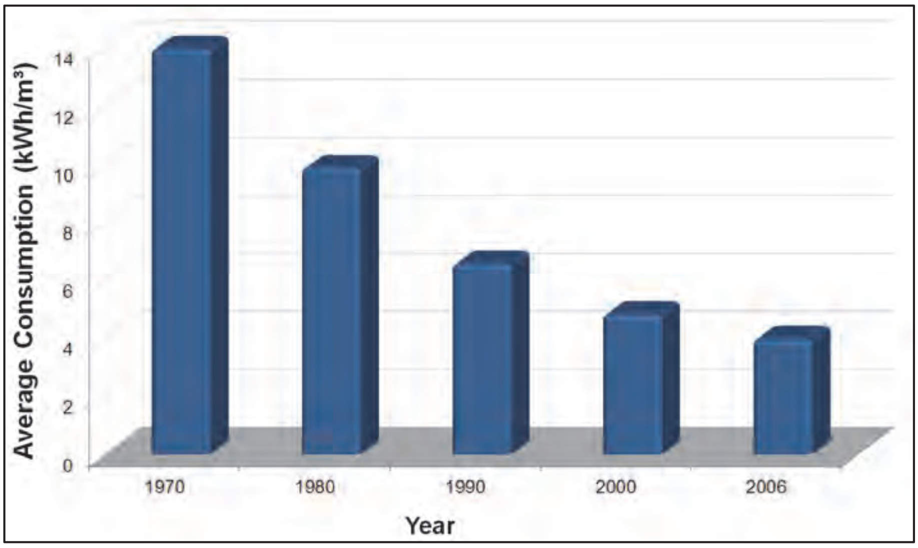


Figure 2.11: Trend of Energy Requirement of RO Process

Although the basic application of membrane technology is the same among seawater desalination plants, published reports on the total power consumption of SWRO facilities vary significantly. This is because SWRO projects are specifically designed for the location, accounting for energy costs associated with changes in feedwater salinity and temperature, changes in elevation, the local cost of power and fuel, degree of pre-treatment, distance to feedwater supply source, and the distribution point.

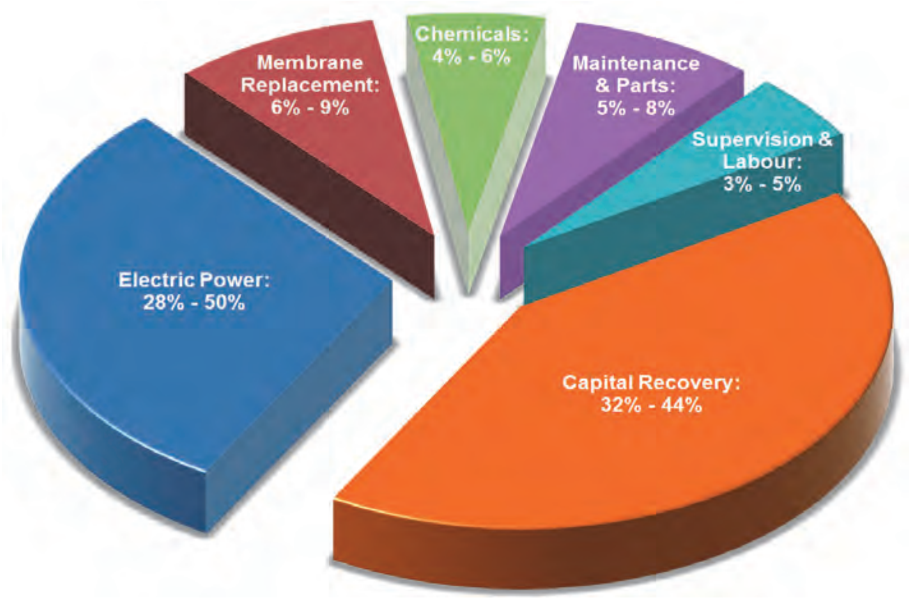


Figure 2.12: Various components of a SWRO facility, based on actual costs at operational SWRO facilities

Figure 2.12 contains a range of costs for the various components of a SWRO facility, based on actual costs at operational SWRO facilities. The energy “slice” is 28% to 50%, which can approach (or exceed) the capital recovery. A range is provided because the specific technical components factoring into the range will vary by project, and the capital recovery cost is driven by many factors such as interest, bond cost, payment time frame, and other financing schemes (WADC, 2011).

2.2.12.3 *Future of Seawater Desalination*

Desalination is process primarily applied in developed countries with financial capability and resources. If the technology continues to produce new methods and better solutions to the issues that exist today, there would be a whole new water resource for more and more countries that are facing drought, competition for water, and overpopulation. Although there are concerns in the scientific world about replacing our current overuse of water with complete reliance on sea water, it would undoubtedly be at least an option for many people struggling to survive or maintain their standard of living.

2.3 WATER REUSE OVERVIEW

The concept of reuse is much less defined than desalination. The treatment of wastewater and subsequent release into the environment is not considered reuse. Similarly, the irrigation of wastewater onto land is not deemed to be reuse in the context of this project. Some relevant concepts often referred to in describing reuse applications are:

- **Water reclamation:** the treatment of wastewater to a quality that will allow its beneficial use.
- **Water recycling:** Synonymous with 'water reclamation'
- **Water reuse:** the use of reclaimed water for beneficial purposes.
- **Direct potable reuse:** the beneficial use of reclaimed water for potable purposes with transfer from the reuse plant directly into the drinking water system, often in conjunction with blending from other conventional sources.
- **Indirect potable reuse:** the beneficial use of reclaimed water after releasing it into the environment for storage or dilution for subsequent raw drinking water supply.
- **Direct industrial reuse:** the beneficial use of reclaimed water treated to a defined standard with transfer from the reuse plant directly to the intended industrial user.
- **Indirect industrial reuse:** the beneficial use of reclaimed water upgraded to a certain quality and released into a natural water body to augment the raw water supply of the intended industrial user.

The infrastructure, activities and technologies involved in water reuse are quite broad. None of the technologies used are exclusive to water reuse, but are also applied to the treatment of wastewater, drinking water and employed in desalination. This is largely due to the fact that the feedwater to the reuse plant can originate from a variety of sources, whilst the target quality of the treated water required for reuse can differ substantially, depending on the intended end use. As such, it is not easy to define the market for reuse. Nevertheless, it is fairly common for reuse systems to include advanced technologies, such as membrane separation systems, oxidation and disinfection techniques, high rate liquid/solids separation, adsorption processes and biological treatment.

In water reuse for potable purposes, reference is often made to a "multi-barrier approach" which implies the use of multiple treatment steps, each intended to act as a treatment barrier for the range of substances or pollutants under consideration. The main objective is typically to reduce the perceived risk associated with water reuse. While primary and secondary wastewater treatment is relatively standardised and inexpensive the removal of personal care by products, pharmaceuticals and endocrine disruptors, as well as specific target pollutant species, can be quite costly and complex with less discernible perceived benefit. The concept of "water should be judged by its quality and not origin" applies.

2.3.1 Historical Timeline of Water Reuse

The reuse of water dates back to the 19th century. In 1867 through the settling of people in the mountains of Central and Southern Arizona after the discovery of copper ore, means to curtail undependable water supply during the months of long hot summers that followed where investigated and applied (SRP, 2012).

Thereafter water reclamation became a strategic option with international interest and research becoming widespread during the 1960s (Odendaal, year unknown). The year 1960 is considered to be a transition point due to the implementation of pollution regulations and inclusion of water reclamation strategies in water management policies in the US leading to the modern era of water reclamation (Levine et al., year unknown). Some key developments and turning points in recent desalination history are summarised in Table 2.4.

Table 2.4: Summary of water reuse history (adapted from ATP, 2012 and Du Pisani, 2004).

Date	Event
1932	The first small urban reuse system begins with the irrigation of Golden Gate Park in San Francisco.
1962	Montebello Forebay, California, USA. First case of indirect potable re-use via groundwater recharge using soil-aquifer treatment.
1965	Israel begins using reclaimed water for crop irrigation.
1966	Florida enters the reclaimed water arena with the construction of the Tallahassee Reclaimed Water Farm.
1968	Goreangab water reclamation plant converted to treat final effluent from Gammams wastewater treatment plant
1977	The City of St. Petersburg, Florida, builds the first large urban reuse system in the United States.
1978	Upper Occoquan Service Authority, Virginia, USA. First case of indirect potable re-use via surface water augmentation.
1984	Tokyo begins using reclaimed water from the Ochiai Wastewater Treatment Plant, which is operated by the Tokyo Metropolitan Sewerage Bureau, for toilet flushing in commercial buildings in Shinjuku District.
1985	Water Conserv II, the largest reuse project that combines agricultural irrigation with aquifer recharge via rapid infiltration basins, begins operation in Orlando, Florida.
1985	Hueco Bolson Recharge Project, Texas, USA. First case of indirect potable re-use via groundwater recharge using direct injection.
1987	Monterey County Water Resources Agency: "Monterey Wastewater Reclamation Study for Agriculture, Final Report" – *Irrigation of raw-eaten vegetable crops and artichokes with reclaimed water was shown to be as safe as irrigation with well water.*
1989	Spain begins irrigation of golf courses with reclaimed water from the Consorci de la Costa Brava wastewater treatment facility.
1996	National Academies of Science, National Research Council: “Use of Reclaimed Water and Sludge in Food Crop Production” study–- *Crops irrigated with reuse do not present a greater risk to the consumer than do crops irrigated from conventional sources.*
1998	Monterey County, California, begins irrigation with reclaimed water, including 12 000 acres of vegetables, such as lettuce, strawberries, cauliflower, broccoli, artichokes, celery and fennel. The vegetables continue to be irrigated with reclaimed water.
1998	“Recycled Water Food Safety Study for Monterey County Water Recycling Projects” – *Recycled water is as safe for irrigation of vegetables as other sources of irrigation water.*
1998	The Virginia Pipeline Project, the largest water reclamation project in Australia, irrigates vegetable crops using reclaimed water from the Bolivar Wastewater Treatment Plant.
2002	New Goreangab Water Reclamation Plant: Upgraded to 21 Mℓ/d included PAC and ozone dosing, BAC filtration and UF filtration.
2003	Florida Department of Environmental Protection: Proceedings of the 19th Annual WateReuse Symposium, “Monitoring for Protozoan Pathogens in Reclaimed Water” – *There is no evidence or documentation of any disease associated with water reuse systems in the United States or in other countries that have reasonable standards for reuse.*
2005	Florida Department of Environmental Protection’s “Water Reuse: Regulatory and Safety Perspectives” report indicates Florida has 40 years of reuse with no illness.
2005	WateReuse Research Foundation – “Irrigation of Parks, Playgrounds, and Schoolyards with Reclaimed Water: Extent and Safety” study
2007	eMalahleni Water Reclamation plant, Mpumalanga, South Africa. First indirect potable re-use plant to re-use acid mine drainage.
2008	David York, et al. – Comprehensive and definitive paper completed on the safety of irrigation of food crops with reclaimed water.
2009	WateReuse Research Foundation – “A Reconnaissance-Level Quantitative Comparison of Reclaimed Water, Surface Water and Groundwater” study
2011	Cloudcroft, New Mexico, USA. First direct potable re-use plant in the US.

2.3.2 Rationale for Water Reuse

The rationale for water reuse was adopted from various sources, namely ATP (2012), Du Pisani (2004) and McKenzie (2005). These are briefly discussed below:

- Water is a finite resource and increasingly becoming scarce thus limiting the luxury of using water only once. The quality of water produced by secondary treatment (activated sludge, trickling filters and stabilisation ponds) is appropriate for many non-potable applications such as irrigation, industrial cooling and cleaning water. This provides an alternative to abstraction of water from already strained freshwater reserves. This in turn enables the meeting of sustainability goals with concomitant management and recovery of nutrients for agriculture.

- The economic feasibility of water reclamation puts into perspective the cost benefits of this application were the treatment of wastewater becomes costly in light of the stringent disposal standards being implemented nowadays. Wastewater produced in urban areas provides a dependable source of water to augment supply especially in drought years.

The greatest benefit to preserve and reclaim water is the sustainability of environmental ethics. By reducing pollution and using water efficiently, water reclamation serves as a potential source and reserve for water.

2.3.3 Water Reuse Technologies

Water reuse is widely practiced throughout the world, both in developed, developing and emerging countries. Almost all these reuse systems are indirect potable reuse or non-potable reuse schemes.

The only real direct potable reuse schemes are in Windhoek, Namibia, Beaufort West, South Africa, Big Spring, Texas, USA and Cloudcroft, New Mexico, USA. The two southern African reuse schemes constitute one of the main reasons for the current studies and research in South Africa to develop monitoring programs based on health-based targets for a wide range of chemicals of emerging concern and disinfection by-products, as well as public acceptance studies (social and institutional research projects).

Reuse plants may make use of a large assortment of treatment processes due to the variability of the feedwater quality and final water standards that pertain to the different reuse plants.

The following list of technologies is typically used by potable reuse plants:

- Coagulation/Flocculation
- Clarification
- DAF (dissolved air floatation)
- Media Filtration
- BAC (biologically activated carbon)
- GAC (granular activated carbon)
- PAC (powder activated carbon)
- Microfiltration
- Ultrafiltration
- Nanofiltration
- Reverse Osmosis
- Ozonation
- UV/H_2O_2

The design of IPR and DPR hinges heavily on the expert design teams and the available industry in that region. Where membrane manufacturers have captured a considerable part of the market in a region there is a tendency to use membrane barriers for suspended and dissolved solids. It seems that there is a re-evaluation as NF and RO have a considerable high cost to get rid of the brine, which renders it unfeasible in an inland application (Swartz et al., 2013).

Locally, conventional as well as advanced treatment technologies for water reclamation have in most instances already been tested and proven for South African conditions. There is therefore a local knowledge base on water reclamation to plan, design, construct, operate and maintain a wide range of treatment technologies. More recently, a number of more sophisticated technologies such as advanced oxidation and membrane treatment have also been applied to a number of local projects (e.g. Durban Reuse Plant and the Beaufort West Water Reclamation Plant).

The South African water industry has the foundation for confidently developing and applying the more advanced water reuse technologies (DWA, 2011). A specialist technical division, the WISA Water Reuse Division, has also recently been established within the Water Institute of Southern Africa, to further improve communication, capacity building and information sharing.

Some examples of advanced tertiary treatment technologies such as advanced oxidation and activated carbon systems are further elaborated below.

Advanced Oxidation System

A conventional activated sludge plant with a sludge age in excess of 15 days will oxidise all the biodegradable chemical oxygen demand (COD) in the incoming wastewater. As a result the COD in the effluent from a works with an appropriate sludge age and aeration system will consist solely of “soluble” non-biodegradable COD and that associated with solids in the effluent. However some of the “soluble” COD will be colloidal in nature and will be retained by the MBR membranes. Generally, approximately 30% of the “soluble” COD will be retained by the membranes. The COD passing through the membranes is anticipated to be approximately 45 mg/ℓ and will place the treated water in Category 4 industrial water quality. In addition, the Natural Organic Matter (NOM) and Total Organic Carbon (TOC) measured in the COD test, has the potential to cause bio-fouling of downstream Reverse Osmosis (RO) membranes.

Ozone has the ability to breakdown non-biodegradable COD and this process step is included in the process train as an addition to the MBR system. A brief description of the system is given below.

Ozone (O_3) gas is used for disinfection, colour removal and breakdown of complex organic matter. Ozone is a highly toxic substance and no ozone will be stored on site. Ozone will be produced on site by ozone generators from air.

The ozonation system will be designed to produce sufficient ozone to dose a maximum dose of 5 g/m³ maximum dosage, based on 85% gas transfer efficiency.

An average ozone concentration of 2 mg O_3/ℓ should be sufficient to ensure the efficiency of the process. This step is included in the process to reduce colour and breakdown a fraction of the non-biodegradable COD remaining, in smaller molecules to prevent bio-fouling of downstream processes. The transformed COD will become biodegradable and will need to be removed biologically in Granular Activated Carbon (GAC) contactors.

The production of ozone will be made from pure oxygen, using latest technology ozone generators. This system permits lower electricity consumption, and needs less maintenance. The ozone concentration in the product gas will be 10% during normal operation and 7% during high ozone demand periods. A residual ozone analyser will be provided at the outlet of the ozone contact tanks to optimise the process. A schematic arrangement of a typical ozone generator is shown in Figure 2.13.

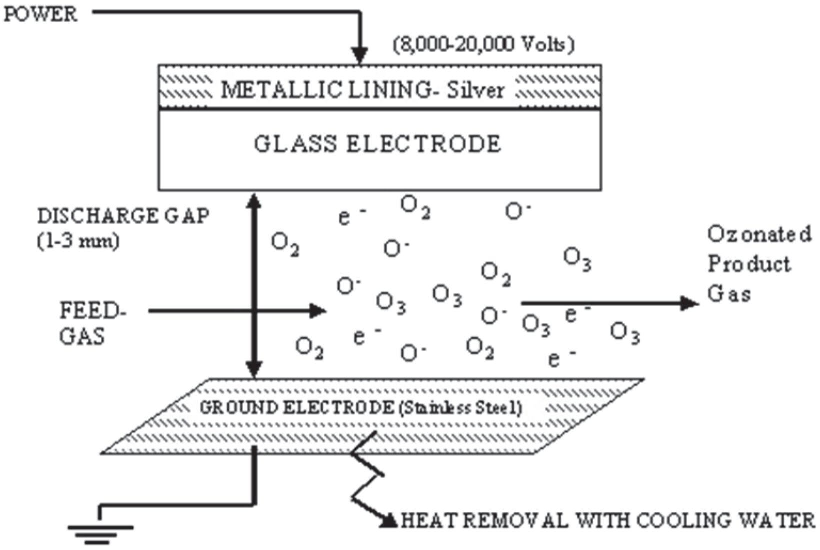


Figure 2.13: Schematic of a dielectric ozone generator

Ozone is introduced into the water phase by fine bubble diffusers mounted on the bottom of the ozone contact tanks.

It is proposed that the tanks be arranged in lanes in order to allow for maintenance and repairs without interruption of the process.

The contact time allowed is 10 minutes. A schematic arrangement of a typical ozone generator is shown in Figure 2.14

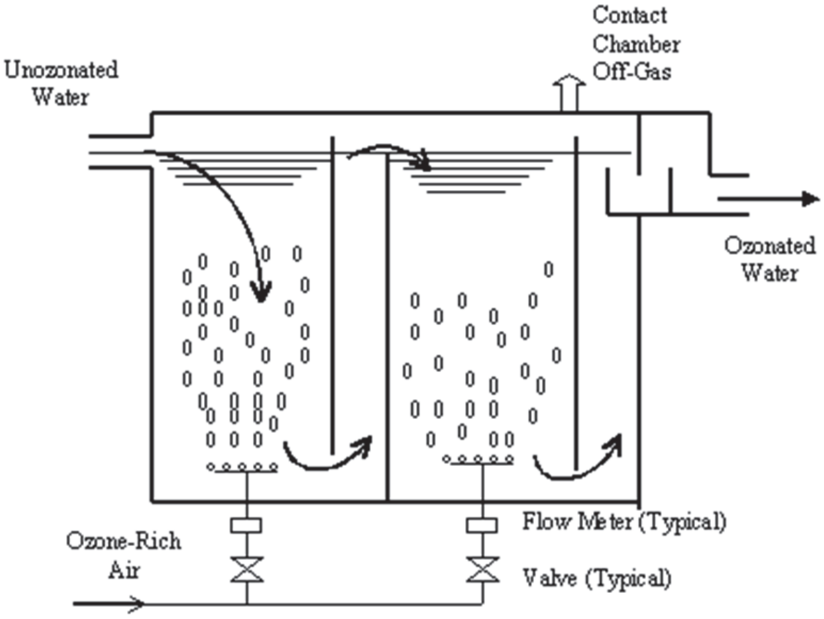


Figure 2.14: Schematic of an ozone contact tank

Residual ozone in the vents from the ozone contact tanks will be eliminated or reduced by thermal ozone destructors to harmless levels. The anticipated maximum ozone concentration in the vents after treatment will be 0.1 mg/ℓ. The atmosphere in the ozone building will be continuously monitored by an ozone gas analyser and an ozone gas alarm initiated upon detection of ozone.

Granular Activated Carbon (GAC) Contactors

In the ozone treatment step the degradation of the COD will make this component biodegradable and Granular Activated Carbon (GAC) filtration will be included to adsorb this component. When GAC follows Ozone treatment, the GAC filters become biologically active and micro-organisms will break down the COD. It is for this reason that when GAC filters follow ozone treatment they become known as Biologically Active Carbon (BAC) filters.

The water flows from the ozone contact tank to the BAC contactors. Although the contactor is basically a filter similar to conventional filters its purpose is to provide contact of micro-organisms attached to the activated granular carbon with the water.

The contactors require backwashing in a similar way to conventional filters but the contactor run cycles are significantly higher (3-5 days). Due to the biological activity in the activated carbon, the carbon does not require as frequent replacement and regeneration as a conventional activated carbon contactor operating on the adsorption principle. Replacement of the GAC is expected after approximately 10 years operation due to attrition of the material.

The contactors will be sized with an empty bed contact time of approximately 15 minutes to enable a period of several days of operation without backwashing to enable micro-organisms to establish themselves after each backwashing sequence.

The filters will be washed in a method that combines a counter-current of wash water at an approximate flow of 8 $m^3/m^2/h$ and the blowing of air at a flow of 20 $m^3/m^2/h$, followed by rinsing with water at a flow of 40 $m^3/m^2/h$. The used backwash water and first filtrate rinse water will be returned to the activated sludge reactor.

Despite the successes and achievements of the New Goreangab water reclamation plant (NGWRP), which performs direct potable reuse without using any RO treatment steps, the use of RO treatment steps have become commonplace at potable reclamation plants with the exception of indirect potable reuse plants that perform groundwater replenishment via soil-aquifer treatment. This is also the case in South Africa where the direct potable reuse plant at Beaufort West has opted to include RO treatment steps, while the George (Outeniqua) reclamation plant makes use of UF only, since the treated water is sent to the Garden Route dam where it is sufficiently diluted and indirectly reused.

Reclaimed water may be used for various applications which depend on the type of technology and desired water quality. There are basically two approaches:

- One (e.g. Windhoek approach) where physical-chemical processes, such as DAF or sedimentation are used as main separation technologies, supplemented by advanced oxidation and maybe MF or UF membrane final barrier, as illustrated in Figure 2.15.
- The other approach is to use MF/UF and RO membranes as the main separation technologies, as illustrated in Figure 2.16.

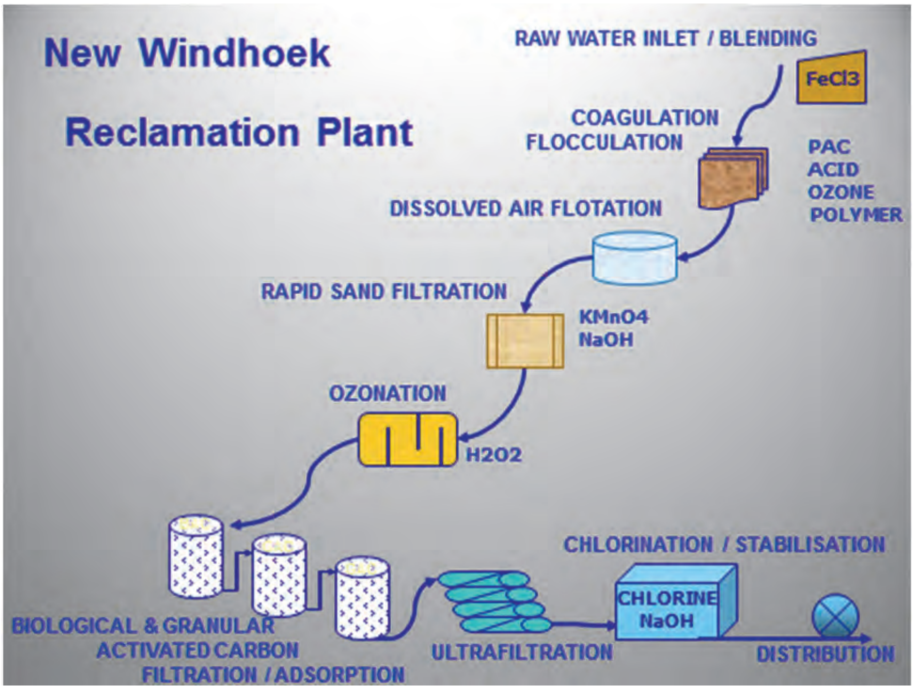


Figure 2.15: Example of physical-chemical approach: Windhoek

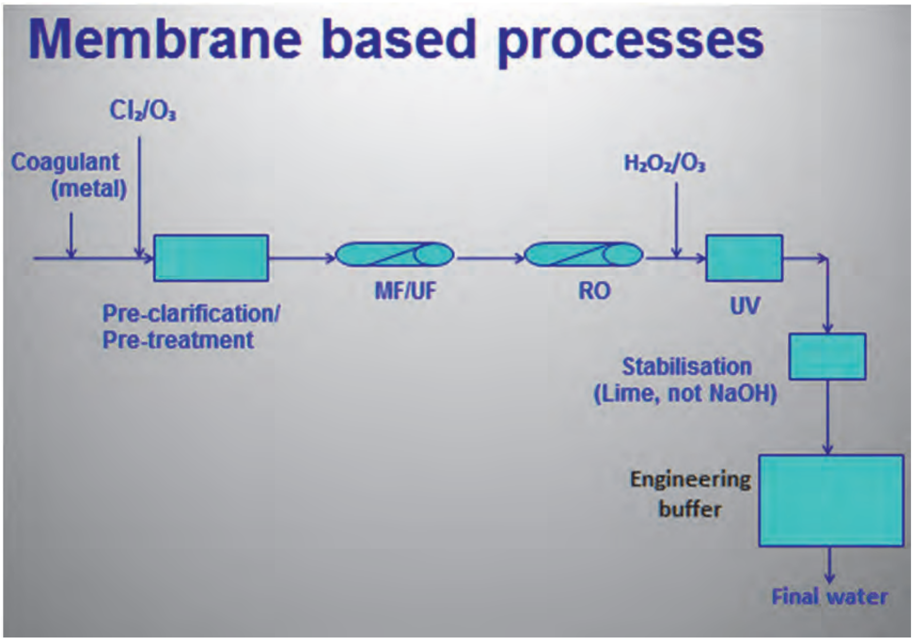


Figure 2.16: Example of membrane based approach

2.3.4 Types of Water Reuse

A combination of the above mentioned technologies can be applied to achieve the desired water and also depending on the selection criteria. Table 2.5 indicates the types of water reuse that can be applied (McKenzie, 2005).

Table 2.5: Types of water reuse

Types of Reuse	Treatment
Urban Reuse	Landscape irrigation, vehicle washing, toilet flushing, fire protection, commercial air conditioners, and other uses with similar access or exposure to the water.
Agricultural Reuse for Non-Food Crops	Pasture for milking animals; fodder, fibre and seed crops.
Indirect Potable Reuse	Groundwater recharge by spreading, or injecting into potable aquifer, or surface water body.
Potable Reuse	Blending in water supply reservoirs, or direct pipe to pipe supply

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APPENDIX A: DESALINATION PROCESS OVERVIEW

1 THERMAL PROCESSES

Widely used thermal desalination processes include multi stage flash (MSF) evaporation and multiple effect distillation (MED) with/without thermal or mechanical vapour compression. These require a heating medium, typically low pressure steam, to evaporate or boil off essentially pure water vapour from the saline feedwater. The vapour is then condensed and converted to a liquid distillate of very low salinity. Thermal processes are mainly applied to the desalination of seawater and sometimes to the concentration of industrial effluents.

The energy demand for thermal desalination is very high (when compared to other desalination processes) due to the energy required for the phase change (liquid to vapour) to boil off vapour from the saline feed and cooling for condensing (vapour to liquid) the vapour to form distillate. As such, thermal processes are often used in arid countries where there is an abundance of energy and sufficient waste heat (e.g. oil & gas fired power stations, refineries), such as the Middle East. Despite this current thinking is to move away from thermal desalination plants in favour of membrane desalination plants, mainly due to a future shift toward nuclear power plants (rather than coal/oil/gas powered) in the Emirates and other Middle East regions (GWI, 2011).

In South Africa the use of thermal desalination processes would typically be limited to situations where co-generation of electricity and water can be effected. An example would be next to a nuclear power station facility where seawater may be used for both cooling of the power station and the generation of fresh water from seawater by utilising the waste heat available. In this instance the seawater intake and brine outfall facilities could also be shared.

This may become remotely feasible if South Africa pursues a Nuclear Fleet strategy as outlined in the Integrated Resource Plan (DOE, 2010).

1.1 MSF process

In the MSF process, seawater is heated in a vessel called the brine heater. This is generally done by condensing steam on a bank of tubes that pass through the vessel, which in turn heats the seawater. This heated seawater then flows into another vessel, called evaporator stage, where the ambient pressure is such that the water will immediately boil, almost exploding or "flashing" into steam.

Each stage operates at a slightly lower pressure than the previous one, thereby resulting in the multi stage flash configuration. The steam generated by flashing is converted to fresh water by being condensed on tubes of heat exchangers that run through each stage. The tubes are cooled by the incoming feedwater going to the brine heater. This, in turn, warms up the feedwater so that the amount of thermal energy needed in the brine heater to raise the temperature of the seawater is reduced.

MSF are generally built in units of about 5 000 to 65 000 m^3/d (Sidem, 2015). The MSF plants usually operate at a top feed temperature (after the brine heater) of 90 to 120°C.

Operating these plants at the higher temperature limits (>120°C) tends to increase the efficiency, but it also increases the potential for detrimental scale formation and accelerated corrosion of metal surfaces.

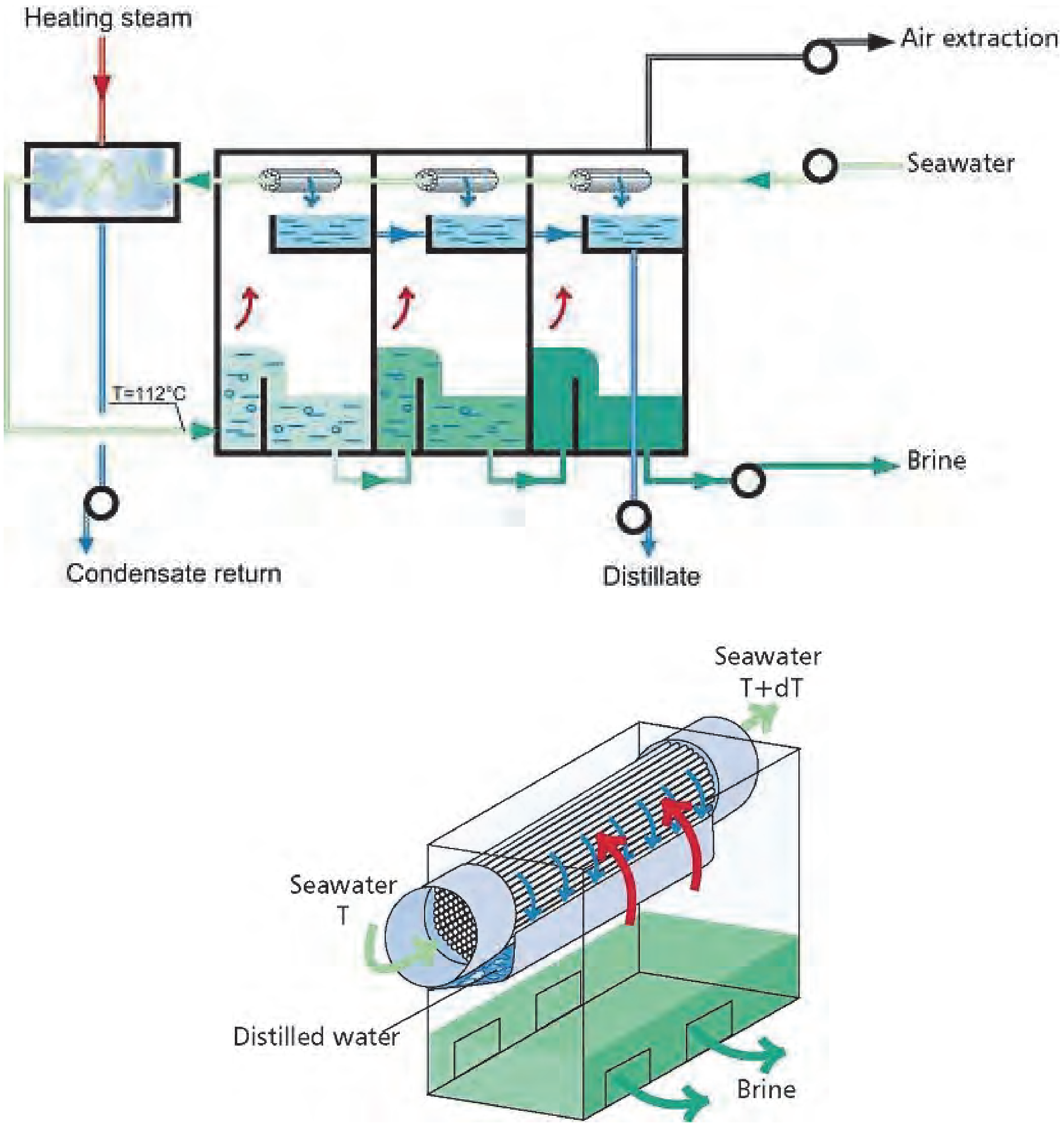

Figure 1: Thermal Desalination Schematic representation of MSF process (Sidem, 2015)

Important points to note about the MSF process are:

- Simple and reliable operation with long and successful track record
- No or minimal feedwater pre-treatment
- Product water quality of 5 to10 mg/ℓ TDS

Weak points may be summarised as:

- Low thermal efficiency (only cost effective if low cost steam available)
- High cooling water requirement
- Only practical for seawater applications

1.2 MED process

The MED process has been used for industrial distillation for a long time. The MED process takes place in a series of vessels (effects) and uses the principle of reducing the ambient pressure in the various effects. This permits the seawater feeds to undergo multiple boiling without supplying additional heat after the first effect.

In most MED plants, the seawater enters all the effects in parallel and is raised to the boiling points after being pre-heated on tubes by steam from a boiler. The condensate from the boiler steam is recycled to the boiler for reuse. Only a portion of the seawater applied to the tubes in the effects is evaporated. The remaining feedwater is collected and fed to the last effect. The tubes in the various effects are in turn heated by the vapours created in the previous effect. This vapour is condensed to fresh water product, while giving up heat to evaporate a portion of the seawater feed in the effects and continues in several effects.

MED plants are typically built in units of 100 to 20 000 m^3/d. The operating temperature is around 70°C, which reduces the potential for scaling within the plant, but in turn increases the need for additional heat transfer area in the form of tubes.

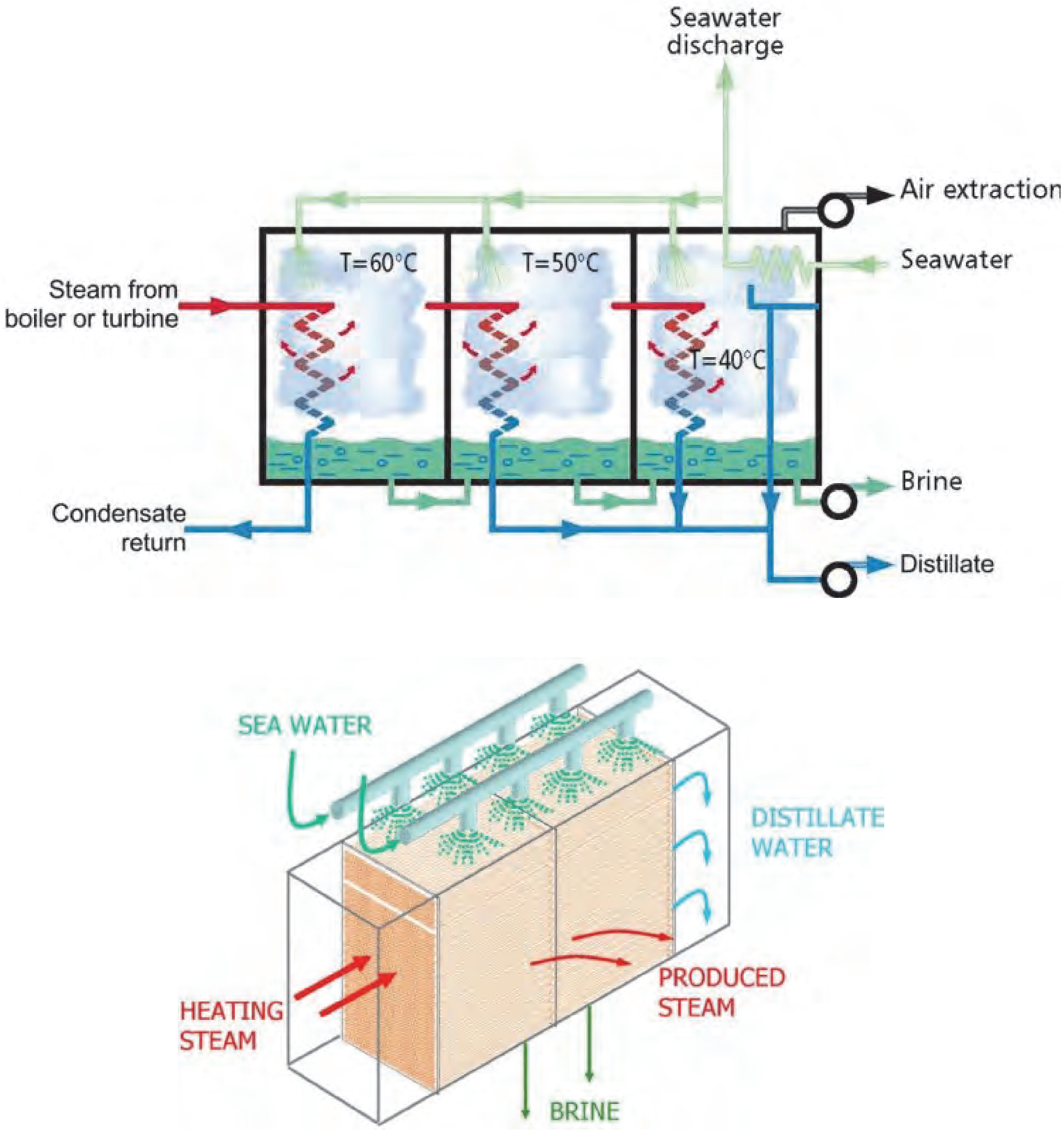

Figure 2: Thermal Desalination Schematic representation of MED process (Sidem, 2015)

Important points to note about the MED process are:

- Thermal efficiency is higher than for MSF
- Lower top temperature operation than MSF
- Uses less cooling water and electrical energy than MSF
- Lower capital cost than MSF
- Product water quality of 5 to 10mg/ℓ TDS
- Weak points may be summarised as:
- More complex and smaller unit sizes than MSF
- May not be cost competitive with RO processes
- Only practical for seawater applications

1.3 Other thermal processes

Other thermal processes worth mentioning are vacuum compression distillation (VCD), vacuum freeze distillation (VFD) and solar distillation. Their present commercial impact is limited hence they are not further discussed for the purpose of this report.

2 CHEMICAL PROCESSES

2.1 Ion exchange process

Ion exchange is based on the chemical-physical process of adsorption using selective ion exchange resins. The process may be used for the desalination of water but is typically limited to the polishing of low salinity feed to produce ultrapure water (e.g. boiler feed, rinse water for the electronics industry). As such, the process is generally referred to as demineralisation.

The principle of demineralisation by ion exchange resin is illustrated in Figure 3. Separate beds of two resin types are used, through which the feedwater is passed. The cation resin has a sulphonate (SO_3^-) functional group to which typically a mobile hydrogen (H^+) ion is linked. The anion resin on the other hand has a quaternary ammonium (N^+R_3) functional group to which usually a mobile hydroxide (OH^-) ion is linked. As the feedwater passes through the cation and anion resin beds the cations in the water selectively exchange with the mobile hydrogen ion on the cation resin, while the anions are exchanged with the mobile hydroxide ion on the anion resin. The equivalent amount of H+ and OH- ions to the anions and cations removed from the feedwater are released into the demineralised product water. These ions immediately combine to form water: $H+ + OH- \rightarrow H_2O$.

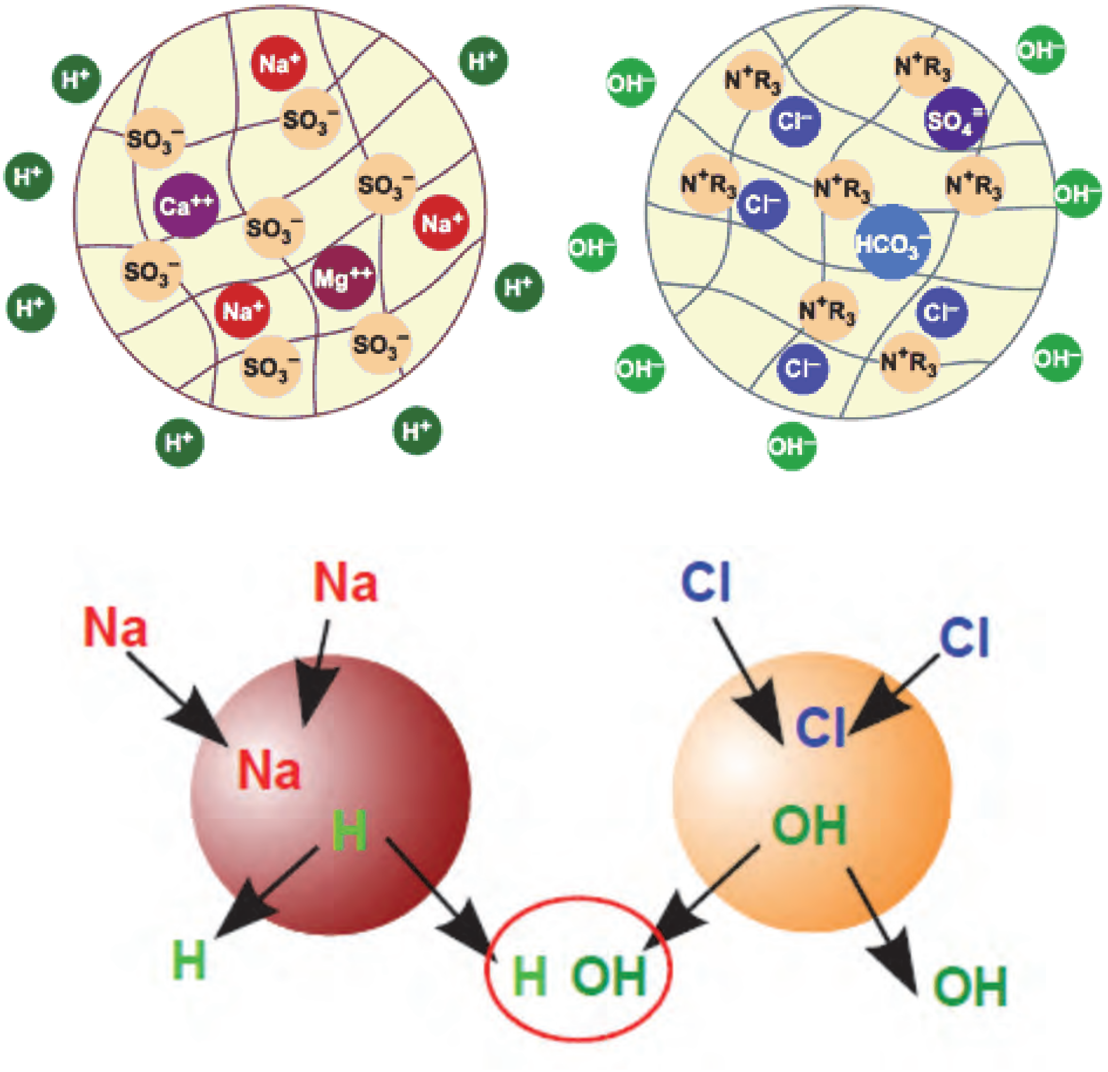

Figure 3: Ion Exchange Schematic representation of demineralisation process

The ionic contaminants in the feedwater are now situated on the resins which become progressively more loaded. Once the resins are saturated they need to be regenerated. This is achieved by driving off the respective ions that have been adsorbed with the use of acid (H^+) and caustic (OH^-) solutions. The process can now be repeated with "fresh" resin having H^+ and OH^- mobile ions again.

2.2 Precipitation processes

These are used to precipitate the targeted dissolved ions in the water by adding a chemical that forms an insoluble compound (precipitate) with the ion in question. The precipitate is then removed from the water by settling, filtration or other means of solid/liquid separation.

Examples are lime/soda-ash softening for the removal of hardness (calcium and magnesium) and the barium sulphate or Ettringite process. These processes are often used in the treatment of raw water and industrial effluents, as well as mining effluent or mining decant (acid mine drainage). As such, they are not further evaluated for the purpose of this report.

3 PHYSICAL PROCESSES

Physical separation technologies used for desalination relate mainly to membrane separation processes. These include electrical driven processes, such as electrodialysis or electrodialysis reversal and pressure driven membrane separation processes, such as nanofiltration and reverse osmosis.

3.1 Electrodialysis

Electrodialysis (ED) or electrodialysis reversal (EDR) is a membrane based desalination process, employs ion-selective membranes and electrical polarity to desalinate water. EDR is not discussed further due to its inability to desalinate high salinity feedwater efficiently and economically since the cost of electrodialysis is directly proportional to the salinity of the feedwater.

Electrodialysis uses a stack assembly of alternating anionic and cationic membranes in conjunction with a direct current source to draw ionic components in solution into their respective brine compartments. The driving force for the process is the applied electric field, which causes anions and cations to migrate in opposite directions in relation to the applied voltage. The ion-selective membranes allow migration of either anions or cations from the feed channels.

The concept is illustrated in Figure 4.

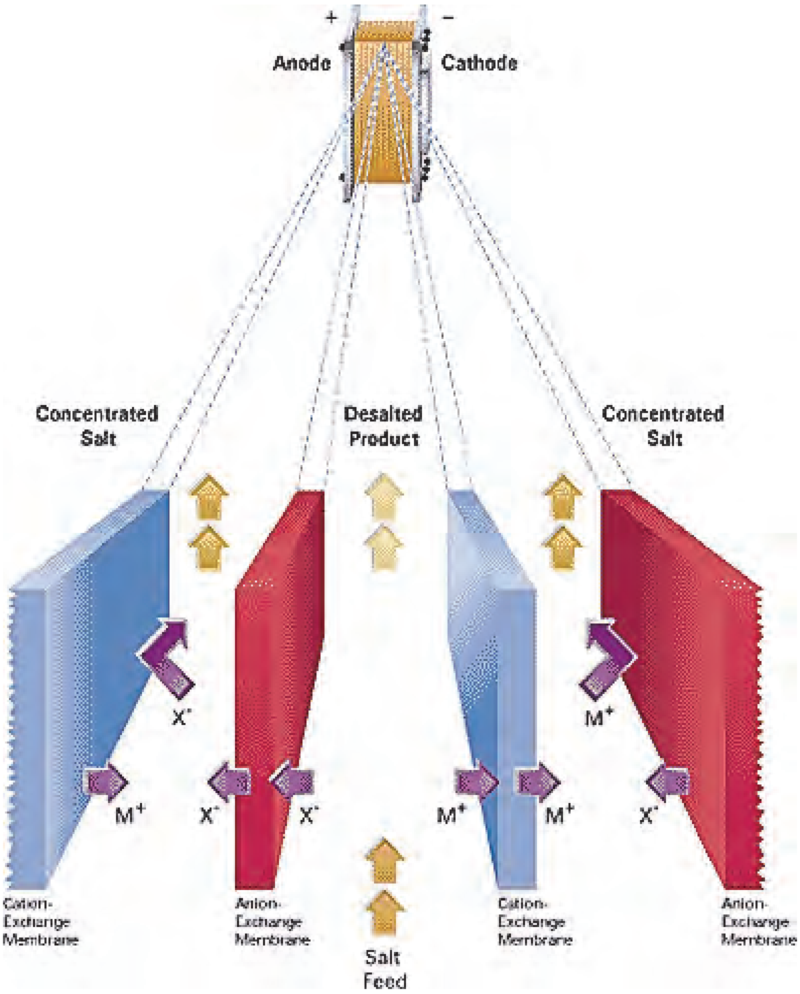

Figure 4: Electrodialysis schematic representation of EDR stack (courtesy of Eurodia)

The membranes are subject to fouling and some pre-treatment is typically required. Scaling on the membrane surface as a result of pH changes may also be problematic. EDR used the technique of changing the polarity at regular intervals to counter fouling and scaling. This effectively results in a switching of feed and brine channels to prevent the potential accumulation of foulants and scale.

3.2 Nanofiltration

Nanofiltration (NF) is typically used for partial desalination application, e.g. softening or the selective separation of mono and multivalent ions. NF membranes are sometimes referred to as “loose” RO membranes with system design and operation being similar to that of reverse osmosis. With respect to main stream desalination applications the equivalent low-pressure RO membranes are more efficient with respect to lower salt passage, while operating at similar feed pressures. Hence nanofiltration has been mostly applied to niche applications, such as softening, recovery of valuables and specialised separation in mostly the industrial sector.

4 COMPARISON OF ESTABLISHED DESALINATION PROCESSES

4.1 Feedwater Salinity

The concentration range of feedwater TDS in which the main commercially established desalination processes can be applied economically may be summarised as follows (Clayton, 2006):

Table 1: Process feedwater range

Process	Applicable Feedwater TDS range (mg/ℓ)
Ion exchange (IX)	10-800
Electrodialysis (ED/EDR)	200-10 000
Reverse osmosis (RO)	50-50 000
Distillation (MSF/MED)	20 000-100 000

In the Southern African context desalination applications would typically relate to seawater and brackish water sources where the production of potable water is desired. Hence the resultant feedwater TDS range of South African seawater and brackish water (1 000 to 36 000 mg/ℓ) fits the RO range.

4.2 Market share

The global market share of the three main commercial seawater desalination technologies and comparison of the major desalination process technologies are illustrated in Figure 5.

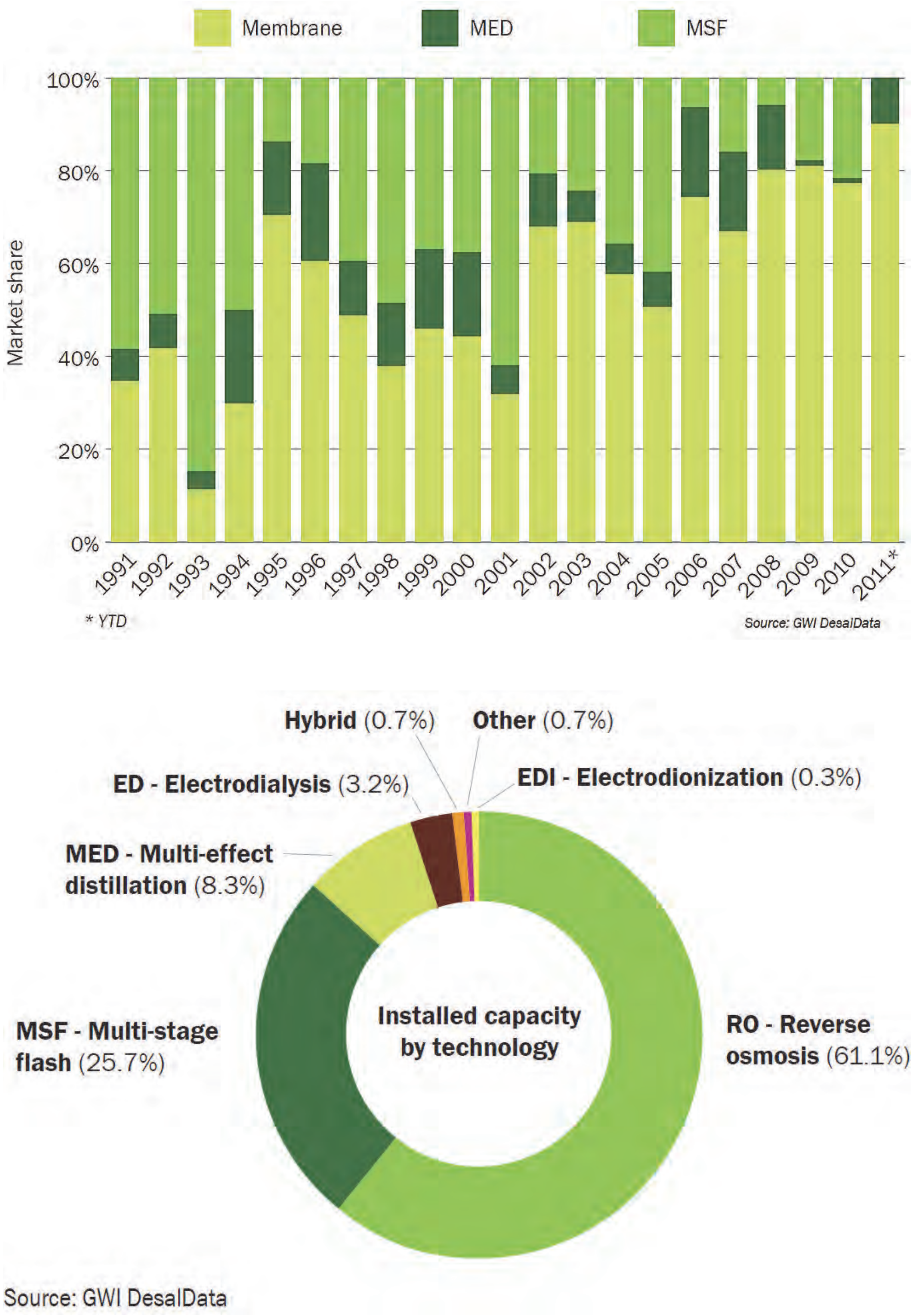

Figure 5: Market Share by process technology and comparison of three main seawater desalination technologies (GWI, 2011)

From the above illustration, it is clear that RO is the dominant technology with respect to desalination projects based on worldwide installed capacity.

The breakdown of global desalination market share by end user category is illustrated by the Figure 6.

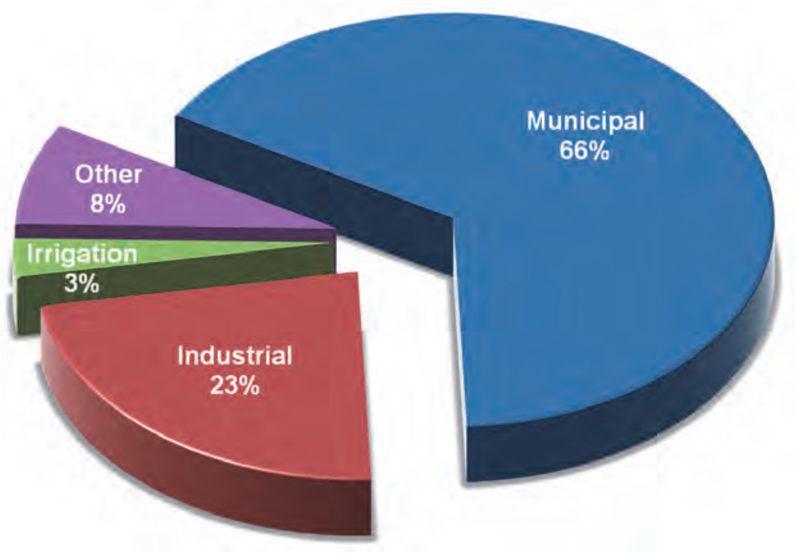

Figure 6: Market share for desalination by end user category

It follows that the municipal sector is by far the largest user of desalination technology. To this end, the production of potable water from seawater and brackish water feed may be seen as the largest application in the market.

4.3 Process comparison

The process characteristics of the three main seawater desalination technologies are summarised below:

Table 2: Main Seawater Desalination Technologies

Process Characteristic	MSF	MED	RO
Pre-treatment required	minimal	minimal	critical
Chemical consumption	low	low	higher
Scaling issues	low	low	lowest
Fouling	low	low	higher
Operational simplicity	lowest	low	higher
Reliability / robustness	lowest	low	pre-treatment dependent
Capital cost	highest	high	lower
Steam consumption – Gain Output Ratio (GOR)	10 : 1	7 : 1	n/a
Electricity consumption (kWh/m^3)	3.5	1.2	4
Feed : product flow	8 : 1	8 : 1	2.2 : 1
Feed pressure (bar)	2	2	65
Concentration factor	1.7	1.7	1.9
Product TDS (mg/ℓ)	< 25	< 25	< 450

The choice of desalination technology may be determined by the following considerations:

Primary considerations

- Produced price of water
- Feed and product water qualities
- Availability of low cost steam
- Scale of project
- Location specific issues

Secondary considerations

- Client preference for a particular desalination technology
- Risk aversion of local water agencies
- Client “resistance” to implement advanced technology

It follows that without access to a source of low cost steam RO technology is the obvious choice. This would largely apply to the Southern African scenario, especially in coastal areas, due to the lack of established oil and gas fields, as well as power plants that have been designed with co-generation in mind.

5 LIMITATIONS OF SEAWATER DESALINATION

A few general setbacks for the processes of desalination also exist.

Dumping the wasted salt solution (most often referred to concentrate or brine) back into the ocean makes the process more difficult and has the potential to harm ocean life.

The energy required to start up and power desalination plants is a huge expense and because most current power sources are derived from burning fossil fuels, it is generally looked upon as just a matter of choosing one environmental crisis over another. Within the energy issue, nuclear energy is potentially the most cost-effective energy source, but remains largely untapped due to public opinion on having a local nuclear power plant or waste facility.

If regions situated away from the coast or in a high altitude try to use desalinated water, it is an even more expensive process. Higher altitudes and far distances require great resources to transport the water from the ocean or body of salt water.

6 EMERGING AND OTHER DESALINATION TECHNOLOGIES

Some of the more promising and intensively investigated alternative desalination technologies include:

- Forward osmosis
- Osmotic power
- Others – crystallisation, humidification, deep ocean and wave driven, solar, etc.

Most of these approaches have yet to demonstrate commercial viability. The list is by no means exhaustive and more detailed descriptions on these technologies may be found in available literature. The list is intended to serve as an indication of the wide variety of approaches that have been investigated, which nevertheless can be categorised into one or more of the basic approaches outlined above, viz. thermal, physical, chemical.

6.1 Forward osmosis

One of the emerging desalination technologies is forward osmosis. This technology uses the difference in osmotic pressures of two solutions as driving pressure. A semi-permeable membrane separates the two solutions. To effect desalination the feed could be seawater and the other a so-called draw solution with a higher osmotic pressure than the seawater. By means of the natural osmosis process pure water would diffuse from the seawater feed through the membrane (rejecting the dissolved salt) into the draw solution. This leads to a dilution of the draw solution and the extracted water must subsequently be recovered from the draw solution in order for the draw solution to be reused. The concept is shown in Figure 7.

The UK company Modern Water, one of the leaders in forward osmosis, prefers to refer to the process as “manipulated osmosis desalination” or MOD (Nicoll, 2012). The recovery or regeneration system may typically be a reverse osmosis system, depending on the type of draw solution used. A variety of draw solutions can be used with the main criteria being that the draw solution has a higher osmotic pressure than the feed solution.

Recent research and development indicates that an ammonia-carbon dioxide draw solution may be useful since it can be recovered by heating the diluted draw solution (McCutcheon, 2006).

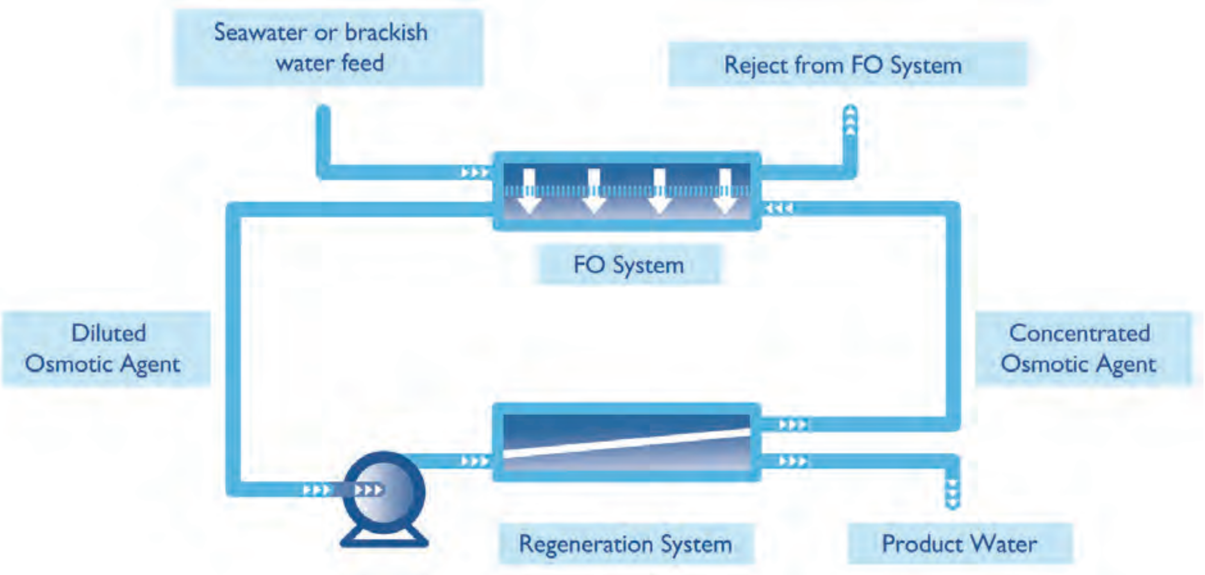

Figure 7: Forward Osmosis simplified process diagram (courtesy of Modern Water)

6.2 Osmotic power

Another version of the forward osmosis process is “pressure retarded osmosis” (PRO) which can be viewed as an intermediate process between reverse osmosis and forward osmosis (Cath et al., 2006). In this case hydraulic pressure is applied in the opposite direction to the osmotic pressure gradient, but with the net water flux still in the direction of the draw solution. This shows promise for the generation of electricity using energy recovery devices normally used in seawater RO systems.

This concept is promoted by the company Statkraft and referred to as “osmotic power” (Halper, 2010) and illustrated in Figure 8.

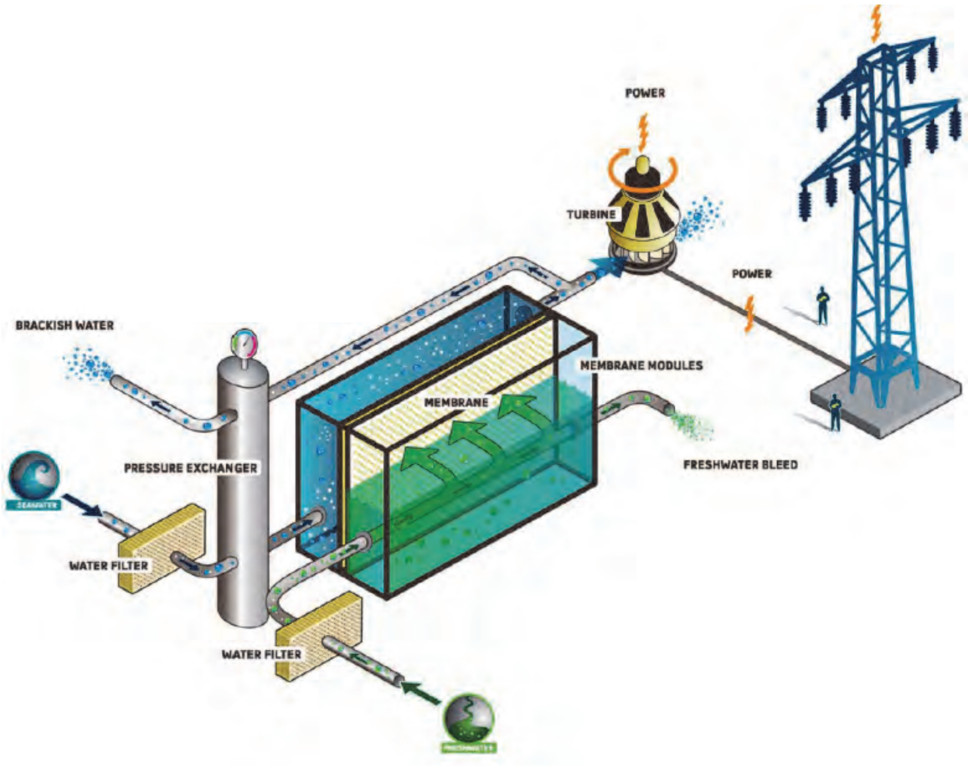

Figure 8: Osmotic Power simplified schematic diagram (courtesy of Statkraft)

Although the concept has been proven the lack of suitable membranes with sufficient energy productivity currently hampers commercialisation. The development of suitable membranes could be the trigger for large and more widespread application of the technology as an alternative to established desalination techniques.

6.3 Other technologies

Examples of other desalination techniques are presented in Table 3 (Miller, 2003). These techniques are only mentioned here and not elaborated on. The list is by no means exhaustive and more detailed descriptions on these technologies may be found in referenced literature. The list is intended to serve as an indication of the wide variety of approaches that have been investigated, which nevertheless can be categorised into one or more of the basic approaches outlined above, viz. thermal, physical, chemical.

Table 3: Other Desalination Techniques

Category	Process
Crystallisation	• Freeze desalination • Gas hydrate processes
Humidification	• Dewvaporation processes • Seawater greenhouse • Membrane distillation • Mechanically intensified evaporation
Deep ocean and wave driven	• Osmotic pump • Deep ocean hydrostatic head • Wave pumps
Solar	Solar stills
Other	Liquid-liquid extraction

7 FUTURE OF SEAWATER DESALINATION

Desalination is process primarily applied in developed countries with financial capability and resources. If the technology continues to produce new methods and better solutions to the issues that exist today, there would be a whole new water resource for more and more countries that are facing drought, competition for water, and overpopulation. Although there are concerns in the scientific world about replacing our current overuse of water with complete reliance on sea water, it would undoubtedly be at least an option for many people struggling to survive or maintain their standard of living.

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INVESTIGATION INTO THE COST AND OPERATION OF SOUTHERN AFRICAN DESALINATION AND WATER REUSE PLANTS

Volume I: Overview of Desalination and Water Reuse

Report to the
Water Research Commission

by

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The publication of this report emanates from the Water RRC project entitled *Investigation into the cost and operation of Southern African desalination and water reuse plants* (WRC Project No. K5/2121),

The report forms part of a series of three reports. The other reports in the series are:

Volume II: Current Status of Desalination and Water Reuse in South Africa **(WRC Report no. TT 637/15)**
Volume III: Best Practices on Cost and Operational Aspects of Desalination and Water Reuse Plants **(WRC Report no. TT 638/15)**.

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EXECUTIVE SUMMARY

The aim of this project was to capture real operational and maintenance data (including associated costs) of selected desalination and water reuse plants, as well as to establish a first-order knowledge base for these types of projects in the augmentation of water supply in a Southern African context. The selected plants are:

No.	Plant	Type of Plant
1	Mossel Bay 15 Mℓ/d SWRO plant	Desalination – direct potable
2	Sedgefield 1.5 Mℓ/d SWRO plant	Desalination – direct potable
3	Albany Coast 1.8 Mℓ/d SWRO plant	Desalination – direct potable
4	Beaufort West 2.1 Mℓ/d reclamation plant	Reuse – direct potable
5	Windhoek 21 Mℓ/d Goreangab reclamation plant	Reuse – direct potable
6	George 10 Mℓ/d UF plant (full capacity tested as 8.5 Mℓ)	Reuse – indirect potable
7	Mossel Bay 5 Mℓ/d UF/RO plant	Reuse – direct industrial

This report (Volume I) provides background and insight into desalination and water re-use. A literature review on desalination and water reuse is presented to place these processes into context and provide an understanding of current state-of-the-art, including how these relate to the technology used at the selected plants.

Volume II follows with a report on the current status of desalination and water reuse in Southern Africa.

Volume III presents descriptions of the selected plants and their main processes, as well as summaries of the capital costs and O&M costs. The report then provides unit costs and comparisons with the other plants, and finally presents summaries of lessons learnt and best practices in desalination and water reuse.

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ACRONYMS & ABBREVIATIONS

ACIP	Accelerated Community Infrastructure Programme
ACWB	Albany Coast Water Board
AOP	Advanced Oxidation Processes
BAC	Biological Activated Carbon
BEE	Black Economic Empowerment
CAPEX	Capital Expenditure
CEB	Chemical Enhanced Backwash
CEC	Contaminant of emerging concern
CIP	Cleaning in Place
CMA	Catchment Management Agencies
CoGTA	Ministry for Cooperative Governance and Traditional Affairs
CPI	Consumer Price Inflation
DAF	Dissolved Air Flotation
DOC	Dissolved Organic Carbon
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation (formerly DWA)
ED	Electrodialysis
EDC	Endocrine Disrupting Compounds
EDR	Electrodialysis Reversal
EIA	Environmental Impact Assessment
ERD	Energy Recovery Device
GAC	Granular Activated Carbon
GDP	Gross Domestic Product
GWWTP	Gammams Wastewater Treatment Plant
HACCP	Hazard Analysis and Critical Control Points
HDD	Horizontal Directional Drilling
IPS	Institute of Polymer Science (University of Stellenbosch)
IRR	Internal Rate of Return
MED	Multi-effect distillation
MFMA	Municipal Finance Management Act
MIG	Municipal Infrastructure Grant
MISA	Municipal Infrastructure Support Agent
MOD	Manipulated Osmosis Desalination
MSA	Municipal Systems Act
MSF	Multi-stage-flash
MWIG	Municipal Water Infrastructure Grant
NACQ	Nominal Annual Compounded Quarterly
NF	Nanofiltration
NGO	Non-Governmental Organization
NGWRP	New Goreangab Water Reclamation Plant
NMBM	Nelson Mandela Bay Municipality
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
OHS	Occupational Health and Safety
OPEX	Operating Expenditure
PAC	Powdered Activated Carbon
PFMA	Public Finance Management Act
PPP	Public Private Partnerships
PSA	Pressurised Swing Adsorption

PST	Primary Settling Tank
RBIG	Regional Bulk Infrastructure Grant
REUSECOST	WRC Water Reuse Costing Model
RHIG	Rural Households Infrastructure Grant
RO	Reverse osmosis
RWU	Regional Water Utilities
SCADA	Supervisory Control and Data Acquisition
SHEQ	Safety, Health, Environmental and Quality
SLA	Service Level Agreement
SST	Secondary Settling Tank
SWRO	Seawater Reverse osmosis
TBMs	Tunnel Boring Machines
TCTA	Trans-Caledon Tunnel Authority
TDS	Total Dissolved Solids
TMP	Transmembrane pressure
TOC	Total Organic Carbon
TOU	Time of Use
TRO	Tubular Reverse Osmosis
TSS	Total Suspended Solids
UAE	United Arab Emirates
UF	Ultrafiltration
USA	United States of America
USDG	Urban Settlements Development Grant
UV	Ultra-violet
VCD	Vacuum Compression Distillation
VFD	Vacuum Freeze Distillation
WABAG	Proprietary technology from VA TECH WABAG Ltd
WHO	World Health Organisation
WINGOC	Windhoek Goreangab Operating Company Ltd
WRC	Water Research Commission of South Africa
WRP	Water Reclamation Plant
WSA	Water Services Authority
WSOS	Water Services Operating Subsidy
WSP	Water Service Provider / Water Safety Plan
WWTP	Wastewater Treatment Plant
WWTW	Wastewater Treatment Work

UNITS OF MEASURE

µm	micrometre
µS/cm	microsiemens per metre
bar(g)	bar gauge pressure
kPa(g)	kiloPascal gauge pressure
kVA	kilovolt ampere
kWh	kiloWatt hour
m^3/h	cubic meter per hour
mg/ℓ	milligram per litre
mS/m	millisiemens/meter
NTU	Nephelometric Turbidity Units
ppm	parts per million

CHEMICAL FORMULAS

$CaCl_2$	Calcium Chloride
$CaCO_3$	Calcium Carbonate (Lime)
Cl_2	Chlorine gas
CO_2	Carbon Dioxide
$FeCl_3$	Ferric Chloride
H_2O_2	Hydrogen Peroxide
H_2SO_4	Hydrogen Sulphate (Sulphuric acid)
$KMnO_4$	Potassium Permanganate
N_2	Nitrogen gas
$NaClO$	Sodium Hypochlorite (bleach)
Na_2CO_3	Sodium Carbonate (Soda Ash)
$NaOH$	Sodium Hydroxide (Caustic Soda)
$Na_2S_2O_5$	Sodium Metabisulphite (also referred to SMBS)
O_3	Ozone

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

South Africa is generally a water scarce country and water could become the limiting factor in sustaining social and economic development in the region in the future. The problem has historically been addressed by exploiting and transferring fresh surface water supplies to economic hubs and the interior of the country through schemes such as the Tugela-Vaal and the Lesotho Highlands projects. However many coastal cities, particularly in the Western and Eastern Cape, as well as KwaZulu-Natal are gradually outgrowing the natural fresh water resources available to them. The country as a whole is reaching the stage where the fresh water resources within its boundaries are nearly fully utilised and it has become necessary to investigate and exploit alternative sources of "new water" to augment existing supplies.

This state of affairs is addressed in the Department of Water and Sanitation’s (formerly Department of Water Affairs) National Desalination Strategy and the Draft National Strategy for Water Reuse (DWA, 2011), which highlight the need to consider desalination and reuse in future water supply schemes.

During the last three decades tremendous development and improvements in the use of membrane technology, both internationally and locally (Lipsett, 2012), have taken place. This allowed the technology to gain popularity in desalination (Than, 2011) and advanced water reclamation schemes (Wintgen et al., 2005) as a means of providing an alternate water resource.

Desalination by reverse osmosis is now considered as playing a considerable role in the future supply of water in South Africa by the general water community (Holman, 2010), as well as at ministerial level (Davis, 2010). To this end, a literature review was conducted on the topic of reuse and desalination to put the treatment approach and technology into context and provide an understanding of current state-of-the-art treatment processes and configurations and how these relate to the technology used at the plants investigated under this research project.

This report concentrates on seawater desalination by reverse osmosis at coastal locations. Although the inland desalination of brackish water sources (e.g. ground or surface water) is also of importance, the desalination plants included in this investigation relate to the production of potable water from seawater.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To evaluate and report on the various costs (capital and operating) of the desalination and reuse plants as a function of the quantity of water produced, as well as the various technologies used with focus on the progression from non-potable to potable desalination and reuse.
2. To report on the technical, as well as operational and maintenance challenges experienced in operating the desalination and reuse plants with reference to project implementation issues.
3. To provide concise Best Operating Practices to maximise production of desalinated and reclaimed water while at the same time ensuring the sustainability of the technology in terms of cost minimisation.
4. To provide a concise report on the various institutional models which can be used to finance and operate desalination plants with a view to minimising risk to the end-user.

1.3 SCOPE AND LIMITATIONS

This report (**Volume I**) covers the initial task, which was to conduct a literature search on the topic of water reuse and desalination to put the process into context and provide an understanding of current state-of-the-art treatment processes and configurations, including how these relate to the technology used at the identified plants. During this period the researcher also made contact with the various collaborating parties to establish communication and flow of information, access specialised knowledge on the subject and determine what additional aspects they would like to see being addressed in the project.

Also available is **Volume II**, where the current status of desalination and water reuse in South Africa is reviewed, as well as **Volume III**, which details the selected desalination and water reuse plants in South Africa, including plant and process configurations, various product end uses, as well as a number of contractors and equipment suppliers. Each plant location and situation has different advantages and challenges to be evaluated for making the best decisions for implementation. Around 2009/10, the Southern and Eastern Cape regions of South Africa experienced the worst drought in known history, and to prevent the risk of complete water supply failure a number of desalination and water reuse projects were undertaken.

Data for the desalination plants at Knysna and Plettenberg Bay is also readily available, and so these plants may be used as comparisons and to provide supplementary data. There has been increasing pressure in recent years on surface water supply to meet the growth in water demand. Water reuse and desalination are now being considered as options both on a local/regional level in the Integrated Development Plans of city councils and municipalities, as well as in national strategies by the Department of Water and Sanitation. The Southern Cape has almost exhausted its terrestrial water resources, particularly as a result of the drought. Furthermore, other parts of the Western Cape, Eastern Cape and KwaZulu-Natal are fast approaching the limits of the terrestrial water resources.

Without adequate freshwater resources, municipalities will have to consider desalination and water reuse to gain access to alternative, as yet less exploited water sources. Without sufficient water, economic growth is likely to stall, resulting in a decline in socioeconomic conditions. In addition to this, health standards are likely to decline. A substantial amount of literature exists in the public domain with respect to cost and water quality aspects for desalination and reuse plants. However, none of these provide real information on cost and water quality obtained from actual plants constructed in South Africa. This research project enhances the knowledge on the subject within the South African water community and will provide information relevant to the South African situation and context. This project entails gathering of cost, operational and other data associated with local (South African) desalination and water reuse plants that have been implemented recently and are planned for implementation in the near future.

The information gathered during the project will be of beneficial use to municipal engineers and the water community as a whole to define real costs for desalination and reuse. This may be used for more effective future planning and comparison of different water supply options.

For reasons of practicality and availability of useable and relevant information, the battery limits for the project were the seven existing desalination plants under investigation, namely:

No.	Plant	Type of Plant
1	Mossel Bay 15 Mℓ/d SWRO plant	Desalination – direct potable
2	Sedgefield 1.5 Mℓ/d SWRO plant	Desalination – direct potable
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7	Mossel Bay 5 Mℓ/d UF/RO plant	Reuse – direct industrial

CHAPTER 2: OVERVIEW OF DESALINATION & WATER REUSE

2.1 INTRODUCTION

Roughly 70% of the earth's surface is covered by water, of which 3% is fresh water and the remaining 97% saltwater in the oceans. In addition most of the fresh water is locked up in glaciers and icecaps as shown in Figure 2.1. Of the available fresh water, only roughly 0.3% is considered renewable, i.e. precipitation that occurs over land and is easily available for human use.

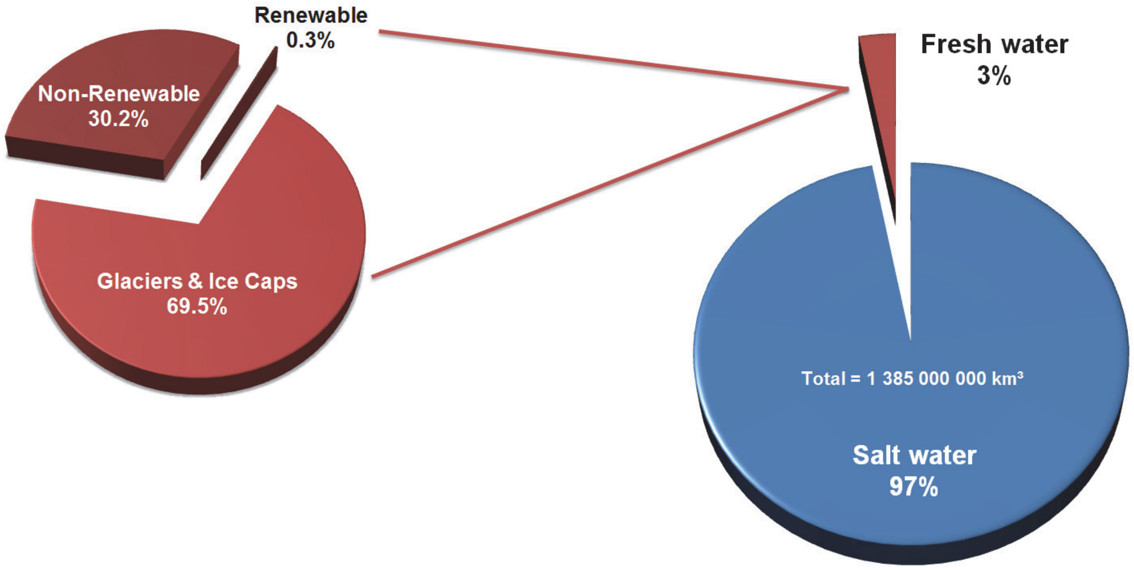


Figure 2.1: Distribution of the World's Water

The renewable fresh water therefore is a small amount, visually illustrated by a sphere with a diameter of 60 km, in relation to the total water sphere that is 1 400 km in diameter. Shown in Figure 2.2, the 60 km sphere of renewable fresh water would be scarcely visible in the image.

The ever-growing world population and adverse climate changes place an increasing strain on suitable water sources, especially in existing water-challenged areas. Another problem is uneven distribution, as many countries have sufficient water, but in the wrong place.

This situation is expressed in the accompanying water scarcity projection chart (IWMI, 2000).

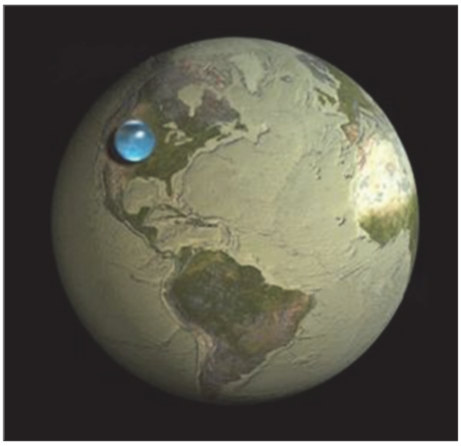


Figure 2.2: Total Water Sphere

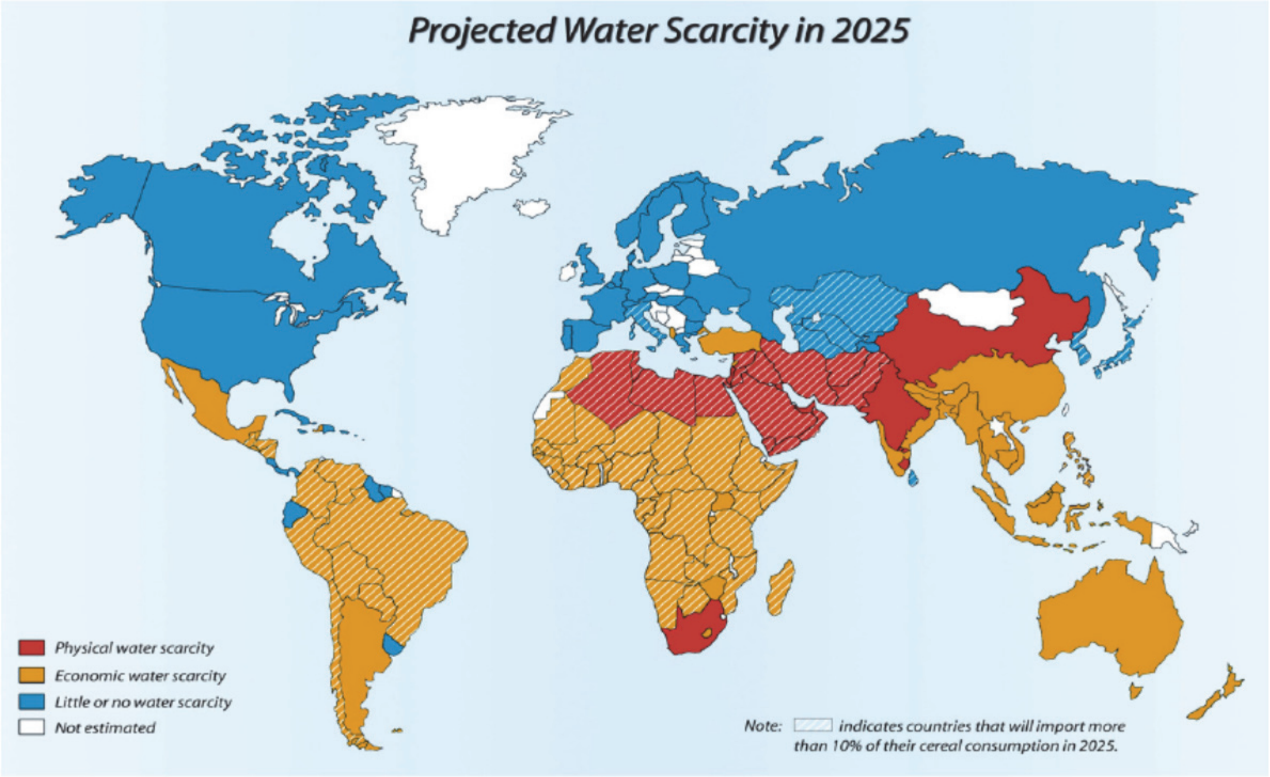


Figure 2.3: Projected Water Scarcity in 2025

Producing potable water from some of the 99.7% fraction of salt and non-renewable water is the challenge for desalination and reuse. To do this the relevant technology must be able to provide solutions for places that need, and will need, water most on a cost-effective and reliable basis.

As pointed out above the increasing water scarcity will challenge the human population more and more in the future. With water being a finite resource the obvious approach to counter this is to focus on efficient use and conservation. Ultimately a number of approaches will be necessary to curb the growing water problem, e.g. implementing policies for water conservation and reuse, slowing population growth and tapping into non-traditional sources to augment fresh water supplies. From a traditional perspective the most practical way of increasing the water supply is to build new dams and to harvest the available renewable water supply more effectively. However, with most resources already being close to fully exploited, the only other alternative to grow the water supply is to create “new” or “produced’ water. This is the objective of desalination and reuse.

From a global perspective desalination and reuse are likely to have a relatively small impact on the total fresh water supply. On a local basis, however desalination and reuse could play a significant role due to the “locality” aspect associated with the supply and use of water mentioned in the previous section.

2.2 DESALINATION OVERVIEW

Desalination refers to processes that reduce the salinity of the water fed to a particular treatment process. All naturally occurring waters contain dissolved substances which contribute to their varying salinities.

The three basic approaches to separate salt from water are by thermal means, physical separation or chemical process.

Thermal means relate to distillation processes where the saline water is boiled to effect a phase change in order to drive off pure water vapour from the salt solution. The main commercial thermal (distillation) processes are multi-stage-flash (MSF) and multi-effect distillation (MED) techniques. Another thermal method refers to the separation of salt from water by freezing of the feedwater, thereby separating fresh water from the saline solution.

A secondary approach is physical separation of the dissolved salts from the saline solution. This is generally done with a membrane, which can be considered to act as an extremely fine "sieve". The two main membrane processes used for desalination are reverse osmosis (RO) and electrodialysis (ED).

Lastly chemical approaches to desalination include physical-chemical processes, such as ion exchange (IX), liquid-liquid extraction and precipitation. Chemical processes are generally too expensive to apply to the production of fresh water as standalone processes. Ion exchange, on the other hand, is widely used for softening or the production of highly demineralised water for industrial applications (e.g. boiler feedwater preparation).

Desalination processes are applied to saline feedwater to typically convert a portion of the feed stream into a product stream of reduced salinity. A simplistic view is that all desalination processes split the saline feed stream into a stream of desalinated (fresh) water and a concentrated (brine) stream by utilising energy. Normally the desalinated stream constitutes the product with the brine being the waste stream, as illustrated in the accompanying schematic.

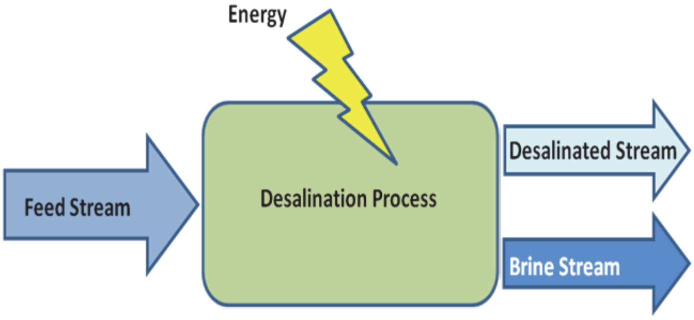


Figure 2.4: Desalination process energy

The energy used by the desalination process can take the form of heat (e.g. thermal desalination), pressure (e.g. membrane desalination) or electricity (e.g. electrodialysis), as shown in Figure 2.4.

The main groups of desalination processes are thermal processes and membrane processes. In saline feedwaters, two main categories can be distinguished, viz. seawater and brackish water.

This report will focus on pressure-driven membrane processes, in particular the reverse osmosis (RO) process as applied to the desalination of seawater. The other desalination approaches are further detailed in Appendix A.

2.2.1 Historical Timeline of Desalination

The concept of desalination for the removal of salts from sea water using primitive methods of distillation is not new and has been applied for thousands of years (Fox, 2012). However, methods applied to desalinate water, were not only limited to the need for recovery of fresh water but also for the need of salt which was a precious commodity. The concept of desalination relates to Greek, as well as 17th century Japanese sailors that used earthenware pots to boil seawater, and bamboo tubes to collect condensed fresh water from the steam. The Romans are reported to have used clay filters to trap salt. There are also biblical references as well as historical accounts from ancient Egyptian, Phoenician and Greek writings, mentioning the purification of brackish water.

The need to supply freshwater to remote locations, such as naval ships resulted in the development of methods to replenish freshwater supplies and this led to the issuing of the first desalination patent in 1852 (GWI, 2012). Some key developments and turning points in recent desalination history are summarised below (adapted from various sources, namely DEPI, 2013 and GWI, 2012).

Table 2.1: Summary of Desalination History

Date	Event
320 BC	First written record of saline water desalination, by Aristotle
1684	Shipboard desalination, UK. "An experiment to produce fresh water out of salt"
1791	First technical report of the desalination process written by Thomas Jefferson (US Secretary of State)
1940s	Mobile and ship based desalination units used extensively by military forces in WWII
1955	Smith from the CSIR laid the foundation for ED theory, later used internationally. Installed ED treatment system at the FS Gold Mines this year
1955	Development of the MSF process
1958	Office of Saline Water, USA established to research and develop desalination technologies
1959	First large scale MED installation, Netherlands Antilles
1961	Development of the first asymmetric, commercially useful RO membrane by Loeb and Sourirajan
1963	First hollow fibre RO membrane produced (DuPont)
1972	First locally produced South African tubular RO, by Bakke Industries, Paarl (later Envig) with WRC funding.
1972	Thin film composite RO membrane developed by Cadotte
1974	First single pass SWRO plant, Bermuda (Polymetrics)
1978	Largest thermal desalination plant capacity ever built, Al-Jubail Phase 2 MSF (908 000 m^3/d)
1980	Entropie's first commercial MED unit, France
1980s	Desalination becomes commercially accepted, widely used and successful, as well as more affordable
1990s	Dramatic increase and improvement in reverse osmosis technology as energy use and costs decrease. Large scale plants constructed across the Middle East, Mediterranean and America
2005	Largest membrane desalination plant ever constructed at Ashkelon, Israel SWRO (330 000 m^3/d)
2006/12	Large SWRO plants constructed, e.g. Melbourne (600 000 m^3/d), Hadera (462 000 m^3/d), Sydney (500 000 m^3/d), Adelaide (275 000 m^3/d)

2.2.2 Current Desalination Technologies

As mentioned before desalination technologies may be divided into the main categories of:

- Thermal processes (e.g. multi stage flash and multiple effect distillation)
- Chemical processes (e.g. ion exchange and precipitation processes)
- Physical processes (e.g. membrane and ion exchange processes)

The salinity of the feedwater is defined according to the total dissolved solids (TDS) concentration, typically expressed in milligrams per litre (mg/ℓ). Feedwater is typically categorised as follows:

- Seawater: 15 000 to 50 000 mg/ℓ TDS
- Brackish water: 1 500 to 15 000 mg/ℓ TDS
- Surface water: 500 to 3 000 mg/ℓ TDS
- Pure water: less than 500 mg/ℓ TDS

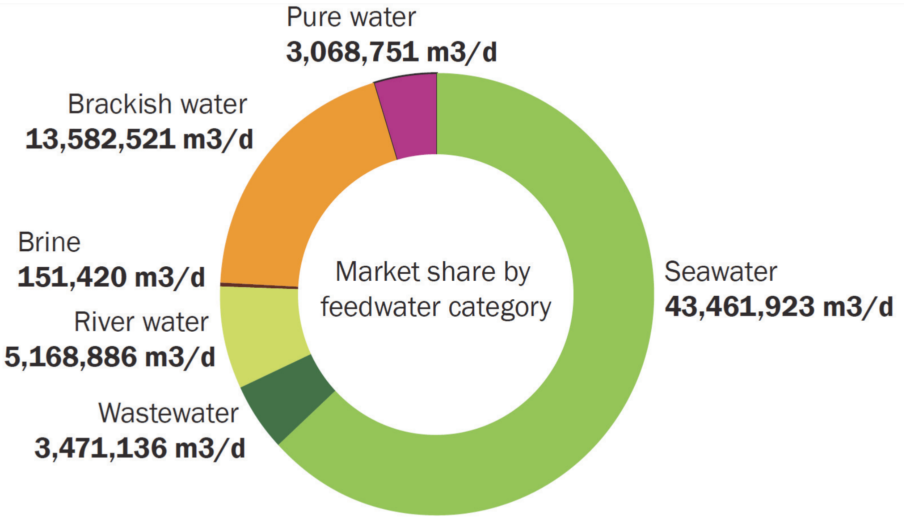


Figure 2.5: Desalination Market by Feedwater Category (GWI, 2011)

A breakdown of the desalination market by feedwater category is shown in Figure 2.5. It follows that the existing emphasis is on the desalination of seawater, followed by the treatment of brackish water and wastewater (which may be considered to include reuse).

2.2.3 Reverse osmosis

Reverse osmosis is the desalination technology of choice in South Africa at present. RO is a pressure driven membrane process with the required energy being provided by high pressure pumps. Pure water is pushed through the semi-permeable membrane by reversing the natural osmotic process (hence the term 'reverse osmosis'). The membrane allows the passage of water, but not dissolved salts. Please refer to Figure 2.6 for a schematic representation of the process. The pressure required must be higher than the osmotic pressure of the saline feedwater. Therefore the required energy depends on the salinity of the feed since higher salinity implies higher osmotic pressure. The net driving force is the difference in applied pressure and osmotic pressure of the saline feed. The use of reverse osmosis in desalination applications was pioneered in the 1960s as a result of the development of a useful reverse osmosis membrane by Loeb and Sourirajan (Loeb, 1981).

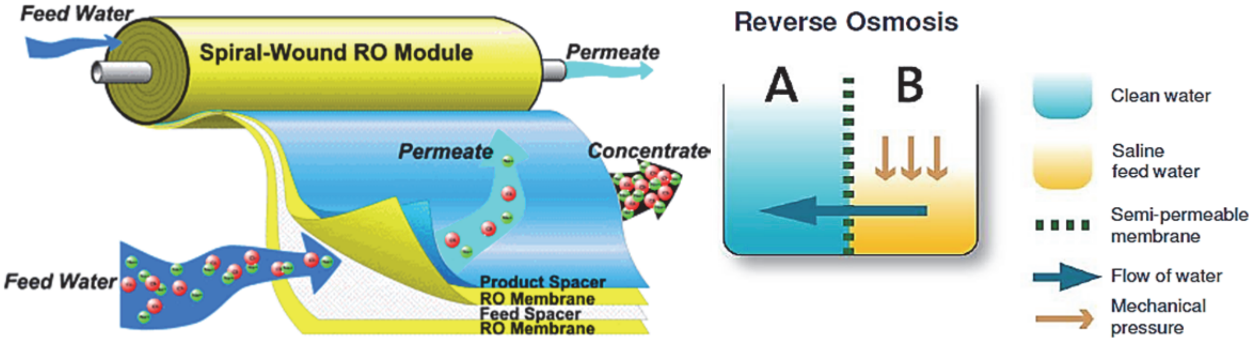


Figure 2.6: Membrane Desalination Schematic representation of RO process

Since commercialisation in the 1970s there has been a tremendous improvement in membrane efficiency and quality, resulting in a dramatic fall in the cost of desalination using RO. The primary difference between seawater and brackish water is the salt content, which has a direct effect on the operating pressure, energy requirement and water recovery (portion of feedwater that is converted to product water).

2.2.4 Geography of desalination

Desalination is currently used by countries that have an extreme need for fresh water, have sufficient financial capability to fund it and have access to energy required to produce it.

The Middle East holds the top spot for desalinated water, due to large facilities installed in several countries, including Saudi Arabia, the United Arab Emirates, and Israel. Other large producers of desalinated water are: Spain, the United States, Algeria, China, India and Australia. The technology is expected to spread increasingly, particularly in the United States, Libya, China, and India.

This is reflected in the desalination market rankings of the top 15 countries with respect to expenditure as illustrated in Table 2.2 (GWI, 2010).

In the United States, the largest desalination plant is located in Tampa Bay, Florida, though it has a very small output compared to most facilities in the Middle East. Other states that are developing plans for large desalination plants include California and Texas. The United States need for desalination plants is not as severe as many other countries, but as the population continues to explode in dry, coastal areas, the need increases.

Table 2.2: Top 15 desalination markets, 2010 to 2013

Position		Country	Capital Expenditure
1	(2)*	Saudi Arabia	$5 159 m
2	(7)*	USA	$4 419 m
3	(3)*	Australia	$3 237 m
4	(16)*	Israel	$2 503 m
5	(13)*	Kuwait	$2 480 m
6	(15)*	Libya	$2 443 m
7	(1)*	UAE	$2 198 m
8	(5)*	China	$1 517 m
9	(9)*	India	$1 293 m
10	(21)*	Chile	$1 200 m
11	(17)*	Caribbean	$1 069 m
12	(29)*	Morocco	$926 m
13	(4)*	Spain	$861 m
14	(11)*	Oman	$785 m
15	(20)*	Iran	$709 m

*The position in brackets represents the country’s market rank during 2008/09

The worldwide emphasis on the desalination of seawater by RO is also illustrated by the annual contracted capacity compared to brackish RO and thermal technologies as shown in Figure 2.7.

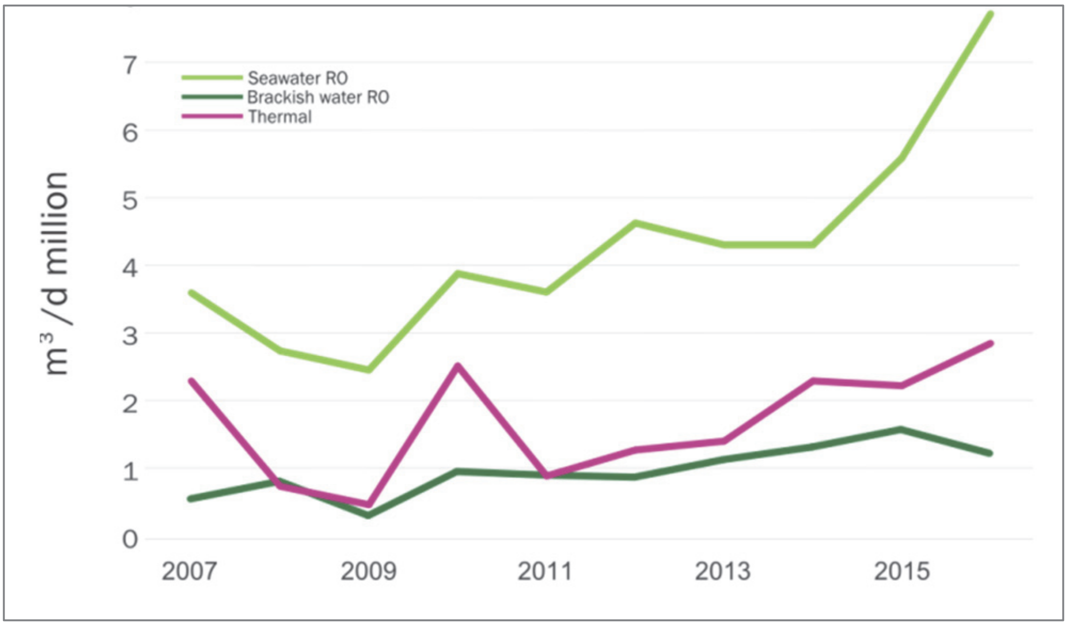


Figure 2.7: **Thermal versus membrane technology by annual contracted capacity (GWI, 2011)**

2.2.5 Basic aspects of seawater desalination by reverse osmosis

The following points summarise some key technical fundamentals of seawater desalination by RO:

- The RO process for the desalination of seawater operates at approximately 40 to 50% recovery, i.e. 40 to 50% of the seawater feed is converted to product water. This means than more than twice the flow of product water required must be pumped from the ocean, and slightly more than the produced flow must be returned. As a result the piping and pumping costs for the seawater intake and the concentrate return are higher per length than the delivery cost of the final product water. The implication is that it is more economical to locate the desalination plant as close as possible to the ocean source.

- In the case of smaller plants (< 2 Mℓ/day) the seawater intake and concentrate return can be accommodated by beach wells. For larger capacities, however, open intake and brine outfall systems are preferred, both from a cost and implementation perspective. Beach wells offer the advantage that the raw water has been pre-filtered naturally, resulting in less additional pre-treatment that is required (depending on suitable soil conditions and absence of pollution ingress). Open intake systems imply that the pre-treatment of the raw water may need to make provision for the removal of elevated levels of suspended solids, turbidity, organics and even microbiological constituents, e.g. phytoplankton, algae, etc.

- Drawing from seawater in deeper open ocean levels, which are unaffected by inflows from land leads to more consistent salinity and lower suspended solids. This is ideal for larger plants, but ocean floor bathymetry, wave action and other considerations that have an effect on plant design need to be taken into account.

- Dispersion of the concentrate from the desalination plant to the sea can be done effectively in the case of open sea outfalls by using diffusers on the outlet pipeline. This, however needs a minimum depth of water (refer bathymetry) depending on the generated brine flows, local currents and other conditions. Dispersion of concentrate via beach wells needs to allow for flushing of the pipelines, as well as take into consideration the permeability of the sand and are only acceptable at lower flows.

- The cost of piping and pumping product water is also significant. It is, therefore, preferable to site the plant at a location where the ocean abstraction point and plant site are relatively close to the point where the water can be introduced into the water supply system. Furthermore, the height to which the product water must be lifted to reach the supply system affects the costs and energy use, so desalination plant sites that are close to areas where lower lifts are required, are preferred.

- The plants are also fairly energy intensive. To this end, it is important that to ensure that sufficient infrastructure for the supply of electricity is available. If not, then this infrastructure will have to be developed, which could have a direct bearing on the suitability of the proposed plant location from a cost and implementation perspective.

- In order to reduce the energy demand of the RO plant the hydraulic energy (as a result of high pressure) remaining in the concentrate stream should be recovered. This may be achieved by fitting the plant with an energy recovery device that reduces the net energy input required to pressurise the feedwater.

- The desalinated water produced (RO permeate) is essentially stripped of all alkalinity and hardness. This, together with an acidic pH makes the water corrosive and aggressive to metal pipe work. The need for remineralisation (i.e. adding back alkalinity and hardness) to reduce the corrosivity of the product water must be considered in relation to potential detrimental effects on the distribution network. The potential blending with other water supplies and the selection of the pipe construction material for conveying RO permeate will have a direct bearing on this aspect.

- Compatibility of the desalinated water with the terrestrial water quality to ensure corrosion and scaling is not excessive over all blending ratios and seasonal changes.

2.2.6 Site selection criteria for seawater desalination by reverse osmosis

The importance of site selection is a critical step in the implementation of seawater desalination plants. The reason for this is that the chosen site can affect a number of aspects to a large extent, e.g. design and operation of the plant, socio-economic and environmental impacts, public acceptance, cost and long-term success of the project.

Basic prerequisites for the construction and successful operation of desalination plants are:

- Suitable access to seawater feed (preferably at relatively constant salinity and quality).
- An acceptable and cost effective method of disposing the brine and waste streams.
- A reliable source of electricity.
- Proximity to a water distribution system to deliver water to the end user.

2.2.7 Suitable access to seawater feed

2.2.7.1 *Seawater intakes*

Seawater intakes for desalination plants can be divided into two broad categories:

- Direct intakes where seawater is drawn directly from the water column by means such as deep water intake structures, jetty mounted pumps or open channels; and

- Indirect intakes where seawater is drawn indirectly from the ocean by means such as beach wells (vertical bores) or seabed infiltration.

A schematic illustration of the categorisation of the various intake types is shown in Figure 2.8. By far the greatest number of intakes associated with large desalination plants are of the direct intake type, normally based on a velocity cap intake. Open channel intakes may be considered where sharing with a power station seawater intake is feasible.

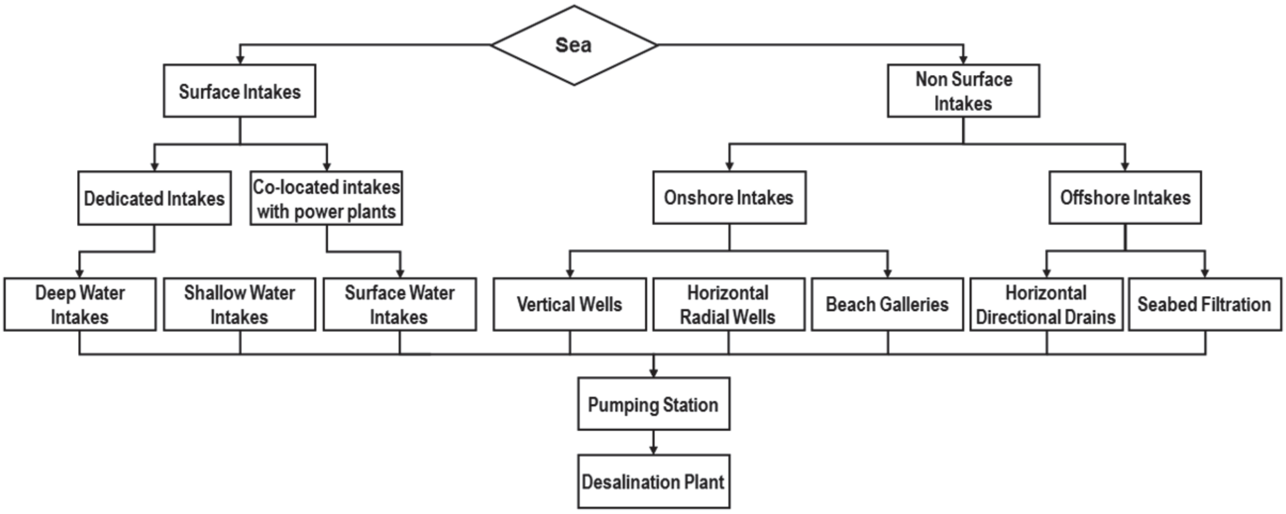


Figure 2.8: A schematic illustration of the categorisation of the various intake types

Intake Depth

The basic difference between the various types of direct intakes is the sea depth at which water is extracted. The depth can range from close to zero metres for open channels (or shoreline intakes), up to 15 m for common intakes and 20 to 35 m for deep water intakes.

Intake depth is important in determining the quality of the desalination plant feedwater for a number of reasons, including:

- **Level of organic matter:** As depth increases there is decreased light and therefore decreased algae quantity (due to the limited photosynthesis).
- **Level of Suspended Solids:** As the total water depth increases (i.e. further distance from shore) there is less turbulence hence there are less suspended solids due to wave action in the water column.
- **Risk of Accidental Pollution:** As depth increases the impact of potential accidental pollution (e.g. from tanker spills, etc.) reduces.
- **Water temperature impact:** As depth increases temperature decreases. Colder water results in better quality desalinated water; although colder water increases water viscosity, decreasing the permeate flux thus increasing the RO feed pressure and therefore energy consumption. Increased depth will generally provide a more stable water temperature, which is more important for plant operation.
- **Impact of low salinity discharges from local creeks, rivers:** As depth increases the risk of extracting low salinity fresh water is reduced, i.e. leads to greater stability of salinity, which is important for the desalination process.

Other factors that may influence the selection of intake depth are:

- **Bathymetry:** Large distances to deep water from the shoreline increase the length and cost of intake conduits making shallower solutions more economical.
- **Tidal conditions:** Large tidal ranges increase the length and cost of intake pipelines making shallower solutions more economical.
- **Geotechnical conditions:** Unfavourable tunnelling or dredging conditions will increase the cost of intake conduit construction making shallower solutions more economical.
- **Wave environment:** the underwater dynamic forces resulting from wave action decrease with water depth. Large waves increase the anchoring requirements for seabed structures making deeper solutions more economical.
- **Shipping activity:** Sufficient freeboard is required over the intake if it is exposed to shipping movements. This can result in deeper solutions. In some circumstances the intake is marked as a shipping exclusion zone and this constraint can be eliminated.
- **Sediment transport:** the higher the intake opening is above the seabed the less likelihood there is of the intake being blocked by sediment. The higher intake opening also means less likelihood of benthic marine species being impacted by the intake.

Conduits and shoreline crossings

The choice of marine conduit is dependent upon a number of factors including:

- **Geology:** consistency and depth of underlying rock and suitability of the ground conditions for tunnelling, drilling, dredging or trench excavation;
- **Weather:** suitability for the use of construction barges;
- **Tidal range and local currents:** suitability for the use of construction barges and equipment;
- **Wave environment:** suitability for the use of construction barges and underwater dynamic forces on pipe and backfill during and after construction
- **Materials:** availability of stone and rock for trench backfill;
- **Diameter, length, alignment and grade:** different approaches have different limits;
- **Environment:** sensitivity of local environment to sediment plumes and seabed disruption; Impact on shoreline, both during and at completion of construction;
- **Cost:** cost of construction.

Conduit construction options

There are a broad range of options that can be adopted for the intake and outfall conduits. The main categories are summarised as follows:

- Trenchless technologies:
  - **Option 1:** excavated tunnels using double-shield tunnel boring machines (TBMs) and lined using pre-cast steel fibre-reinforced concrete segments (Gold Coast, Sydney and Melbourne); and
  - **Option 2:** micro-tunnelling with pipe-jacking using plastic lined pre-cast pipe sections (Perth 2, Adelaide); and
  - **Option 3:** horizontal directional drilling (HDD);
- Pipelines trenched into the seabed (Perth 1 and Mossel Bay);
- Pipelines laid on top of the seabed and anchored in place by various means (Ashkelon, Mossel Bay and Gold Coast diffuser);
- Pipelines constructed on jetty structures.

These options can be used alone or in combination, e.g. tunnelling across the shoreline and wave zone, then trenched pipe to the intake and outfall locations can be used to ensure the shoreline is not disturbed.

Screening

The choice of screen configuration and size is dependent upon the following factors:

- **Marine life:** the type and size or marine life in the area and the risk of entrainment into the intake pipe;
- **Pumps:** the type of pumps proposed and the risk of pump fouling by entrained debris;
- **Pre-treatment:** the type of pre-treatment equipment proposed downstream and its ability to remove and handle solids of various sizes;
- **Cleaning:** the physical location of the screen and the ease of providing a method to clean or back flush the screen and dispose of solids;
- **Tidal range:** can influence the location of an active screen before or after the seawater pumps.

Pump stations

The choice of pump station configuration is dependent upon the following factors:

- **Conduit construction:** various pump station structures have synergies with different conduit construction methods;
- **Screening strategy:** pumps have varying ability to pass solids;
- **Efficiencies: different** styles of pumps have different efficiencies which effects energy costs, particularly at higher pumping pressures;
- **Back-flushing:** the need to reverse flows for back flushing of an infiltration intake;
- **Pump failure:** the need to provide standby pumps or to protect the pump motors from flooding;
- **Maintenance access:** the facilities available to remove pumps and motors.

The above aspects illustrate the complexities associated with the selection of a suitable location for a desalination plant, resulting in increased emphasis on intake (and outfall) design and economics. In fact, intake (and outfall) selection could be considered as the "fatal flaw issue" of new seawater desalination facilities (Pankratz, 2008).

2.2.8 Seawater quality

The seawater quality is the key external input which drives the process design (noting that it can be influenced by the location and type of inlet). Deeper or subsurface inlets can provide improved water quality, and thus reduce the need for pre-treatment prior to the RO system.

The intake selection is generally based on the plant location and should consider, amongst other things, seawater quality, environmental impacts, intake technology and costs. As such, the expected quality of seawater fed to the desalination plant can only be defined within a certain degree of accuracy once the following have been established:

- Location of the seawater abstraction point (e.g. depth, distance from shore, hydrodynamic conditions, seabed stability, sand transport, etc.).
- Preferred choice of intake type and arrangement (e.g. direct surface, indirect off-shore).
- Results from preliminary seawater sampling regime and review of relevant historical water quality data and potential diffuse and point pollution sources in the vicinity of the intake which may impact on source water quality.

Variations in seawater salinity and temperature are fundamental for RO process design with respect to the adopted configuration, recovery, membrane selection and required operating pressure to meet product water quality and plant availability targets.

Equally important for the design of the RO pre-treatment facilities and RO plant is the characterisation of seawater quality with respect to fouling parameters, such as turbidity, TOC and DOC, hydrocarbons, picophytoplankton, metals, nutrient status, as well as the possible occurrence of sulphur outbreaks, algal, jellyfish and seaweed blooms. These will have a direct bearing on the selection of the pre-treatment system (and hence cost) in order to achieve the desired RO feedwater quality (e.g. turbidity and SDI – DOE, 2010) and maintain the required plant availability.

2.2.9 Disposing (and treatment) of Brine and Waste Streams

The desalination plant will produce seawater concentrate, often referred to as brine, which is approximately twice the salinity of the ambient seawater and therefore of a higher density. This brine needs to be disposed of in the ocean in an environmentally acceptable and cost effective manner. Typically the following options are available:

- Pumped seawater dilution option consists of pumping additional seawater through the intake system and then diluting the brine with this additional seawater prior to brine disposal into the marine environment. This reduces the salinity and temperature difference between the background conditions and the discharge and assists with near field dilution. However, this substantially increases the required capacity of the inlet pump station, the inlet pipeline and the outlet pipeline.
- Shoreline discharge, in many areas of the world the concentrated brine is simply discharged back into the ocean at the shoreline with no attempt at dilution or diffusion. For small quantities of brine being discharged into an active surf zone this may be a viable option. However, if large quantities of brine are to be disposed of, it is almost certain that such a design would not gain environmental approval.

- Utilising outfall diffuser is the brine disposal method adopted by all the large seawater desalination plants in South Africa, Namibia, Australia and the world. The diffuser can be either configured as a piped diffuser or rosette style diffuser. The diffusers are generally located far enough offshore so that they are beyond the surf zone and in sufficient depth of water to effect adequate dilution.

2.2.10 Integration with Water Distribution System

Desalination plants generally operate as a base load facility with limited turn-down ratio. However, since they are generally configured in multiple, parallel trains they can be operated in steps by taking one or more trains off-line.

However, this would result in "stranded assets" if not fully utilised. Thus the integration into the water distribution system should be done so that the final staged flow can be accommodated on a continuous basis with the future demand curve for potable water determining the base load and increments.

Water quality aspects and considerations can play an even more important part in operational requirements when desalination plants are connected into existing systems for the following reasons:

- Water quality can be of a lesser or higher standard than the water to which it is being added.
- Pipe flow directions can end up being reversed, especially in relation to customers provided along the route if a separate rising main is not provided.
- Blending of water in a balancing reservoir could change in quality, depending on the ratio of desalinated water to the water provided at the point of mixing.

As such, the integration of the product water with the distribution system is an important aspect in the implementation of a desalination plant.

2.2.11 Electricity Source

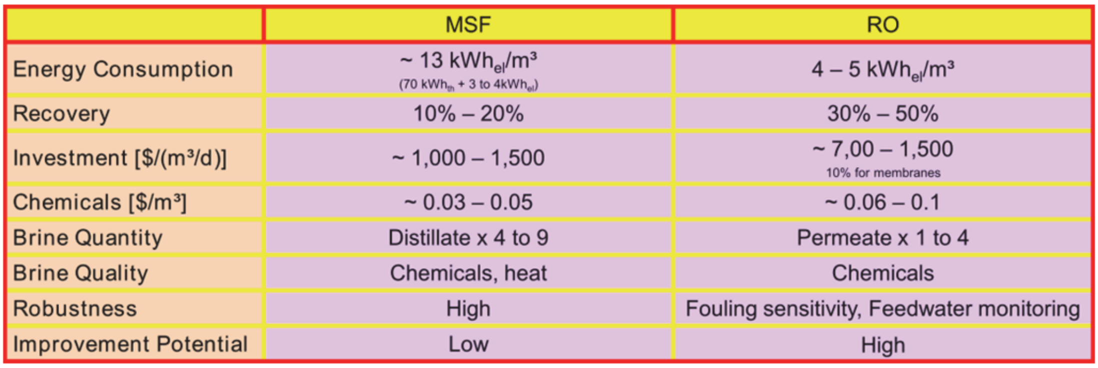
Essentially modern SWRO plants conservatively require about 150-200 kW of power per Mℓ/day of water produced. Other factors may play a role here such as plant elevation (requiring more power for feedwater supply) and the product water pumping system static and dynamic head. The use of energy recovery devices (ERD) serves to minimise the energy consumption on the RO portion of the plant.

It is generally accepted that the conventional power source for a desalination plant will come from the electrical power grid at competitive rates. Nevertheless, the implications of wind and solar energy should be considered as potential alternative power sources to meet the power requirement of the desalination plant.

2.2.12 Cost Aspects of Seawater Desalination by Reverse Osmosis

2.2.12.1 *Basic cost considerations*

The cost of producing drinking water by the desalination of seawater with reverse osmosis may be considered to be high, although RO is substantially less energy intensive than equivalent thermal processes. On the other hand, this must be balanced against the cost and far reaching implications of running out of water as a result of not meeting the water supply demand from conventional sources. To this end, desalination provides an alternative water source that is independent of rainfall and may be considered as "new" water.



	MSF	RO
Energy Consumption	~ 13 kWh$_{el}$/m^3 (70 kWh$_{th}$ + 3 to 4kWh$_{el}$)	4 – 5 kWh$_{el}$/m^3
Recovery	10% – 20%	30% – 50%
Investment [$\$/(m^3/d)$]	~ 1,000 – 1,500	~ 7,00 – 1,500 10% for membranes
Chemicals [$\$/m^3$]	~ 0.03 – 0.05	~ 0.06 – 0.1
Brine Quantity	Distillate x 4 to 9	Permeate x 1 to 4
Brine Quality	Chemicals, heat	Chemicals
Robustness	High	Fouling sensitivity, Feedwater monitoring
Improvement Potential	Low	High

Figure 2.9: Thermal vs. membrane comparison (Banat, 2007)

It must be kept in mind, however, that the basic RO plant itself is only a part of the total scheme. With known feedwater and target product water qualities the basic plants are relatively standard and consistent in price. However, the infrastructures in front of (intakes, pre-treatment, etc.) and after (waste discharge, product water pumping systems) the basic plant building block (membrane system) are major variables in determining the capital and operating costs of the selected solutions. Each location and situation has different advantages and challenges that need to be evaluated for making the best decisions for implementation from a holistic point of view. Although the individual cost category factors that contribute to the overall cost of the desalination scheme are largely the same for each project, their individual contributions may vary significantly from project to project thereby often resulting in large cost differences. The cost categories associated with SWRO desalination projects are shown below (WADC, 2011).

Figure 2.10: Cost categories contributing to SWRO projects (adapted from WADC, 2011)

2.2.12.2 *Selection of intake and discharge*

As illustrated before the variety of intake options and the associated construction aspects cover a wide range of possibilities. Besides being site and project specific the ultimate choice and configuration may also be affected by the legislative and environmental requirements of the country in which the plant is located. A comparison of selected aspects for various intake types is given in Table 2.3.

Table 2.3: Comparison of various seawater desalination intake types (WADC, 2011)

Intake Type	Relative Values			Reliability
	Cost (for equal capacity)	Intake Space Requirements	Pre-treatment Space Requirements	
Beach Wells	Low	High	Theoretically less	Variable based on subsurface lithology
Horizontal Directional-drilled	Medium	High	Theoretically less	Unknown
Radial Wells	Medium	High	Theoretically less	Unknown
Constructed seabed/infiltration gallery	High	Medium	Theoretically less	Unknown
Submerged open intake	Medium-low	Low	More	High
Surface: open intake	Low	Low	More	High
Co-located intake	Low	Low	More	High

Various methods for the disposal of the concentrate stream exist, e.g. open sea outfall, co-disposal with power plant or waste water treatment works outfall, deep well injection, evaporation ponds and zero liquid discharge arrangements. For coastal desalination plants however the open sea outfall arrangement is the most common.

The costs associated with intake and discharge arrangements vary widely due to many site-specific variables, in particular conveyance costs. Higher than normal cost trends for intake and discharge systems seen in recent large-scale Australian desalination projects are attributed to these plants being located in the vicinity of highly sensitive marine habitats requiring special environmental consideration.

There has been a downward trend in the costs and energy use of desalinated water due to the technological advances that have improved the efficiency of the RO process. Since its inception the electrical consumption of RO has been reduced by a factor of four due to more efficient membranes and energy recovery systems (Figure 2.11). Similarly, the cost of desalination by RO has reduced substantially due to more advanced production techniques and increased production rates of membranes and the maturation of the technology. Due to the increasing scarcity of surface water and subsequent higher cost of its augmentation, the cost of desalination has become competitive in many instances.

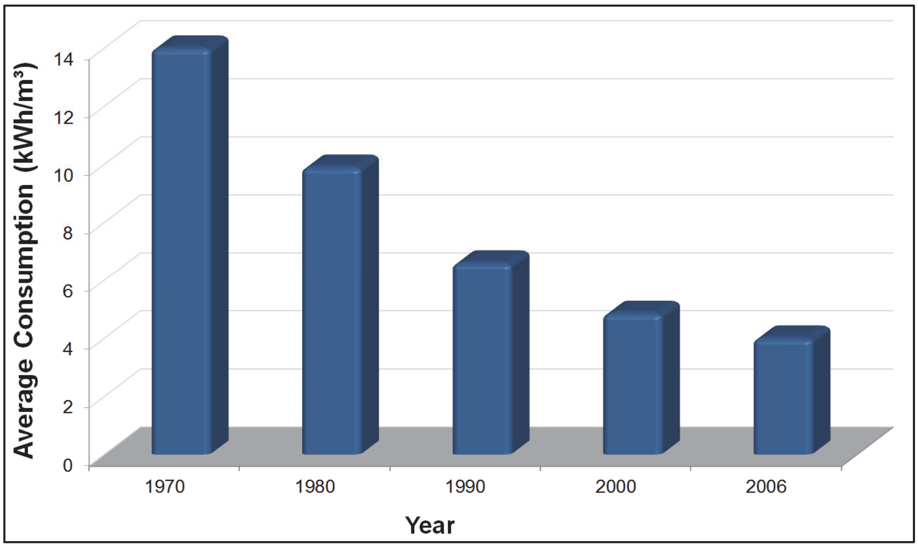


Figure 2.11: Trend of Energy Requirement of RO Process

Although the basic application of membrane technology is the same among seawater desalination plants, published reports on the total power consumption of SWRO facilities vary significantly. This is because SWRO projects are specifically designed for the location, accounting for energy costs associated with changes in feedwater salinity and temperature, changes in elevation, the local cost of power and fuel, degree of pre-treatment, distance to feedwater supply source, and the distribution point.

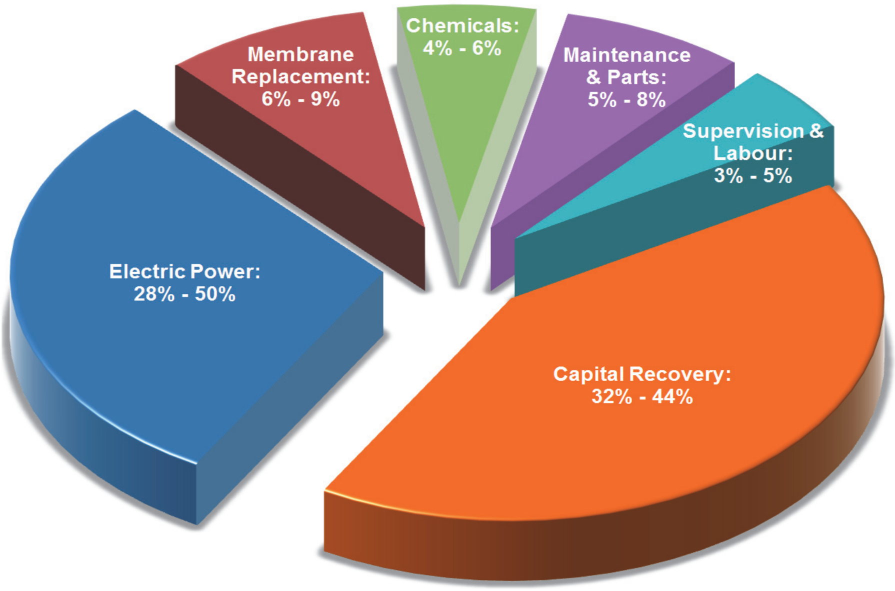


Figure 2.12: Various components of a SWRO facility, based on actual costs at operational SWRO facilities

Figure 2.12 contains a range of costs for the various components of a SWRO facility, based on actual costs at operational SWRO facilities. The energy “slice” is 28% to 50%, which can approach (or exceed) the capital recovery. A range is provided because the specific technical components factoring into the range will vary by project, and the capital recovery cost is driven by many factors such as interest, bond cost, payment time frame, and other financing schemes (WADC, 2011).

2.2.12.3 *Future of Seawater Desalination*

Desalination is process primarily applied in developed countries with financial capability and resources. If the technology continues to produce new methods and better solutions to the issues that exist today, there would be a whole new water resource for more and more countries that are facing drought, competition for water, and overpopulation. Although there are concerns in the scientific world about replacing our current overuse of water with complete reliance on sea water, it would undoubtedly be at least an option for many people struggling to survive or maintain their standard of living.

2.3 WATER REUSE OVERVIEW

The concept of reuse is much less defined than desalination. The treatment of wastewater and subsequent release into the environment is not considered reuse. Similarly, the irrigation of wastewater onto land is not deemed to be reuse in the context of this project. Some relevant concepts often referred to in describing reuse applications are:

- **Water reclamation:** the treatment of wastewater to a quality that will allow its beneficial use.
- **Water recycling:** Synonymous with 'water reclamation'
- **Water reuse:** the use of reclaimed water for beneficial purposes.
- **Direct potable reuse:** the beneficial use of reclaimed water for potable purposes with transfer from the reuse plant directly into the drinking water system, often in conjunction with blending from other conventional sources.
- **Indirect potable reuse:** the beneficial use of reclaimed water after releasing it into the environment for storage or dilution for subsequent raw drinking water supply.
- **Direct industrial reuse:** the beneficial use of reclaimed water treated to a defined standard with transfer from the reuse plant directly to the intended industrial user.
- **Indirect industrial reuse:** the beneficial use of reclaimed water upgraded to a certain quality and released into a natural water body to augment the raw water supply of the intended industrial user.

The infrastructure, activities and technologies involved in water reuse are quite broad. None of the technologies used are exclusive to water reuse, but are also applied to the treatment of wastewater, drinking water and employed in desalination. This is largely due to the fact that the feedwater to the reuse plant can originate from a variety of sources, whilst the target quality of the treated water required for reuse can differ substantially, depending on the intended end use. As such, it is not easy to define the market for reuse. Nevertheless, it is fairly common for reuse systems to include advanced technologies, such as membrane separation systems, oxidation and disinfection techniques, high rate liquid/solids separation, adsorption processes and biological treatment.

In water reuse for potable purposes, reference is often made to a "multi-barrier approach" which implies the use of multiple treatment steps, each intended to act as a treatment barrier for the range of substances or pollutants under consideration. The main objective is typically to reduce the perceived risk associated with water reuse. While primary and secondary wastewater treatment is relatively standardised and inexpensive the removal of personal care by products, pharmaceuticals and endocrine disruptors, as well as specific target pollutant species, can be quite costly and complex with less discernible perceived benefit. The concept of "water should be judged by its quality and not origin" applies.

2.3.1 Historical Timeline of Water Reuse

The reuse of water dates back to the 19th century. In 1867 through the settling of people in the mountains of Central and Southern Arizona after the discovery of copper ore, means to curtail undependable water supply during the months of long hot summers that followed where investigated and applied (SRP, 2012).

Thereafter water reclamation became a strategic option with international interest and research becoming widespread during the 1960s (Odendaal, year unknown). The year 1960 is considered to be a transition point due to the implementation of pollution regulations and inclusion of water reclamation strategies in water management policies in the US leading to the modern era of water reclamation (Levine et al., year unknown). Some key developments and turning points in recent desalination history are summarised in Table 2.4.

Table 2.4: Summary of water reuse history (adapted from ATP, 2012 and Du Pisani, 2004).

Date	Event
1932	The first small urban reuse system begins with the irrigation of Golden Gate Park in San Francisco.
1962	Montebello Forebay, California, USA. First case of indirect potable re-use via groundwater recharge using soil-aquifer treatment.
1965	Israel begins using reclaimed water for crop irrigation.
1966	Florida enters the reclaimed water arena with the construction of the Tallahassee Reclaimed Water Farm.
1968	Goreangab water reclamation plant converted to treat final effluent from Gammams wastewater treatment plant
1977	The City of St. Petersburg, Florida, builds the first large urban reuse system in the United States.
1978	Upper Occoquan Service Authority, Virginia, USA. First case of indirect potable re-use via surface water augmentation.
1984	Tokyo begins using reclaimed water from the Ochiai Wastewater Treatment Plant, which is operated by the Tokyo Metropolitan Sewerage Bureau, for toilet flushing in commercial buildings in Shinjuku District.
1985	Water Conserv II, the largest reuse project that combines agricultural irrigation with aquifer recharge via rapid infiltration basins, begins operation in Orlando, Florida.
1985	Hueco Bolson Recharge Project, Texas, USA. First case of indirect potable re-use via groundwater recharge using direct injection.
1987	Monterey County Water Resources Agency: "Monterey Wastewater Reclamation Study for Agriculture, Final Report" – *Irrigation of raw-eaten vegetable crops and artichokes with reclaimed water was shown to be as safe as irrigation with well water.*
1989	Spain begins irrigation of golf courses with reclaimed water from the Consorci de la Costa Brava wastewater treatment facility.
1996	National Academies of Science, National Research Council: “Use of Reclaimed Water and Sludge in Food Crop Production” study–- *Crops irrigated with reuse do not present a greater risk to the consumer than do crops irrigated from conventional sources.*
1998	Monterey County, California, begins irrigation with reclaimed water, including 12 000 acres of vegetables, such as lettuce, strawberries, cauliflower, broccoli, artichokes, celery and fennel. The vegetables continue to be irrigated with reclaimed water.
1998	“Recycled Water Food Safety Study for Monterey County Water Recycling Projects” – *Recycled water is as safe for irrigation of vegetables as other sources of irrigation water.*
1998	The Virginia Pipeline Project, the largest water reclamation project in Australia, irrigates vegetable crops using reclaimed water from the Bolivar Wastewater Treatment Plant.
2002	New Goreangab Water Reclamation Plant: Upgraded to 21 Mℓ/d included PAC and ozone dosing, BAC filtration and UF filtration.
2003	Florida Department of Environmental Protection: Proceedings of the 19th Annual WateReuse Symposium, “Monitoring for Protozoan Pathogens in Reclaimed Water” – *There is no evidence or documentation of any disease associated with water reuse systems in the United States or in other countries that have reasonable standards for reuse.*
2005	Florida Department of Environmental Protection’s “Water Reuse: Regulatory and Safety Perspectives” report indicates Florida has 40 years of reuse with no illness.
2005	WateReuse Research Foundation – “Irrigation of Parks, Playgrounds, and Schoolyards with Reclaimed Water: Extent and Safety” study
2007	eMalahleni Water Reclamation plant, Mpumalanga, South Africa. First indirect potable re-use plant to re-use acid mine drainage.
2008	David York, et al. – Comprehensive and definitive paper completed on the safety of irrigation of food crops with reclaimed water.
2009	WateReuse Research Foundation – “A Reconnaissance-Level Quantitative Comparison of Reclaimed Water, Surface Water and Groundwater” study
2011	Cloudcroft, New Mexico, USA. First direct potable re-use plant in the US.

2.3.2 Rationale for Water Reuse

The rationale for water reuse was adopted from various sources, namely ATP (2012), Du Pisani (2004) and McKenzie (2005). These are briefly discussed below:

- Water is a finite resource and increasingly becoming scarce thus limiting the luxury of using water only once. The quality of water produced by secondary treatment (activated sludge, trickling filters and stabilisation ponds) is appropriate for many non-potable applications such as irrigation, industrial cooling and cleaning water. This provides an alternative to abstraction of water from already strained freshwater reserves. This in turn enables the meeting of sustainability goals with concomitant management and recovery of nutrients for agriculture.
- The economic feasibility of water reclamation puts into perspective the cost benefits of this application were the treatment of wastewater becomes costly in light of the stringent disposal standards being implemented nowadays. Wastewater produced in urban areas provides a dependable source of water to augment supply especially in drought years.

The greatest benefit to preserve and reclaim water is the sustainability of environmental ethics. By reducing pollution and using water efficiently, water reclamation serves as a potential source and reserve for water.

2.3.3 Water Reuse Technologies

Water reuse is widely practiced throughout the world, both in developed, developing and emerging countries. Almost all these reuse systems are indirect potable reuse or non-potable reuse schemes.

The only real direct potable reuse schemes are in Windhoek, Namibia, Beaufort West, South Africa, Big Spring, Texas, USA and Cloudcroft, New Mexico, USA. The two southern African reuse schemes constitute one of the main reasons for the current studies and research in South Africa to develop monitoring programs based on health-based targets for a wide range of chemicals of emerging concern and disinfection by-products, as well as public acceptance studies (social and institutional research projects).

Reuse plants may make use of a large assortment of treatment processes due to the variability of the feedwater quality and final water standards that pertain to the different reuse plants.

The following list of technologies is typically used by potable reuse plants:

- Coagulation/Flocculation
- Clarification
- DAF (dissolved air floatation)
- Media Filtration
- BAC (biologically activated carbon)
- GAC (granular activated carbon)
- PAC (powder activated carbon)
- Microfiltration
- Ultrafiltration
- Nanofiltration
- Reverse Osmosis
- Ozonation
- UV/H_2O_2

The design of IPR and DPR hinges heavily on the expert design teams and the available industry in that region. Where membrane manufacturers have captured a considerable part of the market in a region there is a tendency to use membrane barriers for suspended and dissolved solids. It seems that there is a re-evaluation as NF and RO have a considerable high cost to get rid of the brine, which renders it unfeasible in an inland application (Swartz et al., 2013).

Locally, conventional as well as advanced treatment technologies for water reclamation have in most instances already been tested and proven for South African conditions. There is therefore a local knowledge base on water reclamation to plan, design, construct, operate and maintain a wide range of treatment technologies. More recently, a number of more sophisticated technologies such as advanced oxidation and membrane treatment have also been applied to a number of local projects (e.g. Durban Reuse Plant and the Beaufort West Water Reclamation Plant).

The South African water industry has the foundation for confidently developing and applying the more advanced water reuse technologies (DWA, 2011). A specialist technical division, the WISA Water Reuse Division, has also recently been established within the Water Institute of Southern Africa, to further improve communication, capacity building and information sharing.

Some examples of advanced tertiary treatment technologies such as advanced oxidation and activated carbon systems are further elaborated below.

Advanced Oxidation System

A conventional activated sludge plant with a sludge age in excess of 15 days will oxidise all the biodegradable chemical oxygen demand (COD) in the incoming wastewater. As a result the COD in the effluent from a works with an appropriate sludge age and aeration system will consist solely of “soluble” non-biodegradable COD and that associated with solids in the effluent. However some of the “soluble” COD will be colloidal in nature and will be retained by the MBR membranes. Generally, approximately 30% of the “soluble” COD will be retained by the membranes. The COD passing through the membranes is anticipated to be approximately 45 mg/ℓ and will place the treated water in Category 4 industrial water quality. In addition, the Natural Organic Matter (NOM) and Total Organic Carbon (TOC) measured in the COD test, has the potential to cause bio-fouling of downstream Reverse Osmosis (RO) membranes.

Ozone has the ability to breakdown non-biodegradable COD and this process step is included in the process train as an addition to the MBR system. A brief description of the system is given below.

Ozone (O_3) gas is used for disinfection, colour removal and breakdown of complex organic matter. Ozone is a highly toxic substance and no ozone will be stored on site. Ozone will be produced on site by ozone generators from air.

The ozonation system will be designed to produce sufficient ozone to dose a maximum dose of 5 g/m³ maximum dosage, based on 85% gas transfer efficiency.

An average ozone concentration of 2 mg O_3/ℓ should be sufficient to ensure the efficiency of the process. This step is included in the process to reduce colour and breakdown a fraction of the non-biodegradable COD remaining, in smaller molecules to prevent bio-fouling of downstream processes. The transformed COD will become biodegradable and will need to be removed biologically in Granular Activated Carbon (GAC) contactors.

The production of ozone will be made from pure oxygen, using latest technology ozone generators. This system permits lower electricity consumption, and needs less maintenance. The ozone concentration in the product gas will be 10% during normal operation and 7% during high ozone demand periods. A residual ozone analyser will be provided at the outlet of the ozone contact tanks to optimise the process. A schematic arrangement of a typical ozone generator is shown in Figure 2.13.

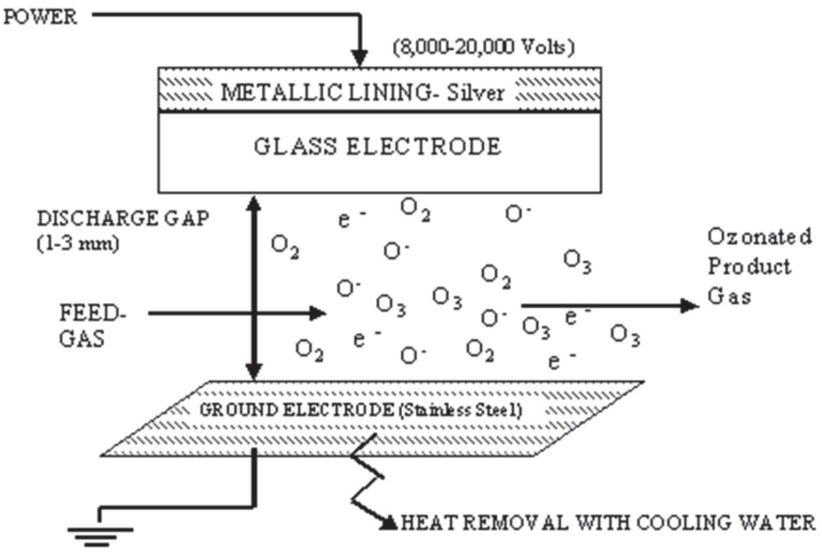


Figure 2.13: Schematic of a dielectric ozone generator

Ozone is introduced into the water phase by fine bubble diffusers mounted on the bottom of the ozone contact tanks.

It is proposed that the tanks be arranged in lanes in order to allow for maintenance and repairs without interruption of the process.

The contact time allowed is 10 minutes. A schematic arrangement of a typical ozone generator is shown in Figure 2.14

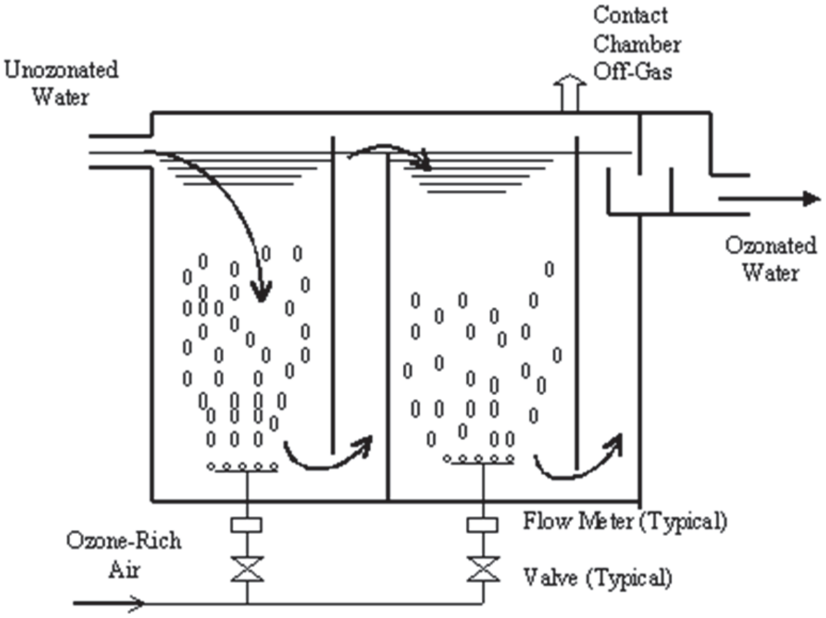


Figure 2.14: Schematic of an ozone contact tank

Residual ozone in the vents from the ozone contact tanks will be eliminated or reduced by thermal ozone destructors to harmless levels. The anticipated maximum ozone concentration in the vents after treatment will be 0.1 mg/ℓ. The atmosphere in the ozone building will be continuously monitored by an ozone gas analyser and an ozone gas alarm initiated upon detection of ozone.

Granular Activated Carbon (GAC) Contactors

In the ozone treatment step the degradation of the COD will make this component biodegradable and Granular Activated Carbon (GAC) filtration will be included to adsorb this component. When GAC follows Ozone treatment, the GAC filters become biologically active and micro-organisms will break down the COD. It is for this reason that when GAC filters follow ozone treatment they become known as Biologically Active Carbon (BAC) filters.

The water flows from the ozone contact tank to the BAC contactors. Although the contactor is basically a filter similar to conventional filters its purpose is to provide contact of micro-organisms attached to the activated granular carbon with the water.

The contactors require backwashing in a similar way to conventional filters but the contactor run cycles are significantly higher (3-5 days). Due to the biological activity in the activated carbon, the carbon does not require as frequent replacement and regeneration as a conventional activated carbon contactor operating on the adsorption principle. Replacement of the GAC is expected after approximately 10 years operation due to attrition of the material.

The contactors will be sized with an empty bed contact time of approximately 15 minutes to enable a period of several days of operation without backwashing to enable micro-organisms to establish themselves after each backwashing sequence.

The filters will be washed in a method that combines a counter-current of wash water at an approximate flow of 8 $m^3/m^2/h$ and the blowing of air at a flow of 20 $m^3/m^2/h$, followed by rinsing with water at a flow of 40 $m^3/m^2/h$. The used backwash water and first filtrate rinse water will be returned to the activated sludge reactor.

Despite the successes and achievements of the New Goreangab water reclamation plant (NGWRP), which performs direct potable reuse without using any RO treatment steps, the use of RO treatment steps have become commonplace at potable reclamation plants with the exception of indirect potable reuse plants that perform groundwater replenishment via soil-aquifer treatment. This is also the case in South Africa where the direct potable reuse plant at Beaufort West has opted to include RO treatment steps, while the George (Outeniqua) reclamation plant makes use of UF only, since the treated water is sent to the Garden Route dam where it is sufficiently diluted and indirectly reused.

Reclaimed water may be used for various applications which depend on the type of technology and desired water quality. There are basically two approaches:

- One (e.g. Windhoek approach) where physical-chemical processes, such as DAF or sedimentation are used as main separation technologies, supplemented by advanced oxidation and maybe MF or UF membrane final barrier, as illustrated in Figure 2.15.
- The other approach is to use MF/UF and RO membranes as the main separation technologies, as illustrated in Figure 2.16.

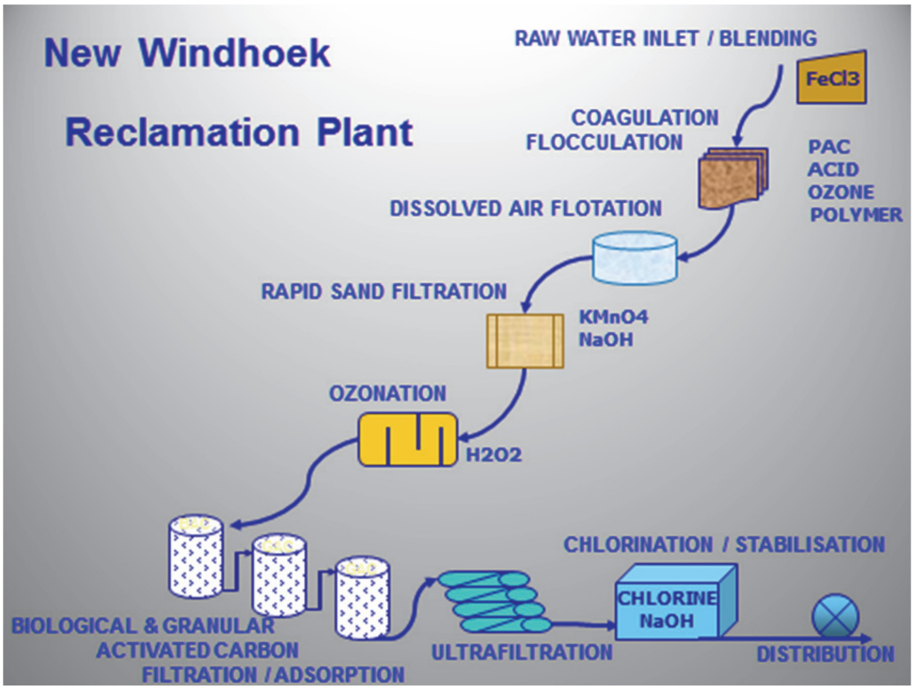


Figure 2.15: Example of physical-chemical approach: Windhoek

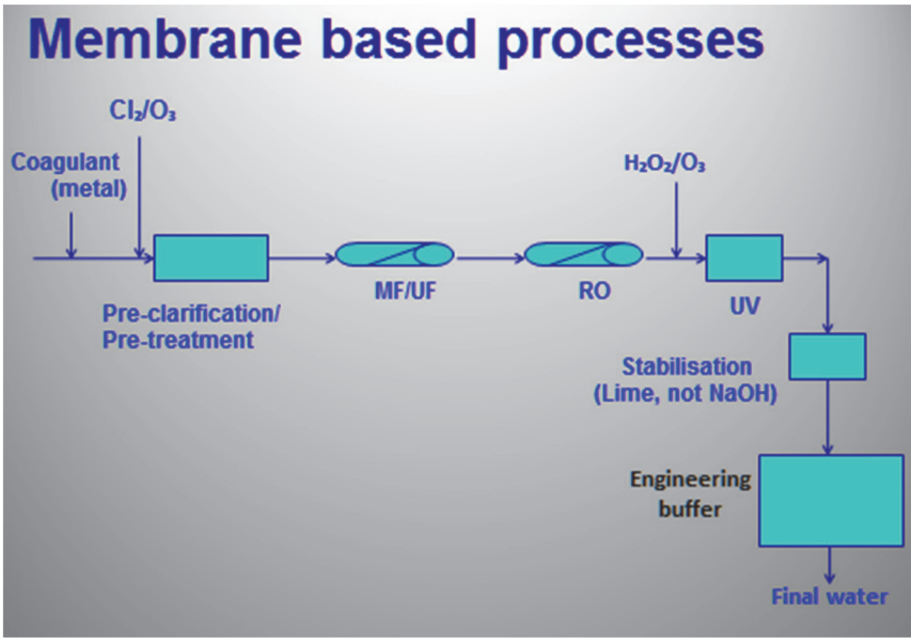


Figure 2.16: Example of membrane based approach

2.3.4 Types of Water Reuse

A combination of the above mentioned technologies can be applied to achieve the desired water and also depending on the selection criteria. Table 2.5 indicates the types of water reuse that can be applied (McKenzie, 2005).

Table 2.5: Types of water reuse

Types of Reuse	Treatment
Urban Reuse	Landscape irrigation, vehicle washing, toilet flushing, fire protection, commercial air conditioners, and other uses with similar access or exposure to the water.
Agricultural Reuse for Non-Food Crops	Pasture for milking animals; fodder, fibre and seed crops.
Indirect Potable Reuse	Groundwater recharge by spreading, or injecting into potable aquifer, or surface water body.
Potable Reuse	Blending in water supply reservoirs, or direct pipe to pipe supply

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APPENDIX A: DESALINATION PROCESS OVERVIEW

1 THERMAL PROCESSES

Widely used thermal desalination processes include multi stage flash (MSF) evaporation and multiple effect distillation (MED) with/without thermal or mechanical vapour compression. These require a heating medium, typically low pressure steam, to evaporate or boil off essentially pure water vapour from the saline feedwater. The vapour is then condensed and converted to a liquid distillate of very low salinity. Thermal processes are mainly applied to the desalination of seawater and sometimes to the concentration of industrial effluents.

The energy demand for thermal desalination is very high (when compared to other desalination processes) due to the energy required for the phase change (liquid to vapour) to boil off vapour from the saline feed and cooling for condensing (vapour to liquid) the vapour to form distillate. As such, thermal processes are often used in arid countries where there is an abundance of energy and sufficient waste heat (e.g. oil & gas fired power stations, refineries), such as the Middle East. Despite this current thinking is to move away from thermal desalination plants in favour of membrane desalination plants, mainly due to a future shift toward nuclear power plants (rather than coal/oil/gas powered) in the Emirates and other Middle East regions (GWI, 2011).

In South Africa the use of thermal desalination processes would typically be limited to situations where co-generation of electricity and water can be effected. An example would be next to a nuclear power station facility where seawater may be used for both cooling of the power station and the generation of fresh water from seawater by utilising the waste heat available. In this instance the seawater intake and brine outfall facilities could also be shared.

This may become remotely feasible if South Africa pursues a Nuclear Fleet strategy as outlined in the Integrated Resource Plan (DOE, 2010).

1.1 MSF process

In the MSF process, seawater is heated in a vessel called the brine heater. This is generally done by condensing steam on a bank of tubes that pass through the vessel, which in turn heats the seawater. This heated seawater then flows into another vessel, called evaporator stage, where the ambient pressure is such that the water will immediately boil, almost exploding or "flashing" into steam.

Each stage operates at a slightly lower pressure than the previous one, thereby resulting in the multi stage flash configuration. The steam generated by flashing is converted to fresh water by being condensed on tubes of heat exchangers that run through each stage. The tubes are cooled by the incoming feedwater going to the brine heater. This, in turn, warms up the feedwater so that the amount of thermal energy needed in the brine heater to raise the temperature of the seawater is reduced.

MSF are generally built in units of about 5 000 to 65 000 m^3/d (Sidem, 2015). The MSF plants usually operate at a top feed temperature (after the brine heater) of 90 to 120°C.

Operating these plants at the higher temperature limits (>120°C) tends to increase the efficiency, but it also increases the potential for detrimental scale formation and accelerated corrosion of metal surfaces.

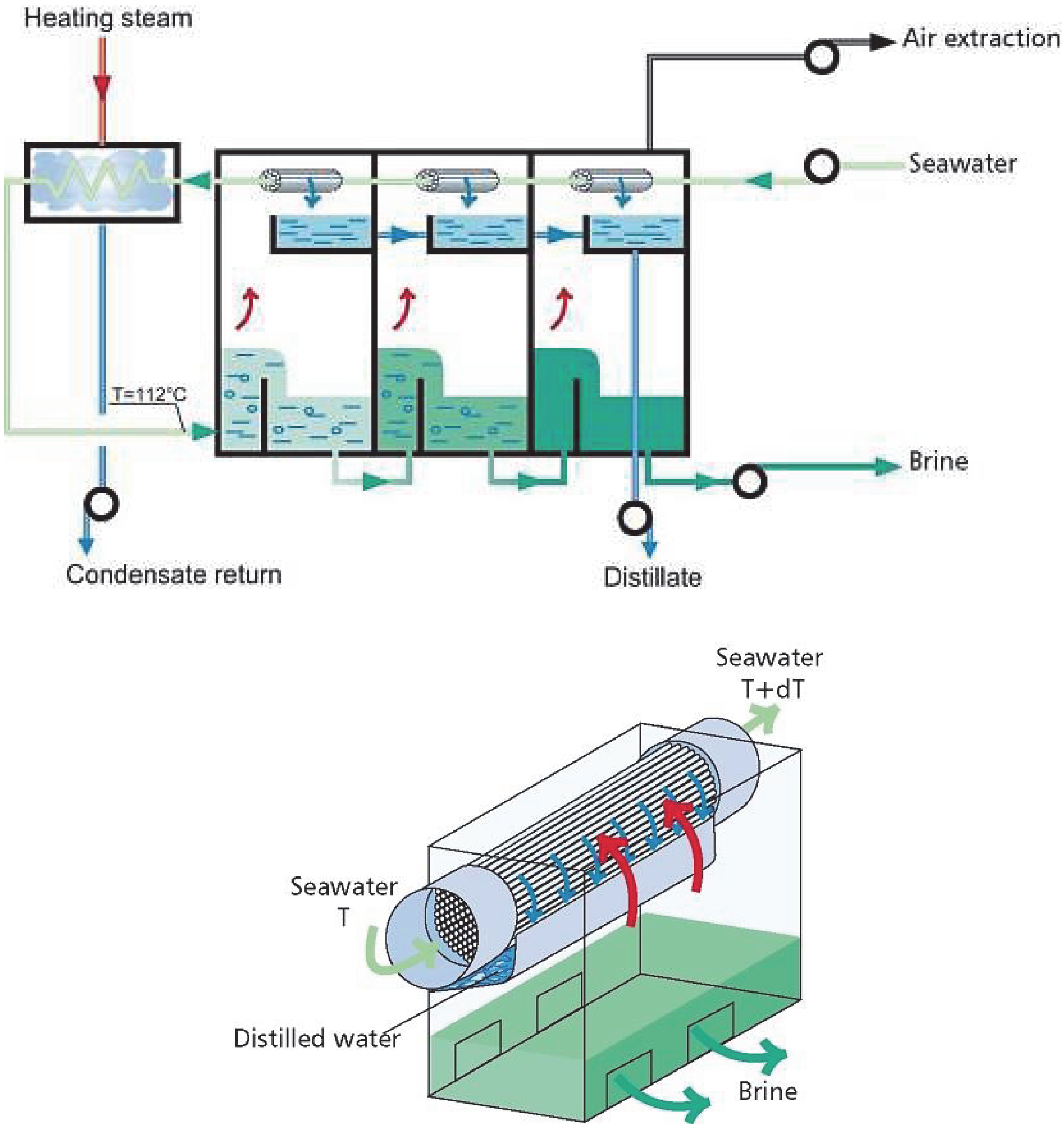


Figure 1: Thermal Desalination Schematic representation of MSF process (Sidem, 2015)

Important points to note about the MSF process are:

- Simple and reliable operation with long and successful track record
- No or minimal feedwater pre-treatment
- Product water quality of 5 to10 mg/ℓ TDS

Weak points may be summarised as:

- Low thermal efficiency (only cost effective if low cost steam available)
- High cooling water requirement
- Only practical for seawater applications

1.2 MED process

The MED process has been used for industrial distillation for a long time. The MED process takes place in a series of vessels (effects) and uses the principle of reducing the ambient pressure in the various effects. This permits the seawater feeds to undergo multiple boiling without supplying additional heat after the first effect.

In most MED plants, the seawater enters all the effects in parallel and is raised to the boiling points after being pre-heated on tubes by steam from a boiler. The condensate from the boiler steam is recycled to the boiler for reuse. Only a portion of the seawater applied to the tubes in the effects is evaporated. The remaining feedwater is collected and fed to the last effect. The tubes in the various effects are in turn heated by the vapours created in the previous effect. This vapour is condensed to fresh water product, while giving up heat to evaporate a portion of the seawater feed in the effects and continues in several effects.

MED plants are typically built in units of 100 to 20 000 m^3/d. The operating temperature is around 70°C, which reduces the potential for scaling within the plant, but in turn increases the need for additional heat transfer area in the form of tubes.

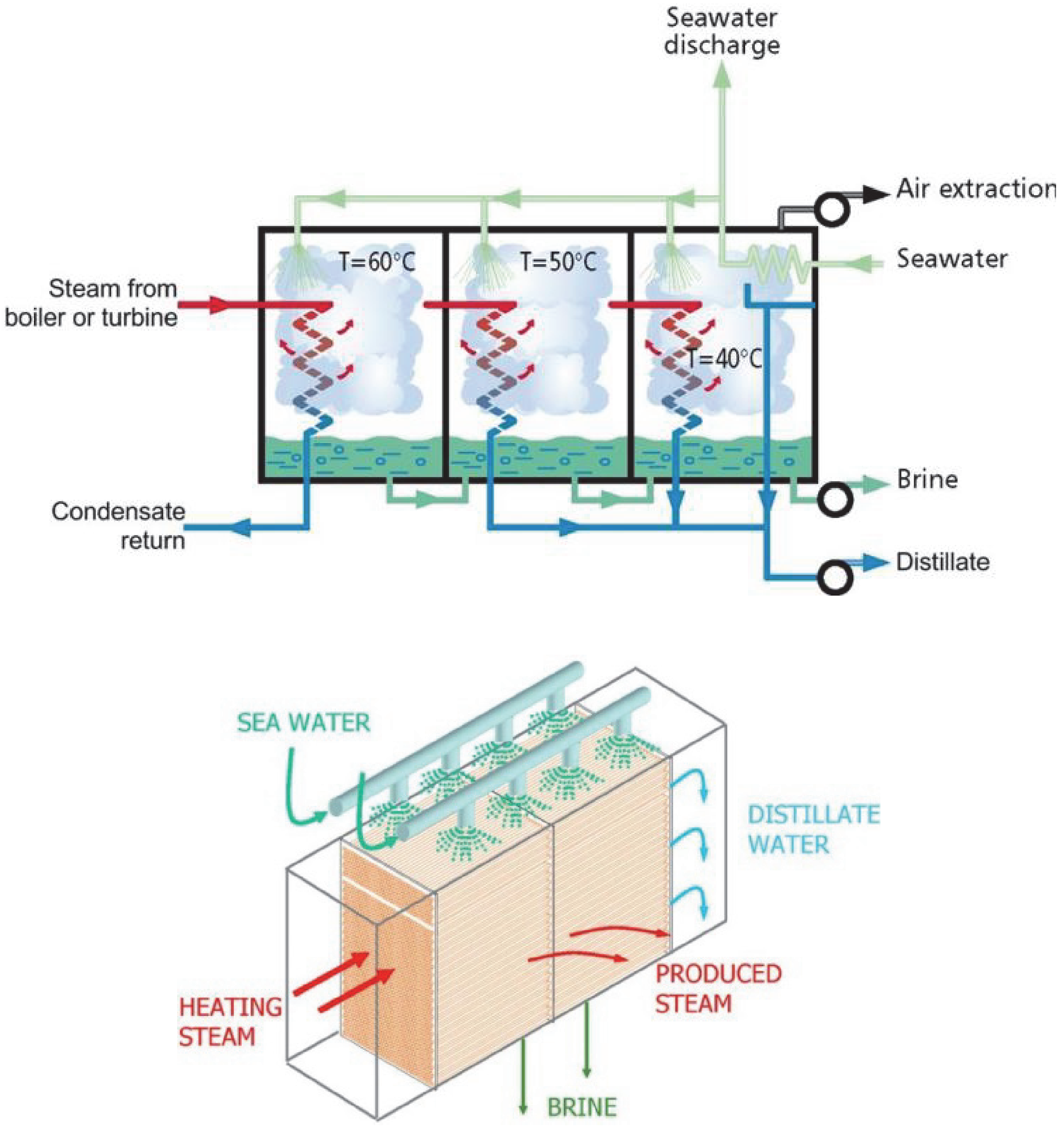


Figure 2: Thermal Desalination Schematic representation of MED process (Sidem, 2015)

Important points to note about the MED process are:

- Thermal efficiency is higher than for MSF
- Lower top temperature operation than MSF
- Uses less cooling water and electrical energy than MSF
- Lower capital cost than MSF
- Product water quality of 5 to 10mg/ℓ TDS
- Weak points may be summarised as:
- More complex and smaller unit sizes than MSF
- May not be cost competitive with RO processes
- Only practical for seawater applications

1.3 Other thermal processes

Other thermal processes worth mentioning are vacuum compression distillation (VCD), vacuum freeze distillation (VFD) and solar distillation. Their present commercial impact is limited hence they are not further discussed for the purpose of this report.

2 CHEMICAL PROCESSES

2.1 Ion exchange process

Ion exchange is based on the chemical-physical process of adsorption using selective ion exchange resins. The process may be used for the desalination of water but is typically limited to the polishing of low salinity feed to produce ultrapure water (e.g. boiler feed, rinse water for the electronics industry). As such, the process is generally referred to as demineralisation.

The principle of demineralisation by ion exchange resin is illustrated in Figure 3. Separate beds of two resin types are used, through which the feedwater is passed. The cation resin has a sulphonate (SO_3^-) functional group to which typically a mobile hydrogen (H^+) ion is linked. The anion resin on the other hand has a quaternary ammonium (N^+R_3) functional group to which usually a mobile hydroxide (OH^-) ion is linked. As the feedwater passes through the cation and anion resin beds the cations in the water selectively exchange with the mobile hydrogen ion on the cation resin, while the anions are exchanged with the mobile hydroxide ion on the anion resin. The equivalent amount of H+ and OH- ions to the anions and cations removed from the feedwater are released into the demineralised product water. These ions immediately combine to form water: $H+ + OH- \rightarrow H_2O$.

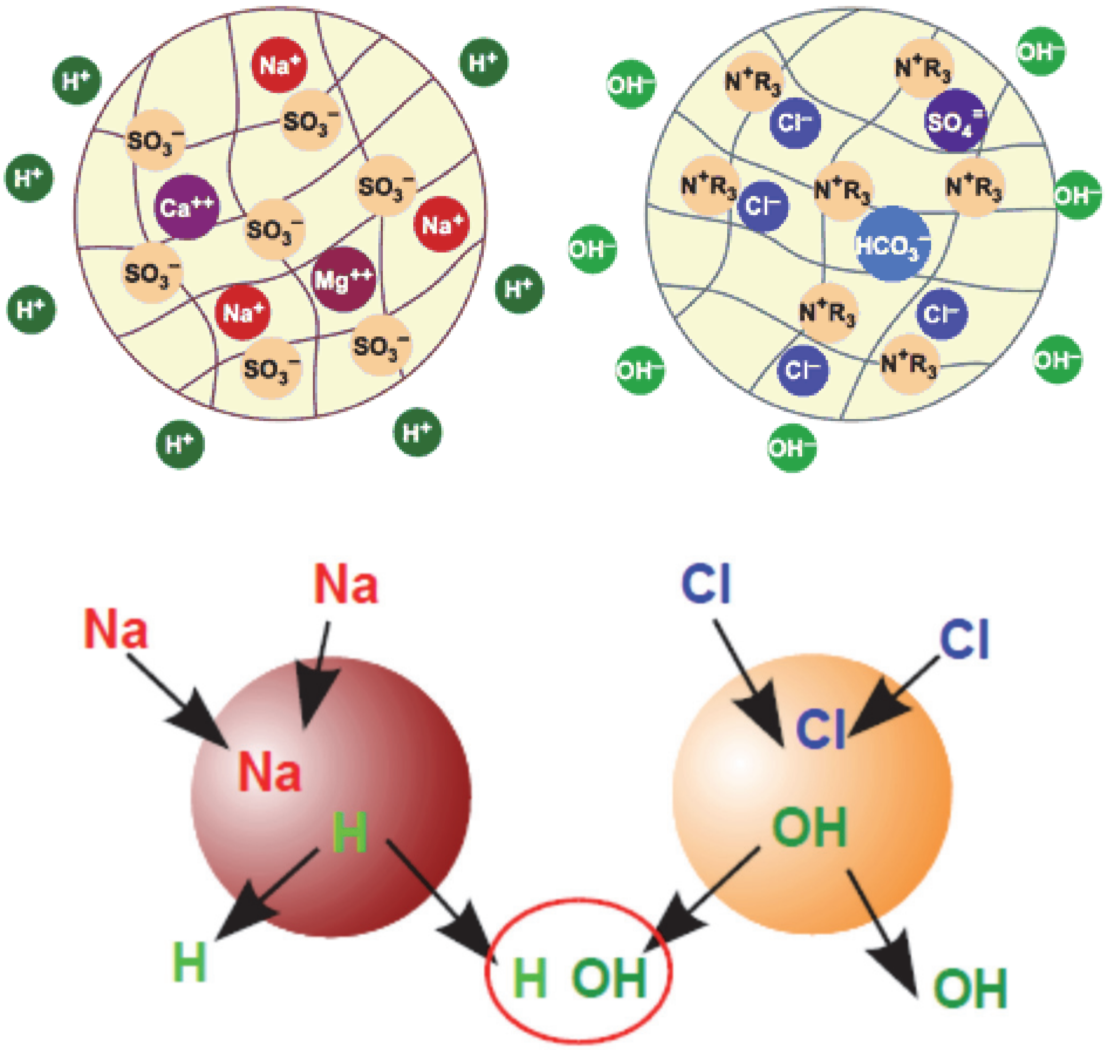


Figure 3: Ion Exchange Schematic representation of demineralisation process

The ionic contaminants in the feedwater are now situated on the resins which become progressively more loaded. Once the resins are saturated they need to be regenerated. This is achieved by driving off the respective ions that have been adsorbed with the use of acid (H^+) and caustic (OH^-) solutions. The process can now be repeated with “fresh” resin having H^+ and OH^- mobile ions again.

2.2 Precipitation processes

These are used to precipitate the targeted dissolved ions in the water by adding a chemical that forms an insoluble compound (precipitate) with the ion in question. The precipitate is then removed from the water by settling, filtration or other means of solid/liquid separation.

Examples are lime/soda-ash softening for the removal of hardness (calcium and magnesium) and the barium sulphate or Ettringite process. These processes are often used in the treatment of raw water and industrial effluents, as well as mining effluent or mining decant (acid mine drainage). As such, they are not further evaluated for the purpose of this report.

3 PHYSICAL PROCESSES

Physical separation technologies used for desalination relate mainly to membrane separation processes. These include electrical driven processes, such as electrodialysis or electrodialysis reversal and pressure driven membrane separation processes, such as nanofiltration and reverse osmosis.

3.1 Electrodialysis

Electrodialysis (ED) or electrodialysis reversal (EDR) is a membrane based desalination process, employs ion-selective membranes and electrical polarity to desalinate water. EDR is not discussed further due to its inability to desalinate high salinity feedwater efficiently and economically since the cost of electrodialysis is directly proportional to the salinity of the feedwater.

Electrodialysis uses a stack assembly of alternating anionic and cationic membranes in conjunction with a direct current source to draw ionic components in solution into their respective brine compartments. The driving force for the process is the applied electric field, which causes anions and cations to migrate in opposite directions in relation to the applied voltage. The ion-selective membranes allow migration of either anions or cations from the feed channels.

The concept is illustrated in Figure 4.

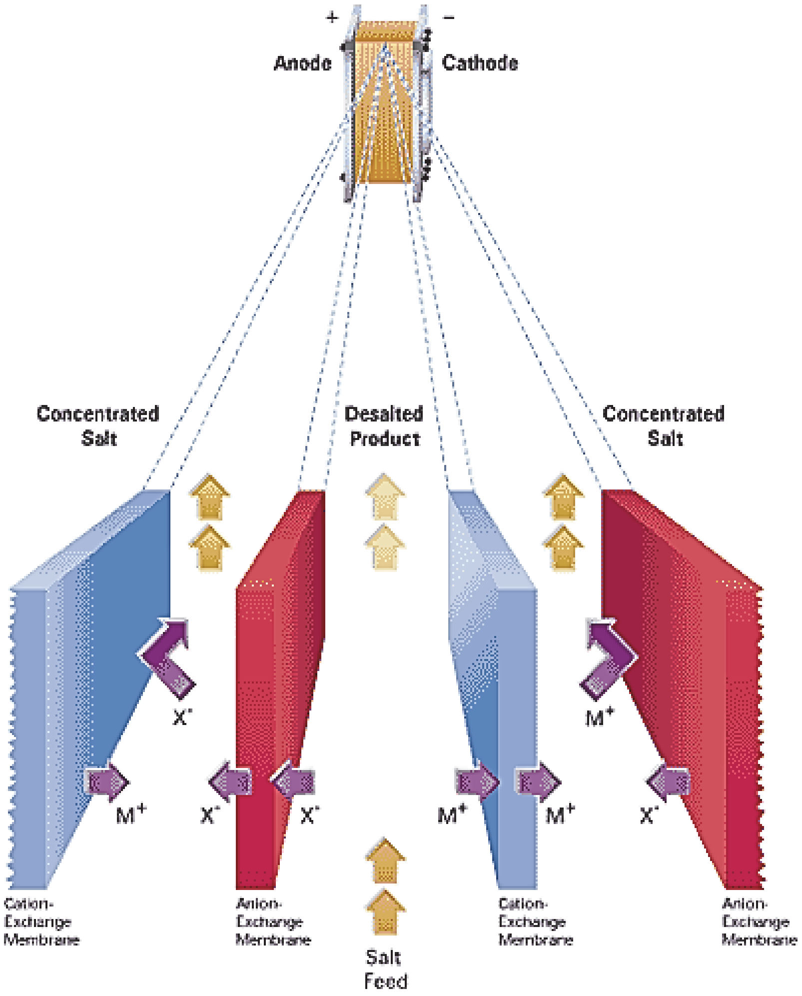


Figure 4: Electrodialysis schematic representation of EDR stack (courtesy of Eurodia)

The membranes are subject to fouling and some pre-treatment is typically required. Scaling on the membrane surface as a result of pH changes may also be problematic. EDR used the technique of changing the polarity at regular intervals to counter fouling and scaling. This effectively results in a switching of feed and brine channels to prevent the potential accumulation of foulants and scale.

3.2 Nanofiltration

Nanofiltration (NF) is typically used for partial desalination application, e.g. softening or the selective separation of mono and multivalent ions. NF membranes are sometimes referred to as “loose” RO membranes with system design and operation being similar to that of reverse osmosis. With respect to main stream desalination applications the equivalent low-pressure RO membranes are more efficient with respect to lower salt passage, while operating at similar feed pressures. Hence nanofiltration has been mostly applied to niche applications, such as softening, recovery of valuables and specialised separation in mostly the industrial sector.

4 COMPARISON OF ESTABLISHED DESALINATION PROCESSES

4.1 Feedwater Salinity

The concentration range of feedwater TDS in which the main commercially established desalination processes can be applied economically may be summarised as follows (Clayton, 2006):

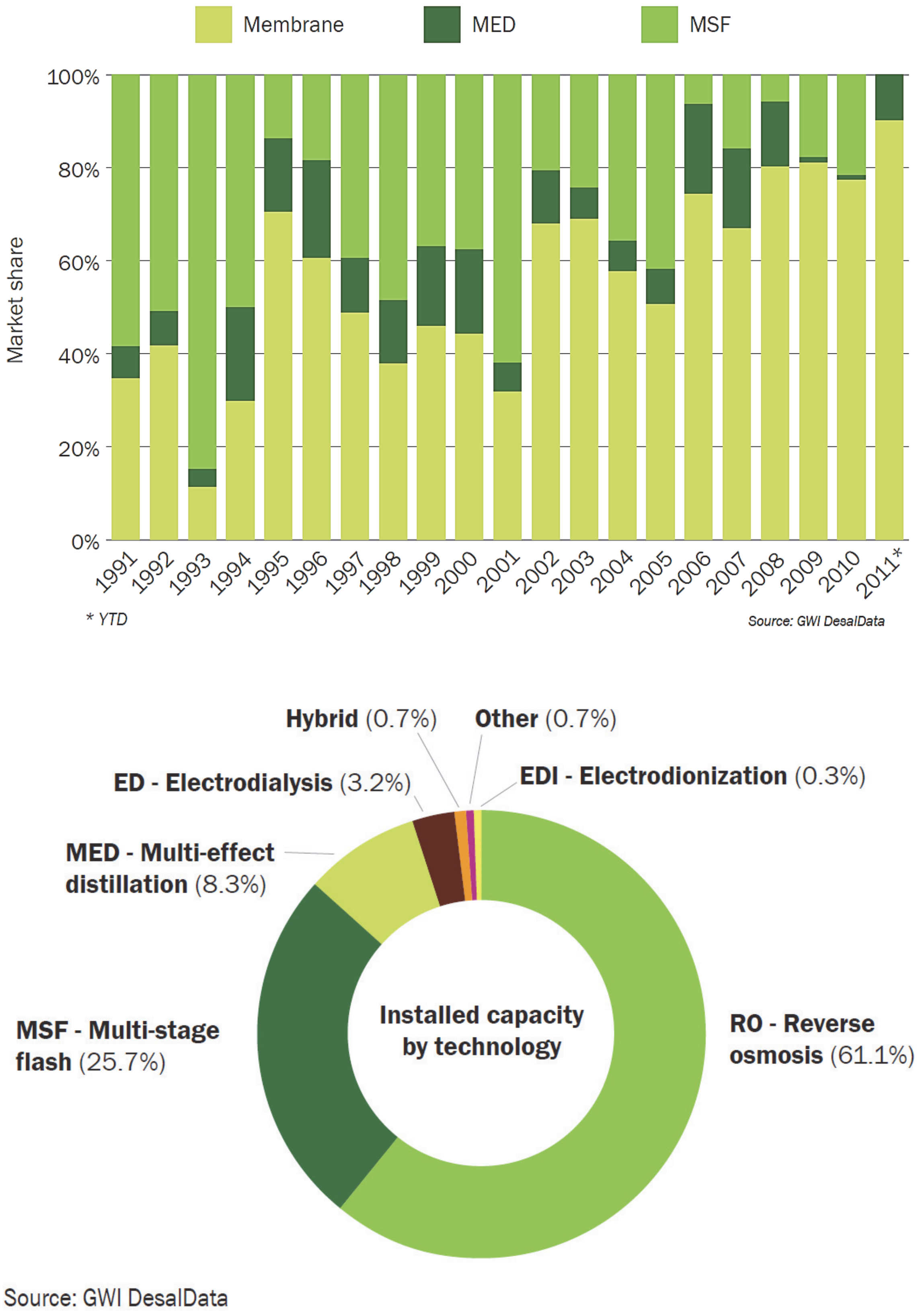
Table 1: Process feedwater range

Process	Applicable Feedwater TDS range (mg/ℓ)
Ion exchange (IX)	10-800
Electrodialysis (ED/EDR)	200-10 000
Reverse osmosis (RO)	50-50 000
Distillation (MSF/MED)	20 000-100 000

In the Southern African context desalination applications would typically relate to seawater and brackish water sources where the production of potable water is desired. Hence the resultant feedwater TDS range of South African seawater and brackish water (1 000 to 36 000 mg/ℓ) fits the RO range.

4.2 Market share

The global market share of the three main commercial seawater desalination technologies and comparison of the major desalination process technologies are illustrated in Figure 5.



Source: GWI DesalData

Source: GWI DesalData

Figure 5: Market Share by process technology and comparison of three main seawater desalination technologies (GWI, 2011)

From the above illustration, it is clear that RO is the dominant technology with respect to desalination projects based on worldwide installed capacity.

The breakdown of global desalination market share by end user category is illustrated by the Figure 6.

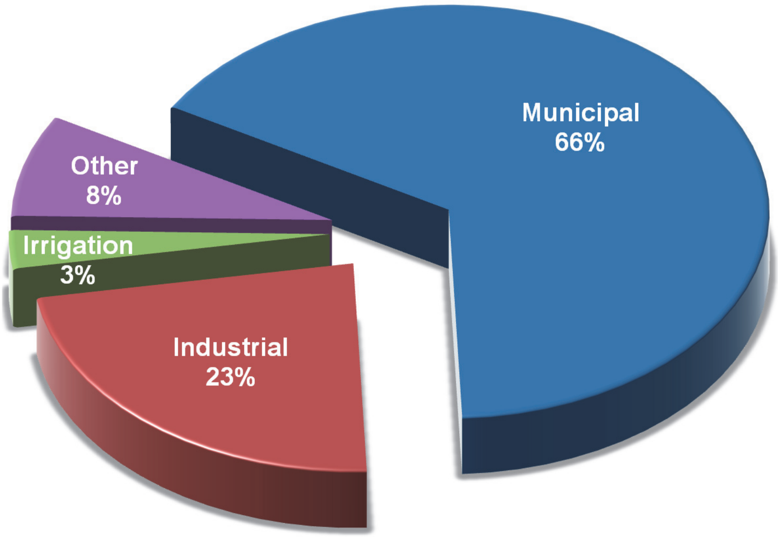


Figure 6: Market share for desalination by end user category

It follows that the municipal sector is by far the largest user of desalination technology. To this end, the production of potable water from seawater and brackish water feed may be seen as the largest application in the market.

4.3 Process comparison

The process characteristics of the three main seawater desalination technologies are summarised below:

Table 2: Main Seawater Desalination Technologies

Process Characteristic	MSF	MED	RO
Pre-treatment required	minimal	minimal	critical
Chemical consumption	low	low	higher
Scaling issues	low	low	lowest
Fouling	low	low	higher
Operational simplicity	lowest	low	higher
Reliability / robustness	lowest	low	pre-treatment dependent
Capital cost	highest	high	lower
Steam consumption – Gain Output Ratio (GOR)	10 : 1	7 : 1	n/a
Electricity consumption (kWh/m^3)	3.5	1.2	4
Feed : product flow	8 : 1	8 : 1	2.2 : 1
Feed pressure (bar)	2	2	65
Concentration factor	1.7	1.7	1.9
Product TDS (mg/ℓ)	< 25	< 25	< 450

The choice of desalination technology may be determined by the following considerations:

Primary considerations

- Produced price of water
- Feed and product water qualities
- Availability of low cost steam
- Scale of project
- Location specific issues

Secondary considerations

- Client preference for a particular desalination technology
- Risk aversion of local water agencies
- Client "resistance" to implement advanced technology

It follows that without access to a source of low cost steam RO technology is the obvious choice. This would largely apply to the Southern African scenario, especially in coastal areas, due to the lack of established oil and gas fields, as well as power plants that have been designed with co-generation in mind.

5 LIMITATIONS OF SEAWATER DESALINATION

A few general setbacks for the processes of desalination also exist.

Dumping the wasted salt solution (most often referred to concentrate or brine) back into the ocean makes the process more difficult and has the potential to harm ocean life.

The energy required to start up and power desalination plants is a huge expense and because most current power sources are derived from burning fossil fuels, it is generally looked upon as just a matter of choosing one environmental crisis over another. Within the energy issue, nuclear energy is potentially the most cost-effective energy source, but remains largely untapped due to public opinion on having a local nuclear power plant or waste facility.

If regions situated away from the coast or in a high altitude try to use desalinated water, it is an even more expensive process. Higher altitudes and far distances require great resources to transport the water from the ocean or body of salt water.

6 EMERGING AND OTHER DESALINATION TECHNOLOGIES

Some of the more promising and intensively investigated alternative desalination technologies include:

- Forward osmosis
- Osmotic power
- Others – crystallisation, humidification, deep ocean and wave driven, solar, etc.

Most of these approaches have yet to demonstrate commercial viability. The list is by no means exhaustive and more detailed descriptions on these technologies may be found in available literature. The list is intended to serve as an indication of the wide variety of approaches that have been investigated, which nevertheless can be categorised into one or more of the basic approaches outlined above, viz. thermal, physical, chemical.

6.1 Forward osmosis

One of the emerging desalination technologies is forward osmosis. This technology uses the difference in osmotic pressures of two solutions as driving pressure. A semi-permeable membrane separates the two solutions. To effect desalination the feed could be seawater and the other a so-called draw solution with a higher osmotic pressure than the seawater. By means of the natural osmosis process pure water would diffuse from the seawater feed through the membrane (rejecting the dissolved salt) into the draw solution. This leads to a dilution of the draw solution and the extracted water must subsequently be recovered from the draw solution in order for the draw solution to be reused. The concept is shown in Figure 7.

The UK company Modern Water, one of the leaders in forward osmosis, prefers to refer to the process as "manipulated osmosis desalination" or MOD (Nicoll, 2012). The recovery or regeneration system may typically be a reverse osmosis system, depending on the type of draw solution used. A variety of draw solutions can be used with the main criteria being that the draw solution has a higher osmotic pressure than the feed solution.

Recent research and development indicates that an ammonia-carbon dioxide draw solution may be useful since it can be recovered by heating the diluted draw solution (McCutcheon, 2006).

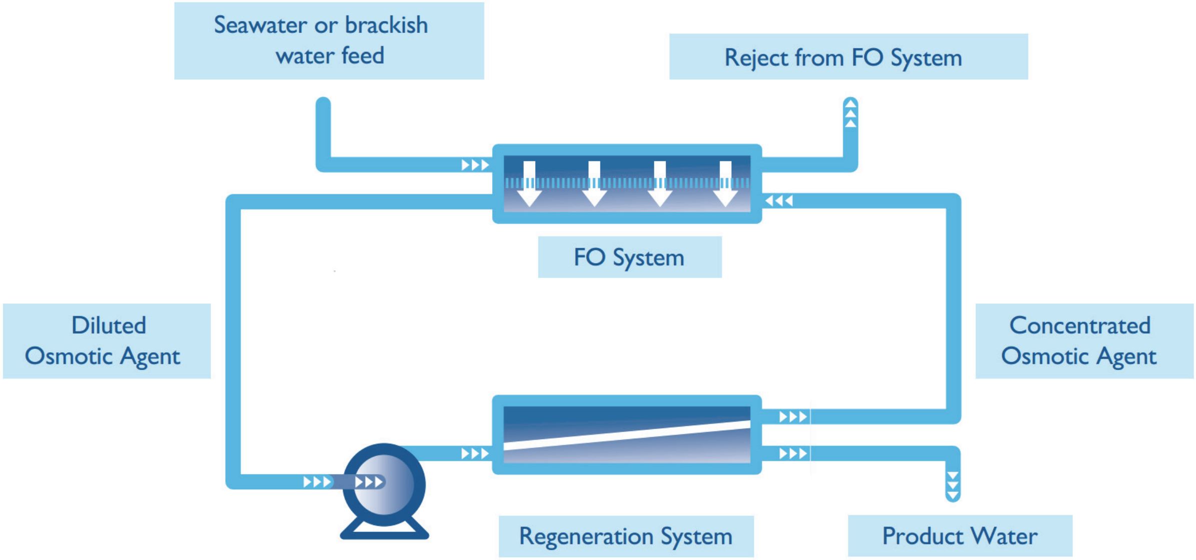


Figure 7: Forward Osmosis simplified process diagram (courtesy of Modern Water)

6.2 Osmotic power

Another version of the forward osmosis process is "pressure retarded osmosis" (PRO) which can be viewed as an intermediate process between reverse osmosis and forward osmosis (Cath et al., 2006). In this case hydraulic pressure is applied in the opposite direction to the osmotic pressure gradient, but with the net water flux still in the direction of the draw solution. This shows promise for the generation of electricity using energy recovery devices normally used in seawater RO systems.

This concept is promoted by the company Statkraft and referred to as "osmotic power" (Halper, 2010) and illustrated in Figure 8.

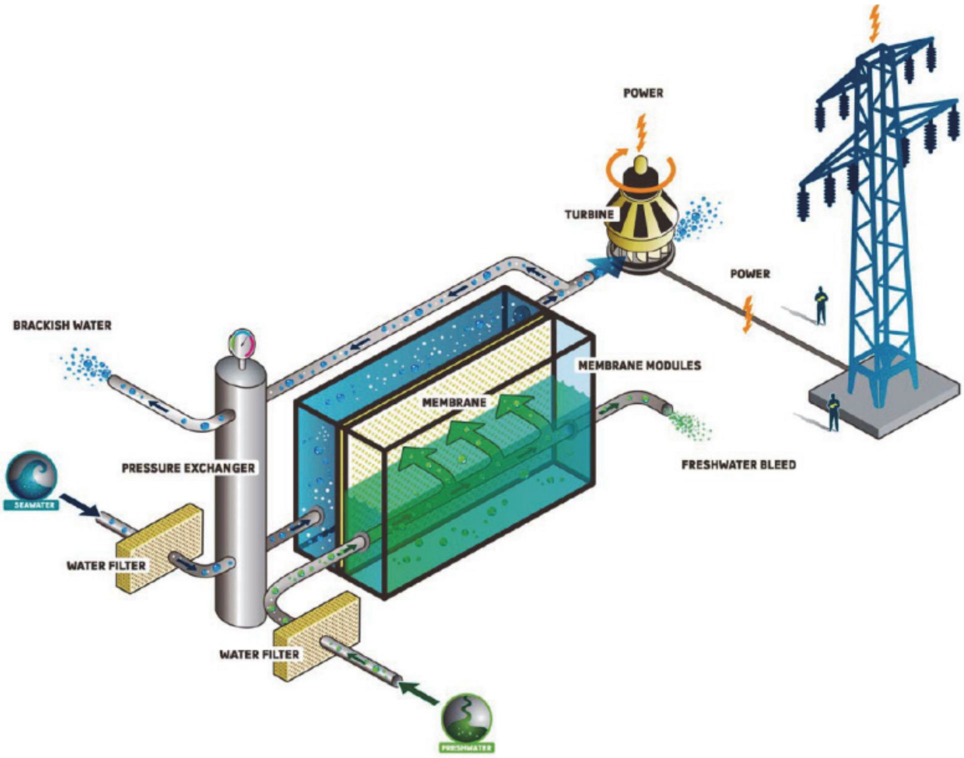


Figure 8: Osmotic Power simplified schematic diagram (courtesy of Statkraft)

Although the concept has been proven the lack of suitable membranes with sufficient energy productivity currently hampers commercialisation. The development of suitable membranes could be the trigger for large and more widespread application of the technology as an alternative to established desalination techniques.

6.3 Other technologies

Examples of other desalination techniques are presented in Table 3 (Miller, 2003). These techniques are only mentioned here and not elaborated on. The list is by no means exhaustive and more detailed descriptions on these technologies may be found in referenced literature. The list is intended to serve as an indication of the wide variety of approaches that have been investigated, which nevertheless can be categorised into one or more of the basic approaches outlined above, viz. thermal, physical, chemical.

Table 3: Other Desalination Techniques

Category	Process
Crystallisation	• Freeze desalination • Gas hydrate processes
Humidification	• Dewvaporation processes • Seawater greenhouse • Membrane distillation • Mechanically intensified evaporation
Deep ocean and wave driven	• Osmotic pump • Deep ocean hydrostatic head • Wave pumps
Solar	Solar stills
Other	Liquid-liquid extraction

7 FUTURE OF SEAWATER DESALINATION

Desalination is process primarily applied in developed countries with financial capability and resources. If the technology continues to produce new methods and better solutions to the issues that exist today, there would be a whole new water resource for more and more countries that are facing drought, competition for water, and overpopulation. Although there are concerns in the scientific world about replacing our current overuse of water with complete reliance on sea water, it would undoubtedly be at least an option for many people struggling to survive or maintain their standard of living.

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