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Evaluation of desalination techniques for treating the brackish water of Olushandja sub-basin

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Now that the journey has eventually caught up with its destination, I wanna look back and around to assess the terrain where I trembled and the sources of vitalization and inspiration that brought me here.

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Abstract

The groundwater of Olushandja sub-basin as part of Cuvelai basin in central-northern Namibia is saline with TDS content varying between 4,000 ppm to 90,000p pm. Based on climatic conditions, this region can be classified as a semi-arid to arid region with an annual rainfall during summer time varying between 200 mm to 500 mm. The mean annual evaporation potential is about 2,800 mm, which is much higher than the annual rainfall. The southern block of this sub-basin is of low population density. It has not been covered by the supply networks for electricity and water. Therefore, the inhabitants are forced to use the untreated groundwater from the hand-dug wells for their daily purposes. This groundwater is not safe for human consumption and therefore needs to be desalinated for that purpose.

The goal of this thesis has been to select a suitable desalination technology for that region. The technology to be selected is from those which use renewable energy sources, which have capacity of production from $10m^3$ to $100m^3$ per day, which are simple and robust against existing harsh environmental conditions and have already been implemented successfully in some place. Based on these criteria, the technologies which emerged from the literature are: multistage flashing (MSF), multi effect distillation (MED), multi effect humidification (MEH), membrane distillation (MD), reverse osmosis (RO) and electro dialysis reversed (ED). Out of these technologies, RO & ED are based on membrane techniques and MSF, MED & MEH use thermal processes whereas MD technology uses a hybrid process of thermal and membrane techniques for desalinating the water.

For evaluation of technical performance, environmental sustainability and financial feasibility of the above mentioned desalination techniques, the following criteria have been used: gained output ratio, recovery rate, pretreatment requirements, sensitivity to feed water quality, post treatment, operating temperature, operating pressure, scaling and fouling potential, corrosion susceptibility, brine disposal, prime energy requirement, mechanical and electrical power output, heat energy, running costs and water generation costs. The data regarding the performance standards of the successfully implemented desalination techniques have been obtained from the literature of performance benchmarks.

The Utility Value Analysis Tool of the Rafter-Group of Multi-Criteria Analysis (MCA) has been used for measuring the performance score of a technology. To perform the utility analysis, an evaluation matrix has to be constructed through the following procedures: selection of the decision options (or assessment groups), identification of the evaluation criteria, measurement of performance and transformation of the units. Then the criteria under the objective groups are assigned a level of importance for determining their weights.

To perform the sensitivity analysis the level of importance of a criterion is changed by giving more weight or rate to the assessment group of interest (or study). Within the assessment group of interests, the best performing desalination technology has been selected according to the outcome of the sensitivity analysis.

The important conclusions of this study are the identification of the capabilities of thermal and membrane based small scale desalination technologies and their applicability based on site specific needs. The sensitivity analysis indicates that the MED technology is the most environmental friendly technology that uses minimum energy and produces least concentrated brine for disposal. The ED technology has emerged to be technically suitable, but it is only applicable when source water has less than 12.000ppm salt content. The MSF process has favorable thermal efficiency and it is insensitive to feed water quality. Its major drawbacks are energy needs and post treatment requirements that affected its net score. The MD and MSF process have scored the lowest for the technical and economic assessment groups and are concluded not to be suitable for Olushandja sub-basin. The MEH process is cheaper and technically more appropriate than the MED in the two assessment groups.

Based on the above mentioned evaluations, this study concluded that Olushandja sub-basin needs more data collection on the geological profile, distinctive identification of aquifers and evidence on the interaction between the aquifers. From the best available data obtained, it could not be established with certainty where the highest level of salinity can be found in the profile, or how the geological profile is layered. More data on ground water quality for spatial overview of the trends and pattern of the sub-basin will be useful in drawing better conclusion on the specific desalination technology needed which is suitable for a specified village or living space.

Zusammenfassung

Das Olushandja Wassereinzugsgebiet im zentralen Norden Namibias zeichnet sich durch semiarides bis arides Klima aus. In der Regenzeit fallen Niederschläge von 200 mm bis 500 mm p.a., die aber infolge der hohen potentiellen Verdunstung von bis zu 2.800 mm p.a. nur begrenzt nutzbar sind. Es ist Teil des Cuvelaibeckens und beinhaltet aufgrund der insgesamt geringen Austauschrate Grundwasser mit einer Salinität von ca. 4.000 ppm bis 90.000 ppm. Der südliche Teil des Olushandja Einzugsgebietes ist dünn besiedelt und es gibt keine sichere Wasserversorgungs- und Energieinfrastruktur. Die dort lebenden Bewohner sind gezwungen sich über handgegrabene Brunnen mit oberflächennahem Grundwasser zu versorgen. Der Konsum dieses Wassers stellt für die Bevölkerung eine Gesundheitsgefahr dar, weswegen es für den menschlichen Gebrauch einer Entsalzung unterzogen werden muss.

Im Rahmen dieser Studie werden zur Auswahl geeigneter Entsalzungstechnologien für diese Region eine Reihe von Randbedingungen definiert, unter denen u.a. durch Einsatz erneuerbarer Energien, salzhaltiges Wasser mit einer täglichen Produktionsleistung von $10m^3$ bis $100m^3$ zu Trinkwasser aufzubereiten werden kann. Darüber hinaus sollten die Technologien unter den gegebenen Standortbedingungen möglichst technisch einfach und nachweislich robust für einen sicheren, dauerhaften und ökonomisch leistbaren Betrieb sein. Entsprechend wurden nach einer Literaturanalyse folgende Entsalzungstechnologien ausgewählt: Multi-stage Flash Distillation (MSF), Multi-effect Distillation (MED), Multi-effect Humidification (MEH), Membrane Distillation (MD), Reverse Osmosis (RO) und Electro-dialysis Reversed (ED). Die RO- und die ED-Verfahren basieren auf einem Membrantrennungsprozess, während die MSF-, MED- und MEH-Technologien auf einem thermalen Prozess mit Phasenübergang beruhen. Die MD-Technologie stellt diesbezüglich ein hybrides Verfahren unter Verwendung eines Phasenübergangs und einer Membranbarriere dar.

Zur Bewertung der verschiedenen Entsalzungsverfahren wurden die folgenden Kriterien verwendet: Gained-Output-Ratio (GOR) und Recovery Rate, Anforderungen an die Vorreinigung, Sensitivität gegenüber der Qualität des Rohwassers, Anforderungen an die Nachbehandlung, Betriebstemperatur, Betriebsdruck, Scaling-/Foulingpotential, Korrosionsanfälligkeit, Entsorgung der Brine, Primärenergieeinsatz, Einsatz mechanischer und elektrischer Energie, Wärmeenergie, Betriebskosten und Wassergenerierungskosten. Die Erfüllung der Kriterien wurde dabei aus historischen Leistungsbenchmarks von erfolgreich arbeitenden (Demonstrations-)Anlagen auf der Basis von in der Literatur beschriebenen Ergebnissen abgeleitet. Die genannten Bewertungskriterien sind dabei darauf ausgelegt, die technische Leistung, die ökologische Nachhaltigkeit sowie die finanzielle Durchführbarkeit der ausgewählten Entsalzungsverfahren miteinander zu vergleichen.

Zur Bewertung wurde eine Nutzwertanalyse mit den identifizierten Kriterien und den erhobenen Leistungsdaten durchgeführt und gewichtet verschiedenen Oberzielen zugeordnet. Anhand einer Sensitivitätsanalyse, bei der eine Variation der Gewichtungen erfolgte, wurde die Stabilität der Reihung der Verfahren überprüft. Innerhalb der jeweiligen Bewertungskategorie wird die Entsalzungstechnologie mit der höchsten Punkteanzahl gewählt.

Das Ergebnis dieser Studie ist die Identifikation der Leistungsfähigkeit kleinskaliger Verfahren zur Entsalzung mit und ohne Phasenübergang und ihre Anwendbarkeit unter den ortsspezifischen Anforderungen. Die Sensitivitätsanalyse deutet darauf hin, dass der MED-Prozess der umweltfreundlichste ist, nämlich jener mit dem geringsten Primärenergieverbrauch und einer gering konzentrierten Brine. Der ED-Prozess ist grundsätzlich ebenfalls technisch geeignet, ist aber nur sinnvoll einsetzbar bei Rohwässern mit weniger als ca. 12.000ppm Salzgehalt. Der MSF-Prozess ist vorteilhaft in seiner thermalen Effizienz und ist unempfindlich gegenüber hohen Salzgehalten im Rohwasser. Seine größten Nachteile sind der hohe Energieverbrauch und die Anforderungen an die Nachbehandlung des Wassers, welche seine Bewertung verschlechtert haben. Der MD- und der MSF-Prozess haben die niedrigste Bewertung im technischen und ökonomischen Bereich erhalten und sind daher nicht für den Einsatz in der Region geeignet. Der MEH-Prozess ist günstiger und technisch besser angepasst als der MED-Prozess in diesen beiden Bewertungskategorien.

Im Ausblick kommt diese Studie zu dem Ergebnis, dass weitere Datenerhebungen im Projektgebiet im Hinblick auf das lokal stark differierende geologische Profil, die genaue Analyse der Grundwasseraquifere und deren räumliche Ausdehnung bzw. Verbindungen notwendig sind. Die Summe aller räumlich höher aufgelösten Daten, insbesondere zur sehr stark variierenden Grundwasserqualität im Einzugsgebiet, könnten bessere Rückschlüsse auf die Auswahl und nachhaltige Bewertung der standortspezifisch besser geeigneteren Entsalzungstechnologie geben.

Symbols, Abbreviations and Glossary

Symbols

%	percentage
€/m^3	Euro per cubic meter
μm	micro meters
μS/cm	micro siemens per centimetre
atm	atmosphere
Ba	barium
Br-	bromide
Ca	calcium
Cl_2	chlorine
Cl^-	chloride
e^-	electrons
Fe	iron
H	hydrogen
I^-	iodide
Li	lithium
M_f	feed water flow rate
Mg	magnesium
Mp	permeate flow rate
Na	sodium
NO_3^-	nitrate
O	oxygen
^oC	degree Celsius
OH^-	hydroxide
Ra	radium

SO_4^{2-}	sulphate
Sr	strontium
X_f	feed water concentration
X_p	permeate concentration

Abbreviations

AWWA	American water works association
CEB	Cuvelai-Etosha basin
DRFN	Desert research foundation of Namibia
ED	electro dialysis
EDR	electro dialysis reversal
GCS	Groundwater Consulting Services
GWA	gender and water alliance
IWAR	Institute of water and sanitation at TUD
kg/s	kilogram per second
kJ/kg	kilojoules per kilogram
kWh/(m^2.day)	kilowatt hour per square meter a day
kWh/m^3	kilowatt hour per cubic meter
m amsl	meter above mean sea-level
m/s	meter per second
m^3/h	cubic meter per hour
MAWF	ministry of agriculture, water and forestry
MAWRD	ministry of agriculture, water and rural development
MCA	multiple criteria analysis
MD	membrane distillation
MED	multi effect distillation
MEH	multi effect humidification

mg/L	milligram per litre
Mm	millimetre
MME	ministry of mines and energy
MSF	multistage flash
MVC	mechanical vapour compression
PP	Polypropylene
ppm	parts per million alternatively expressed in mg/l
PTFE	Polytetrafluoroethylene
RO	reverse osmosis
SR	salt rejection
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
TVC	thermal vapour compression
TUD	Technical University of Darmstadt
UNICEF	united nation children fund
VC	vapour compression
WASH	water sanitation and hygiene
WHO	world health organization
GOR	gained output ratio
SDI	silt density index
EC	electric conductivity
CIP	clean-in place (system)

Glossary

BOD	biochemical oxygen demand – A measure of the amount of oxygen used by bacteria in the degradation of organic matter.
CBA	cost benefit analysis – It is a decision tool for which the ranking and scoring is based on the net present value and the internal rate of return.
CEA	cost effective analysis – It is an analytical technique designed to compare the costs and effectiveness of alternative measures.
CUA	cost utility analysis- it is an economic evaluation framework that requires monetary units as inputs for quantifying projects' viability for decision making.
DWA	department of water affairs within MAWF – This is a department within the Ministry of agriculture, water and forestry in the government of the Republic of Namibia.
EIA	environmental impact assessment – It's a procedure that identifies, describes, evaluates and develops means of mitigating potential impacts of proposed activities on the environment.
ILWRM	integrated land and water resources management – This concept refers to a meaningful participation of all stakeholders in the development, planning and management of water and land resources, institutions and mechanisms put in place and legislation enacted within the context of local, regional, national and international principles.
MF	micro filtration- It is a membrane process that have a pore size of 0.05 - 5μm. It is used for microbial and particle removal primarily and can be operated under ultra-low-pressure conditions.
NDP	net driving pressure- It is the available force to drive the water through the membrane minus the permeate and osmotic backpressures.
NF	nano filtration- Is a membrane process that rejects all viruses, bacteria, cysts, and other pathogenic organisms. It has a pore size of 0.5 – 1.5nm (nano meter).
SMADES	"is the acronym of a project titled "PV and thermally driven small-scale, stand-alone desalination systems with very low maintenance needs." It is funded by European Commission and co-ordinated by Fraunhofer Institute.
UF	ultra filtration- It is a pressure driven process by which colloids, particulates and high molecular-mass soluble species are retained by a mechanism of size exclusion. It has a pore size of 0.02 – 0.3 μm.

Table of Content

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Objective

The groundwater of the Olushandja sub-basin is brackish with total dissolved solids (TDS) ranging between 4,000 and 90,000ppm (IWAR Lab tests, 2008 and 2009). This water is a health hazard and is not suitable for human consumption according to Namibia Water Corporation' (NamWater) drinking water quality guidelines (**Appendix A**).

In addition to the above, the southern settlement part of the sub-basin is not entirely served by the current water conveying network. This part of land is predominantly an inhabitation of rural villages with residents whose proximity to the nearest water supply point is too wide to reach on a daily basis. Access to the nearest water supply points is in excess of 20km for most of the households or villages (Mendelsohn, 2000). These rural residents have resorted to the use of groundwater, which they access locally through hand dug wells (DRFN, 2005).

The settlement pattern of the sub-basin is characterized by clusters of family units that are scattered on a prismic ratio of one to two kilometers apart.

On the regional level, the scenario and conditions of Olushandja sub-basin are a representation of a number of specific sites in the larger Cuvelai-Etosha Basin (CEB). Olushandja sub basin is one of the four sub basins in the CEB. The other three are: Iishana sub-basin, Tsumeb sub-basin and Niipele sub-basin (Bittner, 2006).

Olushandja sub-basin is selected as the focal area for this study because the preliminary work and studies executed so far shows that most people living in the southern part of the sub basin are isolated from the water supply networks and are therefore using the brackish water directly as drinking water. In some parts of the sub-basin the water brackishness is more saline then the normal range of 1,000- 10,000ppm quality of brackish water, yet it's being used by the village communities without any treatment. The groundwater yield is reported to be reasonably acceptable (at 4 to 30m^3/h, Mendelsohn, 2000) for treatment works on a sustainable basis for the sizes of communities settled per village in the sub-basin. The above facts indicate that a solution needs to be sought to the water quality and supply problem of Olushandja sub-basin.

From a global perspective, Olushandja sub basin has a semi-arid (alternatively referred to as steppe) to arid climatic conditions where precipitation is below the potential evapotranspiration, with temperature ranges from 20 to 39^{o}C during the summer and 6 to 25^{o}C during the winter periods. The mean annual rainfall ranges from 200 to 500mm, with mean annual evaporation potential at 2,500mm. The evaporation potential exceeds the precipitation volume by a factor of six per annum (Mendelsohn, 2000). The sub-basin falls within the hot semi-arid (alternatively referred to as BSh) climate classification of the Southern hemisphere. This classification also covers the southern belt of Northern Africa and South-Eastern part of Australia (Peel, 2007). This climate regime (of high evaporation and low rainfall) together with the natural presence of gypsum in the geological profile, the salts are either dissolved during the rainy season, increasing the salinity in the ground water sources or the salts are precipitated to crystals and remain in the geology and on the pans surface, during the dry hot season.

Should a suitable solution be drawn from the worldwide experience to the water quality situation in Olushandja sub-basin, it could be utilized for other parts in Namibia with similar environmental and climatic conditions. The BSh characteristic condition covers almost the entire Northern block of the country, starting from the middle of the east-western stretch, with the remaining part of the country being hot arid or desert type (also referred to as BWk) climate characteristic.

Explorations to best cover the Cuvelai Basin with water supply are recorded since the 1960s, with reports detailing options that included desalination, but due to the cost of desalinating water and the cost of extending pipelines spatially to the highly scattered settlements was found not to be feasible at the time (MAWRD, 1990).

The rural inhabitants of Olushandja sub-basin need clean water to improve their health and hygiene situation and to eliminate vulnerability and safety issues associated with the setting up and operation of hand dug wells, as well as the hazardous quality from these wells (Deffner et al, 2010).

To date, it is hypothetically believed that brackish water in remote rural areas as Olushandja sub basin rural villages can be treated under their conditions, utilizing simple and robust desalination technology and renewable energy.

The Rural section which is mainly the southern block of Olushandja sub-basin has semi-arid to arid climatic conditions and it is in isolation from the main supply and service networks of water, electricity and transport.

In order to resolve the water quality predicament of the rural people of Olushandja sub-basin, a scientific review of the existing proven desalination methods needs to be carried out in order to establish the suitability of these technologies to the prevailing social, technological and environmental conditions.

In this investigation the author attempts to attend to the following questions:

- Which desalination techniques having capacities from $10m^3$ up to $100m^3$ per day, utilizing renewable energy are successfully implemented or piloted anywhere around the world?
- How can the implemented technology be adapted to the conditions in Olushandja sub basin, in terms of simplicity, robustness and safety?
- What are the maintenance requirements of these desalination technologies?
- How much energy is required to run and meet the power requirements of the selected technology and is there sufficient renewable energy that can be sourced in Olushandja sub basin?

– What would be the best approach to meet the demand, hygiene, accessibility, environmental and aesthetic conditions of Olushandja sub basin' consumers and surrounding?

1.2 Methodology

The water of Olushandja sub-basin needs to be desalinated to remove the excessive presence of the salty ions. To get a solution to the water quality problem of the sub-basin, a number of schemes or plants that are already implemented or are successfully piloted around the world have to be sought and evaluated for replication or as potential implementable solution to Olushandja sub-basin conditions.

For the selection and evaluation of these desalination techniques, the following criteria are to be applied:

The desalination technique and scheme should be:

- Treating brackish water,
- Using renewable energy,
- Have a capacity of $10m^3$ up to $100m^3$ per day,
- Successfully implemented or piloted anywhere in the world,
- Technically simpler compared to large scale,
- Proven robust against any harsh environmental conditions,
- Flexible in terms of modularity and mobility adjustable to source water availability
- Made with materials and parts that can be imported and be accessible locally
- Environmentally sustainable, with the source water meeting the technology requirement and also be available for the people living in Olushandja and for their traditional need in livestock farming and irrigation.
- The technology should be socially within reach at least 500m from the users, should provide capacity development and be managed by the capable local people, including women.
- Institutionally accepted by the local people and open for them to be part of it, whether it is by running the supply or taking responsibility of ownership.

A number of economic evaluation frameworks exist that can be applied to measure values and benefits of options and criteria. Within these frameworks some methods uses the monetarisation approach, while others use both monetary indices and performance benchmarks.

The evaluation of this study is mainly to assess various desalination techniques performance benchmarks in producing potable water from the brackish ground water in a most feasible and sustainable way.

In order to select an evaluation method for the desalination technology options, the following criteria are compiled from the selected desalination techniques' performance. The criteria are to be used as indications for the performance level.

- Gained Output Ratio
- Recovery Rate
- Pretreatment Requirement
- Sensitivity to feed water quality
- Post Treatment
- Operating temperature
- Operating Pressure
- Scaling and/or fouling potential
- Corrosion Susceptibility
- Permeate Quality
- Brine Disposal
- Mechanical and Electrical power input
- Heat energy
- Prime Energy Requirement
- Running costs
- Water generation cost

The criteria selected are normative because they are derived from the documented standard performance of the selected desalination techniques. The normative criteria approach is based on the decision theory that involves prescriptive and rational measures (Peterson, 2009). In such a theory, rational criteria based on past experiments, tests and pilot plants are compiled in accordance with the conditions of Olushandja sub-basin to decide on a suitable technology based on their technical, environmental and long-term cost performance.

In this study it is assumed that small-scale desalination technologies exist that can be utilized with renewable energy. Such technology has been tested and has yielded results that can be reproduced somewhere else, given similar conditions technically and environmentally.

Normative criteria constitute a list of indicators and their associated proven standards of performance. The proven standards of performance are based on scientific empirical performance data quoted in literature, on which the various technologies have given best results. In order to draw optimal value for decision making, these scientific benchmarks will be used for evaluation in a pre-set framework or assessment groups' methodology.

The methodology to evaluate the criteria has two routes. First the criteria need to be transformed into quantifiable data, and then the data has to, where applicable, be used in a spreadsheet formula to obtain achievements from certain targets and partial utility data.

As part of the process in the spreadsheet' calculation, three levels of importance are assigned to all criteria and are used in the formula to obtain and allocate weights of target to all criteria.

Please refer to **Appendix B, C and D**, at the back of this report, to get detailed spreadsheets of all techniques, assessment groups and criteria evaluation, using the allocation of weights and level of importance.

On page 84, 86 and 89 in the thesis, details on transformations formulae and the use of the spreadsheet bottom formula for evaluation are given.

1.3 Limitations and Data quality

In this research and study project, information and data is drawn from existing literature. This data and information is about the area profile that is in focus and data from the literature covering desalination technology, processes, performance standards and implementation or piloting success. The area profile data is to support the conditions, both environmentally and socially in putting up selection criteria that are to meet these conditions, when selecting the appropriate desalination technique.

Olushandja sub-basin as an area is having very limited information in literature that is documented specifically on the sub-basin. The sub-basin is part of the larger basin named Cuvelai-Etosha basin and cover parts of the four political Regions within this basin, where more than fifty percent of Namibia population is settled.

Documentation on this section of the Northern Region either covers the Cuvelai-Etosha basin or the individual political regions that are covering the Northwestern block of the country. Collection of the data and information therefore had to be drawn and derived from a pool of these larger units and collated into the Olushandja sub-basin. Numerously data references were just outside or at the borders of the sub-basin, and extrapolated for the whole larger unit. This is data such as for the hydrological information, meteorological data collected and hydro-geological data.

The Namibian meteorological data collection center for the Cuvelai basin is well outside the Olushandja sub-basin, but information used for weather related projection and transformation is for the whole basin. It was in this case my prerogative to translate and reference the data to my area of focus, as part of the background information. The hydrological information on the flow of the floods and rainfall patterns within this period of my study for the Cuvelai basin is collected from telemetry stations set-up within and for the basin, but barely covering the area of focus.

The hydro-geological information documented for the area states that the geological profile of the Cuvelai basin has aquifers and that the soil profile up-to 600m below sub-surface is percolative. Supportive information is documented for this. On further search in other and partly more recent data, the profile is shown to have mud, silt and clay that provide for non-percolation layers. As contradictory as it may be in some areas, both information is included in this compilation.

The obscurity in the data collection could either be on the time or period of data collection or the means used to collect the data. Remote sensing data collection versus actual drilling and sampling for data collection, together with the season or period in the year when the data was collected might be the cause of the obscurity. Report writing allot of time do not coincide with the time when the data was collected.

On the technical data collection for the desalination technology, a number of discomforts were observed. Somehow, the proven data of the desalination techniques on both the renewable energy and conventional energy has produced mixed performance. An RO technique, for example, in one literature would be presented to have little energy use at 1.5-2.5 kWh/m^3 and then in another to have 4.5-6kWh/m^3. In such instance, results that are closer to the 4-7kWh/m^3 range are used as they correspond with the desalination pilot results that are currently running in the area that is under review in Namibia.

Otherwise, to make this study more credible and based on realistic and proven performance, much more detailed issues on breakdowns, trouble shooting and financial expenditures would have been useful. But these are the sensitive matters of any project and are not freely reported on in literature for a specific scheme or desalination technique. This information is normally shared confidentially for the members of the project or the sponsors, it is highly unlikely one would get information or feedback on such issues. The pilot desalination schemes reported in details are very few; most data is used to draw hypothetical scenarios in comparing results from various tests and various companies or present potential for a specified activity.

The preceding presentation is to give an overview of the challenges and constraints dealt with.

Chapter 2: Area Profile

2.1 Area Location

Olushandja sub-basin is located in the North Central part of Namibia, as indicated in **Figure 1** below.

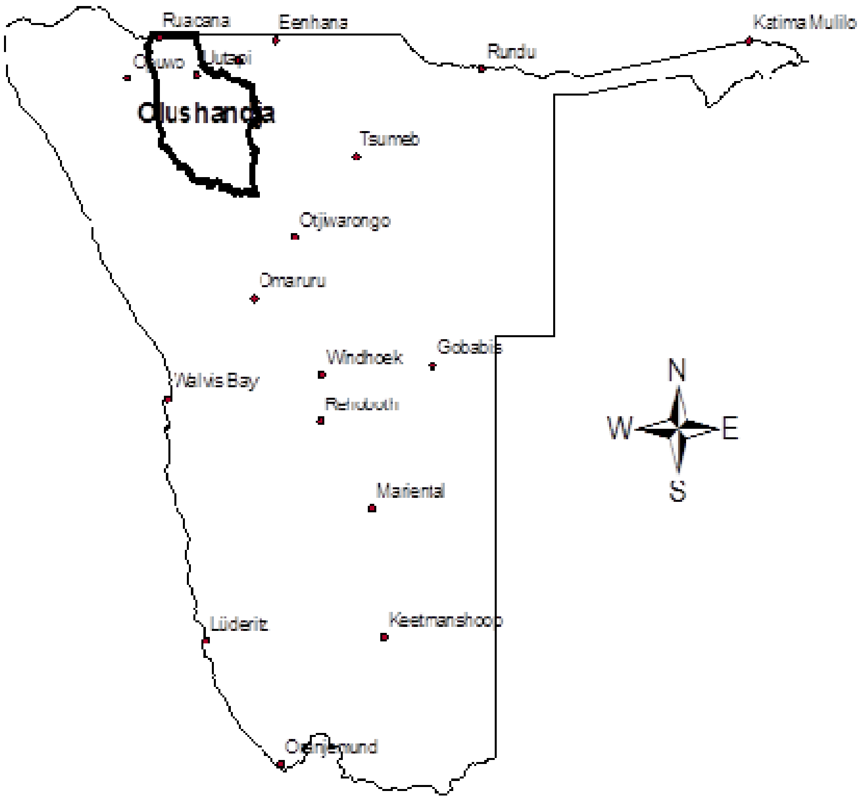

Figure 1: Olushandja sub-basin in Namibia (after Biwac, 2000)

The sub-basin was established in theory as a result of water and land resources management' decentralization approach that is derived from integrated land and water resources management (ILWRM) concept. (DRFN, 2005). It is not functional yet in terms of management of land and water resources according to IWRM ideology.

It is relatively at this point a new establishment in the Namibian water supply industry and a new approach based on the system of ILWRM. The demarcation of the sub basins of the CEB was done taking the following into consideration; water supply networks and sources, water consumption and land use, political administration, and conservancies' management (Bittner, 2006).

The Olushandja sub-basin as part of the four sub-basins in the CEB constitutes more than fifty percent of the country population. Namibia has a population of about 1.8 million people, according to 2004 country census. The larger Cuvelai-Etosha basin covers about one-third of the total country land space (Mendelsohn, 2000).

2.2 Settlement and Current Water supply situation

The population in the Northern Region of Namibia, including Olushandja sub basin is served with water drawn from the Kunene River, abstracted at Calueque dam in Angola. The current formal water supply network serving the sub-basin is exclusively in the Northwestern block as shown by the string of blue points on the map. A large portion of land within Olushandja sub-basin is fenced off as part of the larger Etosha National Park. This area is indicated by the light blue section in this map, in **Figure 2** below. The Etosha national park constitutes the lower elevation ephemeral watercourses pans to which the floods from the upper Olushandja sub-basin flows to during the rainy season.

Figure 2: Settlement pattern and water supply of Olushandja sub-basin (after Bittner, 2006)

The residents in Amarika, Uutsathima and Onamatanga are practicing the traditional means of water abstraction via the hand dug wells (DRFN, 1996).

Explorations to best cover the region with water supply are recorded since the early sixties, with reports detailing options that included desalination, but due to the cost of desalinating water and the cost of extending pipelines spatially to the highly scattered settlement, water provision to some villages in the sub-basin was found not to be feasible at the time (MAWRD, 1990).

From the survey done on two villages in the Olushandja sub-basin, a village has an average population of 700 people, living in proximity of 1-2km apart in homesteads or family units of 3 to 14 family members per unit (CuveWaters workshop report, 2008). The desalination technology scale to be sought should be according to the needs of the village population to be catered for.

The ground water in Olushandja sub-basin is replenished during the rainy season and provides fresh lenses of supply to the rural population during this time of the year. The water from the hand-dug wells during the rainy season has improved salinity quality of less than 1,000ppm due to fresh lenses of the rainy season (DRFN, 2005). The use of desalinated water may therefore be traded off during the rainy season as a cost saving measure by the customers in the villages. The hand dug wells are often built closer and more central to the residents' homesteads, for closer proximity in carrying the water to their homes (Lux et al, 2009).

2.3 Hydrology

The climatic conditions in Olushandja sub-basin are defined as semi-arid, having temperatures ranging from 20 to 39^{0}C during summer season and from 6 to 25^{0}C during winter time (MAWRD, 2009). The precipitation pattern of Olushandja sub-basin' normal range is from 200 to 500mm per annum (NMS, 2008). This is shown in **Figure 3** below, after Bittner 2006. However the 2007/08 season had above normal rainy conditions that averaged at 580mm (MAWRD Hydrology division, 2009).

From the rainfall figures of 200 to 500mm and an average potential evaporation figure of 2,800mm, the sub-basin has an average annual deficit of 2,300mm (**Figure 4**) of water, making it a drought stricken area outside the rainy season (MAWRD, 1988). The single factor index which defines the aridity of an area based on monthly data is the ratio of R/E (R-rain and E-evaporation). When the ratio exceeds 1 then the conditions are wet, but are dry when the ratio falls below 1. The sub-basin has a sandy-calcrete soil type that soaks up most of the first rainwater that occur, before a surplus runoff build up to flow on the surface (Hydrological Perspective, 2008). When evaporation exceeds precipitation, dry conditions may occur, the intensity of which depend upon the duration of the period and the rainfall- evaporation ratio (Davidson, 1934). The recorded potential evaporation of Olushandja sub basin exceeds the rainfall volume per annum, rendering the reported semi-arid to arid conditions (Pointer et al, 1995).

The efficiency of rainfall depends upon the amount and distribution of precipitation together with run-off and percolation through the soil, in relation to the loss due to evaporation. In addition, the distribution of precipitation and soil type are among the secondary factors that determine the degree of wetness or dryness at the soil surface during any defined period (Davidson, 1934).

The area has convective rainfall thunderstorms that have a direct impact on the presence of surface water and on the ground water recharge pattern (BGR, 1997). The high evaporation rates cause the drying up of the pans (Iishana), resulting in the precipitation of salts and increased salinity of the shallow aquifers, in particular in waterlogged areas and areas comprising a low permeable lithology (MAWRD, 1993). The evaporation is governed by the reflective properties of the surface, solar radiation energy, wind speed, temperature of the water and air and relative humidity of the air (Twort et al, 1999).

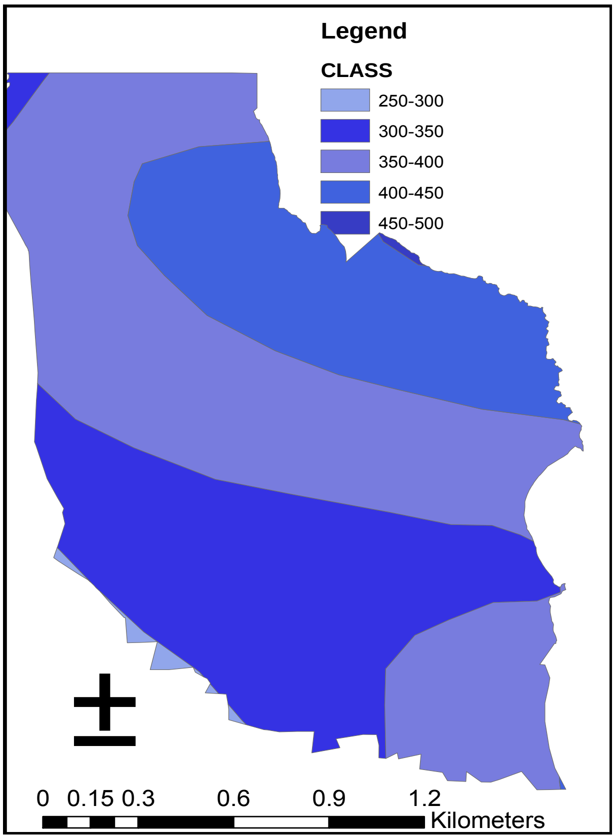

Figure 3: Olushandja sub-basin Rainfall figures (after Bittner, 2006)

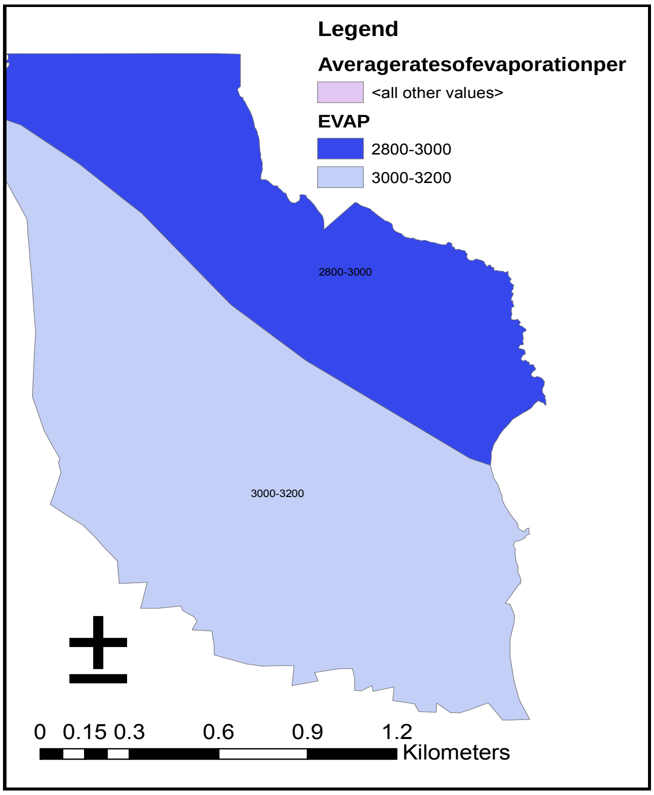

Figure 4: Potential evaporation overview of the sub-basin (after Bittner, 2006)

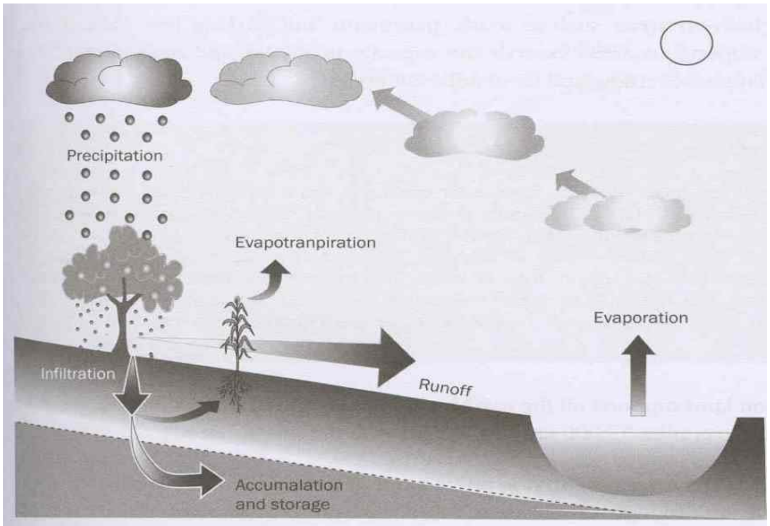

Figure 5: Hydrological cycle model (sourced from Malesu et al, 2007)

Figure 5 is depicting a modeled cycle of a typical hydrological cycle event that is similar to the sub basin. Generally, water evaporates to the air from any open water surface or film of water on soil, vegetation or impervious surfaces, as roads and roofs (Twort et al, 1999). The Iishana are the open surface water bodies where most evaporation occurs. Transpiration is the water used by plants to nurture crops. In the areas where the ground is covered by plants or forest, the term evapotranspiration is used to combine the water loss by both the trees and the surface. For Olushandja sub-basin, the surplus rain water collect in the large open surfaces of Iishana features from where most and more rapid evaporation occur (Mendelsohn, 2000).

2.4 Topography

Bittner states that the topography of the CEB has a major influence on the drainage system with the numerous interconnected channels of the Iishana system.

The landscape appears flat and open with a low relieve of $0.2^{o}/_{oo}$ and limited vegetation (Biwac, 2006). The contour lines on the map (**Figure 6**) show the tilting slope from the west to east dissection, with the lowest topographical level of 1,080 amsl (above mean sea level) on the eastern rim. The southern block of the sub basin is an undulating plain with numerous treeless and saline pans (Biwac, 2006).

The existing ground water quality tests in relation to the topography shows that, the source water deteriorate from west to east direction, giving readings of 4,000ppm around Uutsathima village, around 24,000ppm at Amarika village and scaling up to 90,000ppm around Otamanzi village, with reference to the places shown in **Figure 2** above.

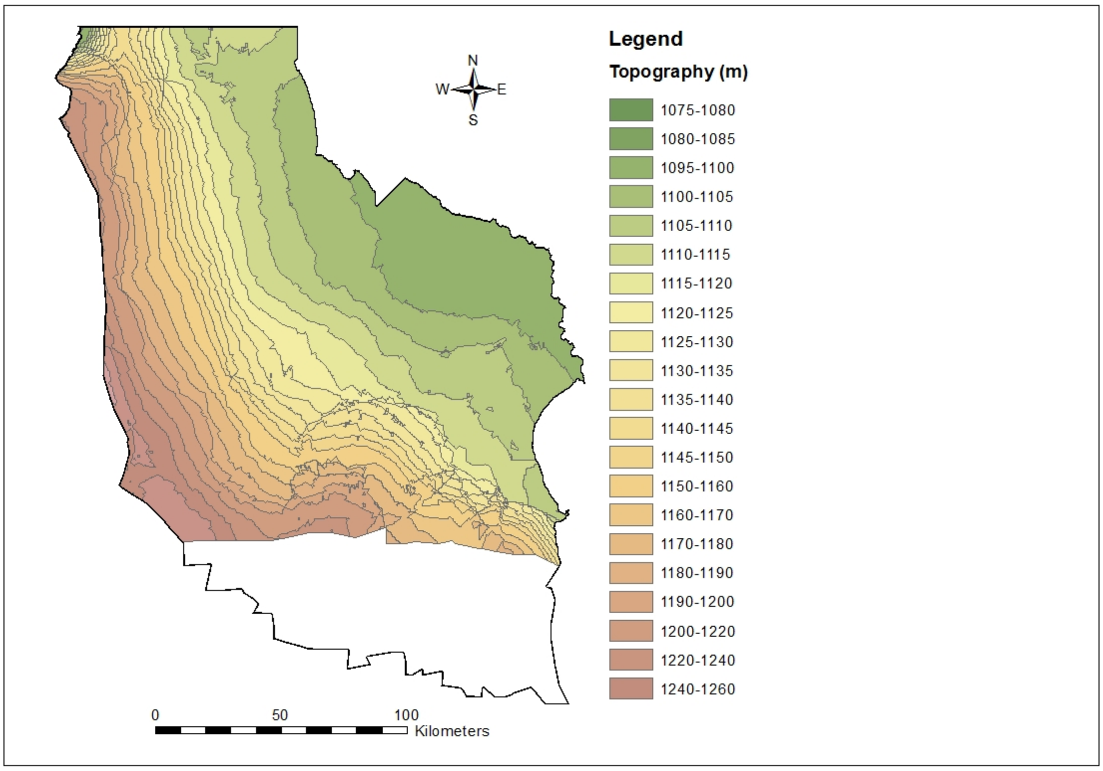

Figure 6: Topography of the sub-basin (after Bittner, 2006)

The people in the Olushandja sub-basin that are affected by the water situation negatively are in the southern block. The uncolored patch indicated in **Figure 6,** cover part of the Etosha National park. This park is largely uninhabited by humans and is predominantly covered by the saline pans and inhabited by wildlife, except for the people working at the lodges and the non-permanent inhabitation by the tour activities agents and tourist to the national park.

2.5 Soil, Geology and Hydrogeology

The Olushandja sub-basin is characterized by percolating sands and fragmented rock covering more than 85% of the surface area soil and part of the geological profile (refer to **Figure 7**). The soil comprise the sands and clays of Aeolian and fluviatile origin and have poor water-holding capacity, but high salt content (Mendelsohn, 2000). The sands and calcrete are a result of a successive deposition of semi- consolidated and unconsolidated sediments of the Kalahari Sequence (GCS, 1992). The Kalahari sequence consists of aeolian material that are made of fine grained well sorted sands (Hipondoka, 2005). The lithology is characterized by up to 600m thick semi to unconsolidated sediments (Christelis and Struckmeier, 2001). The Kalahari sediments are characteristically red beds consisting of conglomerate, shale and sandstone (Biwac, 2006).

According to the drilling operations in 2009, by Miller, the geological profile of Olushandja sub-basin has a combination of clayey sand, sandy clay and silty clay. Up to 9m down the subsurface, the clayey sand starts, after which a bed of sand only stretches for 20m.

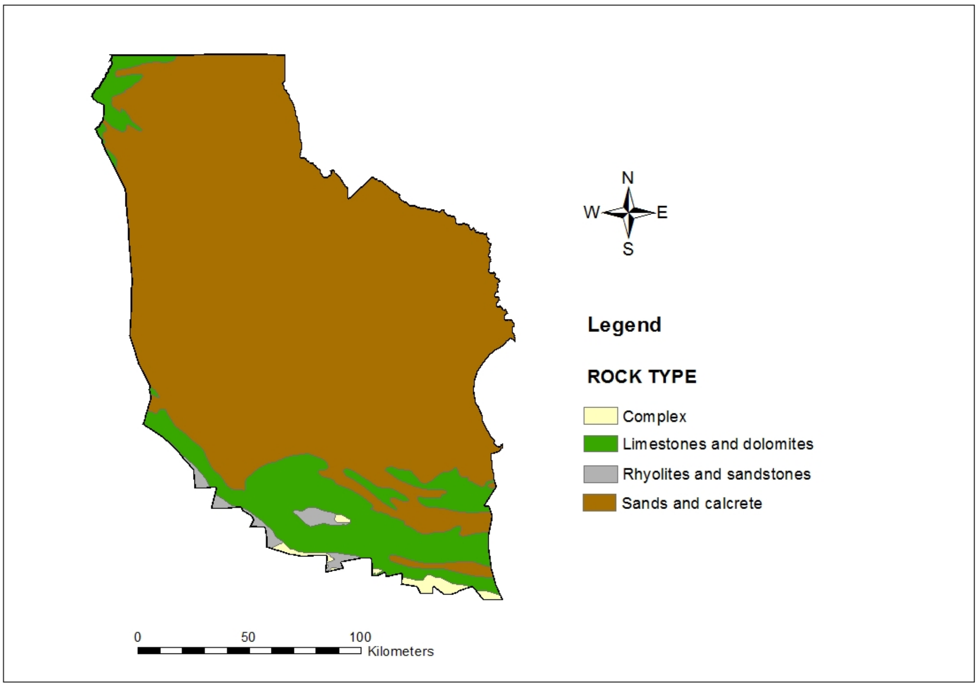

Figure 7: Soil and Geology (after Mendelsohn, 2000)

The sandy clay and clayey sand profiles alternate down to 108m below and then silty clay is hit for 6m. This borehole was drilled for 150m deep and ended with clayey sand the last portion of 21m.

Another borehole that was drilled in 2009 by the CuveWaters team, for abstracting water for the desalination pilot plants is 50m deep (Skrypta, 2010). This borehole is about 430m from the previous borehole described, and it has brought out allot more silty material combined with the sand. The first depth of 8m has fine sand with silt, followed by a 14m profile exhibiting a combination of fine sand, silty and clayey material. The remaining bed of around 26meters has more silty clay and then sandy clayey silt. The above boreholes of 2009 databank, which are drilled in Amarika village in the Southern block of Olushandja sub-basin, have given Transmissivity (T) values ranging from 1.8 $*10^{-4}m^2/s$ to $3.6*10^{-5}m^2/s$, and Filtrations coefficients (K_f) from $1.0*10^{-6}m/s$ to $7.1*10^{-7}m/s$.

Table 1 is showing a tabular geological profile of Olushandja sub-basin. The boreholes were drilled in 1996 and the topographical levels along the surface are shown with the elevation depth in meters above mean sea-level. Along each borehole, the points where the water strikes were detected are also indicated. **Table 1** is further giving details of a top-down profile of sand-sandstones-calcrete-clay configuration. **Figure 8** is depicting the sites where the boreholes were drilled and are shown to be mainly in the central block of the Olushandja sub-basin.

Table 1: Olushandja sub-basin historical boreholes' profiles data (after InterConsult, 1996)

WW No.	Date	Elevation (m)	Depth (m)	Yield (m)	Strikes (m)	RWL (m)	TDS (ppm)	Lithologies drilled
35502	16-Sep-96	1149	150	>30	16-129	23.4	840	Sandstone, dolomite
35499	24-Jun-96	1136	57	<0.3	17,51	26.55	4100	Sand, sandstone, clay
35498	18-Jun-96	1129	41	<0.5	28	20.4	4000	Clay, sand, sandstone
35501	30-Jun-96	1128	204	>16	28-197	10.08	1400	Calcrete, sandstone, gravel, shale
35500	28-Jun-96	1124	42	4.5	21,28	10.85	1000	Calcrete, sandstone, clay
35495	03-Jun-96	1117	47.5	1	37	7.02	7600	Sand, sandstone
35496	10-Jun-96	1116	45	1.5	14,22	6.56	4000	Clay, calcrete, sandstone,
35503	16-Dec-96	1116	175	1	45-137	9	4500	Sandstone, conglomerate, basalt
35505	15-Oct-96	1114	91	1	20-76	5.15	4400	Sandstone
35506	10-Dec-96	1114	156	1	21-118	6.6	4100	Sandstone, basalt
35497	12-Jun-96	1110	51	5	22,25,36	6.7	3600	Clay-sand, clay, sandstone
35504	23-Sep-96	1109	150	11.4	9-129	4.8	6600	Sand, sandstone, calcrete
35507	10-Jun-96	1109	56	2	54	5.04	6700	Clays-sand, sandstone

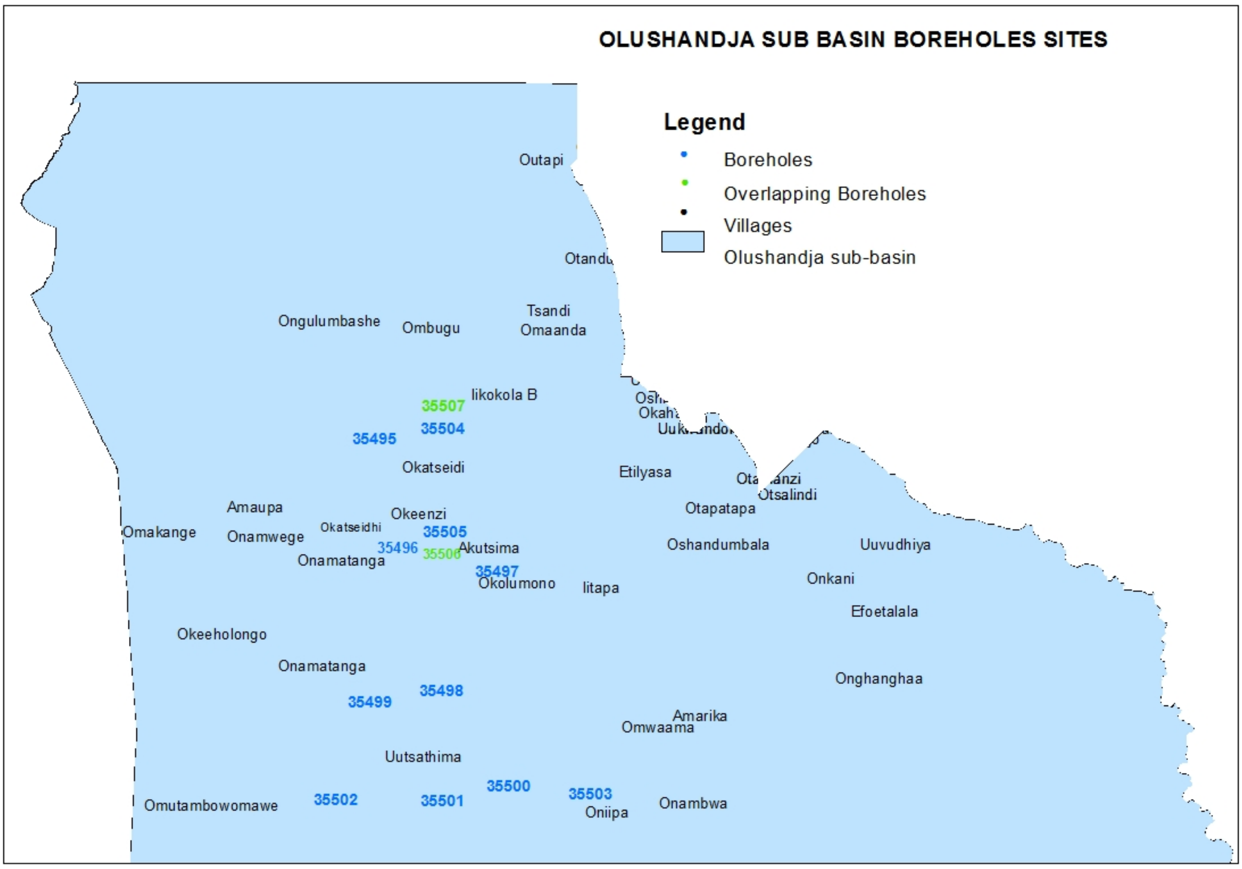

Figure 8: Profile boreholes sites in Olushandja sub-basin area (after InterConsult, 1996)

According to the best available data, Olushandja sub-basin consist of four distinctive aquifers, namely Oshana multi layered, Olushandja aquifer, Etosha limestone and Omusati multi zoned (Mendelsohn, 2000). Aquifers in the sub-basin are further described to be of the Kalahari and Damara sequence distribution, which is mainly unconsolidated sands, silts, gravel, dolomite and limestone (MAWRD, 1990).

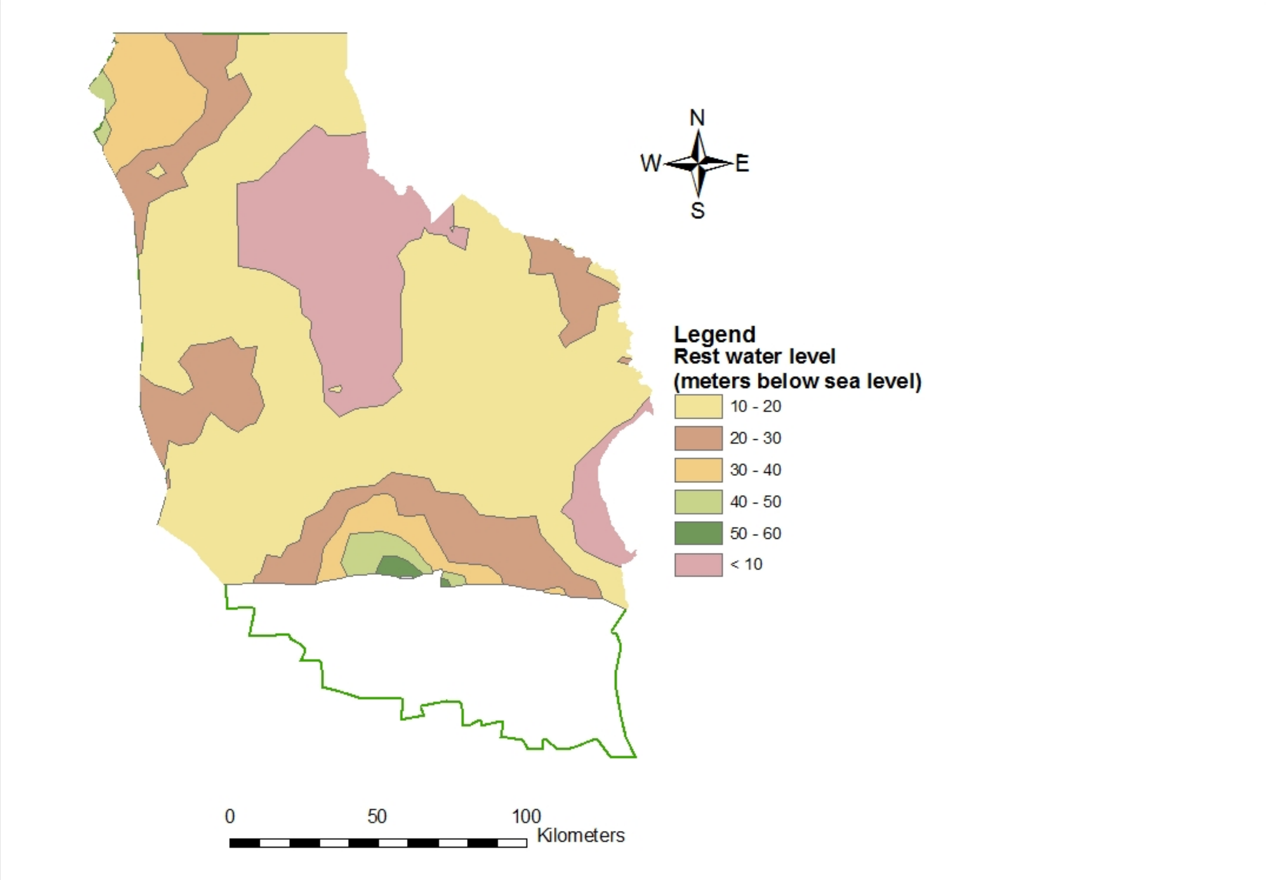

Figure 9: Potential groundwater yield of the sub-basin (after Bittner, 2006)

The groundwater capacity in Olushandja sub-basin is reported to have good yields, starting from $1m^3/h$ up to $30m^3/h$, with the higher yields being more in the eastern central part (Mendelsohn, 2000). The rest water level is from 10meters below the surface level and deeper as indicated in **Figure 9**.

The rest water levels are shallower after the recharges during the rainy season, providing lenses of fresh water during and for short period after the rainy season (Biwac, 2006). Whenever groundwater is pumped from an aquifer, there is always some modification of the natural flow in this aquifer. Some brackish water aquifers are density stratified and when water is pumped from the top portion of the aquifer, higher salinity groundwater propagates upwards increasing source water salinity over time (Domenico et al, 1990). The aquifers in the sub-basin are the Kalahari semi confined to unconfined and may have a common boundary with other aquifers of different water quality (Christelis et al, 2001).

The elevated topography in the eastern rim of the sub basin, characterized by the unconsolidated sandy soils direct the ground and surface water flows towards the western part, joining the ephemeral river features namely Ekuma and Oshigambo towards Etosha national park. The pans in the Etosha national park are identified as the lowest points in the CEB (Biwac, 2006).

2.6 Hydro-chemistry

The chemical quality of the groundwater is determined by the abundance of rainfall, the topography and the chemical composition of the geological formations through which the groundwater percolates before it accumulates in an aquifer (MAWRD, 1990).

In the Olushandja sub-surface, large gypsum deposits still exists as proof for the existence of the Proto-Etosha Lake. The gypsum is said to be responsible for the high sulphate concentration in the ground water of the aquifers which covers the Olushandja sub-basin making the water brackish. It is further stated that the thick evaporitic deposits believed to have remained in the geological profile are to date been dissolved by rainwater with each rainy season, resulting in the brine lake conditions of the sub-basin in the subsurface (Shanyengana, 2001).

According to the groundwater investigation by InterConsult-SRK, 1996, gypsum crystals were observed in the top 10-30m of formations drilled in the Olushandja sub-basin vicinity. **Figure 10** is depicting a chart that is illustrating the Lithologies in the sub-basin. Gypsum has a high solubility; hitherto groundwater in equilibrium with gypsum is expected to be brackish and very sulphate rich (InterConsult, 1998). It is further proven and stated by the Namibia Groundwater Consultancy in 1992, that boreholes that were collared at a higher elevation produced lower EC (electric conductivity) water in the region where Olushandja sub-basin is. EC readings are directly proportional to the presence of salinity or TDS (total dissolved solids) in the water (Gebel et al, 2008). According to table 2, salinity results range from 840ppm in BH 35502 at elevation 1149mamsl to 7600ppm in BH 35495 at elevation of 1117mamsl. BH 35503 which is at a lower elevation of 1116mamsl has 4500ppm. **Table 2** below is giving the salinity associated with elevation and water strikes level along the profile as drilled around 1996, in Olushandja sub-basin.

Table 2: Boreholes and TDS status in 1996 in Olushandja sub-basin

WW No.	Elevation (m)	Depth (m)	Strikes (m)	RWL (m)	(ppm)
35502	1149	150	16-129	23.4	840
35499	1136	57	17,51	26.55	4100
35498	1129	41	28	20.4	4000
35501	1128	204	28-197	10.08	1400
35500	1124	42	21,28	10.85	1000
35495	1117	47.5	37	7.02	7600
35496	1116	45	14,22	6.56	4000
35503	1116	175	45-137	9	4500
35505	1114	91	20-76	5.15	4400
35506	1114	156	21-118	6.6	4100
35497	1110	51	22,25,36	6.7	3600
35504	1109	150	9-129	4.8	6600
35507	1109	56	54	5.04	6700

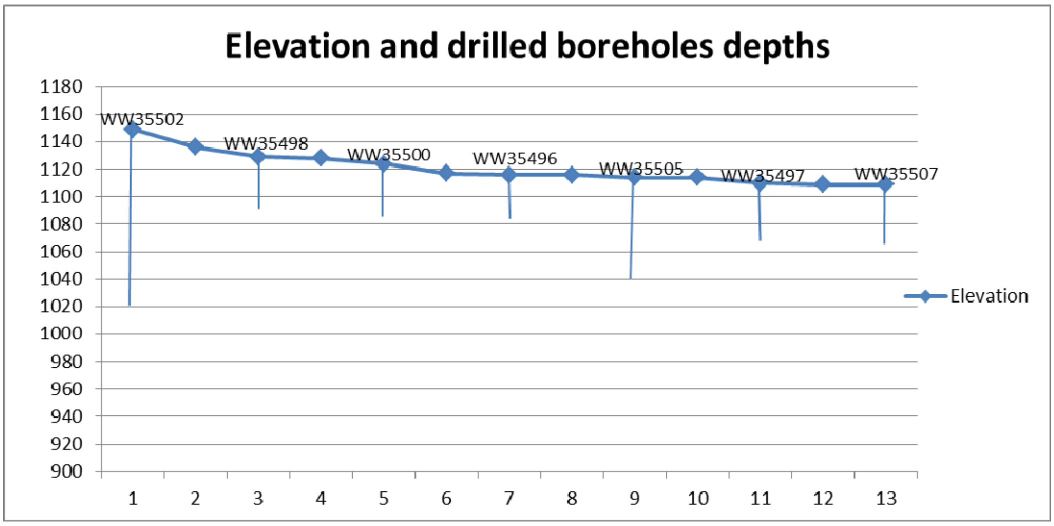

Figure 10: Boreholes and drilled boreholes depths (sourced from InterConsult, 1996)

Table 3 below is showing the raw water quality in two different areas of Olushandja sub-basin and over two different periods in one place (Amarika). The presence and severity of salinity in the Olushandja sub-basin in the two villages where the desalination pilot plants are currently running are depicted in the table.

Table 3: Source Water Laboratory Results

	Laboratory 1 (July 2008)IWAR	Laboratory 1 (May '08) IWAR	Laboratory 2 (July '10) proaqua	Units
Place/ Village	**Akutsima**	**Amarika**	**Amarika**	
pH		7.3	7.33	
Conductivity	4.96	40	32.5	mS/cm
Total TDS in ppm	**4 811**	**26 838**	**22 410**	**mg/l**
Sulphate	3190	8979	7970	mg/l
Chloride	217	7164	7501	mg/l
Fluoride	2.87	1.2	0.28	mg/l
Nitrate	120	7.1	54.60	mg/l
Total hardness		2001	107.4	mg/l
T-alkalinity ($CaCO_3$)		391		mg/l
Calcium	523	315	378	mg/l
Magnesium	400	295	330	mg/l
Sodium	309	7583	6068	mg/l
Potassium	49.2	75	82.5	mg/l

The laboratory tests are illustrating the abundant presence of the sulphate due to the gypsum, and the salts of sodium and chloride. In arid areas, its documented, gypsum occur like in a flowerlike form, coming in sizes of up to 11meters long and are among the largest crystals found in nature, in the form of selenite. The mineral has thick evaporite beds that are associated with sedimentary rocks. Gypsum in its origin is deposited into lakes and ocean water from volcanic vapors and sulfate solutions stream into veins. The hydrothermal anhydrite that ends up in ground veins is hydrated to gypsum by groundwater in near surface exposures (Price, 1998).

The change in period over Amarika results, are notable in the higher presence of nitrates that is also conspicuous in Akutsima data. Amarika and Akutsima villages are in the so-called rangeland district in the Olushandja sub-basin that was in earlier times not inhabited by humans and livestock. The increased presence of nitrates may indicate the increase of livestock in the area and human activities as reported by Klinternberg, 2007. Organic nitrates traces are normally higher in livestock and are derived from high consumption of plants that take up elemental nitrogen (Kiely, 1997). Hydrogen carbonate and sulphate-chloride water is generated due to the slow washing out of the salt. This is chloride, sodium and calcium water with high mineral content (Gebel et al, 2008). The pH readings for brackish water ranges from 7.3 to 7.7 (Gabelich et al, 2002). This scenario is similar to Olushandja sub-basin brackish condition.

The salinity of the villages in Olushandja sub-basin ranges from above 5,000ppm to more than 90,000ppm as given in **Table 4** below. The three villages are 30 to 40kilometers apart in the Southern stretch of the sub-basin. The water strike in the villages were at 50meters and deeper down the subsurface. The salinity in Amarika is expectedly higher at deeper levels, drilled at two different periods. The three boreholes at 150meters, 90meters and 126 meters were specifically drilled for re-infiltration purposes of the desalination pilot plants of the CuveWaters project in the vicinity.

Table 4: Salinity in various villages in Olushandja sub-basin

Area	Period	Depth [m]	Salinity [mg/l] TDS	Conductivity [µS/cm]
Oponono	Oct-07	50	95,863	179,100
Uuvudhiya	Oct-07	50	67,025	122,800
Amarika WW200231	Oct-07	50	26,939	44,700
Amarika WW200232	Oct-07	20	Dry	Dry
Amarika	Jul-09	150	38,542	62,200
Amarika	Jul-09	126	33,128	53,300
Amarika	Jul-09	90	28,993	45,800
Akutsima	Aug-08	40	Dry	Dry
Akutsima Ehamalyondjaba	Aug-08	50	5,365	9,325

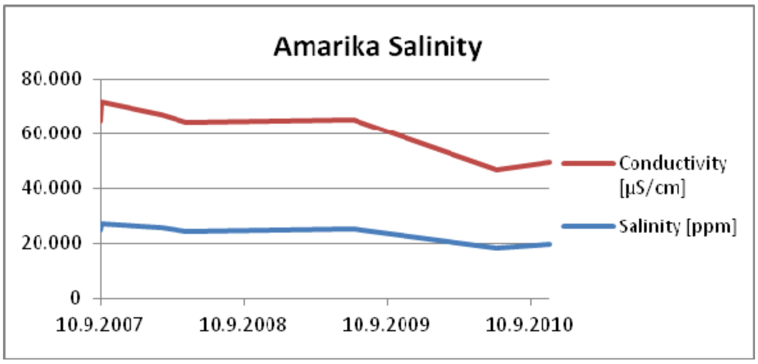

Figure 11: Groundwater salinity in Amarika

The salinity in Amarika (**Figure 11**) is indicating to have come down between year 2007 and 2010, according to the laboratory results. This pattern could be attributed to groundwater replenishment by the good rains in the last 4 to 5 years in the larger Cuvelai-Etosha basin.

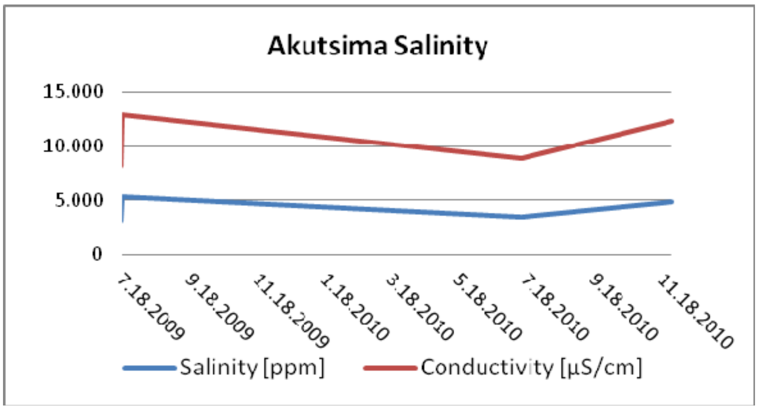

Figure 12: Groundwater salinity in Akutsima

The trend is also observed in Akutsima village in Olushandja sub-basin (**Figure 12**), until middle of the year 2010. Akutsima is about 40 km away from Amarika village. Akutsima salinity drastically increased before the end of the year 2010. This phenomenon is observed and still under monitoring with CuveWaters project activities. Akutsima is not subjected to any activities of potential contamination. The salinity rise may be due to lithological activities or instrument measurement recurrent error.

Among other requirements, determinants for selecting an appropriate desalination method require temperature and specific pH value of the water environment in order to derive the solubility context of the elements involved (Bachman et al, 1995). The highest percentage in the solubility equilibrium from the source water data came out to be calcium sulphate ($CaSO_4$) (Hydranautics, 2008). This confirms the presence of gypsum as the major cause of brackishness of Olushandja sub-basin.

2.7 Energy options available in Olushandja sub-basin

The social and environmental conditions in Olushandja sub-basin may be rural and are characteristic of barren open surface land where to date no substantial productive activities are happening, but it is among the world identified areas where the higher to highest figures of sun radiation heats the planet (MME, 2006).

In this section, the potential energy opportunities mainly in solar and wind will be described and the prevalent conditions socially and technically that need to be met for successful implementation of desalination technology in Olushandja sub-basin will be presented as well.

The following map is showing that Olushandja sub-basin is having the potential to generate 5-6kWh/m^2/d from a world view. It is further stated that Namibia has more than 300 days of sunshine and 9-10 hours of sunshine per day (MME, 2006).

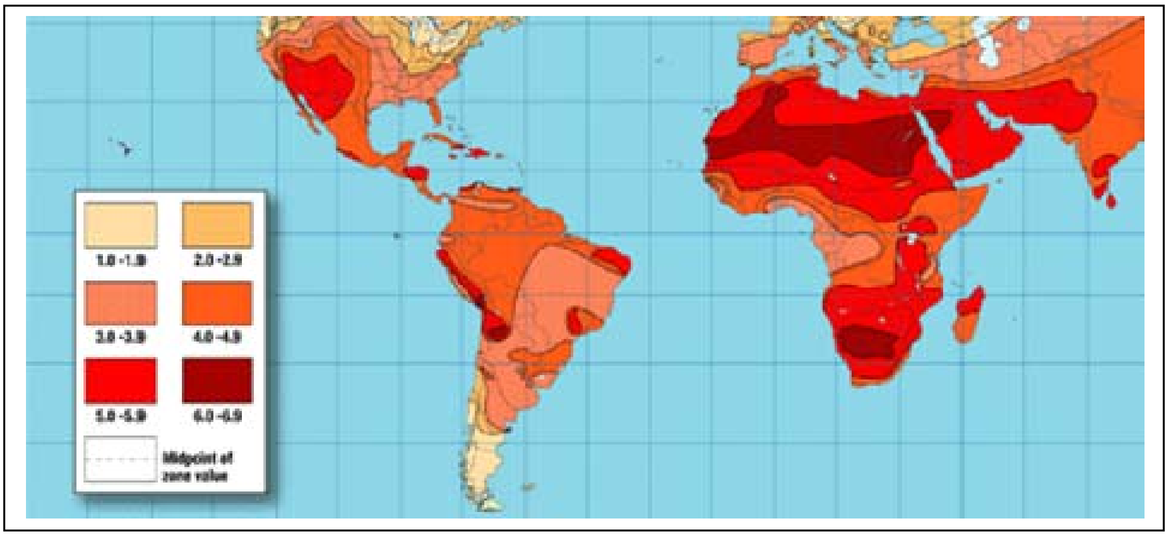

Figure 13: World solar radiation (after www.matthewb.id.au)

Namibia is among the regions with the darkest spots that are illustrated as the areas with the world highest solar radiation. The legend colors range from 1 – 1.9 kW/m^2.day in the lightest color indicator, second 2 – 2.9, third 3 – 3.9, fourth 4.0 – 4.9, fifth 5.0 – 5.9 and number 6 is 6.0 – 6.9 kWh/m^2.day in the darkest color area. This observation is an affirmation of the areas with the arid to semi-arid climatic classification of the BSh.

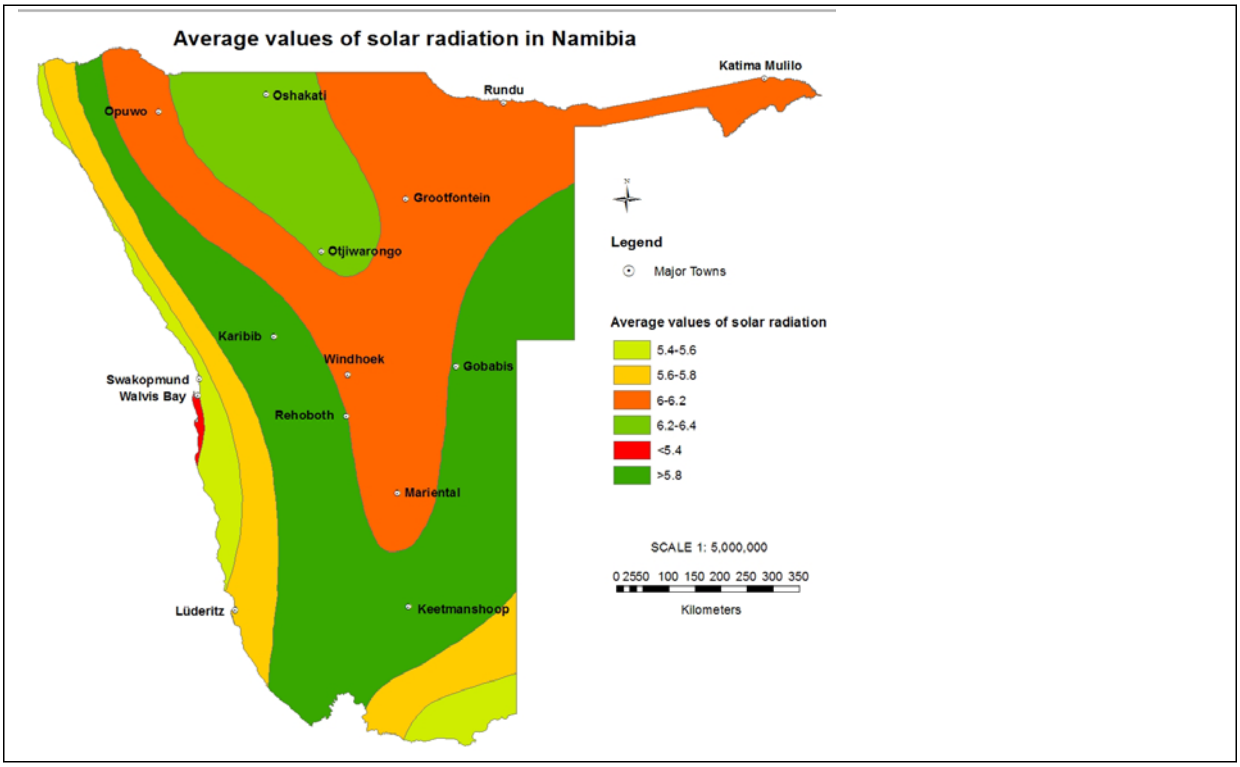

Figure 14: Namibia Solar radiation map (sourced from MME, 2006)

The highest solar radiation in Namibia is in the North-central block covering most of the Olushandja sub-basin. According to this study by Acacia project done at the University of Cologne in Germany conducted through the ministry of mines and energy (MME) in Namibia, the area within Olushandja sub-basin has the potential of generating from 5 to greater than 6.2kWh/(m^2.day).

Figure 15 temperature variations are between 5 and 39°C as shown in the chart below. October to April is the summer season in Namibia and temperature start increasing from October and is highest between November and February.

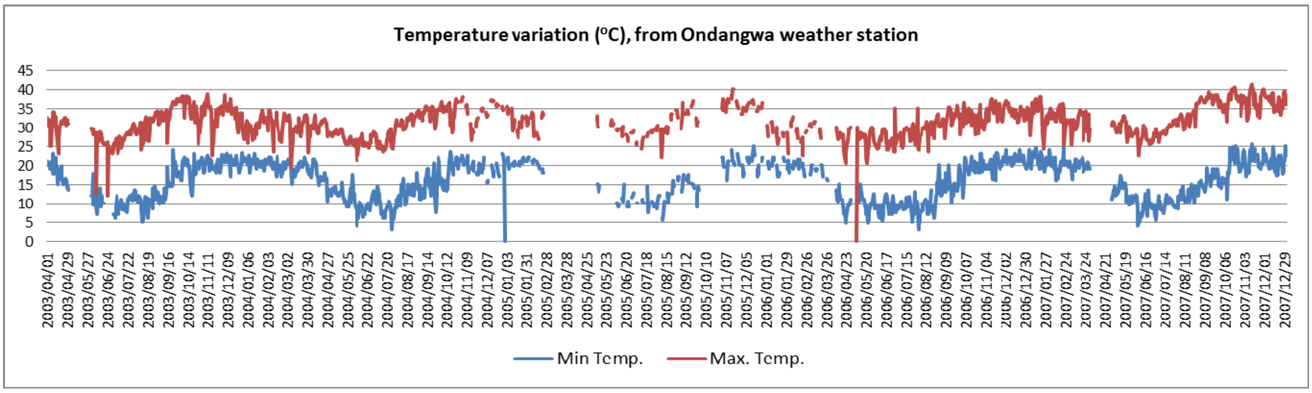

Figure 15: Temperature Variation in Northern Namibia (NMS, 2008)

It is further recorded that the wind conditions in Namibia are on average 5-6m/s along the coastal areas. Due to the relatively flat plain topography, Olushandja sub-basin experiences cross winds of 4-5m/s influenced by its proximity to the northwestern region of the country (MME, 1998).

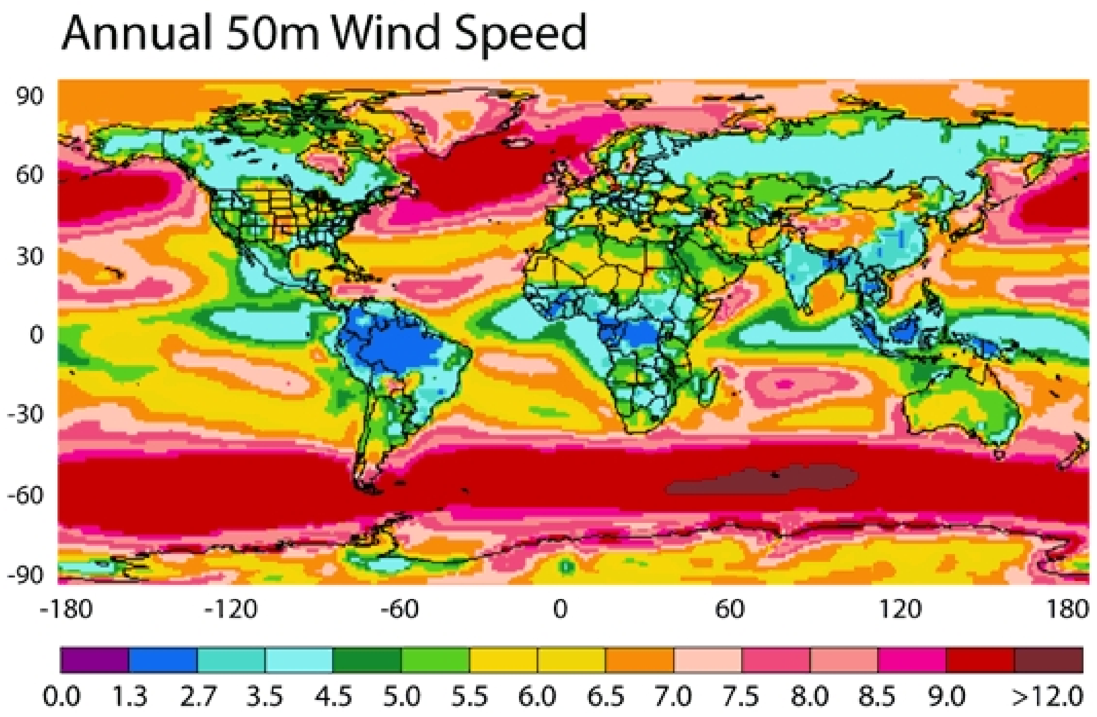

Figure 16: World Wind speed Map (after TNC Energy, 2012)

Such wind speed could generate wind energy in the order of 4kWh/day depending on the climatic conditions. Wind energy is a form of kinetic energy (*KE*) calculated from the formula $KE=\frac{1}{2}MU^2$, M for mass flow and U for wind speed. The mass of air moving through a windmill in a unit time can be calculated as $M=\rho AU$ with A being the area swept by the windmill rotor and ρ the density (Liu et al, 2009).

Olushandja sub-basin conventional energy is currently not available to the rural villages in the southern block of the sub-basin. Besides this, the sub-basin is more than 800km to the western coastline and more than 500km to the northwestern coastal area. The supply of wave energy may be possible but may not be feasible as it is far and out of reach compared to solar and wind. Nevertheless, Ocean Waves represent renewable energy created by wind currents passing over open water. Ocean wave energy is captured directly from surface waves or from pressure fluctuations below the surface. Wave energy devises are classified according to the distance of installation from the shore, and they are: Shoreline devices, Near-shore and Offshore devices. The use of wave energy for desalination is mainly realized via power generation using pump turbine systems, where power can be continuously produced using alternators. One such Wave/RO coupling was commissioned in India in 2004. The plant has a capacity of 10m^3/d, and is treating sea water salinity of 35,000ppm, reducing the TDS to 500ppm (Tzen, 2009).

Another energy source is geothermal that is applied mostly on thermal processes desalination operations. This energy source comes from the natural generation of heat, primarily due to magma, as well as the decay of the naturally occurring radioactive isotopes of uranium, thorium and potassium in the earth. On average the temperature of the earth increases about 30^{o}C/km of depth. At 10km the temp would be at 300^{o}C (Goosen, et al, 2010). The geothermal energy is drawn from a hot fluid from underground and passed to the surface through a heat exchanger. This enthalpy potential can be onshore below sea level or offshore below surface level.

Geothermal wells deeper then 100m can be used to power desalination plants. This energy source is said to be suitable for thermal processes and has been used for the process of MED (Chaibi et al, 2009).

The energy sources available in Olushandja sub basin will be assessed in conjunction with the other social and environmental criteria that will be described next.

2.8 Conditions and Criteria for desalination in Olushandja

2.8.1 Conditions for desalination in Olushandja sub-basin

In order to select and implement a sustainable water supply option to the people of Olushandja sub-basin, the following criteria ought to be kept in the loop of all activities, starting with the planning stages to implementation level.

Table 5: Prevailing conditions for desalination in Olushandja sub-basin

Conditions	Guiding strategic statement
	Technical
Raw water Availability	The water from the source should be sufficient for un-interrupted operation of the technology and for continuation of use from hand dug wells. Cost of water is a financial burden for use in rural settings. Option for livestock use from the tradition wells will always be pursued by the locals. Provision for both options will avoid conflict over technology and cost of obtaining water.
Feed water quality	Unlike the typical range of brackish water of 3,000 to 10,000ppm, the range of Olushandja sub-basin is 4,000 to 38,000ppm, with isolated test cases of 50,000 and 95,000ppm. The technology to be selected should either be insensitive to feed water quality or robust enough to handle the sub-basin source quality.
Energy availability or options	The villages are remotely situated from formal service networks. Grid supply is not an option currently. However, the area has temperature conditions of 20 to 39oC during winter to summer daytime conditions. Solar energy is therefore first and foremost available in abundance. According to current projects calculation there is potential energy of around 5.5kWh/m^2.d available under the given temperature conditions.

	The wind speed is 4-6m/s.
Technology simplicity for operation	The larger group of the population is semi-illiterate to illiterate and local manpower will be needed. The technology should be simple to learn and can be operated by local caretakers to minimize cost of operation by skilled laborers from outside. Simple to operate will minimize mal-operations and malfunctioning of technology in the long run.
Availability of spare parts of selected technology	Any breakdown that causes water supply interruption should not exceed 48 hours, and should be curbed with available reserve until repair. Therefore imported technology spare parts should be stocked with the relevant agencies in the country. The reservoirs should be able to curb the breakdown period.
Environmental	
Consumption Demand	The water should meet the minimum requirement of 20liters per person per day, according to WHO (world health organization) guidelines. A village in Olushandja sub-basin has an average population of 750 people.
Product water quality	The primary goal is to improve health and hygiene of the rural people of the sub-basin. The product quality should at least meet the B if not A-class rating of drinking water guidelines of Namibia.
Sustainability versus environmental conditions	The Olushandja sub-basin is characterized by geographical features called Iishana. These inundating open field areas that accumulate flooding water during the rainy season, divide people from essential service centers, as schools, clinics and shops. Establishment of the technology should ensure minimal damage and optimal access by the consumers.
Land Use	The people in the rural areas of the sub-basin are dependent on land for field ploughing during the rainy season and for livestock farming. Their subsistence constitutes mainly their staple food crops pearl millet and spinach, chicken and meat. Demarcation and withdrawal of land for producing clean water against their traditional farming activities should be weighed in with care and explained thoughtfully to the community members to avoid conflict of interest. The vitality of clean water as a basic necessity for human life and as a nutritional and hygienic element in the equation should be emphasized.
Energy Use	The provision of energy for the desalination technology should where possible be planned with the inclusion of local use by the village people. It will be an opportunity for once off investment that may be a positive return on the economy of scale.
Social	
Accessibility to clean water	The water supply will not be connected to the houses and should be in a walking distance of 0.5 to 1.0 kilometers, as per Government Directive in the Department of Rural Water Supply guidelines.
Gender Participation	Water supply infrastructure can only be managed effectively and efficiently when both men and women are involved from the planning stages to implementation and operation, according to UN GWA (United Nations Gender and Water Alliances) guidelines. Typically women in the villages use the water most and they therefore need to be involved.
Control and	A local water point committee that is selected by the community

ownership	members should run the regulation of controlling and supplying water. This will minimize conflict with traditional activities related to ploughing and trading in the rural areas. This is the existing practice and arrangement between the government regional authority and local communities.
Cultural activities	Supply points in rural settings are social meeting points for networking, bonding for women and playing for children. The technology should provide for a terrain that do not cause harm or restrict these activities.
Affordability	The cost of desalinating brackish water using renewable energy is high compared to conventional supply systems it is reported in most literature. The pragmatic approach for desalinating in this case is to save lives and improve conditions for the rural people of Olushandja sub-basin and to do it on a sustainable and environmentally appropriate way. Cost should therefore be preceded by social and moral responsibility towards life and the conditions of remoteness and absence of other options. Water subsidization maybe need in this case.
Training	It will be cheaper for the technology and for long-term cost of water in the village if local manpower is utilized. Some intensive training will be required for the identified candidates to run the technology. This is going to be a new technology for the region and more so a new exposure to the rural community who have limited access to education and is therefore predominantly semi-illiterate to illiterate.

The table outlines the conditions of Olushandja sub-basin and the expectations and needs of the people living there. The suitable desalination technology has to meet the set out criteria.

2.8.2 Criteria for desalination technology planning

In order to select a suitable desalination technology, there are criteria that need to be considered for environmental and financial purposes. The commonly and critically considered issues are the following:

- **Location**

The primary factors to be considered for planning a desalination plant location, is that there should be; a reliable source of feed water supply, a consistent source of energy supply and predictable water quality type for appropriate designing of a desalination technology. These factors are considered in conjunction with the environmental factors, the concentrate disposal and other site restrictions (associated with regulations and environmental constraints), resulting from the desalination technology selection.

- **Intake wells**

For brackish water aquifers, vertical wells and radial collector wells are used because their productivity is relatively small and are less costly. The subsurface intake wells pre-treat the water collected via slow sand filtration in the area of source water extraction.

- **Anaerobic aquifers**

Anaerobic aquifers have a unique environmental condition of water discoloration, taste and odor issues in the water. These are wells that contain hydrogen sulfide. During abstraction, the conveyance systems should remain pressurized to prevent formation of elemental sulfur, and after desalination product water must be degasified to prevent taste and odor problems. Discoloration occurs when the reduced iron and manganese salts from the anaerobic wells are exposed to oxygen, causing a dark color to the source and product water.

- **Feed water volume requirements**

The feed water volume requirements for inland brackish water desalination have to be at least 25% more than the production volume for reverse osmosis processes. The distillation processes require more than ten times the production volume, because of the cooling water requirements.

- **Feed water characteristics**

Feed water characteristics should be relatively constant and not subject to rapid and dramatic fluctuations, to have a desalination processing plant that is efficient and predictable. Therefore, seasonal and diurnal fluctuations which include, water temperature, total dissolved solids (TDS), total suspended solids (TSS), membrane scaling compounds (calcium, silica, magnesium, barium) and total organic carbon (TOC) should be reviewed and mitigated to minimize impact on plant operation and process performance.

Subsurface geologic conditions determine to a great extend the quantity and quality of the raw water. Confined and semi-confined aquifers yield the most suitable source of water for brackish water desalination systems (Messimer, 1999).

- **Distribution**

Distribution to water supply networks is one of the key factors in the selection of a desalination plant site and the cost associated with water conveying networks to consumers' points. For small size plants pumping to local service networks would be preferable and adequate.

- **Energy Availability**

The cost of energy is a major factor in determining the cost of water for the desalination process. The choice of the source should therefore be based primarily on the economics.

- **Economics**

Desalination of previously unusable or unused water may stimulate particular sectors of the economy, in terms of new equipment acquisition, employment, interest for other economic activities related to water.

- **Environmental assessment**

Projects in any form normally have effects both positive and negative on the environment during construction and operation. Desalination, as a technology and a project will have impacts socially and economically on the people and the environment of Olushandja sub-basin.

The scale of the desalination plant and the source quality are important factors that determine the type of waste and other pollution as noise that can be generated from a desalination project.

The major factors considered in the environmental impacts assessment (EIA) of desalination projects are siting considerations, coastal zone/marine protection regarding withdrawal and discharge, air pollution from energy production and consumption, groundwater protection from drying beds, leachates, and sludge disposal (Latteman et al, 2008).

An EIA is a procedure that identifies, describes, evaluates and develops means of mitigating potential impacts of proposed activities on the environment. The main objective is to promote environmentally sound and sustainable development through the identification of appropriate mitigation measures and alternatives (NRC, 2001). For smaller projects, a simplified EIA may be warranted due to the limited potential of the project to cause significant environmental impacts. One of the most relevant plans to address desalination projects along with other water supply alternatives is integrated land and water resources management (IWRM) plan (WHO/SDE/WSH/07).

An ILWRM is a process of making sustainable use and management of land and the water resources, ensuring that stakeholders are involved to achieve social equity and economic efficiency. It is a systematic process that engages sustainable development, allocation and monitoring of land use and water resources in the context of social, economic and environmental objectives (Namibia IWRM, 2008).

The ILWRM plan is perceived to be more comprehensive and engages all stakeholders from policy administrator to contractual implementers, while addressing all elements and areas of a system or society (Helmholtz, 2009). However, it is a new concept compared to the longer existing practice of EIA.

An EIA should predict the impacts related directly or indirectly to the implementation of the project. This requires an interdisciplinary approach covering relevant issues relating to potential impacts to people and communities (Younos, 2005). Hence the public participation is considered a fundamental element of an EIA, in order to involve the public in the evaluation of potential impacts and in decision making.

Desalination projects are typically driven by the limited availability of alternative lower cost water supply resources such as ground water or fresh surface water (rivers, lakes, and so on). Implementation of desalination projects can consume considerable community resources, as economic and social capital, land and energy that could otherwise also benefit them in a different way. It should therefore be regarded as a community asset and a valuable resource from which opportunities for multiple-use should be sought (WHO/SDE/WSH/07).

The groundwater source available for the desalination abstraction has potential yield of 3 to $10m^3$ per hour (Skrypta, 2010), while an average village in Olushandja sub-basin needs $16m^3$ per day. The source supply will therefore be environmentally sufficient to cover for the technology and for the village people alternative needs.

- **Social assessment**

The social aspects for the desalination option in Olushandja sub-basin are about having clean water that is accessible and done so in a safe manner. The water infrastructure should meet the demand and supply should be managed by the local people. The Namibian Government directive, through the Regional Management of Rural Water Supply offices, states that the water supply points being established for use by the rural communities should not be more than 500meters from homesteads.

The Gender and Water Alliance (GWA) of UNICEF (United Nations Children Fund) has stated the importance of mainstreaming gender in water management in all water sectors. Through this alliance, the WASH (water sanitation and hygiene) project was established and a number of issues were investigated regarding women, water, hygiene and gender based water management issues. This evidence report project was undertaken on 122 water projects around the world (WASH, 2010).

In this evidence report it is presented that the role of both gender groups are very important in having successful water projects for rural communities. It is further illustrated how water has improved allot of conditions for mainly women and girls in the rural set-ups, regarding hygiene and self-esteem. The WASH project has in addition emphasized the role of traditional and cultural living patterns where women are most involved with water related activities in the households and therefore have better insight and understanding of water sources and know the value for water availability. It was simultaneously also found that the effectiveness of a project was six to seven times higher where women were involved than where they were not.

The results of involving women in the design and planning stages are multiple, from reducing corruption, increasing management transparency, better financial management and empowering women. Women bear the main responsibility for keeping their households supplied with water, caring for the sick, maintaining a hygienic domestic environment and bringing up healthy children. It is they who are most likely to know what is required and where. Getting these important details right means better services and quality of life for all in the community.
According to the UN Interagency Task Force on Gender and Water, women have been found to be the most effective managers in several UN water projects in Africa, where water has been used for income generation and where women have control over income earned from their small scale enterprises. Women’s cooperatives connected to water points in Mauritania, for example, have become very dynamic and women take a more active and prominent role through capacity building and provision of credit. A key component of any WASH project is to raise awareness about the importance of carrying out safe hygienic practices. Women play a vital role in awareness raising about these issues, as they take the main responsibility for domestic duties and for developing safe and hygienic habits in children.

Olushandja sub-basin is a rural set up with a gender and age mixed population. The preliminary workshops by CuveWaters project have seen more women than men participating in the village meetings. However participations to invitations for workshops in the urban centers are normally dominated by more men than women. This discrepancy will have to be assessed when responsibilities for managing the infrastructure are to be allocated, so that capacity building is given to the appropriate and capable people in the village, as per above experience from projects around the world.

- **Institutional assessment**

The standing procedure in the Regional authorities of Namibia is that, the Directorate of Rural Water supply manages the water supply and control water projects implemented by the government in their regions. Therefore establishment of water infrastructure in the rural villages that are not privately installed resort under the Regional Directorate of the Namibia Government.

Through act of parliament, the Namibia Water Corporation, a state owned parastatal run the water industry for the Government and manages most of the water supply to local and regional authorities. The Regional Directorates of Rural water supply manages all water supplies to rural communities around the country. The needs for clean water in Olushandja sub-basin are in the parts that are still rural, and there are no functional proclaimed local authorities. In such areas, the traditional headman is normally the administrative body whose permission is sought for any activity on the land that he is responsible for.

The regional directorate through the traditional headman seeks the participation of the community members to elect a committee that is responsible for water supply in the village. This committee appoints a secretary and a chairman that sees to it that money is collected for the water used by all households. The regional management team of the government in most cases remains responsible for the maintenance of the infrastructure. The appointed chairperson liaises with the regional office for assistance, breakdowns or conflicts around water supply in the village. The committee decides on the daily operational matters of the supply point. The water supply point is normally opened certain times during the day where people go and fetch water for their domestic needs and there are times when the cattle troughs are filled for the livestock to be taken by the herdsmen for drinking. The homesteads with allot of livestock pays more, according to the sizes of the livestock and the quantity. The cattle drink more water than the goats, sheep and chickens. This disparity in the payment structure typically brings conflict over the water supply among the rural communities.

Chapter 3: Desalination Technology

Processes Overview

In this chapter the criteria for selecting the suitable desalination techniques for the technical, environmental and economic conditions of Olushandja sub-basin are described. It is followed by a description of the selected desalination techniques, in terms of the process engaged, the pretreatment needs, the maintenance and operations activities undertaken and then the advantages and disadvantages of the techniques are summarized. At the end of the described techniques, exemplary schemes implemented or piloted around the world that are within the given desalination technique selection criteria are described briefly, according to available published data and information.

The desalination impacts, maintenance undertakings and pretreatment needs for membrane techniques, which are RO and ED processes, are described at the end membrane technology descriptions. Similarly, the impacts of desalination, maintenance needs and pretreatment requirements for thermal processes are outlined at the end of the thermal techniques and not repeated under each thermal process.

3.1 Selection of the suitable desalination techniques

Desalination technology and processes are employed when water TDS is above the required level that it is needed for, to remove excess salts. The required level can be for either human use, for livestock, for irrigation or other specified salt level tolerant use. According to the World Health Organization (WHO) drinking water guidelines, water is unfit for human consumption when it has a TDS of 500ppm or more (Hespanhol, 1994).

Water is brackish when it has a TDS range of 3,000 – 10,000ppm and it is categorized as having high salinity when it is above 10,000ppm. The sea water has an average salinity of 35 000ppm, with a minimum of 10 000ppm for the Baltic Sea and a maximum of 45 000ppm in the Arabian Gulf (Cipollina et al, 2009).

The water of Olushandja sub-basin has TDS ranging from an excess of 5,000ppm to more than 90,000ppm (as **referenced in Table 4 on page 19).** This water needs to be desalinated, as it is mainly contaminated with sulphate, chloride and sodium salty elements. The other elements are magnesium, potassium and calcium, which cause hardness of the water. The desalination technology in general accounts for elemental sciences and their reactions and interaction with the infrastructure (OTA, 1988). One major role of elemental sciences in desalination lies at the point of solutes-liquid separation. Rejection of solutes by RO membranes for instance depends in a complex fashion on the chemistry of the solute-membrane interactions. According to the lyotropic rule, ions of higher valency tend to be rejected more than are ions of lower valency (Mallevialle et al, 1996). Hitherto, the lyotropic series predicts that the rejection of cations by RO membranes obey the following order: Mg> Ca> Sr> Ba> Ra> Li> Na> K and anion rejection occurs in the following order: SO_4^{2-} > Cl^- > Br^- > NO^{3-} > I^- .

The following table (**Table 6**) indicates the contamination level of Olushandja sub-basin groundwater and the referral quality level required for excellent water quality for human consumption, according to water guidelines of Namibia water utility company (NamWater). For the contaminants level, the table is depicting results of water sampled at Amarika village in July 2010.

Table 6: Contamination and Potable Levels

	Element contamination level (ppm)	**Excellent A Level quality, required for human use (ppm)**
Sulphate	7,970	200
Chloride	7,501	250
Sodium	6,068	100
Magnesium	330	70
Calcium	378	150

The saline elements fall in the discipline of inorganic chemistry. The saline elements are normally bonded as inorganic compounds that in nature are referred to as minerals. One such inorganic compound is calcium sulfate that is found in soil as gypsum. Soil may also contain other inorganic compounds as iron sulfide that is referred to as pyrite and Epsom salts (Kiely, 1997). In the case of Olushandja sub-basin, the presence of high sulfate and calcium confirm the presence of gypsum in the soil as a naturally occurring mineral. There are no industrial activities or suspicious potential pollution points that can suggest otherwise.

According to ProDes (promotion of renewable energy for water desalination databank, www.prodes-project.org) and other sources, there are over (but not limited to) 60 small scale schemes of capacity ranging from 50 liters to 100m^3 per day around the world that are specifically treating brackish and autonomous source water quality and are exclusively using renewable energy for desalination processes. However, the list indicate that the reverse osmosis technique is implemented more numerously then the other techniques over the last three decades at small scale. Implementation of the other techniques under the above boundaries have mostly occurred from the beginning of year 2000 after some years of research and testing.

The following table lists a number of techniques that are either tested or implemented for piloting in various parts of the world and are within the selected boundary scale range of 10 to 100m^3/d.

Table 7: Desalination Technologies of less than 100m^3 implemented using Renewable energy

Desalination Technology	Energy Source	Number of plants implemented or piloted (ProDes, 2010)
Multi Stage Flashing (MSF)	Solar Pond, Solar Collectors	2
Multi Effect Distillation (MED)	Solar Energy	3
Multi Effect Humidification (MEH)	Solar Thermal Collectors (solar flat plate and solar evacuated tube collector	8
Membrane Distillation (MD)	Corrosion-free solar thermal collectors, Photovoltaic	5
Reverse Osmosis (RO)	Photovoltaics, Wind Mill, Solar Energy	35
Electro Dialysis (ED)	Photovoltaic	3

Before a suitable desalination technology can be selected on the basis of the requirements and conditions of Olushandja sub basin, the given boundary conditions, and the limits and applicability of the various desalination processes, the various technologies modes of operation will be described, the pretreatment required, and issues of operations and maintenance. The advantages and disadvantages of using the various techniques are pointed out. A summarized overview of an exemplary plant piloted or implemented using the particular technique will also be given.

3.2 Desalination Techniques

3.2.1 Processes Overview

Desalination is factually the process or technique of removing saline and hard elements from water. Through this process, the salt-free permeate or stream is separated from the sea or brackish water, leaving the concentrated salts in a rejected brine stream. The desalination methods can either be based on thermal or membrane techniques (Gebel, 2008). The processes under the thermal category are said to employ phase change, whereas the membrane process of reverse osmosis utilizes the differential osmotic pressure as a one phase process. The ED uses electric field influence for ions attraction through anionic and cationic membrane stacks. The operating principle of phase change processes entails reusing the latent heat of evaporation to preheat the feed water while at the same time condensing steam to produce fresh water, while the principle of membrane processes are driven mechanically (Kalogirou, 2005).

To separate the desalination principle, from the technology behind the process, Ettourney defined the technology as “the art of devising units that constitute the processes that desalinate brackish or saline water, depending on its source, quality and characteristics” (Ettourney, 1996).

The thermal techniques which are referred to as phase-change processes, from the above list in **Table 7** are:

- ✓ Multi Stage Distillation (MSF)
- ✓ Multiple Effects Distillation (MED)
- ✓ Multi Effect humidification (MEH)

The following lists of techniques are also thermal processes used for desalting water but will not be considered in this study, as they are not among the schemes that meet the selection criteria required for Olushandja sub-basin conditions.

- ✓ Vapor Compression (VC)
- ✓ Freeze Distillation
- ✓ Solar Distillation
- ✓ Humidification/Dehumidification

The vapor compression technique can be used as thermal vapor compression or mechanical vapor compression. These processes are reported to be suitable for small scale application due to limitation for large size vapor compressors (Eltawil et al, 2009). However no publications of plants having less than 100m^3 capacities and using renewable energy were found for these VC techniques.

The techniques of freezing and humidification/dehumidification in the available literature are indicated not to be industrially matured, as they exhibited technical problems during their testing and implementation phases (Kalogirou, 2005). They were therefore not among the successfully implemented or piloted techniques to be considered for this study. However, the humidification/ Dehumidification concept is the main principle behind the MEH technique to be discussed later under the thermal processes.

The solar distillation process, have the Watercone technology on the market. The Watercone is reported to be implemented in India and other parts of the world. However, the Watercone only has capacity of 3-5liters per square meter (m^2), making it more suitable for domestic and individual acquisition. Olushandja sub-basin village clusters have up-to 700 people per village. The use of a Watercone, with a requirement of minimum 20liters per person per day, would need a huge land area for implementation. The Watercone will therefore not be considered for the need of Olushandja sub-basin.

The membrane techniques that are also commonly referred to as one phase processes are subdivided into:

- ✓ Reverse Osmosis (RO)
- ✓ Electro-dialysis (ED)

Covering both thermal and membrane process simultaneously is:

- ✓ Membrane Distillation(MD)

Apart from being in two classifications of thermal and membrane processes, the techniques are further categorized according to the type of energy used by the process for desalination. The energy types are: Mechanical, Thermal and Electrical.

- MVC and RO use mechanical energy,
- Electro Dialysis uses electrical energy,
- Freezing uses thermal energy through the process of heat removal,
- Solar distillation uses thermal energy for heat addition, but solar energy exclusively,
- MED, MSF, MEH, Humid/Dehumidification, TVC and MD use thermal, for heat addition through steaming.

The principle modes of operation of the six selected desalination techniques will be described further in the following sections.

3.2.2 Multi Stage Flash (MSF)

3.2.2.1 Process Description

A multi stage flash process is made up of a series of elements called stages. The stages are evacuated chambers, each fitted with distillate trays that collect the product water. These stages are arranged in series, also referred to as vessels or elements. In these vessels, the inlet water is preheated by the condensing steam from the distillate tray before the temperature is raised to saturation at a maximum system pressure through heat exchange with the solar collectors. The water then enters the first stage through an orifice where the pressure is reduced. When pressure is reduced the water becomes superheated and flashes into steam. The vapor produced passes through the demister (wire mesh) to remove any entrained brine droplets, and then condense from the cold feed water tubes, dripping into the distillate tray.

The vapor steam generated by flashing is converted to fresh water by being condensed on the tubes that run through each stage. The process is repeated stage by stage at successively decreasing pressures. Condensation of vapor is accomplished by regenerative heating of the feed water (Prakash et al, 2009). The principle of operation of a solar energy fed MSF plant is shown in the following diagram (**Figure 17**).

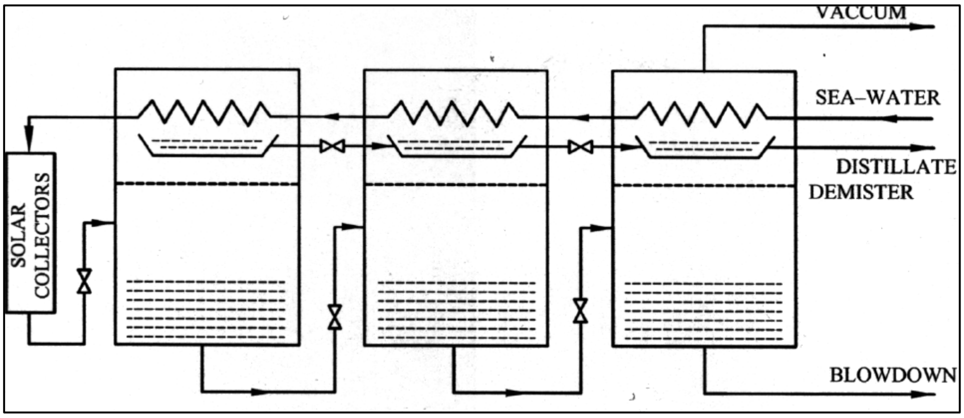

Figure 17: Multistage Flash Flow diagram (sourced from Kalogirou, 2005)

Stages are normally between 10 and 30 commercially, with temperature drop of 2^{o}C per stage. The minimum temperature drop has to exceed the boiling point elevation for flashing to occur at an infinite rate (Kalogirou, 2005). The plants normally operate at temperatures of 90 to 110^{o}C.

3.2.2.2 Advantages, disadvantages and MSF operationalized scheme

Advantages of the MSF process

- ✓ The MSF system has been longer in use and is perceived to be more stable and reliable.
- ✓ The plant can handle larger capacities compared to other systems.
- ✓ The plant can handle higher levels of biological or suspended matter without operation problems
- ✓ The salinity of the feed water does not have an impact on process or cost.
- ✓ The water quality produced is higher (at less than 10ppm TDS).
- ✓ Pretreatment is not always a requirement and can be minimal.
- ✓ The system can be joined to an electricity generation plant, using the heat energy from there.

Disadvantages of MSF process

- ✓ Has low recovery rate
- ✓ The plant cannot be operated below 70-80% of the design capacity
- ✓ The system is more expensive to build and operate, and require a high level of technical skills.
- ✓ Uses allot of heat energy for boiling the feed water

- ✓ The high quality product water needs to be blended, whenever they fall below 50mg/L TDS.
- ✓ The water produced is normally at an elevated temperature and need to be cooled before distribution.
- ✓ Can be susceptible to corrosion if materials used are not chosen appropriately.

Desalination Schemes utilizing MSF technique

A pilot plant for desalinating saline water from the ocean was set up using the MSF process at Kuwait Scientific Institute Research Centre and reported by Moustafa et al in 1985. This plant was run with the use of renewable energy and had a capacity of $10m^3/d$. The plant is reported to have been self-regulating accounting for independent and robust operation.

The plant consists of three main subsystems which are: heat collection, thermal storage and multi stage flash desalinating units. The system is further equipped with a pre-de-aerator, anti-scaling chemical treatment and chlorine dosing units. The MSF process was having 12 stages.

The performance of the MSF desalination unit was checked through the amount of heat energy required for the production of a given unit of fresh water. This is the specific heat consumption defined as kilojoules (KJ) heat per kilogram (kg) water. This indicator is controlled for optimum performance by regulation of pressure in all stages according to hot brine temperatures and the second part is by monitoring the temperature of the brine to be discharged and of the incoming feed water. The second monitoring control is by regulating the pressure in order to keep the temperature difference minimal.

The plant achieved a range of 380 to 490KJ/kg for specific heat consumption and GOR between 6.5 and 8.

It was further remarked that the system was producing ten times output compared to a solar still of a similar solar collector area.

One of the graphs is indicating an output of 3.6% recovery rate at 10^oC and 6.2% at 40^oC. This however is reported as the distillate and brine flow rates as a function of the difference between hot brine and inlet salt water temperatures. It is therefore not reported what the plant recovery rate was specifically.

3.2.3 Multi Effect Distillation (MED)

3.2.3.1 Process Description

The multi effect distillation process is composed of a number of elements which are called effects.

In the first effect, vapors are generated due to the absorption of thermal energy by the feed water. This vapor which is also sometimes referred to as steam is used as heating medium in the next effect. The produced steam goes through to the next effect while condensing; it also makes part of the solution evaporate. This process uses external steam supply at low temperature of 70°C. For the steaming, condensation and evaporation process to continue successively, the heated effect must be kept at a pressure lower than that of the effect from which the heating steam originates. The condensed solution from the effects is used to preheat the entering feed water. Even though some flashing due to progressive reduction in pressure do occasionally occur in an MED process, most of the produced distillate is generated from boiling instead (Kalogirou, 2005).

Figure 18 is depicting the ideal diagram flow of an MED system that is utilizing solar energy for operation. The inflow mass in an MED process is operated as a once through load, without brine re-circulation around the plant. To enhance evaporation rate, the thin film designs are used with the feed liquid being distributed on the heating surface in each effect.

The multi effect stack (MES) shown in **Figure 19**, is a type of multi effect distillation/boiling system which is regarded as the most appropriate for solar energy application because of its stability and insensitivity to changing temperature conditions (Kalogirou, 2005). An example of an MES with 1862m^2 evacuated tube collectors is installed in Abu Dhabi, United Arab Emirates.

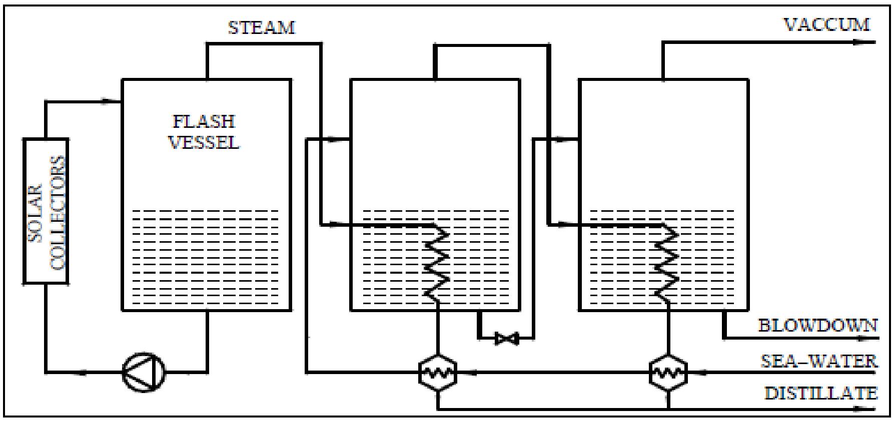

Figure 18: MED solar collectors' process diagram (sourced from Kalogirou, 2005)

The low pressure in each effect is created by the vent-ejector system. In the first effect, steam from the solar collector system condenses inside the tubes.

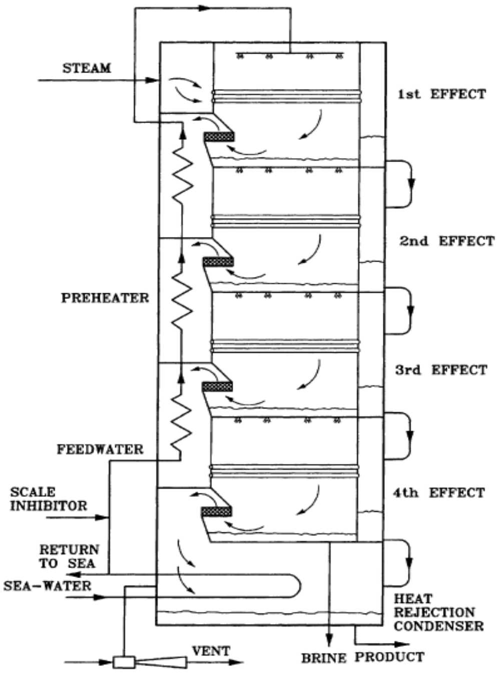

Figure 19: MED process multi effect stack version diagram (sourced from Kalogirou, 2005)

3.2.3.2 Advantages and disadvantages of an MED technique

Advantages of the MED process

- ✓ MED plants are reliable without strict adherence to maintenance schedules.
- ✓ The plant can handle higher levels of biological or suspended matter without operation problems
- ✓ The salinity of the feed water does not have an impact on process or cost.
- ✓ The water quality produced is higher (at less than 10ppm TDS).
- ✓ Pretreatment is not always a requirement and can be minimal.
- ✓ The system can be joined to an electricity generation plant, using the heat energy from there.
- ✓ It requires minimal operating staff, as most operations are automated.

Disadvantages of the MED process

- ✓ It has moderate recovery ratio

- ✓ The system is more expensive to build and operate, and require a high level of technical skills.
- ✓ Uses allot of heat energy for boiling the feed water
- ✓ The high quality product water needs to be blended, whenever they fall below 50mg/L TDS.
- ✓ The water produced is normally at an elevated temperature and need to be cooled before distribution.
- ✓ Can be susceptible to corrosion if materials used are not chosen appropriately.

3.2.4 Multi Effect Humidification (MEH)

3.2.4.1 Process Description

The multi effect humidification (MEH) process use either solar thermal energy, diesel or gas motor waste heat and gas or diesel burner as sources of energy, and is based on the principle of humidification-dehumidification. It is a thermal process and conceptually involves distillation as the means of getting salty water desalted.

The technique comprises three subsystems, the water heater, the humidifier (also referred to as the evaporator) and the dehumidifier (also referred to as the condenser). The inlet water is heated through heat exchangers that transfer the heat from the sun, and then it gets into the evaporation chambers, where it evaporates and the produced steam is transported to the condensers. The MEH concept utilizes the closed-air open-water system. In this system, the humidifier is irrigated with hot water and the air stream is heated and humidified using the energy from the hot water stream (Narayan et al). Air from the humidifier is extracted at various points and supplied to the dehumidifier at corresponding points, as shown in **Figure 20**. This enables continuous temperature stratification to keep the process running, resulting in a higher heat recovery from the dehumidifier. The extracted air condensates into a distillate that in turn drip into the tray.

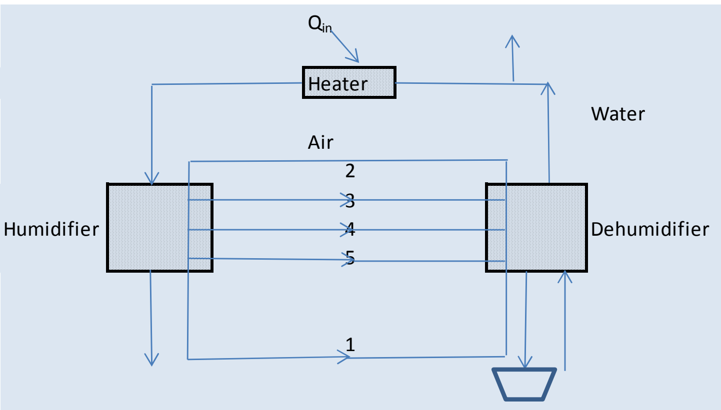

Figure 20: MEH diagram (sourced from Narayan)

In an MEH system the energy use is around 120kWh/m3 or less because of high heat recovery. The GOR is 3 to 4.5. The MEH system has a standard recovery of 70% (Muller-Holst, 2010 InterSolar, US). Specific water production- this is water produced per m^2 of solar collector area per day. The MEH systems produce anything from 25 to 35 per square meter (m^2) of collector area (Muller-Holst, 2010).

The latest technology of MEH systems comes in pre-packed containers, at various scales, which are small, medium and large sizes. The sizes below $5m^3$/d are the small ones, with the 5-$9m^3$/d size being the medium, and the $10m^3$/d and above the large size.

A medium size scheme is installed at a solar farm, in Saudi Arabia, using wind and solar thermal energy, for pumping the ground water and for running the MEH desalination system (Alawaji et al, 1995).

Another $5m^3$/d schemes are also established at Jeddah, Saudi Arabia and in Dubai, also using thermal collectors for supply of energy to the scheme (Mage Water, Muller-Holst).

All sizes schemes, from 1 to $50m^3$/d are implemented in the Canary Islands. Its further reported that the $1m^3$/d scheme only takes $38m^2$ for solar collector area, $5m^3$ size takes $150m^2$, $10m^3$ takes $300m^2$ and $50m^3$ takes $1500m^2$ land for solar energy collection.

3.2.4.2 Advantages and disadvantages of an MEH technique

Advantages of MEH process

- ✓ Uses high quality materials, stainless steel or polypropylene
- ✓ No moving parts in the distillation unit
- ✓ The highest water recovery rate of 70% among thermal processes
- ✓ The plant can handle higher levels of biological or suspended matter without operation problems
- ✓ The salinity of the feed water does not have an impact on process or cost.
- ✓ The water quality produced is higher (at less than 10ppm TDS).
- ✓ Pretreatment is not always a requirement and can be minimal.

Disadvantages of MEH processes

- ✓ Uses allot of heat energy for boiling the feed water
- ✓ The high quality product water needs to be blended, whenever they fall below 50mg/L TDS.

- ✓ The water produced is normally at an elevated temperature and need to be cooled before distribution.
- ✓ Can be susceptible to corrosion if materials used are not chosen appropriately.

3.2.5 Typical impacts and effects of thermal processes, pre-treatment requirements, maintenance and operations

3.2.5.1 Impacts

Impacts are conditions that either changes infrastructure or water quality due to the processes of thermal desalination techniques' interaction with the water. They will be listed and described as follows:

- **Scaling**

Scaling occurs when the feed stream become concentrated and saturated with the less soluble alkaline and non-alkaline elements. Most of the scaling in the thermal processes occurs in the tubes. The calcium sulfate $CaSO_4$, magnesium hydroxide $Mg(OH)_2$ and Calcium Carbonate, $CaCO_3$ in the water causes the scales on the tube surfaces. $CaSO_4$ is a salt whose solubility decreases when the feed stream temperature increases. This salt is tolerant when levels are kept at 1.9 above the concentration of the feed water and the operations are maintained within and up to 110°C and up to 120°C when the plant is using acid treatment.

Magnesium Hydroxide and Calcium Carbonate are the alkaline compounds that cause soft scale. Scale formation is higher when there is no pH control.

Scaling generally has been recognized as a nearly universal problem in design and operation and affects the operation of equipment in two ways:

The scaling layer has a low thermal conductivity. This increases the resistance to heat transfer and reduces the effectiveness of heat exchangers.

As deposition occurs, the cross-sectional area is reduced, which causes an increase in pressure drop across the apparatus. The attached image is showing a classical example of a tube affected and a tube with a side that is not affected by scaling deposits.

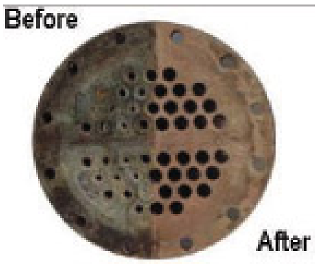

Figure 21: Tubes scaling blockages (sourced from Lenntech)

The scaling in the thermal tubes is indicated by low GOR readings which drop due to fouling of the heat recovery section tubes.

- **Corrosion**

Corrosion is defined as the degradation of material due to a reaction with its environment. In addition corrosion occurs through three types of mechanisms, which are chemical, electrochemical and physicochemical corrosions. These mechanisms cause corrosion in different forms, which in desalination are commonly known as; pitting corrosion, crevice corrosion, galvanic corrosion, stress cracking corrosion, corrosion fatigue, cavitation corrosion and erosion corrosion (Schmitt, 2009). **Figure 22** is illustrating the effect of galvanic corrosion on metallic surfaces.

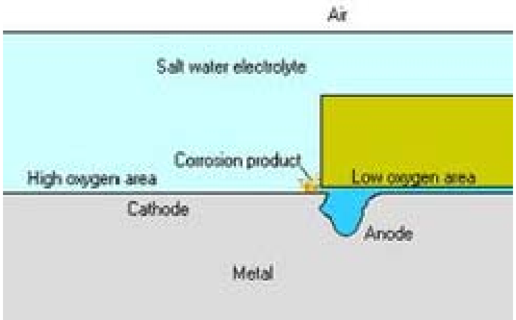

Figure 22: Galvanic Corrosion (sourced from www.Copper.org)

This is an electrochemical action of two metals that are not similar in the presence of an electrolyte and an electron conductive path. The galvanic corrosion in this case occurs when the two metals that are not similar are in contact.

Figure 23 below is illustrating pitting corrosion. This type of corrosion is localized and it occurs at microscopic defects on a metal surface. The pits are found underneath surface deposits caused by corrosion product accumulation. This corrosion process takes place through the oxidation-reduction reactions. The iron is oxidized when it losses electrons to the nonmetal through the process $Fe \rightarrow Fe^{+2} + 2e^{-}$ and the ion atom which gain the electrons is said to have been reduced through the reaction: $4H^{+} + O_2 + 4e^{-} \rightarrow 2H_2O$.

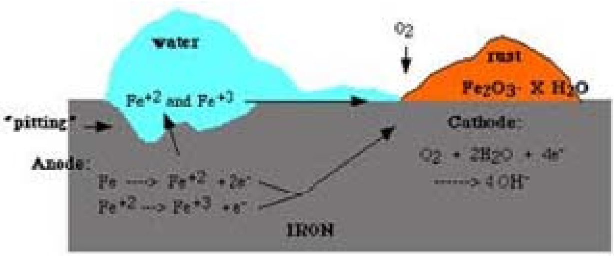

Figure 23: Pitting Erosion (sourced from Corrosion.ksc.nasa.gov)

Thermal plants are subject to corrosion, because the feed water, especially in seawater desalination, has imbalanced pH, high temperatures, dissolved gasses and high chloride concentration. And because of low minerals, imbalanced pH and high temperature, the product waters are very aggressive to metal and concrete.

Corrosion is minimized by use of corrosion-resistant materials as high performance steel, throughout the feed and concentrated streams. The flash chambers' corrosion is kept minimal with proper pretreatment and proper choice of materials.

- **Bio-fouling**

Bio-fouling in thermal processes occurs from marine organisms, other organic material or bacteria that slip through the initial screening stages and also due to insufficient chlorination in the pretreatment. These growths normally occur in the feed water intake and supply lines.

- **Scaling of the heat exchanger tube surfaces from calcium and magnesium salts**

To prevent or minimize scaling of calcium and magnesium, the plant can be operated at lower temperature or antiscalant can be used. The antiscalant or scale inhibitors like phosphonates and polycarboxylic acids have dispersant properties on calcium and magnesium salts and they prevent the compounds from precipitating and adhering on equipment. This option is used in most thermal processes. In the MSF process, the inhibitor sulphuric acid is used to lower the pH of calcium carbonate, in order to avoid the formation of magnesium hydroxide. Alternatively, Nano-filtration is also used as pretreatment technique to reduce calcium sulphate scaling. Oxidizing agent or biocide is used to control fouling polymer blend and anti-foam surfactant is used to inhibit scales.

- **Corrosion of the plant components from dissolved gases**

To remove the gases entering the evaporator, a decarbonator is used to prevent carbon dioxide, while a de-aerator is used to remove oxygen. In addition, sodium bisulfate is an oxygen scavenger added to the stream exiting the de-aerator to remove residual traces of oxygen or chlorine. The latter is mostly used in MSF systems.

- **Erosion by suspended solids**

Sand is a danger to tubes and spray nozzles in the thermal desalination process. It should be prevented to enter the system with good sieving where it may be sneaking in.

- **Effects of other constituents as oil, growth of aquatic organisms and heavy metals**

Hydrogen sulfide which is mostly found in some ground water reacts with copper and nickel which are typically used for heat transfer surfaces. These reactions reduce the heat transfer potential, leading to tubes failure. The oil fouls the evaporator tube surfaces, resulting in heat loss.

Ion traps are used to remove heavy metals and chlorine shock treatments are used for eliminating organisms in the feed water.

Chlorine shock treatment and regular small dosing of chlorine are used to control and keep the organisms or other organic materials out of the system.

3.2.5.2 Effects of thermal processes and pre-treatment requirement

- **Gained output ratio (GOR)**

The GOR is also referred to as the performance ratio (PR) in some literature, but they both refer to the thermal efficiency of the distillation process. The measure has no dimension units, because it’s defined as the total distillate produced divided by the low pressure (LP) steam consumption. Both are measured in the same units of tons per hour (t/h) or kilograms per second (kg/s).

The GOR measure is the main indicator of tubes performance in the thermal process. It most commonly drops when the tubes in the heat recovery section are having scales due to fouling. The higher temperature tubes build up scale at a faster rate than those in lower temperature stages. This scale also affect the water production as the heat transfer is lowered due to fouling or scaling of the tubes.

In the waterboxes, the GOR is dependent on the effectiveness of the heat recovery section to absorb the flashed heat from the flash chambers. Effective heat absorption by the tubes in the stages, will give rise to temperature in the adjacent waterboxes whereas fouled tubes show poor heat recovery.

The gained output ratio (GOR) in an MSF plant is the ratio of fresh water produced to the heating steam. It is thus a relationship of two mass flows, the distillate flow and the heating steam flow (Gebel, 2008). To check the thermal process performance using Gained Output Ratio the following formula or ratio can be used: GOR = mass of distillate/ specific heat capacity of the process. GOR is further described as the ratio of the latent heat of evaporation of the distillate produced to the heat input absorbed by the solar collector (Narayan, 2004). To evaporate 1kilogram of water requires 0.645kWh (Schwartze, 2010).

- **Recovery Ratio**

This is the ratio of the amount of water produced per kg of feed. For some systems, this parameter is deliberately low to avoid complex brine pre-treatment or brine disposal processes.

- **Energy Re-use factor**

Energy re-use factor: this is the energy recovered from the heated fluid to the energy supplied to the heated fluid. This factor enhances the GOR performance in the system.

- **Pre-treatment requirement**

Thermal desalination systems are normally quite robust and do not include physical treatment, other than the screening at the intake point. The pretreatment chemical conditioning for the thermal process is utilized in the cooling stream and make up water. The cooling stream is the water from the heat rejection section that is returned to the feed source and the make-up water is the stream that is re-circulated in the system. The cooling stream is the larger flow, and is treated to control fouling in the thermal process, while the make-up stream is dosed with scale inhibitors continuously, and intermittently with antifoam surfactant.

3.2.5.3 Operations and maintenance needs in thermal processes

All thermal processes mainly involve the process of feed water being heated in a vessel, releasing vapor that contain very minimal impurities. The vapor is directed towards a cooler, usually a tubular heat exchanger, where it condenses to form product water. All distillation processes use this basic concept for desalination. Water normally boils at lower temperature when the pressure is reduced in the boiling vessel.

For thermal processes, the following activities are under taken as part of the routine operations:

- **Checking for leaks;** leaks can normally be seen at flanges and/or observation windows. Leaks may occur due to gaskets expansion with the heat. However they need to be noted in case they become permanent leaks and need to be attended to during scheduled maintenance shut downs.

- **Mechanical problems;** these are related to hot bearings at pumps, vibrations and lower than normal discharge pressures or flow.

- **Ejector vacuum;** problems in the ejectors are noted on the gauges. Such problems can be caused by dirty or blocked condenser tubes, air leaks from the distillers and partially blocked ejector nozzles can contribute to ejector vacuum malfunctioning.

- **Normal performance;** worn rings in a pump, instruments errors and valve positions are some of the causes of obscured differences in the normal flows and pressure readings.

- **Boiling and flashing stages or effects;** poor flashes or boiling may be due to poor recovery of heat than usual. Observations through the windows and from the waterbox temperature should be done for correction and optimal operations.

- **Steam flow;** the temperatures of the condensate and the steam are normally measured and are expected to be giving the same reading. Should a difference be observed then it can be from the measuring instrument inaccuracy. However, should a higher steam than normal be observed, this can be due to a defect within the plant. These are related to fouled tubes, vacuum or venting problems or incorrect setting of the brine transfer orifices.

- **Distillate production rate;** internal spillage of distillate or leakage from the distillate trays or channels may lower and therefore affect the expected production.
- **Distillate quality;** a high distillate conductivity reading will indicate contamination of product water. Such contamination may be due to fouled demisters, poor venting, fouled tubes, tube leaks, and even over production. The reason and source should be investigated immediately for rectification.
- **Brine concentration;** a high brine temperature increases the rate of scaling in the tubes and demisters. Increasing the feed water may rectify the situation, but it is recommended that the antiscalant dosing rate also be increased proportionally.

Apart from the routine operational checks, the data collection record for a thermal process constitutes the following variables:

- ✓ Operation; running hours and shut downs
- ✓ Distillate production; Total water produced and the production rate
- ✓ Steam used; read from condensate to calculate operation efficiency against the distillate production
- ✓ Water quality monitoring; Distillate conductivity should be taken continuously, preferably on the entire period of operation in a day.
- ✓ Antiscalant; type and concentration should be recorded.
- ✓ Operating hours between the acid washes and between the overhauls should be recorded.
- ✓ Operating temperatures should be recorded to compare the minimum and maximum operating temperatures.

The above recorded data is used to monitor;

- ✓ The water quality, determined from conductivity readings. A steady flow of around 20µS/cm would indicate a plant to be in a good condition.
- ✓ The distillers load factor is expressed in percentage and is derived from the production versus the design rate and the running hours. The following formula is used: Load factor= (actual production rate/ designed rate)x availability %
- ✓ The reserve capacity is used to determine standby possibility for some distillers or taking distillers out of operation for maintenance or repairs. Its calculated from the formula: Reserve Capacity = (Maximum production rate – Mean production rate) x running hours + standby hours x mean production rate

- ✓ The thermal efficiency is calculated from the formula: Total water produced/condensate used to determine the performance ratio. The performance ratio (PR) is expected to be the same for all distillers built to same specifications. Normally dirt in tubes affects the PR to drop.
- ✓ Reliability and availability can be determined using the operational hours, including the standby hours, and divide by the total hours in the month. The times for shut downs are to be noted at all time and kept on record with all reasons and durations.
- ✓ Acid wash operating hours are to indicate the effectiveness of the antiscalant dosing.

Maintenance activities

Corrosion: Newer designs and material improvements of the distillers have eliminated most of the problems related to corrosion. The salty water is corrosive to carbon steels and can affect many of the stainless steels and copper-based alloys. On the stainless materials, most corrosion affects the welded area.

The following areas are normally monitored for potential corrosion in the thermal plant:

- o External shell- can be affected with leakages by salt sprays if a plant is close to the sea, or when an ejector is mounted on the roof and at flange welds and instrument tapping points.
- o Internal shell- corrosion can be a problem above the demisters and at vent points. During maintenance, repainting and replacing the gaskets is done.
- o Observation windows- scale forms on the inside of the observation windows due to high temperature operations. A suitable weak acid is prepared to remove and clean the scale from the glasses. Rubber joints deteriorate with heat and time as well and need to be replaced when necessary.
- o Pipe work- painting or lining with rubber or Cu Ni (Copper Nickel) is recommended and maintained with that.
- o Waterboxes- should have sacrificial anodes to protect the linings and tubes. These anodes are of iron and should be cleaned or replaced at overhaul periods. Debris accumulated in the waterboxes has to be taken out and cleaned, mainly in the heat rejection section. In addition, the concrete structures are after sometimes damaged due to corrosion of the reinforcing bars inside the concrete.

- **Tube Leaks**

Detection of leaking tubes is noted through rising conductivity.

Re-tubing is recommended when more than 10% of the tubes are plugged.

- **Demister cleaning**

Demister pads needs to be cleaned at least once a year to remove scales. They are washed in a bath of dilute hydrochloric acid and then an inhibitor to neutralize the acid.

- **Internal painting**

At the time of overhaul, waterboxes are inspected and most of the paint work is done. The hydrojet is used for tube cleaning. Else tubes may also be cleaned using special brushes. These are push-fit design for mainly the heat rejection section tubes.

- **Pumps, Valves and instrumentation**

Maintenance is normally decided upon on site specific by the engineer in charge of the plant and standard procedures are normally included in operation and maintenance manuals.

- **Acid cleaning of distiller tubes**

This is done with either sulphuric acid or hydrochloric acid or crystal form sulphamic acid. Inhibitors are used during acid wash to reduce the corrosion rate of the metals of the distiller.

3.2.6 Membrane distillation (MD)

3.2.6.1 Process Description

"Membrane distillation is a hybrid thermal/membrane desalination process in which pure water vapor from salt solution passes through a hydrophobic membrane, driven by a difference in temperature, and condenses on the opposite side" (Koschikowski, et al, 2009). **Figure 28** below is showing the process flow of an MD system and the conceptual activities of the hydrophobic membranes.

The thermal energy is used for phase changing of liquid water into vapor. The membrane is permeable for vapor only and separates the pure distillate from the retained solution (Shungang, 2008).

The membranes used in the MD are hydrophobic and has a pore diameter size of 0.1 to 0.4μm. Unlike the hydrophilic membranes that are used in reverse osmosis process, the hydrophobic membranes are not that sensitive to fouling and scaling (Walton et al, 2000). The process is most effective at a temperature range of 60 to 90^{o}C (Martinez-Diez et al, 1999).

The driving force in an MD process is the vapor pressure difference between the evaporator and the condenser channel, for vapor permeation through the membrane. This force involves two activities of mass and heat transfer in the MD process (Fath et al, 2006).

The mass transfer activity is based on the convection and diffusion of water vapor through the micro-porous membrane. Through the Knudsen diffusion and Poiseuille flow, a mass flux can be calculated from the following simplified formula: $N_w = C*\Delta p$, C being the transport coefficient and p the pressure difference across the membrane (Koschikowski, et al, 2009).

The heat transfer occurs in three stages: The first stage is the heat transfer from the hot bulk stream in the evaporator channel to the membrane interface. The second stage is the heat transfer through the membrane. The third stage is the heat transfer from the cold membrane interface to the cold bulk stream in the condenser channel (Walton et al, 2000).

Principle process flow behind the membrane distillation technology is shown in the two figures below:

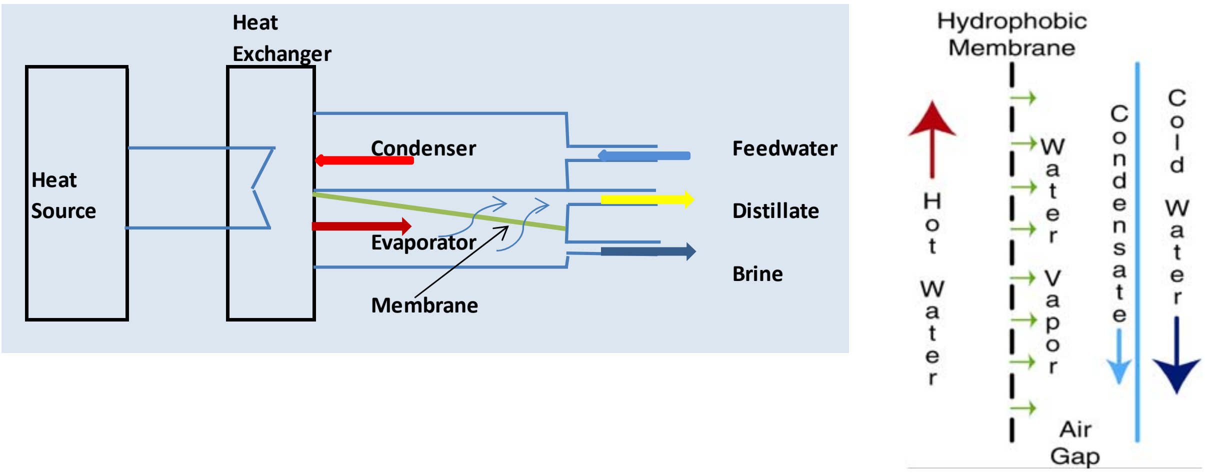

Figure 24: MD conceptual stream flow diagrams (sourced from Fath et al and Walton et al)

The brackish water to be distilled is passed through the condenser and heated in the heat exchanger area before it gets into the evaporator. In the evaporator, the water diffuses through the membrane (**Figure 24**) and with the cooling from the condenser; the water condenses on the cooler surface and drip out as distillate. The overall process is driven by the gradient in the water vapor pressure, then the total pressure (Walton et al, 2000). The air-gap shown is the area where vaporization and condensation occur, where water vapor diffuses into and condensate on the cool surface.

The MD system is mainly made up of materials out of polymer, which are PP, PTFE and synthetic resin. Though the plastic material have lower heat transfer coefficients compared to steel material, the plastic material has worked well so far and have proven to advantageous against typical thermal processes' corrosion problems (Heyn et al, 2009).

3.2.6.2 Advantages and disadvantages of an MD technique

Advantages of the MD process

- ✓ They have low thermal capacity as they have simple system configuration without heat storage
- ✓ No high operating pressure
- ✓ Simple, modular plant construction
- ✓ Most components are made of plastic material
- ✓ It has an option for integrating heat recovery that lead to lower specific energy consumption.
- ✓ With the operation temperature of 60 to 80^{o}C means that standard solar thermal collectors can be used.
- ✓ The plant can handle higher levels of biological or suspended matter without operation problems
- ✓ The salinity of the feed water does not have an impact on process or cost.
- ✓ The water quality produced is higher (at less than 10ppm TDS).
- ✓ Pretreatment is not always a requirement and can be minimal.

Disadvantages of MD processes

- ✓ Limited endurance of the membranes
- ✓ Sensitivity of the wettability by organic substances
- ✓ Uses allot of heat energy for boiling the feed water
- ✓ The high quality product water needs to be blended, whenever they fall below 50mg/L TDS.
- ✓ The water produced is normally at an elevated temperature and need to be cooled before distribution.
- ✓ Can be susceptible to corrosion if materials used are not chosen appropriately.

Desalination Schemes utilizing MD technique

A membrane distillation desalination scheme was set up at Alexandria University in Egypt as one of the five pilot plants that were installed under the SMADES European funded project. (SMADES is a development of stand-alone desalination systems for arid and semi-arid remote regions where there is lack of portable water but have high solar radiation). The units utilize exclusively solar energy, where both solar thermal and solar PV are integrated. The desalination energy is supplied by the solar thermal collector and the electrical energy is supplied by the photovoltaic batteries.

The three important advantages of the membrane distillation technology are embedded in the fact that the process works at low temperature of 60 to 90^{o}C, no chemical pre-treatment of the feed water is necessary, (except simple pre-filtration), the membranes can handle any TDS load encountered and it's a stand-alone with long-term maintenance free operation, according to technology manufacturers.

Results were collected for cloudy and clear days, and are presented separately.

During a clear day in Alexandria, the solar energy accumulated amounted to 41.6kWh/day, at 7.25kWh/m^{2}day. This energy produced 64 liters per day, with a permeate quality of 3µS/cm, from feed water of 5263µS/cm. The salt removal efficiency was 99.5%.

However, on a cloudy day, only 23.6liters/day was produced, with electric conductivity readings of 23µS/cm, from 6723µS/cm. The solar energy accumulated was 29.5kWh/day, at 5.15kWh/m^{2}day.

The energy consumption of the desalination plant ranged from 100 to 200kWh/m^3.

3.2.7 Reverse osmosis (RO)

3.2.7.1 Process Description

Reverse osmosis (RO) is a widely used desalination membrane process. The water permeates under high pressure utilizing mechanical energy through the semi-permeable membranes, leaving behind highly concentrated salty compounds in the brine solution (*Mallevialle et al, 1996*).

An RO system normally consists of the following components:

- Feed water supply unit,
- Pretreatment system,
- High pressure pumping unit,
- Membranes unit,
- Instrumentation and control system,
- Post treatment and storage unit and
- System Cleaning unit

Figure 25 below is showing the ideal process flow in an RO plant. Feed water after abstraction is screened through 5μm filtration cartridges, before it's dosed with anti-scalants to remove scaling compounds and chlorinators to remove bio-foulants, for pretreatment. Scaling and fouling elements clog and block the membranes shortening its lifespan. The water is then pushed through the membranes modules by high pressure pumps, where the permeate is separated from the brine. The product water is collected in a reservoir, where post-treatment of disinfection and pH adjustment is done.

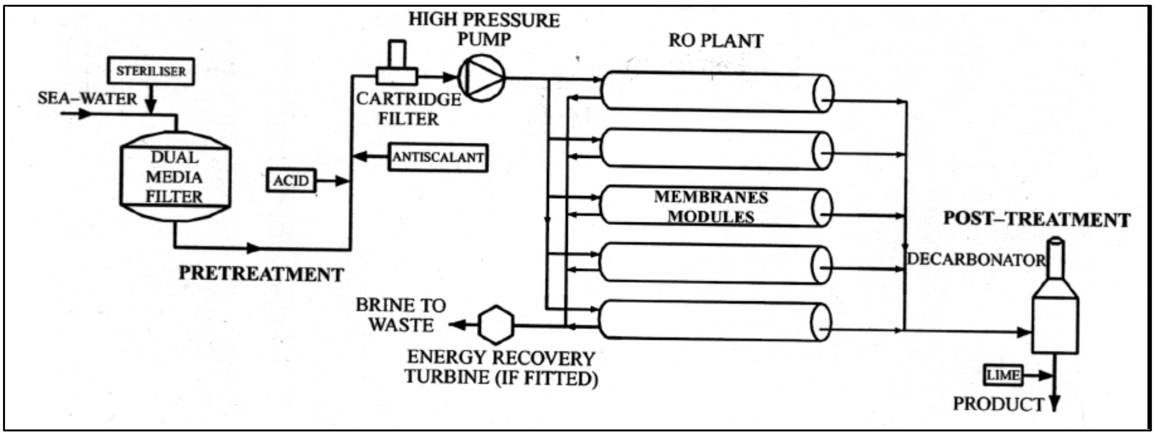

Figure 25: RO process flow diagram (sourced from Kalogirou, 2005)

The RO process performance is defined in terms of the following variables, according to Ettourney et al, 2002:

- Osmotic and operating pressure
- Salt rejection
- Recovery Rate
- Scaling and Fouling

Osmotic pressure (π) can be determined experimentally by measuring the concentration of dissolved salts in the solution, in both the feed water and the permeate. The difference between the two concentrations is then multiplied by a given constant. Effectiveness of salt rejection is determined by the semi-permeable membrane and the mechanical pressure applied through the conceptual model shown in **Figure 26** below. In a reverse osmosis process, pressure is applied to the salt solution causing a solvent flow of clean water across the membrane, leaving a concentrated solute behind.

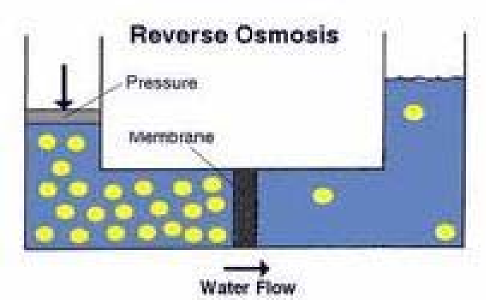

Figure 26: RO process semi-permeable membrane ideal activity (sourced from membrane shop)

In a normal osmotic flow where no pressure is applied, the pure water crosses the membrane to the salt solution side until equilibrium of the chemical potential is restored. Equilibrium, according to Ettourney occurs when the hydrostatic pressure differential resulting from the volume changes on both sides is equal to the osmotic pressure.

The point of solution crossing is a medium called a semi-permeable membrane. This is a membrane that allows the solvent to pass through, but not certain dissolved molecules or ions and colloidal substances.

The typical operating osmotic pressure for RO techniques is from 20 to 50 Bar. However 50 to 80 bar for is applied when more pure water is needed. The separation mechanism is solution/diffusion, based on the differences in solubility and diffusivity of materials in the membrane (Cheah, 2004).

The operating pressure normally has to be set higher to overcome the adverse effects of the osmotic pressure, which are enhanced by friction losses, membrane resistance and permeate pressure. In essence the water quality required determines the level of pressure to be applied and the required pressure limit prescribe the type of membrane to be used.

Salt rejection and recovery rate are two important parameters that determine the performance of the RO system and they are highly dependent on the technology of the membranes used. Most of the membrane technologies provide salt rejection values of above 99% for both the seawater and brackish water (Ettourney et al). The recovery rate of the permeate is affected by the salt retention and water flow across the membrane. As the recovery rate increases, the salt concentration on the feed solute side increases but this also causes an increase in salt flow across the membrane.

The following formulas are used to determine the efficiency of the RO process through the salt rejection and the recovery rate.

Salt Rejection (SR) is defined by: SR = 100% $(1-(X_p/X_f)$

Recovery (R in %) is the conversion of feed water to product water and is defined as follows:

R= 100% (M_p/M_f) (M_p is the permeate flow rate and M_f is the feed water flow rate)

The membranes for the RO processes are designed according to the pressure limit they can handle. They are classified into high, medium and low pressure categories. They are applied according to the molar concentration in the solution. The higher the salinity of the source water is to be desalinated, the higher pressure will be needed and the more durable and resistant membrane type is required. This is also dependent on the permeate quality needed.

The RO membranes are formed of thin film of polymeric material and are made to be stable over a wide range of pH and temperature, with good mechanical integrity.

They are commercially made of cellulose acetate or composite polyamide. The membranes for RO desalination are manufactured in two configuration modules, which are hollow fine fiber and spiral wound. The tubular, plate and frame are mainly used in the food and dairy industry.

3.2.7.2 Advantages, disadvantages and exemplary scheme

Advantages of RO processes

- ✓ The technology can be built cheaply and quick, using durable plastics and non-metals.
- ✓ The RO system can handle any amount starting from few liters to 750m^3/day for brackish water and capacity can be increased by adding required modules.
- ✓ It has high production capacity ratio, ranging from 25 to 60 m^3 /day/m^2.
- ✓ The process has lower energy consumption compared to thermal processes.
- ✓ The membranes remove all contaminants in the water, not only salt.
- ✓ The process has low requirement of chemicals for cleaning purposes.
- ✓ The modular design of the system allows partial shutdown of the plant for scheduled maintenance purposes.

Disadvantages of the RO process

- ✓ Pretreatment of the feed water is required to prevent fouling of the membrane so that they last longer.
- ✓ RO membranes are expensive and have a life expectancy of 2 – 5 years.
- ✓ The high pressures required for operation sometimes causes mechanical failures of equipment.
- ✓ Excessive bacterial growth on the membrane can cause problems of taste and odor in the product water
- ✓ The system specialized and need for high quality equipment necessitate maintenance of extensive spare parts inventory.

- ✓ The RO system requires high quality standard of materials and specialized equipment for its operation.
- ✓ High chemical requirement in pretreatment
- ✓ Product water quality is relatively higher from RO process compared to permeate from thermal processes

Desalination Schemes utilizing RO technique

The RO process is the most widely implemented technology in the world, at small scale and using renewable energy. One such plant is the photo voltaic Reverse osmosis plant in Ksar Ghilene which is in operation for more than five years. It is in the Northern Region, where climatic conditions are semi-arid to arid. The plant has a production capacity of 22m^3/day and was installed in 2005. The solar irradiation is estimated at 5600kWh/m^2 at an ambient temperature average of 26^{o}C per annum. The water is brackish and is drawn from an artesian well. The source water quality has total dissolved solids (TDS) of 3500mg/l, with a temperature of 35^{o}C. There are about 51 households, with a population of around 300 people in Ksar Ghilene (Germadi et al, 2009).

The plant recovery rate is 70%, with feed water TDS reduced from 3000ppm to <500ppm, at 84% efficiency and only uses energy of 2kWh/m^3.

Another RO plant is the prototype wind powered small scale plant for desalinating brackish water that was constructed and tested on Coconut Island, off the windward coast of Oahu, in Hawaii (Liu et al, 2002). The objective was to develop an alternative water supply for small Pacific islands and other remote coastal communities where both freshwater and electricity are in short supply. Since brackish water is readily available and the Pacific islands have constant trade winds and strong solar radiation, a pilot plant was implemented. The system was operated entirely on renewable energy, using wind power to drive the RO desalination process and using solar photo voltaic energy to drive system instruments for data acquisition and control (Liu et al, 2009).

The daily average wind speed in the study period ranged from 2 to 8m/s. The TDS concentration of the feed water was between 2000 and 3000mg/L with temperature between 25 and 28^{o}C.

Raw water of 1.5 to 2.5*l*/s quantity was pumped through the system yielding a recovery rate of the product water averaged at 22%; the efficiency of the desalination unit was 95%.

In another case, the process of desalting brackish water of over 1500ppm source quality using NF and RO membranes was tested to determine how much energy can be saved while still having acceptable quality water for human use. The plant capacity was designed for a 0.56m^3/h. The area has solar radiation potential of 8000W/m^2 a day in June and 3000W/m^2 a day in December in Arava Valley. The project as will be described below was reported by Germadi et al, 2009.

The infrastructure includes a pretreatment step that consists of a micro filter of 5µm pore size and an active carbon cartridge filtration. The energy supply was from a PV module, but a possible supply from a grid source was also included with a control box to switch between the DC and AC supply options in an event where it may be needed. A positive displacement pump with a helical rotor was selected for the high pressure operation of the membrane modules. Two membrane types; Dow Filmtec BW30-4040 reverse osmosis membrane with a total active area of $14.49m^2$ and Dow Filmtec NF90-4040 for nano-filtration membrane with a total active area of $15.24m^2$, are used in the pilot plant.

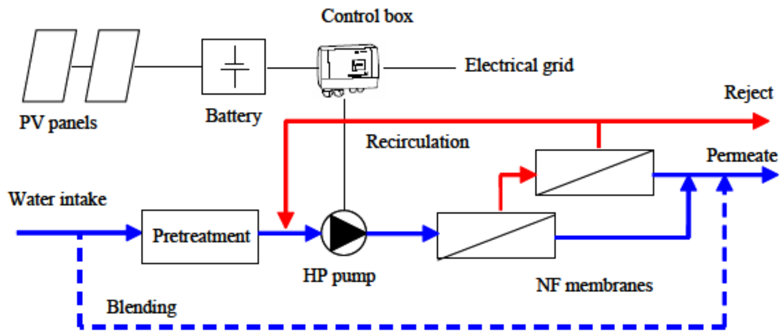

Figure 27: Nano filtration flow diagram (sourced from Ghermadi et al, 2009)

The combination of renewable solar energy and desalination for the production of irrigation water is a particularly appealing solution in hot arid countries (Ghermadi et al, 2009).

Arava valley in Southern Israel is identified as an extreme water scarce area and is characterized by hot and dry conditions. It has an annual average precipitation of 32mm and summer temperatures above 40°C. Despite the conditions, the farmers in the area have been profitable producing about 60% of the country high-value export crops. They have managed this with the advantage of mild winter conditions, and intensive use of greenhouses, cooling systems and water-efficient irrigation techniques.

To augment the efforts of successful crop production, a pilot plant is set up at Hatzeva to test the advantages of using Nano-filtration (NF) membranes (**Figure 27**) in producing irrigation water, using less energy than Reverse Osmosis membranes and abstracting less water with higher recovery.

The results indicate a 40% reduction in energy use for a NF membrane ($0.89kWh/m^3$) compared to a reverse osmosis membrane ($1.49kWh/m^3$). The NF membrane operates at 45% less pressure (5.00bar) then RO membrane (9.04bar). The blending option is expected to bring more energy savings on the system, by reducing the NF energy consumption to $0.76kWh/m^3$.

The recovery rate was 80% for both membranes, generating $0.31m^3/h$; permeate quality of 65ppm for RO and 318ppm for NF membranes. In this scenario, the higher quality water from the NF membranes was suitable for the water needed for irrigation. The contributing ions to the high reading of permeate quality, which are calcium, magnesium, and sulphates are essential for plant growth for which the water is needed in Arava valley. However the quality of 300ppm is also acceptable for human consumption as it meets the portability standard required.

At Odeniz Primary school in Turkey, another NF plant of capacity 6.9m^3/day was piloted as part of Adira projects in 2001. This plant was operated on solar energy at a total installed power capacity of 2.88kW solar panels. The temperature ranged from 17 to 22^{o}C in the period June 2007 to June 2008.

The infrastructure of the plant constituted of: a dosing of feed water with hypochlorite for oxidizing and disinfecting the water as it enters before it is pretreated; the pretreatment unit consisted of a kliptonite 70μ filter, an activated carbon tube and 5μ cartridge. The NF system comprised of an antiscalant dosing unit, the membranes, re-mineralization with a calcite filter and disinfection with an ultra violet (UV) lamp before the water is distributed for drinking.

The results observed shows that the feed water conductivity was 930 – 960μS/cm (595.20-614.40ppm) and was brought down to 400 - 480μS/cm (256-307.20ppm), at an average of 22% recovery. The energy consumption was 3.19kWh/m^3. The high pressure pumps were operated at 4 Bar.

More than 90% of the water rejected from the membranes is re-circulated into the feed system as shown. An option to blend the water with feed water where it is aimed for irrigation is also included in the system.

3.2.8 Electro dialysis (ED)

3.2.8.1 Process description

Electro dialysis is an electrochemical separation process that uses electrical currents to move salt ions selectively through a membrane, leaving fresh water behind (Ali et al, 2009). The ions are transported through a semi permeable ion exchange membrane charged with an electrical potential (Ali et al, 2009). In **Figure 28** the principle of ED operation is shown. Electrodes which are normally constructed from niobium or titanium with a platinum coating are connected to an outside source of direct current as battery or PV source in a container of salty water. When the electric current is carried through the solution, the ions migrate to the electrode with the opposite charge. The positively charged ions migrate to the cathode and negatively charged ions migrate to the anode. The membranes consist of flat sheet polymers that permit the transport of ions, while ion-exchange sites incorporated into the membrane's polymer matrix promote membrane selectivity. Anion-permissible membranes allow anions to pass through to the positively charged electrode, but reject cations. Conversely, cation permissible membranes allow cations to pass through to the negatively charged electrodes, but reject anions (Almadani, 2002). **Figure 29** is depicting an ED system that is operated with renewable PV array and is an exemplary scheme in this ED category.

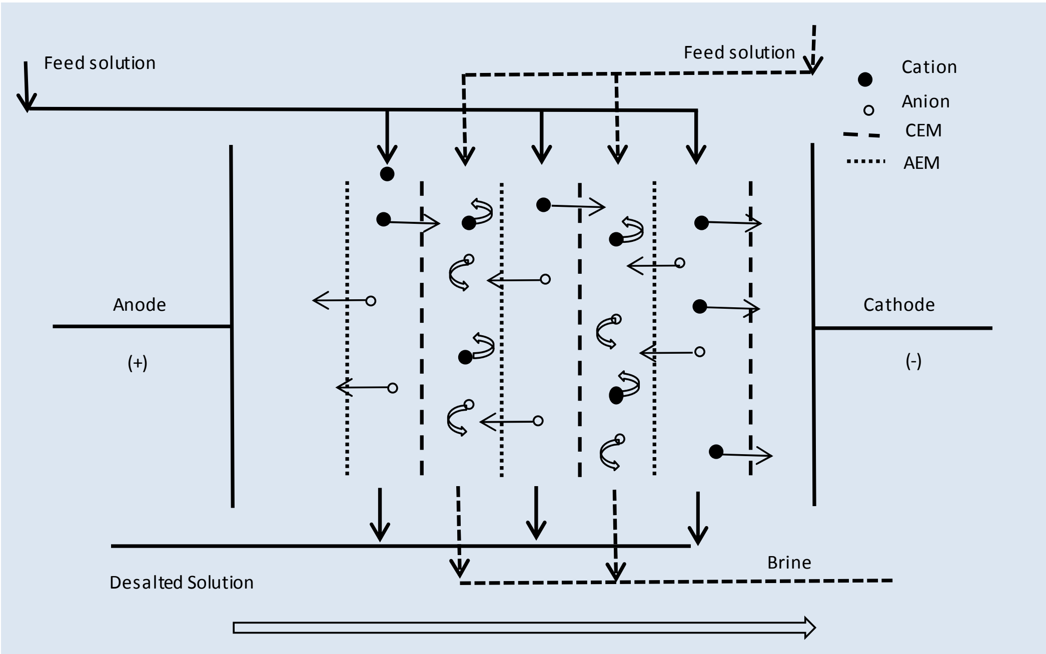

Figure 28: ED conceptual desalination process (sourced from Almadani, 2002)

3.2.8.2 Advantages, disadvantages and exemplary scheme of ED

Advantages of ED process

- ✓ The ED process has high recovery rate of 85 – 94%
- ✓ The ED system can treat feed water with higher level of suspended solids.
- ✓ The energy usage is not according to the volume of water treated but is proportional to the salts removed.
- ✓ Pretreatment has low chemical usage
- ✓ The life expectancy of the membranes is 7 – 10 years.
- ✓ The membranes are not susceptible to scaling or silica growth.
- ✓ Process is operated at low to moderate pressure.
- ✓ Scaling can be controlled whilst the process is online and the membranes can be cleaned manually.

Disadvantages of the ED process

- ✓ The ED system only removes specific ions, the rest as bacteria, turbidity and non-ionic substances remain in the product water for further treatment.
- ✓ The membrane stacks do leak sometimes.

- ✓ It is required that the membranes are cleaned periodically with chemicals.
- ✓ It is only suitable for brackish water of salinity up to 12 000mg/L TDS.

Desalination Schemes utilizing ED technique

An ED unit (**Figure 29**) that consists of the following basic components: pretreatment system, membrane stack, low pressure circulation pump, power supply for direct current and post treatment system is installed at the University of Alicante (Ortiz et al, 2008).

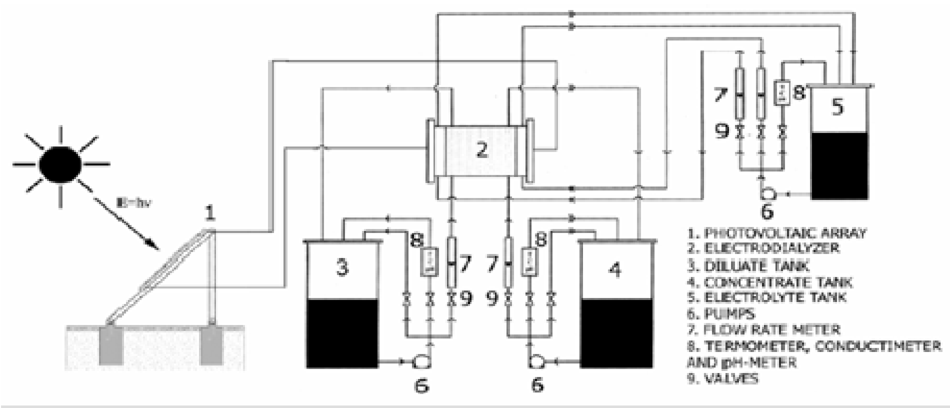

Figure 29: ED process diagram (sourced from Ortiz al, 2005)

This pilot set-up was run at a university of Alicante in Spain. The feed water had TDS of 2300 to 5100ppm and was brought down to 99 – 459.5ppm, at 0.92 to 1.69kWh/m^3 energy consumption. This has given 91 to 95% ED desalination efficiency, at 22% recovery rate.

The Electro-dialysis reversal (EDR) was introduced about a decade after the ED technology, to avoid organic fouling problems of the membranes (Mihara and Kato, 1969). It is reported to be an improved version of the common ED process.

3.2.9 Typical impacts of membrane processes, pre-treatment requirements, maintenance and operations

3.2.9.1 Impacts

Impacts are conditions that either changes infrastructure or water quality due to the processes of membrane desalination techniques' interaction with the water. They will be listed and described as follows:

- **Scaling**

Membrane scaling is induced by the formation of the following compounds: Calcium carbonate, Calcium sulfide, Silica complexes, Barium sulfide, Strontium sulfide and Calcium fluoride

The scaling is the increase of salt at the surface of the membrane that forms a boundary layer that reduces the actual product water flow. The obscurity in the flow rate as compared to theoretical estimates shows the impacts of scaling. Whereby the following normally happens:

- ✓ There is greater osmotic pressure at the membrane surface than in the bulk feed solution, $\Delta\pi$, and reduced net driving pressure differential across the membrane.
- ✓ Water flow across membrane is reduced
- ✓ There is increased salt flow across membrane
- ✓ Precipitation at the membrane surface increases, causing membrane scaling.

The scaling compounds occur in the following environments:

Calcium carbonate precipitates in an alkaline solution, increasing temperature, decreasing carbon dioxide concentration and when calcium or bicarbonate is increasing.

Calcium sulphate crystallizes into scales on the ionic concentrations of Calcium and Sulfate beyond the solubility level in the brine stream.

Silica complexes precipitate with iron, aluminum and magnesium on the increase in temperature and increased concentration of the silica in the brine stream.

The organic compounds can be rejected or permeated through the membranes, but they equally foul the membranes and reduce the performance.

Scaling compounds that slips through the membranes also have an impact on the piping system of the water distribution network. A typical piping is affected by scaling as in the attached **Figure 30**, which is a collection of scale on the inside of the pipe.

Figure 30: Pipe scaling (sourced from www.water.me.vccs.edu)

- **Bio-Fouling**

Bio-fouling is a micro biological activity that can occur in various units in the desalination system (*Mallevialle et al, 1996*). The following factors causes the bio-fouling activities

- ✓ The presence of micro-organisms in the water,
- ✓ Available membrane surface which can be colonized by microorganisms and

- ✓ Rejected cells that adhere to membrane and initiate the bio-filming and bacterial growths in media filters, activated carbons and pipelines connecting different units.

Bio-fouling affect the RO system performance negatively and this include decrease in the permeate flux, increase in pressure drop and decrease in salt rejection (*El-Dessouky et al, 2002*).

The feed water may contain various concentrations of suspended solids and dissolved matter. The suspended solids normally consist of inorganic particles, colloids and biological matter, which includes microorganisms and algae. The dissolved matter may consist of soluble salts as chlorites, carbonates, sulfates and silica.

The bio-fouling potential is increased in higher temperature conditions and when feed water storages or reservoirs stand for too long without pretreatment or disinfection. Microbial adhesion in membranes is enhanced by the electrostatic charge of the conditioning film (El-Dessouky, 2002).

In order to minimize and control the impacts of scaling and fouling in the process of desalination, pretreatment is in most cases a necessary step in the RO process system and it shall be described next. Pretreatment needs for ED are similar to RO process, except that the feed water quality is lower, hence the need may be lower depending on the water quality used.

3.2.9.2 Pre-treatment Requirements

Pretreatment is necessary to improve the quality of the raw feed water to the desalination plant, to ensure consistent performance and the desired output volume of the process. However, the level and type of prevention required depend on the source and quality of the feed water and the desalination technology chosen (USDI, 2003). Feed water is first screened as it enters the treatment plant, and then pretreated to ensure that turbidity/suspended solids and the quantity of organic and inorganic foulants are within the acceptable range for the further steps in the desalination process equipment. In addition, the water is also pretreated to remove other unwanted constituents that may be present such as hydrocarbons or algae.

Pretreatment process can consist of one or more of the following activities, depending on the raw water quality to be desalinated, as stated in the following Table:

Table 8: Membrane Technology Pretreatment Options

Pretreatment Option	Purpose
Addition of scale inhibitor	To control membrane fouling and scaling from metal oxides, colloids and inorganic salts.
Flocculants aids	Used for open water intake to control SDI
Reduction of alkalinity by pH adjustment	To maintain anaerobic conditions in the process

Water disinfection with chlorine or other biocides	To remove or minimize bio-fouling by organic materials
Reduction of free chlorine using bisulfite or activated carbon filters	To minimize and control membrane degradation by oxidizing agents
Scale Removers	Used with activated carbon and sand filtration to remove all molecules and ions of scaling, fouling and oxidizing agents to the membranes.
Media filtration (Ultra or Micro Filters)	Ultra-filtration (UF) differs from microfiltration (MF), by the pore size of 0.1μm. The UF membrane operations are for clarification and disinfection, removing coarsest particles, especially all microorganisms as viruses and bacteria, whereas the MF is used for clarification primarily. Both membranes operate at 50 to 500kPa
Sand filtration	Used for removing larger particles after flocculation/ coagulation in open water intakes
Final removal of suspended particles using cartridge filters	The inlet to the RO membranes can only be 1 μm or less. Cartridges of pore size 1 μm or less are used for this.

Pretreatment in membrane processes is essential for proper operation of desalination equipment. The presence of suspended solids in the source water can reduce the quality and quantity of the permeate or lead to shorter membrane life than anticipated and membrane performance that is substandard. The cumulative parameter called silt density index (SDI) is used to measure and indicate the membrane fouling tendency. Most membranes require an SDI of less than 5 in order to maintain a steady and predictable performance. Pretreatment in membrane processes are to address and control the impacts of fouling and scaling on the membranes.

Scale inhibitors as polyelectrolyte polymer blends are used to increase solubility salts that cause scaling such as calcium and magnesium carbonates and sulfates. This is primarily used in brackish water desalination that is utilizing either ED or RO processes and is being operated at high recovery. Coagulants as ferric chloride or ferric sulphate are used to improve the removal of suspended solids.

Flocculants aids (usually cationic polymer) are used when the feed water SDI is unusually high in open intake RO for seawater.

Oxidizing agents are used to control bio fouling mainly in large systems while small systems use biocides. It is recommendable that the anaerobic conditions be maintained throughout the process, by keeping the iron to 2mg/l or less and the manganese to 0.5mg/l or less.

Reducing agents in the form of bisulfite need to be used to eliminate oxidizing impacts on the RO membrane, especially the membranes using polyamide. Oxidizing agents can cause membrane degradation. Else the membranes made of acetate polymers are said to be insensitive to chlorination impacts.

The scale removing electrodes, removes scale from the water. The electrodes are the functional sub-unit that is eliminating most of the scaling elements and producing essential chlorination for preventing fouling in the gravel filters. The electrodes consist of iridium and ruthenium mixed oxides. These oxides are known for their excellent performance in their electrical conductivity properties and produces chlorine when immersed in water containing salts.

The electrodes elements are made of titanium plates which are coated with iridium and ruthenium oxides. Titanium element is from the Group 4 transition metals that are identified as being among the very good coatable metals with strong adhesion. The iridium/ruthenium oxides produce chlorine in the form of hypochlorous and free chlorites at their phase boundary with water containing salt at the induction of electric current through the anodes. This reaction produces the disinfecting species, whilst at the cathode area the precipitation of scale takes place. There is a direct relationship between the electrodes surface area, and the energy consumed during electrolysis (Kraft, 2008).

In the case of Amarika desalination pilot plant installation, the $CaSO_4$ is the main precipitate to be removed with Mg $(OH)_2$ to a lesser extent. A high pH environment is generated through the cathodic reactions of: $2H_2O + 2e- \rightarrow H_2\uparrow + 2OH^-$ (1) *as first reaction*, and $O_2 + 2H_2O + 4e- \rightarrow 4OH^-$ (2) *as second reaction* around the cathode electrode causing scale precipitation in the compartment.

While at the anode electrode, the chlorine gas is produced in the presence of chloride ions in the water. This occurs through the reaction, $2Cl^- \rightarrow Cl_2\uparrow + 2e-$. The $CaCO_3$ and $Mg(OH)_2$ are formed as calcerous deposits at the cathode, in the water containing calcium and magnesium ions.

The electrodes are de-scaled or cleaned of scale formation by applying reversed polarity. The electrodes installed at Amarika have a lifetime of about one year, but the reversed polarity can reduce the lifetime of the electrodes. The electrodes installations in general differ according to the purpose they are expected to serve. The scale removing installation is a model of anodic thin titanium, mixed oxides coated electrodes, in a tubular casing of stainless steel cathodic material (Kraft, 2008).

The pretreatment chemicals are also used on conventional granular media pretreatment options. Micro filtration or ultra-filtration membrane systems can alternatively be used as pretreatment to desalination. Even though these systems do not require source water conditioning, they use chemicals for backwashing cleaning of the membranes. Depending on site specific conditions, chemical enhanced backwashing can be necessary.

Table 9 below is giving a summary of the typical pretreatment activities required for all desalination techniques described above. The table is used later for transformations and evaluation purposes.

Table 9: Pretreatment activities for all desalination techniques

	RO	ED	MSF	MED	MEH	MD
Screening	X	X	X	X	X	X
Scale inhibition	X	X				
Fouling prevention	X	X				

3.2.9.3 Maintenance needs and Operations monitoring

The membrane processes normally occur in an open, sometimes ventilated room with all infrastructures intact and in most cases modular.

For maintenance in a membrane process set up, mainly the pretreatment filters, the activated carbon and removable parts to the high pressure pumps needs to be replaced. However, the replacement rate is in most cases after two years of operations.

Meanwhile the normal plant maintenance service is undertaken every 3 to 6 months. During this service, for small systems, the cartridges for pre-filtration to the reverse osmosis section are replaced, and the membranes are backwashed with an acidic solution.

For routine operations, the high pressure pumps gauge readings at the inlet and water outlet, are an important element to monitor. The deviation from the normal or daily pressure readings, mainly when it is higher than the trend, necessitate membrane cleaning. A higher pressure reading on the water inlet pressure gauge is an indication of blockages or scale collection on the membranes. The membranes are cleaned with a specially prepared acidic solution and then inhibited with a specially prepared alkaline solution.

The following data is collected daily as part of operations, for the performance analysis of the RO plant:

- ✓ **Operation hours of the pumps-** The pumps running hours are used to indicate the need for maintenance. Normally a pump is maintained as part of routine or scheduled maintenance after every 8000 hours of operations and/or within 2 years.
- ✓ **RO unit Pressure-** The pressure gauge readings are used to determine the need for maintenance of the membranes.
- ✓ **Feed water and product water meters-** This data is used to monitor and check the plant recovery rate efficiency through the formula (permeate/feed water) x 100(%).
- ✓ **Power supplies in kilo watt hours-These readings are** used to monitor the plant energy consumption. In an event where the plant is using more energy per unit water produced, an investigation needs to be launched for check where energy is being wasted or overused in the desalination plant process, including the instrumentation and other auxiliary connections to the power supply as air-conditioning of the electronics.
- ✓ **Inlet and permeate conductivities-** Conductivities are recorded to monitor the plant membranes efficiency. The feed water concentration is compared to the resulted product water concentration, to check total dissolved solids removed from the water.
- ✓ **Inlet and outlet water temperature-** the temperature needs to be monitored and recorded. Bigger fluctuation in the inlet water temperature may have an impact on the plant performance.
- ✓ **pH meter-** readings are useful in checking acidity and alkalinity levels of the water.

In Electro dialysis desalination, current trends are ED and EDR systems that are designed with fully automated controls. The daily operations are based on checking control settings and operating parameters. These systems are supported with detection sensors that recognize operation levels or critical conditions according to set points implemented.

Therefore, the operators check the values and alarms related with temperature, conductivity, pH, current voltage, intensity, flows and pressures. Data are directly logged for the different streams in the ED system.

The membranes are cleaned periodically and mostly when necessary. This is to remove mineral scale, organic matter, biological growth or slime, colloidal particles or insoluble constituents which build up on the surface. To prevent excessive build-up of scaling and fouling, the ED and EDR systems are equipped with a clean-in-place (CIP) system to allow periodic flushing of the membrane stack and piping with an acid solution. The CIP is therefore made of a chemical feed pump and a storage tank for this operation. The acidic solution is continuously fed into the electrode stream of the cathode to prevent scaling.

According to AWWA, 1995 the only chemical solutions that should be used for stack cleaning are:

- ✓ A solution with 2 – 5 % hydrochloric solution is used to remove scale and bio-fouling in periodic cleaning, using hydrochloric acid.
- ✓ Sodium chloride (NaCl) solution is used to remove organic foulants from the membranes; 3-5 % NaCl solution is used. The solution should have a pH between 8.0 and 10.0, adjusted with NaOH (sodium hydroxide). A pH greater than 11 can damage the anion membrane. The NaCl application is inhibited with a flush of HCl to remove excess salt.
- ✓ Chlorine solution- of 20-50mg/L is used to disinfect the membranes and the hydraulic piping.

If maintenance of repair or manual cleaning is needed, the stack can be disassembled. When removed or disassembled, the stacks need to be kept in water, as the membranes can get easily damaged when left dry for long periods. In addition, a correct component orientation needs to be maintained at all time and should be rebuilt in the same order it was disassembled. Incorrect assembly can reduce performance or cause scaling.

The other important daily operation and maintenance issue to be checked in the ED systems is the inter-membrane voltage. Inter-membrane voltage is required to be similar along the entire stack, as excess current can melt or burn the membranes and spacers. The systems are built such that the inter-membrane voltage is 80% of the current that can potentially cause burning. The limits is determined by water temperature, conductivity of the source water, membrane stack size, and the internal manifold that splits flow into concentrate and dilute streams.

3.2.10 Post-Treatment for All Desalination Techniques Permeate

Product water from desalination plants is characteristically low in mineral content, alkalinity and pH, and therefore requires post-treatment prior to final distribution and use, whether for portable use or industrial application. Product water from thermal desalination processes typically ranges between 0.5 and 50mh/l total dissolved solids (TDS) and product water from membrane processes can range from 25 to 500mg/l TDS, depending on the application.

Nevertheless, post treatment practices are normally mandated by law or are included as a process step toward regulatory compliance. It is needed to protect public health and to safeguard the integrity of the water distribution system. Low concentrations of minerals components as calcium and bicarbonate alkalinity in water supply systems result in water being aggressive or unstable.

Typically the following measures are taken for post-treatment, depending on the need or adjustment to be done:

- Stabilization by addition of carbonate alkalinity

Chemicals as; Caustic soda (NaOH), Sodium bicarbonate ($NaHCO_3$), Soda ash (Na_2CO_3), Chemical lime (CaO) and Hydrated lime ($Ca(OH)_2$ can be used for stabilizing the water. These chemicals are normally dissolved in water before injected into the product water according to quantities measured to be dosed.

- Corrosion inhibition

Corrosion may be mitigated by adding chemicals to form a protective layer (film) on the surfaces of the pipes and tanks. The inhibitors used for drinking water are; chemicals that cause calcium carbonate scale formation, inorganic or glassy phosphates and sodium silicate.

- Re-mineralization by blending with high mineral content water

Mixing with brackish water containing significant amounts of calcium or bicarbonate from another source can be an effective method. However, for optimal stabilization, a pH adjustment may be necessary. A mass balance approach is used to determine the amount of blending that can be carried out.

- Dissolved gas stripping

The most common technique used for air stripping, is a packed tower with either forced or induced draft. CO_2 and H_2S are removed in an air stripping.

- Disinfection

Chlorine treatment is achieved using chlorine gas, hypochlorite, chlorine-dioxide, electrochemical or ultra violet light disinfection.

Table 10 below is indicating the post treatment needs for the various desalination processes.

Table 10: Post Treatment activities

	RO	ED	MSF	MED	MEH	MD
Stabilization	X	X	X	X	X	X
Corrosion inhibition			X	X	X	X
Re-mineralization			X	X	X	X
Disinfection	X	X	X	X	X	X

3.3 Potential Impacts from the desalination processes

Projects in any form normally have effects both positive and negative on the environment during construction and operation. Desalination, as a technology and a project will have impacts socially and economically on the people and the environment of Olushandja sub-basin. In this section the typical issues encountered and/or anticipated in the development and operation of a desalination plant will be reviewed and presented.

Desalination projects are typically driven by the limited availability of alternative lower cost water supply resources such as ground water or fresh surface water (rivers, lakes, and so on). Implementation of desalination projects can consume considerable community resources, as economic and social capital, land and energy that could otherwise also benefit them in a different way. It should therefore be regarded as a community asset and a valuable resource from which opportunities for multiple-use should be sought (WHO/SDE/WSH/07).

The following section describe the main elements that are inadvertently impacted in the process of implementing desalination projects in any given environment or community.

- **Land Use**

The area required for the desalination facility will vary, depending upon the process used and the source of water to be treated. Generally, plants treating brackish water need less space. In the case of Olushandja sub basin, the land use is predominantly for subsistence production and farming and will need to be withdrawn from these activities.

- **Energy Use**

Desalination activities require a significant amount of electricity and heat depending on the process, temperature and source quality. The thermal desalination processes releases discharge load with elevated temperature to the environment. The discharge dissipates this thermal energy in the environment as a thermal pollution load. Energy source and availability is an important element needed by the desalination processes and a resource to be shared with local needs.

- **Pretreatment chemicals**

Pretreatment is mostly required for the membrane and sometimes required for thermal desalination processes. When membrane desalination is used for salt separation, pretreatment involves filtration and other physical-chemical processes whose primary purpose is to remove the suspended solids and oil and grease contained in the source water. For thermal processes, it is used to protect downstream piping and equipment from corrosion and from formation of excessive scale of hard deposits on their surface.

The pretreatment waste stream is normally discharged with the brine reject from the desalination process elevating the blend with turbidity, TSS and occasionally BOD.

From the pretreatment chemicals by-products a trihalomethanes (TTHM of 500 to 2000mg/liter) are generated from the addition of chlorine, if the source water has high organic levels. Chloramination generate both chloramines and bromamines. Bromamines have high oxidation strength which has a negative impact on the integrity of the membranes and subsequently deteriorate the water quality. The ferric salts can cause reddish discoloring of the plant discharge.

The membrane pretreatment systems normally produce 1.5 to 2 times larger volume of spent filter backwash water then the granular media filters.

- **Desalination Brine**

Concentration of minerals in the brine is usually 2 to 10 times higher than that of the source water and is a function of the TDS of the source water and the plant recovery.

In the thermal desalination process, the brine TDS concentration is generally 1.4 to 1.8 times higher than the raw water make up, with the temperature being >3 to 5^{o}C warmer. In addition, the cooling water that is returned to the source is normally 8 to 12^{o}C warmer than the ambient conditions (Glater et al, 2003).

The brackish water desalination plants operate in a recovery range of 40 to 60%; with a TDS level of concentrate in a range of 1500 to 25 000mg/liter. The TSS and BOD are normally below 5mg/l in the brine because they are removed by the pretreatment system.

There are a variety of management methods for handling or disposing the desalination concentrate that will discussed below.

3.4 Brine disposal options

- **Deep well injection**

This is an injection of desalination plant concentrate into an acceptable confined deep underground aquifer below a freshwater aquifer, using a system of disposal wells. This system also includes a set of monitoring wells to confirm that the concentrate is not propagating to the adjacent aquifers. Depths of the wells are typically 300 to 2400m in porous rock formations. The rock formation receiving the waste must possess the natural ability to contain and isolate it (Mickley et al, 2006).

The design considerations for injection wells are therefore, first of all site selection. The site is selected based on the geologic and hydrologic conditions. The suitable underground strata capable of receiving the waste must be present and separated from any underground sources of drinking water by impermeable strata. The most important element in the evaluation for selecting a site is the capability by the underground formations to possess the natural ability to contain and confine the injected waste. Rock formations such as sandstone are highly porous and are able to take in large volumes of liquid. While the other types as shales and clays are essentially impermeable and act as confining layers that make it possible to dispose of liquids underground into porous strata and prevent migration of the waste water into portable aquifers.

Water sources with lower salinity and mineral content are normally located at near surface, and the ground water quality usually deteriorates with increased depth (Mickley, 2006), making the deeper aquifers water quality quite poor and not potential sources of drinking water.

In order to build wells with integrity, it is required that the casing and cementing should prevent the movement of fluids into or between underground sources of drinking water. The casing and cement used in the construction of each well are to be designed for the life expectancy of the well. For appropriate casing and cementing requirements, the following factors are to be taken into consideration. These are; depth to the injection zone and injection pressure, external pressure, internal pressure, and axial loading. Casing and cementing stabilizes and seals the upper strata of the well. Normally three to four casing transitions are installed. These transitions provide zones and isolates deep contaminated aquifers from the purer water contained in shallower aquifers. The injection tube is run from the surface to the deep aquifer where the water will be injected. The tube is encased in cement at least 127mm thick not to have any environmental impacts.

In general, the design of a deep well disposal system requires specifications of the flow rate of the concentrate stream, the depth of the well and the diameter of the injection tube. They are the first variables for planning and design.

The costing for deep well disposal therefore consists of;

- Pumps to inject the concentrate,
- Site tests that involve logging, surveying and testing,
- Formation of the injection well, that include drilling, tubing and packer and casing and grout,
- Monitoring wells to check for leakage of the waste,
- Mobilization and demobilization, assembling and disassembling the drilling rig, and
- Operating costs, which include well maintenance, pumping power and operating labor.

The deep well method is mostly used for concentrate disposal from all sizes of brackish water desalination plants, while beach well disposal is practiced for small to medium size seawater desalination plants.

- **Evaporation ponds**

This method utilizes the natural solar evaporation process of the concentrate in a man-made lined earthen pond. However, this method is found to be suitable for disposal from small volume flows and for regions that have a relatively warm, dry climate with high evaporation rates, level terrain and where land costs are low (Mickley, 2006).

The evaporation ponds function by transferring liquid water in the pond to water vapor in the atmosphere above the pond. The rate at which an evaporation pond can transfer this water governs the size of the pond (Fakir-Dama et al, 2009). In general, the pond must have adequate depth for surge capacity and water storage, storage capacity for precipitated salts, and free board for rainfall and wave action (Bose, 2001).

Evaporation rate is lower for saline water because salinity reduces evaporation. This is because the vapor pressure of the saline water is lower than that of fresh water and because dissolved salts lower the free energy of the water molecules. The cohesive forces acting between the dissolved ions and the water molecules may be responsible for inhibiting evaporation, making it more difficult for the water to escape as vapor (Miller, 1990).

For water saturated with about 26% sodium chloride salt, it is reported that the solar evaporation is generally 70% of the rate for fresh water and of 10 to 20% sodium chloride. The evaporation rate is 78 to 93% respectively (Coleman, 2000). It is therefore arrived at the conclusion that an evaporation factor of 0.70 be used when determining the needed area and depth of the evaporation pond.

Ponds are reported to be maximizing the evaporation rates optimally when they have a depth between 25 and 450mm. It is also further shown that, shallow ponds are subject to drying and cracking of the liners and may not be functional in long-term service for concentrate disposal. For contingency purposes, a 20 percent space is normally applied to the surface area of the pond or its capacity to continuously evaporate water.

The following formulas determine the sizing of the pond:

$V=Ad$, this can determine the volume that can be held by pond of a known area (A) and depth (d).

$\Delta V = Q_i + P - Q_o - E - S$, Change in volume ($\Delta V$) over time can be determined from influent water to the pond (Q_i), rainfall over time (P), effluent from pond to land (Q_o), evaporation rate (E) and seepage (S) over time.

The hydraulic Loading Rate (HLR) and the Application Rate (AR) are used to manage the land area of the pond. The HLR is the amount of wastewater to be applied to the land per year or month and AR is the depth of water to be applied during each loading cycle.

$V= [HLR/f][A]$, V represent volume during one loading, f is for frequency of application (times /month), hydraulic loading rate (in meters/month)and area in m^2. This formula can indicate the volume that can be released into the pond per month.

The cost factors involved in an evaporation pond are;

- ✓ Land cost,
- ✓ Earth work, include land clearing and dikes.

- ✓ Lining,
- ✓ Miscellaneous cost, include fencing, maintenance roadways, disposal, seepage monitoring and contaminated land clean up.
- ✓ Operation and Maintenance, is mainly for operating cost of security and damage inspection labor.

  - **Zero liquid discharge process**

This method uses the technology of brine concentrators, crystallizers and dryers that convert the concentrate to highly purified water and solid dry product suitable for landfill disposal or else, recovering useful salts. The process uses mechanical evaporation to reduce the concentrate to the dry salts.

The methods are; brine concentrators using vapor compression evaporator system, crystallizer technology, spray dryers and the modernized integration of membrane and thermal systems.

The design variables are feed flow rate and the rejection level of the brine concentrator, with the costs elements being;

- ✓ The brine concentrator,
- ✓ Crystallizer,
- ✓ Spray dryer,
- ✓ Energy and
- ✓ Construction and installation.

The method can be costly because of high energy requirement and it's normally the last option, in the absence of any other method available. It has very limited use currently as it is still being researched and developed.

  - **Discharge to sewers and surface waters**

Discharge to sanitary sewers is widely used for brackish water desalination plants, and rarely practiced for seawater desalination applications. This disposal method is limited by the hydraulic capacity of the waste water collection system and by the treatment capacity of the waste water treatment plant receiving the discharge. The biological treatment process can typically handle TDS concentrations of up to 3000mg/liter salinity and this has to be maintained with the influent added to the system.

For surface water disposal, the method involves the discharge of the desalination concentrate to a surface body that is nearby, as ocean, sea, river estuary, bay or lake. This discharge can either be direct through an ocean outfall, or can be shared through an existing waste water treatment plant outfall, or through an existing power plant outfall. However, the ambient conditions of the receiving body need to be considered. These conditions include the geometry of the receiving water bottom, and the salinity, density and velocity.

For the ocean outfall, very small capacity plants with production of 400m^3/day or less, an open-ended pipe is constructed, extending about 100m into the tidal zone of the ocean.

For bigger scale desalination plant, hydrodynamic modeling software is used to determine the salinity threshold of the mixing/transport capacity of the tidal zone. This is because if the mass of the saline discharge exceeds the threshold of the tidal zone's salinity load transport capacity, the excess salinity would begin to accumulate in the tidal zone and could ultimately result in long-term salinity increment in this zone beyond the level of tolerance of the aquatic life (Purnama et al, 2004).

The large outfalls are equipped with diffusers in order to provide the mixing necessary to prevent heavy saline discharge plume accumulating at the ocean bottom.

Blending of desalination concentrates with waste water outfalls have shown toxicity impacts on the fertilized sea urchin eggs. This is believed to be due to ion ratio imbalance contributed by the waste water. The ratios of key ions in the TDS rejected by the treatment plant is different from the ions rejected by the membrane process utilizing sea water or similar feed water as the surface open water for disposal.

In seawater most organisms can tolerate a departure of approximately 1ppt (parts per thousand from the normal salinity, which represent a 3% deviation from the ambient conditions.

The cost elements included in the disposal to ocean outfall is;

First conveyance of concentrate to shoreline that consist of:

- ✓ Pump
- ✓ Pipeline
- ✓ Fabrication
- ✓ Trenching of pipeline

Secondly is the pipe from the shore to outfall:

- ✓ Pipeline
- ✓ Possible underwater fabrication
- ✓ Drenching/trenching
- ✓ Outfall structure
- ✓ Pipe diffuser

- ✓ Risers
- ✓ Ports
- ✓ Fabrication
- ✓ Possible trenching

  - **Used for irrigation of crops or landscaping**

Many crops and plants cannot tolerate irrigation water that contains over 1000mg/liter of TDS. Boron/Borates levels in the effluent could also limit agricultural reuse because borates are herbicides. Most plants cannot tolerate chloride levels above 250mg/liter.

This method is applicable for irrigation of salinity tolerant crops or ornamental plants as lawns, parks, and golf fields and is restricted to small scale desalination plant.

Fundamental considerations in land application systems include knowledge of the waste water characteristics, vegetation and public health requirements for successful design and operation. Contamination of the groundwater and runoff into surface water are key concerns.

The following elements are part of the design consideration:

- Salt, trace metals and salinity- the SAR (sodium adsorption ratio) is used to determine the intensity of salt. The formula $SAR = Na/[(Ca + Mg)/2]^{1/2}$ Na is sodium, Ca is calcium and Mg is magnesium, all in unit meq/L (milli-equivalent per liter). When the SAR is greater 9, then the permeability of fine textured soils is affected, and can sometimes be toxic to plants.
- Site selection- a moderately permeable soil capable of infiltration up to 50mm on an intermittent basis is preferred.
- Pre-application treatment- where required the concentrate may be blended with biologically treated waste water before application.
- Hydraulic loading rate- is required in spray irrigation systems. The loading rate is used to calculate the required irrigation area and is a function of precipitation (PPT), evapotranspiration (ET) and percolation (PER). HLR = ET+ PER- PPT
- Land requirements- for spray irrigation include allowances for buffer zones and storage.

  A=Q*KI/ALR, A is irrigation area, Q is concentrate flow, ALR is annual hydraulic loading rate and KI is = $0.00112d*m^3*area/(hr*liters*m^2)$.
- Vegetation selection-depends on location of the irrigation site and natural conditions as temperature, precipitation and topsoil condition.
- Distribution techniques- sprinkling and land application are used for distribution.

- o Surface runoff control- depends mainly on the proximity of surface water. Beams can be built around the irrigation field to prevent runoff.

- **Used for Land application of aquifer recharge**

Concentrate applied to soils may affect either the surface or ground water resources. Blending the concentrate with available lower salinity waste waters may be necessary before land application for artificial aquifer recharge.

3.4.1 Disposal methods analysis

From the six disposal methods given above, the following can be analyzed:

The deep well injection method could be suitable in some parts of Olushandja sub-basin, provided that more data on the geological profile is sampled. From the available data, the profile is not known with certainty how it is laid out across the area. According to data from early 2000, the profile is presented to be percolative, having a sandy soil layer with a depth of up to 600m. However below the 600m, it's not given what earth crust there is. Deep well injections that are reported are typically from the depth of 300 to 2400m.

The latter information is showing that in the Amarika village area, the soil profile has layers of mud and clay from the depth 42m down already. More clay is also sampled from 75 and at 100m in the subsurface. Clay has low porosity and could therefore provide the non-permeable layer needed for the deep well injection.

Deep well injection is one of the methods that can be applied at Olushandja sub-basin, provided the geological profile is known in the site specific area and the source water is monitored closely through the observation wells.

The evaporation ponds is another alternative in Olushandja sub-basin that could be suitable. For this method, mainly land availability and the supporting temperature conditions are the important elements. The characteristic *Iishana* depressions in the area are normally uninhabitable as they pose risk of flooding of properties and houses during the rainy season. The pearl millet irrigation fields in the area are preferable not built in the *Iishana* depressions, due to possible quick inundation by the first rain and the salty patches that remain after each rainy season when the water has evaporated. Unlike the northern block, the southern block of the Olushandja basin has lower population density with larger open surface area. The area has temperature conditions up to $40^{o}C$ and has evaporation figures exceeding the rainfall volumes by a factor of 6 to 8. These conditions support evaporation ponds as suitable disposal option for the desalination brine in the area.

Zero liquid discharge is a method that is not widely practiced yet and it's a high technology option that require allot of capital injection. For the scale of desalination in Olushandja sub-basin and the simple and robust technology needed, this method does not fulfill the conditions of being taken to the area. In some industrialized parts of the world it is just being researched on for possible use, as in Germany, but it's currently in the research and development stage.

On the method of discharge to sewers and surface waters, there are no sewers or perennial surface water running in Olushandja sub-basin. The man-made Olushandja dam in the northern block is a source for the treatment plants in the area and the water is drawn from canal that conveys water from the bordering river to the central part of the Cuvelai basin.

The use of brine for irrigation of crops or for landscaping only need appropriate information as to which crops are tolerant to high salinity exposure. Otherwise landscaping is not a suitable option for Olushandja sub-basin because it is predominantly a rural area that does not feature landscaping.

3.5 Desalination energy sources options

The energy supply source used to power desalination technology can be from conventional non-renewable sources which is; fossil fuel or from renewable sources which are nuclear, solar radiation, geothermal, wind and tidal.

There is great interest in using renewable energy sources for purposes of enhancing environmental compatibility and for decentralization. If desalination is accomplished by conventional energy technology, then it requires the burning of substantial quantities of fossil fuels, which brings in the concern of CO_2 emissions and the greenhouse effect (Gude et al, 2010). For areas without central power supply and where small scale applications for desalination are needed, renewable energy is most probably the only option of choice or most preferred option (Kalogirou, 2005).

According to the available meteorological information, the closest weather station which is in Ondangwa, it is reported that Olushandja sub-basin vicinity has an average temperature intensity of 32^{o}C, ranging from the lowest of 22^{o}C in winter and the highest of 41^{o}C in summer, during the day (NMS, 2010). From this data it is estimated that Olushandja sub-basin has the potential to produce 5.38kWh/m^{2}d solar energy (Schwarzer, 2009).

The following sections give an overview of different methods of acquiring both non-renewable and renewable energy and how they have been sourced and used for desalination:

3.5.1 Non-Renewable Energy

- **Fossil fuels**

Fossil fuels are hydro carbons such as coal, oil and natural gas, which are burnt and the energy released can be harnessed to produce electricity. Oil and gas are formed from the organic remains of marine organisms which become entrained within sea-floor sediments whereas coal on the other hand is formed from the remains of land vegetation. To produce electricity, fossil fuels are non-renewable energy sources, and the geological processes which create them can take millions of years (California Energy Commission, 1994-under www.energyquest.ca.gov). Fossil fuels are used in gas or steam turbines to create electricity, through a process of combustion, into mechanical energy that operate an electrical generator.

The energy used by desalination plants is designed according to the energy type needed, which can be thermal, mechanical or electrical, in various combinations. Conventional energy supply for desalination can be provided through the following possibilities: Steam engine power plant, Steam boiler, Block type thermal power station, gas turbine power plant and combined cycle(gas and steam turbine) (Gebel, 2008). The gas and steam turbine combination is also used to supply the waste heat through co-generation to desalination, and electricity to be used for other applications (domestic and industrial) by the local authority or municipal service providers.

Fossil fuel is the conventional energy supply source supplied via electricity grid; it is used for most of the big scale desalination plants mostly in urban and industrial areas around the world (Gebel, 2008).

Fossil fuel electricity can also be supplied via diesel generators as a source of energy for a desalination plant. Electricity from diesel generators is mostly used for RO, EDR and VC processes. Diesel generators can also be used in conjunction with renewable energy sources to supply energy during the periods when the renewable energy source is unavailable (World Bank Report, 2004).

A diesel generator is the combination of diesel engine with an electrical generator (often called an alternator to generate electric energy (World Bank Report, 2004). They are in most case used in areas where there is no connection to power grid and come in sizes ranging from 1kVA to 10 kVA, the small portable ones. A diesel generator use the portable option of energy supply. It is in most cases used for augmentation or for standby in the desalination processes. This ensures continuity and no interruptions in the case of fluctuations or low conduction of energy supply to the process of the highly sensitive desalination technology options.

- **Nuclear Energy**

Nuclear reactors, which can be a pressurized water reactor or boiling water reactor are used and are fueled by either uranium or plutonium to produce electricity. Energy is released from uranium when an atom is split by a neutron. As the uranium atom is split into two, energy is released in the form of radiation and heat. This nuclear reaction is called fission process. In a nuclear power station, the uranium mineral is first formed into pellets, and then into long rods. These uranium rods are kept submerged in water to keep them cool. A nuclear reaction takes place when these rods are removed from the water, causing heat. The amount of heat required is controlled by raising and lowering the rods in the water. The raising increases the heat, whereas the lowering decreases the heat (IAEA, 2002).

Nuclear energy is categorized as a non-renewable energy source and it’s endorsed for use of desalinating sea water to curb water shortages (American Nuclear Society, 2005). Japan and Kazakhstan are reported to be among the long experienced users of nuclear reactors for desalination (Majumdar, 2002).

The most common energy generation facilities used for desalination are: Pressure Water Reactor (PWR) and Liquid Metal-cooled Reactor (LMR).

The PWR reactor is used on RO, MSF and MED desalination processes so far, that are having capacities ranging between 200 and 3900m^3/d and salinity of 35 000ppm, in Japan.

The LMR is used in Kazakhstan, on a capacity of 80 000m^3/d and salinity averaging at 13 500ppm, using MSF and MED desalination processes.

The nuclear energy in general is reported to be covering 16% of the world energy supply.

3.5.2 Renewable Energy

- **Solar radiation**

Solar radiation as a source can be used to produce heat through solar thermal systems or electricity using photo voltaic systems (Gebel, 2008).

In a solar thermal process, energy is in simple terms used to evaporate water, separating pure from brine. Solar thermal collectors are used to convert solar radiation into thermal energy. There are two types of solar thermal energy collection, which are non-concentrating or stationary, and concentrating. The non-concentrating collection device has the same area for intercepting and absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun beam radiation to a smaller receiving area, thereby increasing the radiation flux (Chaibi et al, 2009). For converting solar radiation into thermal energy, there are special kinds of heat exchangers that transform solar radiation energy to internal energy of the transport medium (Elsayed et al, 1994.

The stationary collector types are; salt-gradient solar ponds, flat plate collectors, evacuated tube collector and compound parabolic collector. The concentrating devices has the collector types; linear Fresnel reflector, parabolic trough collector and cylindrical trough collector, as single axis tracking. The two-axis tracking concentrating devices are dish reflector and heliostat field collector (Chaibi et al, 2009).

Solar ponds can produce thermal energy at temperatures in the range of 50-100^oC. Flat plate collectors can produce thermal energy at temperatures in the range 70-200^oC. Concentrating collectors produce thermal energy in a wider range of 90 to 350^oC.

Solar thermal energy is used on the following desalination processes through solar energy collectors: Solar Stills, Solar Stills combined with Greenhouses, Multiple Effect Distillation, Membrane Distillation, Humidification/Dehumidification, Multiple Effect Humidification, Thermal Vapor Compression and MSF plants.

Photovoltaic (PV) systems directly convert the sunlight into electricity by solar cells. These solar cells which are also referred to as PV cells are made from semi-conductor materials as silicon. PV cells are the semi-conductors that produce electrons when photons strike the surface producing a few watts of direct current. The PV cells have conductors called contacts to collect electrons and have surface coatings to reduce light reflections. The PV cells are interconnected in groups of 72 or more, to form photovoltaic modules. The PV modules are combined in any number to form an array, which supplies the power load required. With the PV module, power conditioning equipment which are charge controller and inverters, and energy storage equipment which are batteries, are added to supply energy to a desalination plant.

Photo voltaic can drive processes using electric energy, such as mechanical vapor compression and reverse osmosis (Fiorenza et al, solar desalination for the 21st century). According to Fiorenza, for low-to-medium scale desalination applications, the coupling options with the highest potential are the RO process powered by photo voltaic modules.

- **Wind**

In a typical wind turbine, the kinetic energy of the wind is converted to rotational motion by the rotor. The rotor turns a shaft which transfers the motion into the nacelle (large housing at the top of a wind turbine). From the nacelle, the rotating shaft is transferred to the gearbox that greatly increases the rotational shaft speed. The resulting high speed is converted to a generator that converts the rotational movement into medium-voltage electricity. The amount of energy which the wind transfers to the rotor through the blades depends on the density of the air, the rotor area and the wind speed (Tzen, 2009).

The wind speed is very important for the amount of energy a wind turbine can convert to electricity. A typical mean annual wind speed required for a viable development is around 7m/s, but turbines utilizing mean speeds of 5m/s are also in operation.

Wind turbines can be used as standalone to power RO desalination process or it can be used as a hybrid system with photo voltaic or diesel generator and batteries in remote locations. Wind/RO units is the second most installed renewable energy combination, after photovoltaic/RO coupling (Tzen , 2009).

- **Bio-fuel**

Biofuels are generated from biomass in three categories, namely;

- ✓ Edible sugars and starches
- ✓ Non-edible plant materials
- ✓ Algae and other microbes

Sugars and starches are used to generate bioethanol, which is an alcohol made by fermenting sugar components of plant materials. T

The plant materials are also used to produce ethanol, which is used in vehicles or as an additive to increase octane and improve vehicle emissions.

Biodiesel is the other type of energy produced from vegetable oils, animal fats, or recycled greases.

No information could be obtained of desalination plants utilizing biofuels within the boundary criteria above.

3.5.3 Analysis of available energy sources

Olushandja sub-basin is isolated from the main grid of conventional electricity supply. The options are to draw electricity from the closest grid supply, or utilize the renewable sources of energy available. Else, the portable energy sources by means of diesel generators are also potential alternatives.

The available information shows that, Olushandja sub-basin has a number of renewable energy sources available which can be explored for use, as alternative and locally available options. The conventional energy source is only available in the southern block of the sub-basin and can be considered as the first locally available energy source in that part of the sub-basin.

The nuclear energy may be an option if it's considered in relation to the availability of uranium mineral which is mined at the western region of the country, Namibia. But there are currently no nuclear power plants in Namibia that generate nuclear energy, only uranium mineral extraction mining.

The diesel generators are used in some of the remote rural areas for abstracting ground water for use by the village dwellers, where there is no electricity supply. These diesel gensets require monthly maintenance and continuous supply of diesel fuel, which has to be transported from urban centers monthly or biweekly as well. The desalination processes need allot of energy and continuous supply. The use of diesel gensets in the remote rural centers need secured stocking and storage warehouse. The presence of diesel availability on the desalination infrastructure premises increase the risk of vandalism and possible tampering with the infrastructure which may be induced by the presence of diesel gensets and diesel fuel. Diesel gensets and diesel fuel are common sources of electricity supply, sources of fuel supply to motor vehicles and sources of fire lighting in the rural conditions generally.

The wind energy is an alternative locally available source of energy for the desalination technology and if explored optimally may be available for the community as well. However, the known wind velocity as given earlier is only 4 – 6m/s, assumed from the world map and from the readings along the northwest coastal zone of the country. Allot more and specific data need to be collected in the Olushandja sub-basin to prove the actual wind velocity available and its sustainability for energy supply. There is great potential in the use of wind as an energy source. The relatively flat plain of Olushandja sub-basin and the robust wind energy infrastructure will suit the conditions of the remote rural conditions. The variable speed in the wind velocity is supported with feedback control system for operation of the variable pressure needs in the wind-driven pumping system and the pressure driven membrane processing subsystems, as given in the scheme of Oahu, Hawaii. This state of the art technology progress is among the robust qualities of wind energy that is needed for the rural and remote conditions. The use of wind energy is limited for use with membrane processes, as it generates electricity that can be used to drive the mechanical processes but not the thermal processes directly.

The solar energy in Olushandja sub-basin is the other locally available source of energy supply. The recorded information shows that Olushandja sub-basin has potential energy of 5.38kWh/m^2d, according to NASA analysis shown in **Figure 13, on page 21**. Solar radiation or temperature data in the Olushandja sub-basin is recorded regularly by Namibia meteorological services, and therefore accurate energy availability can be derived and its sustainable use can be projected.

The solar energy can be utilized to drive both membrane and thermal (phase change) processes. The solar radiation can be collected via thermal collectors to provide thermal energy, as well as via the silicon solar cells and photo voltaic modules to generate electricity.

Olushandja sub-basin has high temperature conditions and sunshine during most part of the year. This provide for a continuous source of energy supply for the operation of the desalination technology in the remote rural areas.

The energy needed for supply to desalination technology from the solar radiation can be drawn in the needed quantities via the systems capacities installed, PV cells or solar collectors. Heat storage is one of the main elements in the choice of energy source collection. Storage has economic advantages of extended operation, especially at night when some of the energy sources are not available.

In the solar thermal collection devices, energy is stored in the medium used for heat collection. This is either in the water, the solar pond or by heat insulation with absorbing coating. Vacuum insulation support sustainable storage by eliminating the heat loss that is due to convection and conduction.

In the PV cells technology, energy is stored in the batteries, through conversion from direct current to alternative current.

Diesel generators are used to curb fluctuations where storage from the solar devices is not sufficient to sustain the energy need of the desalination technology.

Wind and PV are used as mix energy suppliers in some desalination plants, with the different sources supplying different units in the process, as the desalination unit and the electronic support system (controls and computers) unit separately.

Alternatively, obtaining heat and electricity from the various sources comes at a different rate and thermodynamic process. The solar radiation required to be converted to electricity in order to supply membrane desalination is more than the radiation required to supply heat energy to a solar collector for thermal energy.

In the current practice, where energy is unavailable in the remote villages in Northern Namibia, the communities are utilizing Lister engines (where provided by the government), with one cylinder diesel capacity to abstract groundwater for consumption. The Lister engines are estimated to cost 24 000N$, with a maintenance expenditure of around 3100N$ monthly, excluding transport costs.

There is a cost in acquisition of assets and facilities, in using the diesel generators, the communities will remain with the monthly maintenance costs. The use of solar energy has an initial capital injection of acquiring the equipment needed to collect and store the solar energy, but may evade monthly maintenance costs related to energy consumption.

Chapter 4: Discussion and Evaluation

4.1 Overview and selection of evaluation methods

Generally, a raft of decision tools or frameworks exists to help decision makers' deal with complex problems that need to be taken positions on. Some of these tools are; cost benefit analysis (CBA), cost effective analysis (CEA), cost utility analysis (CUA) and multi-criteria analysis (MCA). Except for MCA, the other three CBA, CEA and CUA tools are economic evaluation frameworks that require monetary units as inputs for quantifying projects' viability for decision making (Hajkowicz, 2007).

The CBA requires the benefits or positive impacts of measures to be expressed in monetary terms. The ranking and scoring is based on the net present value, benefit-cost ratio or internal rate of return, with the outcome being measured in money units. The CEA tool on the other hand is an analytical technique designed to compare the costs and effectiveness of alternative measures. The MCA is viewed as a tool that gives strategic direction, using alternatives, targets, criteria and indicators to weigh the options according to the technologies' performance and assigned rankings (Mysiak, 2001).

An effective way to make a decision requires an explicit structure for jointly considering technological, economic and ecological factors relevant to evaluating alternatives and then making that decision. In order to integrate this heterogeneous information with respect to human aspirations and technical applications needs a systematic and understandable framework. The MCA approach has that framework for ranking or scoring the performance of decision options against multiple objectives. This framework further provides the tools and processes to help the decision maker resolve tradeoffs in a transparent, auditable, and analytically robust manner. The emphasis in the MCA is on decision making and the value measurement is a means to that end. Unlike the above monetary analysis tools, the MCA weights are specified by the decision makers, while the cost analysis, are derived from the market place (Keeney et al 2003).

In many studies, the MCA tool was found to provide transparency and accountability to decision procedures which may otherwise have unclear motives and rationale. The MCA uses formal axioms of decision theory to inform the choice and this framework ensures a robust analysis whilst permitting non-financial and distributional issues to be incorporated.

The evaluation of desalination technology has assessment groups that cover a wide spectrum that include environmental, technical and economic fields. The MCA is therefore found to be the suitable tool in this classification that does not exclusively require monetary units for evaluation. However, the MCA is an umbrella approach with several methods for evaluations.

The MCA represents a body of techniques that are classified as follows, according to Hajkowicz, et al, 2008:

- **Multi criteria value functions**

This is the weighted summation model that is expressed by the following formula.

$$U_i = \sum_{j=1}^{m} v_{i,j} w_j \qquad \mathbf{1}$$

The weights w_j are not negative and they sum to 1 or 100%, $v_{i,j}$ is a transformed performance score on a scale of 0 to 1 or 0 to 10, The overall performance score is given by U_i.

This approach includes the multi attribute utility theory (MAUT) and utility value analysis methods.

- **Outranking approaches**

Apply a utility function which contains criteria weights that determine the amount the one option outperforms another. A pair of decision options is identified and used one at a time. Examples of this classification are the promethee and the electre methods.

- **Distance to ideal point method**

In this MCA category, first ideal and anti-ideal values are identified for the criteria. Then decision options that are closest to the ideal and furthest from the anti-ideal are identified. Where no ideal or anti ideal can be defined, the minimum and maximum criterion values are used. This classification uses the compromise programming, exprom and topsis methods.

- **Pairwise comparisons**

In this approach, pairwise comparisons are involved. Criteria and alternatives in every unique pair are compared, to attain criteria weights and decision option performance scores. They use scaling systems, where the decision maker for instance is asked to express preference for one criterion or option over a nine point scale. Examples of this approach are the AHP (Analytic Hierarchy Process) and Macbeth methods.

- **Fuzzy set analysis**

This is based on a gradual transition from one class to another. In an uncertain situation where an element is partially linked in multiple sets of criteria, the fuzzy approach is used.

- **Tailored methods**

These are adapted methods created to fit the specific needs. One such adapted method was developed under the weighted summation, to create “reliability based approach” to MCA involving the use of rank correlation coefficients (Hyde et al 2004).

The most important part of the MCA approach is the selection of criteria and decision options. An MCA model has always at least two criteria and two options (Hajkowicz et al 2008). The multiple criteria analysis tool further mainly places the focus on choice behavior.

Criteria that cannot be quantified or enumerated with a differentiation among the desalination techniques are normally knocked out or eliminated from the list of evaluation. Such criteria in this study were either enlisted as part of the selection criteria or are eliminated entirely for the evaluation consideration.

The utility value analysis tool belongs to the classification of multiple criteria analysis tools. The preset model in this case is the utility value analysis tool.

In this evaluation mainly the technical performance data under the technical assessment list and a few from the environmental and economic assessment objectives will be used to rate and rank the various desalination options.

4.2 Utility Value Analysis

The utility value analysis approach of Zangemeister is used to rate and rank the criteria of the various desalination technologies chosen. In a utility value analysis the various attributes are ordered by a hierarchically constructed decision system (Hajkowicz, 2008). From an economist point of view the utility analysis approach generally represents the value of goods and services. This approach is split into three steps, which are; the trade-off among two or more goods, the empirical measurement of utilities and utility under uncertainty (Kleijnen, 1980).

Unlike, the few analysis tools that are described above, the utility value analysis deals with criteria that do not necessarily require monetarisation of ecological services, making it the appropriate decision support system for the evaluation of the desalination techniques in this study. The decision options are scored against criteria with performance measures, having specified objectives. The utility value analysis tool is relevant for use in evaluating the desalination technology performance' benchmarks in this case because they are normative values of performance from a widely available pool of data that is recorded under various conditions and scales. With transformations under the utility value tool, the benchmarks can be transformed into quantifiable units that can be compared against each other within the same performance group. In these evaluations, the performance benchmarks are classified into assessment groups named environmental, economic and technical. The utility value analysis tool, under the multi-criteria umbrella, deals with both the economic and technical performance indicators, unlike the CBA, CEA and CUA that only evaluate monetary indices and units.

The utility theory utilizes the valuation matrix and algorithms. This matrix approach uses numerical scores to communicate the merit of each option on a scale. Scores are developed from the performance of alternatives with respect to individual criteria and then aggregated into an overall score. The goal is to find a simple expression for the net benefits of a decision.

The valuation matrix has an approach in which all possible objective grades are mapped onto the interval [0, 10]. This valuation is supported by related interval classes, which are described by verbal valuations from “very bad” to “very good”. According to Zangemeister, the decision maker can choose the objective weights without restrictions. However, in order to determine the weights, one has to apply the pairwise comparison. This means that when a utility is changed, it must have an effect on the objective. Well-defined weights sum normalize to 1 or 100%, whichever absolute value unit is assigned. Alternatively, the aggregation of values is made by weighted addition of the partial utility values under the precondition of a strongly preferential independence of the objectives and cardinally scaled numbers.

The following stages, as proposed by Hajkowicz et al, are taken sequentially to build up the valuation matrix.

- **Decision options**

A list of desalination techniques are selected based on a list of set selection criteria. These techniques are the options for decision making that will be weighted, ranked and scored.

- **Evaluation criteria**

A number of criteria are identified from the options chosen. These criteria are carefully selected against the crucial performance elements that give value to the options chosen. The criteria are grouped into target assessment groups. These target assessment groups are the objectives of scrutiny for the criteria and performance benchmarks by the techniques selected.

- **Performance measures**

The performance measures are drawn from the industry benchmarked performance standards of the selected desalination techniques.

- **Transformation of units**

The criteria with different units are transformed into commensurate units. This is done through formulas that are shown transparently. Refer to **Formula 1 on page 84 Formula 2 on page 89** and the practical approach used obtaining the transformations for the various criteria in the assessment groups.

- **Ranking, weight assignment and calculations of the options**

The criteria are ranked in four groups, namely; very important, moderately important, lowly important and irrelevant criteria. These three groups are assigned weight numbers of 4, 2, 1 and 0 for the environmental assessment group, 3, 2, 1 and 0 for the technical assessment, and 6.25, 1.5, 0.75 and 0 for the economic assessment group. The bigger number is for the most important and the least for the lowest rated which is the irrelevant criteria.

The total number of ranking from the criteria is used to obtain the measuring weight, through the formula: ***1 / (Number of important criteria *assigned level of importance + Number of moderate importance criteria * assigned level of importance + Number of criteria with low importance * assigned level of importance + irrelevant criteria * 0).***

- **Criteria weights**

The weight obtained from the formula is used to assign specific weights of the criteria in the valuation matrix. For example, the criterion that is rated important will have its rank of 4 being multiplied by the total weight obtained from the formula above, to give the weight target.

- **Sensitivity analysis**

The sensitivity analysis is the second last activity to be undertaken in the stages. A systematic variation of the weights, performance measures and ranking algorithms will be applied to see the differences in the robustness, consistency and reliability of the analysis tool.

- **Decision making**

The decision to be taken will be based on the summation of partial utility net score as an ordinal value, together with cardinal rational issues related to the techniques and raised in the study.

4.3 Transformations

Table 11 below presents the transformations that are compiled from the standard performance benchmarks of the selected desalination techniques. The performance benchmarks of the criteria come in different units that need to be transformed into commensurate units, prior to aggregation in the ranking or scoring function (Hajkowicz, 2008). In this table, the empirical data that is having the best performance case is assigned the upper limit and the empirical data with the lower performance is assigned to be the lower limit.

To determine the level of performance by the specific criteria for the evaluation, the following generic formula is used and amended where necessary to express the correct outcome:

$$V_{i,j} = \frac{X_{i,j} - \min_{j=1}(X_{i,j})}{\max_{i=1}(X_{i,j}) - \min_{i=1}(X_{i,j})} \qquad \mathbf{2}$$

$X_{i,j}$ is the performance standard, *min(Xi, j)* is the lower limit, *max(Xi, j)* is the upper limit and *Vi, j* is the target achievement in the evaluation results tables, **Tables 12 – 27**.

The criteria are expressed as follows based on formula ***2:***

- ✓ GOR = (Upper limit – performance standard)/(Upper limit – Lower limit)
- ✓ Recovery rate = Performance standard/ Upper Limit
- ✓ Prime Energy consumption = (Lower Limit – Performance Standard)/ (Lower limit – Upper Limit)
- ✓ Mechanical and Heat energy demand = (Lower limit – Performance standard)/ (Upper limit – Lower limit)

- ✓ Operating Pressure and Temperature= (Lower Limit – Performance standard)/ (Lower limit – upper limit)
- ✓ Sensitivity to feed water quality= (Lower Limit – Performance Standard)/ (Lower limit – Upper Limit)
- ✓ Brine disposal = (100 – recovery rate)/ 100
- ✓ Pre and Post treatment= (Lower Limit – Performance Standard)/ (Lower limit – Upper Limit)
- ✓ Permeate Quality= (Lower Limit – Performance Standard)/ (Lower limit – Upper Limit)
- ✓ Running and Water generation Costs= (Lower Limit – Performance Standard)/ (Lower limit – Upper Limit)
- ✓ The scaling, fouling and corrosion are assigned values based on commensuration as follows:

On a scale of 0 to 100%, 0 is used as the worst case scenario in the lower limit category and 100 is the upper limit and the best case scenario. On this scale where low is the lower limit, its assigned 0%, with high as the upper limit at 100%. A moderate case is regarded as a midpoint between 0 and 100%, which is 50%.

For sensitivity to feed water quality criteria, the limit of the feed water that a particular technique is best suited to treat is used to differentiate and give scores for the various techniques. Alternatively, for pre and post treatment activities, the impacts treated and the activities undertaken are used for scoring. For pretreatment of scaling, fouling, bio-fouling chlorination and corrosion, the techniques are assigned numbers out of 4 according to the pretreatment needs most required for the particular technique, as given in **Chapter 3** under the membrane and thermal processes. Similarly for post treatment, **Table 10, page 68** is used to assign scores according to the post treatment needed by each technique.

The formulas above produce the target achievement for each desalination option that is needed to calculate the partial utility that is summed up for the final score. The target achievement and partial utility values are shown in the evaluation results table in the next section.

The transformation is further subdivided into three assessment groups which are; technical, environmental and economic.

The three assessment groups signify the objectives of performance. While the best technical performance is sought for producing potable water needed for the people of Olushandja sub-basin, the techniques performance for sustainable environmental conditions and producing affordable water on a long-term basis for the rural people of Olushandja sub-basin is briefly reviewed.

Table 11: Transformations Table

Indicators	Strategic Guiding Question	Unit	Upper limit	Lower Limit
Technical Assessment				
Gained Output Ratio	MD(3-6), MSF(8-12), MEH(6-8), MED(10-14)		14	3
Recovery Rate	RO(25-40), MD(45-60), MEH(70), MED(0-65), ED(85-94), MSF(25-45)	%	94	0
Pretreatment Requirement	MD(3), RO(3), MEH(1), MSF(2), MED(2), ED(3)	Activities required (Table 9)	1	3
Sensitivity to feed water quality	MD(30 000), RO(40 000), MEH(95 000), MSF(95 000), MED(95 000), ED(12 000)	ppm	95000	12000
Post-treatment Requirement	RO(2), ED (2), MD(4), MEH(4), MED(4), MSF(4)	Activities required (Table 10)	2	4
Operating temperature	RO(15-40), MD(60-80), MEH(80), MSF(100), MED(70) ED(15-40)	°C	15	100
Operating Pressure	RO(15-25), MD(atmospheric)	Bar	15	25
Scaling and Fouling potential	MD(high), RO(high), MEH(moderate), MSF(moderate), MED(moderate), ED(high)	low/moderate/high	moderate	high
Corrosion Susceptibility	MD(low), RO(moderate), MEH(low), MSF(high), MED(high), ED(low)	low/moderate/high	low	high
Permeate Quality	MD(12.8), RO(200-1000), MEH(10), MSF(10-50), MED(5-10), ED(140-600)	ppm	5	1000
Environmental Assessment				
Brine Disposal	RO(67.5), MSF(65), MED(67.5), ED(10.5) MEH(30), MD(47.5)	%	10	68
Heat Energy input	MSF(294), MED(123), MEH(362), MD(392.4)	kJ/kg	123	393
Mechanical and/or Electrical power input	RO(5-13), MSF(2.5-4), MED(2.2), ED(5-12) MEH(7.5), MD(12.3)	kWh/m^3	2	13
Prime Energy Requirement	MSF (338.4), MEH(432), RO(120), MD(540), MED(149.4), ED(144)	kJ/kg	120	540
Economic Assessment				
Running costs	Operational cost for desalination methods based on $10m^3$ /day scale, using solar energy-MEH(0.7-0.94), RO(1.4-2.1), MED(2.1 -2.8), ED(0.32 for 5011ppm plant), MSF(1.94 for $0.8m^3$/d), MD(0.86)	€/m^3	0.32	2.8
Water Generation Cost	MSF (10-15), MEH(3-5), RO(5-7), MD(8-15), MED(8.12), ED(8-9)	€/m^3	3	15

4.4 Techniques and Criteria Evaluation

For techniques and criteria evaluation as given above, three categories namely: most important, moderately important, criteria of low importance and criteria of irrelevance to a technique are used for weights assignment. The figures of 3, 2, 1 and 0 are correspondingly assigned for weights calculations. Using the formula on page 87, under the title "Ranking, weight assignment and calculations of options", the evaluations has yielded different weights of target, depending on the level of importance of each criteria. The most important factor here is that, the total from the distributed weight-of-target among all criteria should sum up-to 100 per cent. As well as the weight-of-assessment column should also yield a sum of 100 per cent from the three groups.

The target achievement is 100% when the technique is either not affected by the criteria conditions, or has achieved the best performance standard as reflected in the transformation table, **Table 11, page 90**. However, when the level of importance becomes irrelevant, having an assigned value of zero, the partial utility and the weight of target for such criteria turn out to be 0 per cent. Otherwise, the target achievement result in the evaluation results' tables is according to the technique performance on the scale used for calculation, according to ***Formula 2, page 88***. The weight target when summed up is to give a total of 100%, according to ***Formula 1, page 85***. This is called an indication of normalization in the algorithm.

The weight-of-target has direct influence on the criteria objectives, which are technical, environmental and economic, evaluated under the column weight-of-assessment. **Appendix B** has the detailed evaluations and results of all desalination technologies in all three assessment groups. These objectives have the weight assessments that should also equal to 100 percent for a good normalization in the algorithm. The weight assessments are used for sensitivity analysis for which weights assignments are changed among the three objectives, with the focus group being set higher than the other two at a time.

The partial utility is obtained from multiplying the weight target and the target achievement. This column is calculated for each criterion and then summed up to give the final score for the technique. This score is used as an ordinal number to rank the techniques.

Gained Output Ratio

The GOR is a measure of the total distillate produced, divided by the steam consumed. In most cases, the temperature of the condensate in the boiler is used for getting the output of the GOR, instead of the actual steam flow. The GOR is used to measure the thermal efficiency of the thermal (or phase change processes). The GOR in these evaluations range from 3 to 14 and they are only relevant for the thermal processes. The thermal processes use heat energy for the processes of steaming and distillate production through condensation. The specified GOR measure for a distiller is part of the thermal technology design and manufacturing expected performance.

The RO and ED are excluded from **Table 12** below. The two processes are membrane based techniques, and heat induction is not part of the desalination processes that can be evaluated for the two techniques' effectiveness.

The MD process has scored the lowest for GOR performance because it has thermal efficiency of 3 to 6 (Rommel et al 2007). The MED process' equipment design alternatively provide for greater thermal efficiency, with a GOR ranging from 10 to 14 (Kalogirou, 2005), hence the target achievement of 82%, which is the best case scenario in this criteria. For every range, an average or mid-point is used for evaluating the technique.

Table 12: Gained Output Ratio results

	MD	MEH	MED	MSF
Target achievement	14%	36%	82%	64%
Performance standards	3-6	6-8	10-14	8-12

The MSF process is designed with a GOR performance figure ranging from 8 to 12 (Eltawil et al 2009), the average of 10 is used in this evaluation.

The GOR score for MD and MEH are 14 and 36%, indicating lower thermal efficiency. The MEH GOR is between 6 and 8 (Muller-Holst, 2007) and has greater heat retention or recovery in its process, compared to the MD process, hence the difference. The MD process operates between 60 to 80^{o}C temperature range, while the MEH operate at around 80^{o}C and recover the latent heat through temperature stratification designs in the system.

The GOR is further used to monitor the processes effectiveness through regular maintenance and control through standard operations procedures (SOP). The maintenance requirements and SOP are normally part of the commissioning information and design documents handed over by the contractor.

The GOR reading that falls below the design value of the technique is partially used as an indication for maintenance needs or as a breakdown in the process that may need to be assessed.

GOR are monitored for each stage, stack, effect or compartment in a thermal process and normally consistent or comparable figures are expected to be obtained from these sub-section.

GOR is low in a thermal process when the tubes are scaled or fouled; the stages are filled with condensable gases, and when the distillate spill during vigorous flashing off.

Error in the reading or metering of the distillate or condensate flow has an impact on the GOR calculation.

A higher GOR reading means better performance in the thermal efficiency of the particular process. GOR is well maintained when the there are no losses of heat from the thermal process sub-sections/ water boxes, when the heat recovery sections absorbs the heat effectively, when the acid cleaning is carried out as needed to keep the scale and sludge out of the tubes inner walls and when the non-condensable gases are vented from within the heat transfer tube bundles.

The brine transfer orifices and the distillate transfer orifices needs to be controlled accurately, such that there is balance in the flow and controlled flashing or boiling. Efficiency of the distillers are affected when the sizes of the orifices openings are either too narrow causing high brine levels or too wide giving low brine levels. High brine levels affect the height below the demister

and could carry over brine to the distillate tray. A low brine level risk high temperature vapor leaking or slipping into the downstream (next compartment), before effective distillation takes place.
The thermal efficiency can also be improved when a compartment temperature is reduced, by adding more stages. An increase of more stages increases the tube surface area, while decreasing the temperature. It is documented that an extension of stages from 14 to 18, reduces the temperature from 2.8 to 2.2, giving a GOR increase of 8%, for an MSF thermal process. In an MED process, the GOR is highly linked to the number of effects, as the steam from the preceding effect travels directly to the next and preheat the feed water. An MSF process of 13 to 35 stages could have the same GOR measure of 10, while an MED process GOR of 10 can only be for 13 effects.
For solar energy collection, the GOR does not account for the solar collector efficiency, but only the heat obtained by the solar collector. For the MEH and MD processes to improve on their GOR measure, a significant amount of energy needs to be consumed by the process. A GOR of at least 8 may require an energy consumption of around 300kJ/kg. The MEH process recovers the latent heat of condensation in their system to keep their GOR values higher, from the initial low of a typical humidification/dehumidification processes.

Recovery Rate

The recovery rate is the amount of water recovered from the total feed water processed through the desalination sequence. The desalination techniques have recovery rates limits in the designs of the techniques' infrastructure and are demonstrated during commissioning by the contractual performance tests. This parameter is also referred to as the extraction efficiency of the system.

The ED process has the highest target achievement of 95% in the recovery rate criteria from the performance standards range of 85 to 94 percent (Eltawil et al 2009), according to **Table 13** below. An average figure of 89.5 percent is used for the evaluation. Among all the processes, the ED process has a limit of 12 000ppm to the feed water quality it can treat, due to economic reasons. Higher concentrated water will be inefficient for treatment by an ED system, as it will use more energy to recover more clean water.

Table 13: Recovery Rate Evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	35%	95%	56%	74%	35%	40%
Performance standards (%)	25-40	85-94	45-60	70	0-65	25-50

The MEH and MD processes are having good scores in the recovery rates, compared to the other two systems of thermal processes, at 74% and 56% in target achievement. The recovery rate figure for the MD process ranges between 45-60 percent and for MEH is at 70 percent consistently (Muller-Holst, 2007).

The potential production in the thermal process can be changed, by changing the brine temperature, while in the membrane process, specifically the RO, the pressure application can change the production rate. A higher brine temperature increases the production in the thermal and increased pressure also increases the production in the RO process. However, these two variables in both the thermal and RO processes have a direct impact on the energy use in the desalination techniques.

This criterion is different for each desalination process based on the techniques utilized and can be changed based on the capacity of the infrastructure and the energy available.

This criterion is used to measure the amount of water produced relative to the original design capacity. In an event where the infrastructure is underutilized, the reserve capacity can be used for the planning of maintenance. This is by taking out some compartments or modules for proper service. The extra capacity can also be used for potential savings on energy or as standby facilities by being taken out of operation during the low demand period.

For thermal processes, the load factor measure is used to measure the production of individual distillers against the expected design production rate and the hours in operation. Where the load factor exceed hundred percent, it signify good availability and have been operated above the original specified production rate.

For some desalination processes, the recovery rate is deliberately reduced to have less concentrated brine that would otherwise require complicated pre-treatment before disposal.

Pretreatment Requirement

Pretreatment is mainly essential for proper operation of RO and ED systems. It is applied to control the biological fouling, metal oxides fouling and scaling of the membranes. The feed water for ED systems is limited to 12 000ppm, and therefore do not require allot of pretreatment, as the RO system that treat up to 40 000ppm water.

Table 14 is showing the target achievement based on the pretreatment requirements of the various techniques. The thermal processes do not require pretreatment of the feed water in essence, as mainly screening as a minimal pretreatment is needed in the first step of the process. However, pretreatment of the returning water (make-up water) is required to protect the system against scaling and corrosion mainly. Due to high temperatures for operation, bio-fouling is intermittently treated to prevent bacterial growth from organisms slipping in the system. The two thermal processes MED and MSF are assigned 2 each for the treatment against scaling and corrosion. The MEH process is a contemporary desalination process that uses polyethylene materials and do not have a problem with corrosion problem, hence the allocation of 1 out of four pretreatment activities and this is for scaling mainly.

Table 14: Pretreatment evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	33%	33%	33%	100%	67%	67%
Performance standards	3	3	3	1	2	2

Pretreatment is an important part of the membrane processes and is therefore assigned the highest number of prevention activities. The number 3 for the three processes that uses membranes as part of their desalination processes is for the prevention of scaling, fouling against colloidal particles settling on the membrane and the required chlorination control against bio-fouling in the process.

The membranes are susceptible to the buildup of minerals, bacterial attacks and high concentrated brine containing colloids that polarize the membrane surface. The feed water needs conditioning with pretreatment to preserve the membranes and sustain their integrity for longer.

In the latest technology of ED, an EDR component with reversal valves is incorporated. In an EDR system, the polarity of the DC power is reversed two to four times an hour, to help prevent the formation of scale on the membranes. The system is further equipped with a clean-in-place unit to allow periodic flushing of the membrane stack and piping with an acid solution. The only difference between the ED and the RO scaling controls are that, the ED system is able to operate with an SDI of up to 12, whereas the RO SDI can only be up to 3, and then the system would need membrane acid cleaning.

In the thermal processes, the pretreatment is applied to control fouling, scaling and corrosion, due to the high temperature operation environment. In the processes of distillation in the thermal techniques, the feed water quality does not limit the actual effectiveness of the desalination activity. The impacts of scales and corrosion are treated to protect the integrity of the infrastructure and the process efficiencies.

Pretreatment in the thermal processes is applied to the make-up water and cooling water. This is water that has been through the system and its concentration and temperature is higher rendering higher risks of scaling, fouling and corrosion. The heat exchanger surfaces are affected by scales from calcium and magnesium salts and the corrosion occur due to the dissolved gasses. The inlet feed water is screened to ensure that turbidity or suspended solids and the quantity of organic and inorganic foulants are within acceptable range for the desalination process equipment.

Sensitivity to feed water quality

The sensitivity to feed water quality corresponds to the pretreatment needs and the resultant problems of fouling and scaling in the membrane processes. The thermal processes are not sensitive to feed water quality and can therefore desalinate feed water of higher salinity compared to membrane processes.

Table 15 is reflecting the difference between the membrane and the thermal processes in this criterion. The ED and RO membrane processes have scored lower because the feed water have to be pretreated for optimal desalination to occur and above this there is a limit to the salinity level in the raw water that can be desalinated effectively and efficiently.

This feed water salinity limit that the various desalination technique can treat most effectively and efficiently is used in this criterion for scoring. The sensitivity for the three thermal processes, MEH, MED and MSF is set at the limit needed for Olushandja sub-basin, the literature presented repeatedly that the thermal processes are insensitive to feed water quality. The MD process constitutes both membrane and thermal activities in the system. The membrane sub-unit can be impacted by high loads of solutes in the feed water. Partly the steam volatility is affected, and the membrane blockage would occur limiting the distillate diffusion through the hydrophobic membrane. The limit is set at 30 000ppm in consideration of the water quality of Olushandja sub-basin. This is in accordance with the preliminary results of the MD process pilot scheme in Olushandja sub-basin that is showing the scheme to be only coping, but needing amendment to the infrastructure.

Table 15: Sensitivity to feed water quality evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	34%	0%	22%	100%	100%	100%
Performance standards (ppm)	40 000	12 000	30 000	95 000	95 000	95 000

The membrane processes are highly sensitive to the feed water quality, hence the requirement for pretreatment. The ED process is limited to 12 000ppm (Valero et al 2010), the RO can treat the sea water of up to 40 000ppm. The electric field and the selection of membranes to be used are highly dependent on the feed water quality, determined by the ions to be removed. The ED process is only limited to treat water up to 12 000ppm. Due to this limit and ion selective membrane stack, the ED process is insensitive to feed water quality. The limit is due to economic reasons, the more saline the water is, the more energy is required to run an ED process.

Higher salinity for the RO process may prove to be uneconomical, as more frequent maintenance will have to be executed to clean the membrane and service the high pressure pumps. More energy is needed to clean higher salinity of water, membrane replacement may be higher and cleaning chemicals may also be required more for RO process.

Source water quality is one of the defining criteria in choosing the suitable desalination technique for a specified site.

Thermal processes are insensitive to feed water quality and can produce the same permeate quality, regardless of the feed water quality.

The advantage of minimal need for pretreatment and insensitivity to feed water is an advantage for thermal processes as they can be used to treat higher levels of salinity water compared to membrane processes without posing technical trouble shooting.

Post Treatment

Post treatment for desalination water is needed for public health because the water is characteristically low in minerals in most cases and also need to be disinfected. Alternatively, it is also to protect the integrity of the distribution system by adjusting the alkalinity and pH of the water.

The post treatment is more needed for the thermal processes permeate, because the product water has lower TDS readings, compared to membrane permeate outlet and therefore needs re-mineralization and pH adjustment.

The RO process in most cases needs minimal or no post treatment in small scale infrastructure. **Table 16** depictions are based on **Table 10, page 68**. The ED and RO process need moderate post treatment of stabilization and disinfection, out of a list of four steps for post treatment. The thermal processes on the other hand require stabilization, corrosion inhibition, re-mineralization and disinfection.

Table 16: Post treatment requirements evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	67%	67%	0%	0%	0%	0%
Performance standards	2	2	4	4	4	4

With the RO system the availability of different pressure membranes can sometimes determine the product quality to meet the purpose that it is needed for. A low pressure semi permeable membrane may perform different from a high pressure semi-permeable membrane.

In the thermal processes, the desalination process is dependent on the steaming, condensation and distillation, driven by the level of temperature. The volatile gases that escape from the water during the process are vented from the compartments to further minimize the presence of any unwanted ions or contaminants. The product water is therefore stripped of most of the minerals that remain in the brine, as they are heavy and non-volatile to escape with the steam.

The product water from the RO process can be controlled through the membranes pressure levels flexibility. This option provide a permeate quality that require nominal post treatment which are chlorination and pH adjustment in the instances where long term storage could pose hygienic problems due to low demand or corrosivity to distribution infrastructure.

The post treatment is required in the ED because the desalination process do not remove all ions, only the ones that can pass through the selective membrane stacks. The remaining ions are treated during post treatment.

Operating temperature

The temperature level is a very important determining factor in the thermal processes. The water needs to be boiled at a specified temperature level in order to produce steam. The only difference between the processes is how the heat energy is retained and recovered within the thermal systems. The temperature level determines the effectiveness of the desalination process installed.

Unlike the heat energy, the operating temperature is required at a specified level for each desalination process. The effects of temperature are accounted for in the heat, GOR and prime energy requirements criteria.

Each process needs temperature for the environment of operation, and this is reflected in **Table 17**, with the MSF process needing the highest level of temperature. The ED and RO processes can occur in the mildest temperature range of 15 to 40^oC. While the membrane processes do not require heat energy added to the feed water, the RO process is said to have a better flux transmission at the membranes when the water temperature is mild to warm (Ettourney, 2002). The temperature affects the flux and the flux impacts the net driving pressure applied through the RO membranes.

The temperature level for the thermal processes varies highly, from 10 to 30^oC, but this difference is not linked to systems performance and product delivery. The MSF process with the highest temperature requirement has the lowest permeate yield, but is thermal efficient, with a GOR figure that is comparatively on the higher side. The MED process has the lower temperature level from the thermal process of 70^oC (Eltawil, 2009) and good thermal efficiency, but the recovery rate can sometimes be expected to be zero or anything up-to 65%.

Table 17: Operating Temperature evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	76%	76%	32%	21%	32%	0%
Performance standards	15-40	15-40	60-80	80	70	100

The increase in the temperature levels, however, is reported to affect the product quantity and quality favorably. The temperature is maintained at the set levels for the optimum operation of the process and to keep the energy consumption at the set benchmark. The temperature for the thermal processes ranges from 60 to 100^oC.

The temperature has to be maintained at 100^oC for the flashing in the MSF process to occur and continue, and for the steaming, distillation and condensation activities to take place. Due to this need for high temperature, the equipment and the entire infrastructure shall be susceptible to corrosion, if proper care is not taken in selecting the appropriate materials. The high temperature requirement has an impact on the prime energy consumption for the MSF process. The target achievement for the MSF process is zero as it uses the highest temperature.

The membrane processes are not temperature dependent, yet an operating environment within certain levels, makes the process more effective. Hence the low benchmark of 15 to 40°C, for the RO and ED techniques. The benchmark used for the evaluation, is the average from the range of the operating temperature performance standards. While the two membrane processes can operate well in the given range, water below or above the range may need to be adjusted for optimal performance or compromise the process permeate quality.

Operating Pressure

A net driving pressure (NDP) is required in the membrane RO process to allow permeation of the brine. The NDP required is influenced by the concentration factor in the process, and this has direct impact on the water recovery. The thermal processes, including the ED membrane process do not utilize pressure to drive the desalination processes and **Table 18** is depicting this scenario.

Generally, pressure is utilized by all production techniques to boost the flow of water through the system, from one sub-unit to another, and out of the desalination system to the distribution network.

However, high pressure operation for the RO process is the key element that drives the process to produce the

permeate. The operating pressure in the RO process is driven by mechanical energy, just as the thermal process is driven by heat energy. The level of pressure applied to the RO desalination process has the highest impact on the energy used and it is a very important determining factor on the condition of the membranes. The membrane elements blockages increase the pressure level and subsequently increase energy use if not attended to.

Table 18: Operating Pressure evaluation results

Operating Pressure for desalinating water	
	RO
Target achievement	0%
Performance standards (Bar)	15-25

The RO process uses the pumping pressure to drive the desalination process through the semi-permeable membranes. The pressure applied is dependent on the source water quality. The more saline the water is, the more pressure is required to overcome the osmotic pressure on the feed water side.

All the other desalination techniques do not need pumping pressure to drive their processes. However, the MSF process needs pressure for the venting process, in order to have lower pressure in the succeeding stages. This pressure is very necessary for the MSF process, but it is not recorded and documented as part of process optimization exercise and management.

The operating pressure is a criterion that is only unique to the RO desalination process and is therefore an important variable that determines the RO process effectiveness. The benchmark operating standards are from 5 to 25 bar (Banat et al 2007) an average of 15 was used to measure the value out of the RO process.

A number of improvements in the quality of the membranes to withstand the high osmotic pressure needed to drive the process has seen the RO process cost reduced over the years by almost a tenfold every ten years (Banat, 2007).

Scaling and/or fouling potential

Scaling and fouling impacts the membranes of the RO and ED processes to an extent that the processes efficiencies and effectiveness are compromised. The permeation of product water is reduced and the quality is increased in most cases, as polarity on the membranes causes blockages that require higher pressure operation. The higher pressure operation will force more contaminants through the membranes.

The scaling and fouling impacts the process and the product quality highly in the RO process and mainly impacts the process in the thermal process. For the evaluation purposes, this criterion acts as a trade- off to the corrosion criterion which commonly affect the thermal processes.

Table 19 is depicting lowest score for ED, RO and MD processes because impacts of scaling and fouling are severe and can be costly to the process if not controlled with proper pretreatment. The thermal processes are impacted by scaling on the tubes in the heat recovery areas mainly. The 50% is assigned inadvertently to denote the lesser impacts compared to membrane processes, even though the potential practically impacts both processes.

Table 19: Scaling/Fouling potential evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	0%	0%	0%	50%	50%	50%
Performance standards	High	High	High	Moderate	Moderate	Moderate

Blockages of the membranes in the RO process directly decrease the recovery rate and the efficiency of the membranes in terms of the salt rejection. Scaling and fouling is controlled with pretreatment and regular maintenance, to preserve the membranes integrity. Severe and extended scaling and fouling degrade the membranes and require costly replacement in a shorter period of operation. The impacts of scaling and fouling needs to be controlled more vigorously in the membrane process, because it affects the process and the RO desalination important elements.

In the thermal processes, the scales cover the heat exchange surfaces of the tubes, limiting the heat transfer within the system. The limited heat transfer affects the thermal efficiency and decreases the GOR. The scaling and fouling problem require cleaning of the tubes, after 6 000 to 11 000 hours of operation (McGregor, 2006).
The control of scaling and fouling are moderate in the thermal process and is applied to the cooling and make-up water, not the feed water from the source.

Corrosion Susceptibility

The materials of equipment and infrastructure in the thermal processes are susceptible to corrosion due to the high temperature operation environments. Where care is not taken in selecting the materials resistant to corrosion, the infrastructure performance will not last and the quality and quantity of the water will be highly negatively affected.
The membrane processes are not severely affected by corrosion problem, as they do not operate in high temperature environments. However, the RO high pressure operation is partly affected by the erosion and cavitation corrosion after certain period of operation. Erosion corrosion occurs due to movement of corrosive fluid against a metal surface where friction and wear does occur. This is enhanced when there is turbulence in the fluid movement. Cavitation corrosion occurs when gas bubbles are imploded on a metal surface. The sudden variation in pressure related to hydrodynamic parameters causes the corrosion in the RO process.
.
All the thermal processes require to be built with materials that are resistant to corrosion to prevent severe impacts. Even so, corrosion is prevented and controlled with regular maintenance activities on the infrastructure. **Table 20** is reflecting the fact that the MSF and MED thermal processes need to be guarded against corrosion, with target achievement and partial utility scores of 0%. These two processes are still built with the highest quality stainless steel materials, but the welded areas in the processes systems needs continuous monitoring and regular maintenance to control the corrosion impacts. The thermal processes are commonly impacted by the pitting, erosion, stress cracking and the galvanic corrosion types. The corrosion section under MSF in chapter 3 shows action images of pitting and galvanic corrosion.

Table 20: Corrosion Susceptibility evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	50%	100%	100%	100%	0%	0%
Performance standards	Moderate	Low	Low	Low	High	High

The MD technology comprises foil and polyethylene materials to combat corrosion susceptibility. The MEH systems use the high quality stainless steel and polypropylene materials and innovative plastic condensers (Sommer, 2009). The two processes systems are relatively new on the desalination market and have newly innovated systems from many years of research and development activities.

The ED system membranes are made of fine polymer particles with ion exchange groups anchored by polymer matrix. The spacers are formed of plastic separators and the top and bottom plates are steel blocks that compress the membranes and spacers to prevent leakages inside the stack. The electrodes are made of titanium and plated with platinum. The concentrate from the electrode stream is treated in the degasifier unit, to remove and safely dispose of reaction gases, as oxygen, hydrogen or chlorine that may be present. This design is to prevent or keep the corrosion under control.

The materials for the MED system have to be selected appropriately to control the corrosion and have an efficient process in the production and thermal need areas.

Permeate quality

The permeate qualities of the various desalination techniques are shown in **Table 21** below. The permeate quality is most dealt with during pot treatment of the desalination process. It is in this instance being highlighted in terms of the taste imparted depending on the TDS level of the permeate quality. According to product water qualities level requirements, the permeate qualities of the desalination processes are operated to meet these statutory requirements for human health and to protect the distribution systems networks as highlighted in chapter 3, under the post treatment needs.

Nevertheless, the permeate qualities have additional advantages and disadvantages in the level of TDS level they are produced at. Some specialized industries require more dilute permeate qualities, as in the medical and food production environments.

According to recent investigations on the use between water generated from the thermal process and from a membrane process from the pilot plants that are underway in Namibia, there was an obscurity. For some unexpected turn of events, the people in the village where membrane process water was being produced did not use the water as much as the people from the village where a thermal desalination process was running. It was discovered, after an investigation that the people were not used to the salty taste still remaining in the membrane produced water. To the contrary, the people who had access to the thermal produced permeate were using the water more regularly and were particularly fascinated with the soaking effects of their beans staple food, when using the dilute permeate.

In **Table 21**, the thermal processes have scored high in partial utility and target achievement values, as the permeate from these processes are used for special cases in industries.

Table 21: Permeate Quality

	RO	ED	MD	MEH	MED	MSF
Target achievement	40%	63%	99%	99%	100%	97%
Performance standards (ppm)	200-1000	140-600	12.8	10	5-10	10-50

Brine disposal salinity

The brine to be disposed and how it can be disposed is normally dependent on the brine quality. For environmental protection policies, higher concentrate brine may need to be treated before disposal, whereas lower concentrate brine may render more options for disposal.

For this criterion, the recovery rate is used to determine the brine quality from the different desalination techniques. The more water is recovered from a system, the higher concentrate brine stream is left behind. In this evaluation, the brine disposal is based on the concentration level of the brine to be disposed, which is derived from the recovery rate in the calculations.

The ED process with the highest recovery has scored lowest as given in **Table 22** in the brine disposal criterion and the MED and RO have scored highest. This simply implies that the brine from the MED and RO processes is lower in salinity and may not need to be treated before it can be disposed of. High concentrated brine will pose higher environmental constraints to the desalination project.

Table 22: Brine Salinity for Disposal

	RO	ED	MD	MEH	MED	MSF
Target achievement	33%	11%	48%	30%	68%	38%
Performance standards (%)	60-75	6-15	50-55	30	35-100	50-75

The processes are thermal, uses high temperatures to produce dilute quality water, but at moderate to high recovery rate. The higher recovery rate is a trade off against the criteria of brine disposal.

Table 22 percentages for brine disposal are the opposite of the recovery rate. RO process has a recovery rate of 25 – 40%, and this means, 60 to 75% of the water is disposed of as brine. Some desalination schemes have brine recycling units built into the systems and this expectedly will increase the brine concentration level. The reported standard practice from conventional desalination systems showed that the brine concentration level from a thermal process is normally 1.8 times more concentrated, while brine from a membrane process is 3 times more concentrated. The renewable desalination units are having different recovery rates compared to conventional desalination units.

Mechanical and electrical power input

The thermal process mainly consumes heat energy and a small amount of electrical energy for the electronic controls in the system. The membrane process consumes the mechanical energy to drive the whole system, with the highest energy need being for high pressure RO pumps. The ED process uses the electrical energy of 5 to 12khW/m^3 (Valero, et al, 2010) and this is mainly from the electrical field in the salt water environment and at the electrodes provided for the process.

Table 23 below is illustrating that the MD process is using a lot of electrical energy of 12.3kWh/m^3 (Koschikowski, 2010) and the MED process uses the least at 2.2kWh/m^3 (Kalogirou, 2005).

Table 23: Mechanical and/or Electrical power Input

	RO	ED	MD	MEH	MED	MSF
Target achievement	37%	42%	6%	51%	100%	90%
Performance standards (kWh/m^3)	5-13	5-12	12.3	7.5	2.2	2.5-4

The mechanical power input is the main energy drive for the RO process giving it a higher consumption figure in the evaluation criteria. The mechanical input for the MSF and MED processes are nominal, and are limited to the supply of the electronic systems in the processes, giving a favorable rate. However, in MD and MEH processes, the processes are still highly linked to the energy use and require high input of electrical energy. This phenomenon for the two processes is still under review and developmental improvement.

The electrical energy in the ED process is directly proportional to the desalination process, but it's also not suitable to lower salinity water of less than 400ppm. The low conductivity will increase the energy requirements for pure water.

The use of electrical energy for the processes of MD and MEH are quite high considering the thermal use of heat energy mainly. The high energy use may in the case of Olushandja sub-basin be regarded as immaterial, because it is only the renewable energy being considered. However, the market performance standards need to be met for a process integrity and efficiency, to be in good standing and commendable. With high energy use, more collection and storage facilities for energy are needed to sustain the operation of the desalination systems.

The MSF and MED are thermal processes and have attained good scores in the use of mechanical energy, trading off against membrane processes in this criterion.

Heat Energy

The heat energy is the driving force of the thermal processes, which is necessary for the distillation activity. The membrane processes have no requirement for heat energy. According to **Table 23**, the MSF require higher heat energy for optimal performance of the process.

The MEH and MD requirement for heat energy in this criterion is derived from the partial results of electrical energy demand from the solar energy, based on small plants under piloting in Namibia. The calculation approach from the authors Kalogirou and Eltawil et al of converting kWh/m^3 to kJ/kg is used to obtain the transformation data for MD and MEH, by multiplying the electrical energy by a factor of 12. From the electrical energy needs of 12.3 and 7.5 kWh/m^3, the two techniques are reported that they utilizes an estimated daily energy of 100 to 200kWh/m^3 for the MD process (Koschikowski, 2010)and less then 120kWh/m^3 for the MEH process (Muller-Holst, 2009). The two energy needs are differentiated to obtain the specific heat energy used in the desalination techniques. The two processes are highly energy intensive, in both electrical and heat. Though the temperature levels are almost similar at 60 to 80^{o}C for MD and at 70^{o}C for MEH, the MEH process has the heat recovery component in the system as part of the desalination process. This component has favorable impact on thermal efficiency and the GOR value.

Table 24: Heat Energy Consumption

	MD	MEH	MED	MSF
Target achievement	0%	8%	69%	25%
Performance standards (kJ/kg)	392.4	362	123	294

The MED uses lower temperature compared to MSF, for optimal performance, hence the lower heat energy consumption of 123kJ/kg for MED and 294kJ/kg for MSF (Yuan, et al, 2009).

Prime Energy Requirement

The prime energy is the total energy used by each desalination technique for operation of the systems to produce clean water.

The RO process utilizes the least amount of prime energy, according to performance standards from the literature. The prime energy needed to run the MD process is the highest, giving the MD process the worst scenario score in **Table 25**.
The prime energy for RO is the total energy needed thermodynamically to produce the electricity required to run the mechanical process and the other electrical controls. In order to generate electricity from solar conversion, only 30% efficiency is obtained. The prime energy is obtained by multiplying the electrical energy needed three times, according to Kalogirou calculations.

The prime energy for the ED process is the energy covering the electrical field in the water and at the electrodes, and the built in cleaning systems activities.

The thermal systems are mainly based on the heat energy with minimal need for electrical equipment in the system. The prime energy requirement for the MED process is comparable to the need by the membrane process. This is because the MED mainly requires heat energy for the desalination process. The heat energy through the process of thermodynamic combustion has lower losses, compared to combustion for electricity production. The RO process electricity needs in the solar renewable energy are produced from the conversion of sunlight to electricity. These conversion efficiencies are reported to be 30% in the silicon solar cells which are commonly used for photo voltaic panels. While the heat energy is harnessed directly and can be more efficient depending on the solar collector used.

Table 25: Prime energy requirement evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	100%	94%	0%	26%	93%	48%
Performance standards (kJ/kg)	120	144	540	432	149.4	338.4

This criterion is transformed to the unit of the total energy used in kilojoules over the total water produced in mass (kilograms), for all processes.

For the thermal processes, the values are higher due to the intensive use of heat energy for the desalination processes. For the membrane process, the energy need is lower because of the consumption for mechanical and electrical activities primarily.

All desalination processes are driven by energy in different forms and consumption needs. Energy availability is therefore one of the determining factors in the selection of the desalination technique to be implemented.

Running Cost

The running costs for the various desalination techniques are taken from literature, based on desalination capacities that fall within the selection criteria. The running costs give an idea of estimated costs of running the selected desalination techniques and will complete the evaluation picture in terms of the need for economic assessment. Costs based on the specific plants implemented give a true reflection of the particular project. MSF and MED plants are reported to be equally expensive for implementation, but that scale is not taken into account, as no costs for plants with the same capacity and using renewable energy simultaneously could be found.

In **Table 26**, the evaluation results are showing that it is least expensive to run the ED, MD and MEH processes for small scale desalination plants. The MED process is the most expensive plant to run according to the information of the scale used in the transformation.

Table 26: Running cost evaluation results

	RO	ED	MD	MEH	MED	MSF
Target achievement	42%	100%	78%	80%	14%	35%
Performance standards (€/m^3)	1.4 - 2.1	0.32	0.86	0.7 - 0.94	2.1 - 2.8	1.94

The cost of 2.1-2.8 €/m^3 for MED and 1.4-2.1 €/m^3 for RO (Atikol et al, 2005) include solar energy components, membrane replacement at 10% per year, pretreatment chemicals, manpower and maintenance at 10% of the plant cost.

The ED at 0.32 €/m^3 and MSF at 1.94 €/m^3 (Kalogirou, 2005) is based on market research from manufacturers' prices of all elements of the desalination and renewable energy components and contingency use on chemicals, maintenance and estimated manpower cost.

The MEH process cost of 0.7 to 0.94 €/m^3 (Muller-Holst, 2010) cover options of complete solar and solar thermal systems. The price quotes include maintenance, energy costs, spare parts and manpower.

The MD process has a running cost of 0.86 €/m^3 (Koschikowski et al, 2010) and it's based on the plant implemented in Egypt at Alexandria University. This includes equipment cost and cost associated with maintenance, spare parts and manpower. This plant was still a pilot plant when reported in the literature.

The cost factor for a long term desalination installation is an attractive criterion for the MD process. However, it is to be noted, the cost structure does not reflect the same capacity systems for all process selected. The MEH in this case is rated at a 10m^3 per day system, while the MD is rated at a 0.1m^3 per day capacity.

The cost reflected is moderate for the RO process compared to the highest and lower cost over a long-term and it is based on a 10m^3 per day capacity scheme.

Water Generation Cost

The water generation figures obtained from literature are showing that the two desalination techniques RO and MEH that are least expensive to run require the highest investment. The water generation figures named as such and given in **Table 27** below are quoted from the ProDes Roadmap of 2010 (Papetrou et al, 2010). These are costs for the RO, MD, MEH and ED processes and they are calculated based on a 20 year lifetime and at 7% interest rate. These are dynamic prime costs of desalination units using solar energy, having capacities of less than 100m^3 per day and using brackish water as source supply.

The MED water generation cost is quoted from Muller-Holst presentation of 2010, and it states that the plant was running at 3m^3/h capacity. The desalination and energy infrastructure costs are include, but the land cost was not considered in this instance. The ProDes publication has given figures of 1.44 to 4.84 €/m^3, but this is for capacity schemes that are greater than 5000m^3/day. This is generally indicating the economy of scale in the production schemes.

For water generation, the MEH desalination process has a favorable lowest cost gaining higher score in the target achievement and partial utility values. Except for the RO cost, the other four processes are in a close and comparable price range.

The cost for water generation is not shifting and distinctive between the membrane and thermal processes, but is based on the specified desalination process market.

Table 27: Water Generation Cost

	RO	ED	MD	MEH	MED	MSF
Target achievement	75%	54%	29%	92%	57%	21%
Performance standards (€/m^3)	5-7	8-9	8-15	3-5	8.12	10-15

4.5 Sensitivity Analysis and Ordinal Ranking

The sensitivity analysis is in principal to test and verify the consistency of the MCA tool under different conditions. Some changes were made in the various criteria weight of target to observe how the scoring of an option is affected and to also assess where an option's strength is in the performance. Some options have great technical capabilities and are robust for Olushandja sub-basin conditions, but their application could be limited due to other factors, as cost or environmental conditions.

In accordance with the ranking algorithm of ordinal and cardinal scales, the evaluation outcome can be assessed in terms of the quantity and quality the given criteria.

In the ordinal scale, the ranking is strictly based on the final score and nothing further can be assessed on the preference. This scale is said to be invariant up to positive monotone transformations. The cardinal scale on the other hand, is a utility that values behavioral strengths that are related to the preference (Peterson, 2009). The ordinal approach will be used in this section to interpret results of evaluation and sensitivity analysis.

In **Table 28 to 30**, the three groups under assessment are: technical, environmental and economic. These are the assessment groups in the evaluation matrix of the utility value analysis tool. Under the technical assessment group the most important weight group is assigned 3, the moderate weight is given 2, the least important criteria are assigned 1, while the irrelevant criteria to a technology under assessment is assigned 0 for completion sake. For the environmental assessment objective, the weights assignments are also the same as in the technical objective. However, the cost assessment group has lower number of criteria and therefore the level of importance' assignments are changed in order to have higher weight assignment for the two criteria in the group. The most important criteria assignment is a 6.25, the moderate is 1.5 and the lower importance criteria are assigned 0.75. Refer to ***Appendix B*** at the back of this report, for the full tables of evaluation using the various weights assigned according the level of importance.

As a first step under the group assessment, the evaluation is done by allocating weights while balancing and trading off the criteria where necessary. Some criteria as GOR and heat energy in the thermal process are both accounting for the thermal energy and efficiency but are measured differently in the operation of the desalination plants. The data for the two variables is collected for different purposes as outlined under the subheadings above that are describing the partial utility and target achievements. They are both important parameters for the thermal process yet they are assigned weights of moderate importance in order to balance and share the level of importance between the two variables.

In the scenario where the technical assessment group is of interest, the weight assignment for most of the criteria are given the highest level of importance. This is objectively to discover the technology that can clean the water effectively while producing the quantities required and using the least resources in preventing the impacts of desalination. By requiring the least resources for pre-treatment, post-treatment and conditioning chemicals to meet the statutory guidelines for drinking water standards, are two ways of a technology being technically good.

According to **Table 28** below the assigned weights are in favor of the technical assessment group to identify the most effective technology when only technical criteria are considered. In the case of Olushandja sub basin, portable water is only attainable through desalination and using renewable energy. Hence the technical assessment group consideration is an important approach in finding the most appropriate technology. Olushandja sub-basin does not have any infrastructure neither conventional energy against which generic treatment options can be compared. Yet the people living in the sub-basin need to be provided with clean water for their health and hygiene improvements.

To highlight the environmental conditions as the most important variables for consideration, the criteria under this assessment group are all given the most important weights of 4, as per **Table 29** below. The environmental objective is assessing the use of energy by the different desalination group and the quality of the brine to be disposed. These two environmental variables are normally part of the decision process when acquiring desalination technology in an area. There has to be energy available first and for most, and there must be contingency plans in place on how the brine will be disposed of. In Olushandja sub-basin the solar energy is the renewable source of energy mot available because of the high solar radiation observed from temperature conditions. The cost of acquiring the equipment to source the energy is determined by the energy required by the specific desalination technique.

Under economic assessment group, the weights allocation of the most important to the least important had to be amended to fit the group' only two criteria. The utility value analysis methodology in most cases is used to do evaluations of ecological and technical variables, but can also do cost variables as in this case. Cost is an important and sensitive variable that is not openly reported on in most literature, as most pilot schemes or even plants that are run to produce water for a specific reason, do so under specified objectives, as either research or developmental intentions. Cost in this evaluation is quoted and included to highlight the inevitable cost factors involved with projects and what the various technologies are estimated at for operations and maintenance. **Table 30** on the third page from the following is outlining the emphasis of the economic assessment group as the focus area of interest. The economic assessment group in this evaluation of desalination techniques only consists of the cost of running the plants, as well as the cost of capital investment in erecting any of the plant. The quoted figures were not from all equally sized plants, but it is derived closely comparable sizes and activities.

Table 28: Sensitivity Analysis Weights Assigned, for Technical assessment group

Sensitivity Analysis with Technical Assessment being of higher interest					
		Membrane technology		Distillation technology	
	Criteria	**Weight of Assessment**	**Weight of target**	**Weight of Assessment**	**Weight of target**
Technical Assessment	Gained Output ratio	**53.33%**	0.00%	**58.82%**	8.82%
	Recovery Rate		6.67%		5.88%
	Pretreatment Requirement		10.00%		2.94%
	Sensitivity to feedwater quality		10.00%		5.88%
	Post treatment		3.33%		2.94%
	Operating pressure range		10.00%		0.00%
	Operating temperature		3.33%		8.82%
	scaling/ fouling potential		3.33%		5.88%
	Corrosion susceptibility		3.33%		8.82%
	Water quality		3.33%		8.82%
Environmental	Brine Disposal	**26.67%**	6.67%	**23.53%**	5.88%
	Mechanical/Electrical power input		6.67%		5.88%
	Heat energy input		3.33%		2.94%
	Prime energy consumption		10.00%		8.82%
Economic	Running cost	**20.00%**	10.00%	**17.65%**	8.82%
	Water generation cost		10.00%		8.82%
		100.0%	**100.0%**	**100.0%**	**100.0%**

Table 29: Sensitivity Analysis with the Environmental part being of interest

Sensitivity Analysis with Environmental Assessment being of higher interest						
		Membrane technology		Distillation technology		
	Criteria	Weight of Assessment	Weight of target	Weight of Assessment	Weight of target
Technical Assessment	Gained Output ratio	31.03%	0.00%	31.03%	3.45%
	Recovery Rate		3.45%		3.45%
	Pretreatment Requirement		3.45%		3.45%
	Sensitivity to feedwater quality		3.45%		3.45%
	Post treatment		3.45%		3.45%
	Operating pressure range		3.45%		0.00%
	Operating temperature		3.45%		3.45%
	scaling/ fouling potential		3.45%		3.45%
	Corrosion susceptibility		3.45%		3.45%
	Water quality		3.45%		3.45%
Environmental	Brine Disposal	55.17%	13.79%	55.17%	13.79%
	Mechanical/Electrical power input		13.79%		13.79%
	Heat energy input		13.79%		13.79%
	Prime energy consumption		13.79%		13.79%
Economic	Running cost	13.79%	6.90%	13.79%	6.90%
	Water generation cost		6.90%		6.90%
		100.0%	100.0%	100.0%	100.0%

Table 30: Sensitivity analysis with the economic assessment group as stakeholder

Sensitivity Analysis with Economic Assessment being of high interest					
		Membrane technology		Distillation technology	
	Criteria	Weight of Assessment	Weight of target	Weight of Assessment	Weight of target
Technical Assessment	Gained Output ratio	26.73%	0.00%	26.73%	2.97%
	Recovery Rate		2.97%		2.97%
	Pretreatment Requirement		2.97%		2.97%
	Sensitivity to feedwater quality		2.97%		2.97%
	Post treatment		2.97%		2.97%
	Operating pressure range		2.97%		0.00%
	Operating temperature		2.97%		2.97%
	scaling/ fouling potential		2.97%		2.97%
	Corrosion susceptibility		2.97%		2.97%
	Water quality		2.97%		2.97%
Environmental	Brine Disposal	23.76%	5.94%	23.76%	5.94%
	Mechanical/Electrical power input		5.94%		5.94%
	Heat energy input		5.94%		5.94%
	Prime energy consumption		5.94%		5.94%
Economic	Running cost	49.50%	24.75%	49.50%	24.75%
	Water generation cost		24.75%		24.75%
		100.0%	100.0%	100.0%	100.0%

The sensitivity analysis is executed on the three assessment groups using the weights assignments as given above in the three tables, Table 28-30. **Table 31** below is showing the outcome of the evaluations in summary.

Table 31: Sensitivity Analysis result Ranking

Desalination Techniques Sensitivity Analysis Ranking						
Ranking	Technical		Environmental		Economic	
1	MEH	58.5%	MED	66.3%	MEH	66.6%
2	MED	58.0%	MEH	47.7%	ED	59.8%
3	ED	51.5%	MSF	45.9%	MED	51.0%
4	RO	47.6%	ED	45.8%	RO	50.4%
5	MSF	44.7%	RO	44.6%	MD	40.3%
6	MD	39.8%	MD	27.1%	MSF	38.1%

According to the results below the ranking is showing that the MEH technique would be most suitable as it is the best in the two assessment groups of economic and technical, while second in the environmental group. The ED technique has emerged to be closely competitive as a membrane group to be used as a desalination option under the economic and technical criteria. The MSF and MD have ranked at the bottom showing close weaknesses in the economic and technical performance objectives, implying to be most expensive with lower technical performance from the results. The MED technique has scored well in all the assessment groups being among the top three. This performance mean the MED technique has better quality of brine to be disposed and the prime energy requirement is lower compared to other desalination techniques. In addition, it has minimal use for mechanical and electrical input with relatively average financial requirements. **Appendix D** at the back of this report gives more details of all the techniques' performance.

Where the technical objective is the criterion of focus for assessment and is the element of priority for a suitable desalination technique for Olushandja sub-basin, the table is depicting that the MEH process would technically be the most suitable technique for Olushandja sub-basin, on an ordinal approach as a distillation option, while the ED would be the suitable membrane option. MEH is closely followed by MED as the second choice, while MD has scored lowest and shown to be the most unfavorable when considering technical suitability.

MEH and MED processes technically are close in terms of their suitability at 58.5 and 58.0 percentage scores and can be considered as two alternatives capable of rendering equally suitable technical options for desalinating the water of Olushandja quality and that required output. Similarly, the MD and MSF techniques have displayed to be equally in-competitive according to this ordinal result in the technical and economic assessment groups.

Table 31 is further showing that the MED technique is by far most suitable for environmental conditions, having a gap of more than 15% above and ahead of the other techniques. In this assessment, the brine disposal and the prime energy consumption are among the highly considered criteria and are evaluated with regard to their impacts on the environment.

Due to the high requirement for energy both electrical and heat, the MD process will have a high intake of energy from the environment. In the case of Olushandja sub-basin, more solar energy will need to be harnessed and more storage batteries for energy will be required.

The ranking for the economic assessment objective is showing that the MEH technique is the least expensive than the other five techniques. The economic assessment is based on the estimated running cost of the technique and the dynamic prime cost per cubic meter on the infrastructure' capital investment. The ED technique is the second option when considering cost as the most important factor but only for feed water quality of up to 12 000ppm.

4.6 Results Ranking' Cardinal Discussion

In view of the conditions in Olushandja sub-basin, the techniques in this section are assessed further to explore their suitability. According to the results above, the best performing technique in the selected assessment group is able to desalinate the raw water with best results while the lowest scored technique is assumed to have criteria that are performing relatively below the standard performance benchmarks in the desalination industry.

The cardinal scale has two kinds of valuations, namely; interval and ratio scales. The interval scale accurately reflects the difference between the objects being measured. Unlike, the ordinal scale, the interval scale is termed to being invariant up to positive linear transformations. This simply means the interval scale can be transformed into another by multiplying each entry by a positive number and adding a constant. The other type of the cardinal scale is the ratio scale and it plainly reflects ratios. A ratio scale can be accurately transformed into an equivalent ratio scale by multiplying by a positive constant.

In essence, the ordinal scales represent qualitative comparison of objects and information about the differences or ratios that are not given. The cardinal scales, reflects the quantitative comparisons of objects, representing the differences between objects in interval assessments, and representing ratios between objects in ratio scales.

For each option, there are values of target achievement and partial utility that are calculated. The target achievement values are derived from the transformation table, and are an outcome of the performance score. These results are from the formulas listed using the upper limit and lower limit, with the performance standard' data. The tables have most importantly yielded the partial utility results that are based on the multiplication of target achievement and the target weight in the spread sheets, to aggregate to a performance score of each option, through summation of all criteria values.

The partial utility values have traded off between the criteria among the options. In the technical performance assessment target group, the various desalination options traded off mainly along the performance in the thermal and membrane categories. The thermal and membrane desalination categories are separated along the energy needs, pretreatment, GOR performance and post treatment requirements. The technical performance is a strong determining factor in the decision for the suitable desalination technique for Olushandja sub-basin.

The desalination systems are primarily technical units and the performance for obtaining clean water for the village people is strictly based on the technical capability of the techniques, and the utilization of the sources and resources. The utilization of the sources and resources are reflected through the performance in the environmental and economic assessment objective.

The partial utility results indicate the strengths and weaknesses of the various technologies in the chosen criteria. However, the weight assignment is subjective, as it is a personal or group decision based on what is perceived as the most important criteria and less important one. The weight allocation has influence on the score outcome under the partial utility.

According to the displayed results in **Table 31**, the ranking from the sensitivity analysis is discussed at an ordinal scale. The results are placed in accordance with the performance based on the standard benchmarks. However, taking the results in a cardinal category, in the technical assessment, results can be interpreted as follows:

The ED techniques as the technique with one of the higher scoring for technical objectives in a selection of a suitable technology for Olushandja sub-basin will only be suitable in the areas where the salinity is less than 12 000ppm. Except for the requirement for pretreatment and the high potential for scaling, the ED technique has scored points indicating its competitive edge technically.

The source water of Olushandja sub-basin quality ranges from 4000ppm to 90 000ppm and requires a desalination technique that can handle such a condition. MEH as the highest ranking on the technical evaluation, will be suitable whenever the area in Olushandja sub-basin to be supplied with desalinated water has a source water that has no quality constraints. MEH is a thermal technique that is not sensitive to feed water quality. The MEH and MED thermal process have comparable ratings at 58.5 and 58.0 % and they both have the advantage of insensitivity to feed water quality. In addition, the MED technology has obtained the best tolerance level for environmental conditions, while the MEH has scored comparatively well and highest among the thermal processes on cost. The MED technique is one of the older techniques together with the MSF where high quality steel materials is exclusively used and reported to practically need closer and skill-full monitoring and operation. The contemporary techniques MEH and MD that has evolved in later years comparatively use largely plastic materials for manufacturing infrastructure.

In the areas where the feed water is less than 12 000ppm, the ED technique will be suitable, as it has the advantage of utilizing less energy and the environmental conditions are less impacted with its requirement for less prime energy. The ED process has scored second in the economic assessment group and third in the technical assessment objective ranking it among the top three techniques in the two assessment groups.

MED being a thermal technique, is insensitive to source water salinity can therefore treat water with higher salinity, has excellent quality output and the energy intake for the process is lower compared to other thermal processes.

The MSF as a thermal process has performed lowest in the technical and economic criteria. However, from this study it has also been observed that the MSF has been longer in the desalination market compared to the other thermal groups as MEH that has emerged about two decades ago. However, the MEH has lower running cost in the long term and the cost for producing water on a discounted rate is lower compared to all distillation options.

The MD process has yielded the lowest performance score, being at the bottom of the ranking table in two assessment groups. This is indicating it to be unfavorable for Olushandja sub-basin conditions. The disadvantages to the MD process are the high energy consumption and sensitivity to feed water that resulted in low partial utility values in the technical criteria. Nevertheless, the MD process has one of the lowest running costs and does not require pretreatment and excessive use of heat energy.

Chapter 5: Conclusion and Outlook

Olushandja sub-basin has brackish groundwater that has TDS ranging from 4,000 to 90,000ppm. This water is a health hazard and needs to be desalinated for human use.

The sub-basin is located in the northwest part of Namibia, and has temperature conditions that are semi-arid to arid, with a rainfall pattern of 200 to 500mm per annum. This rainfall is exceeded by the mean annual potential evaporation of 2,800mm per annum. The Olushandja sub-basin Southern block is inhabited but is not covered by the service networks of electricity and water. The inhabitants have therefore resorted to using the groundwater through hand-dug wells. There is a natural environmental state of saline groundwater that is attributed mainly to presence of gypsum and Epsom salts in the geological profile. The salinity levels of the groundwater are too high in some parts and can be toxic for human use especially when used outside the rainy season. The current practice of abstracting ground water through hand dug wells by the local residents is hazardous and highly risky for human life as losses of lives are reported to have occurred due to collapsing wells.

The groundwater, though not formally exploited, it is replenished during the rainy season and it's not utilized according to its potential capacity for water supply in the sub-basin. It's currently used informally and at domestic village level needs. The groundwater is therefore in abundance in Olushandja sub-basin, but needs to be treated to make it potable and available to the village communities. The communities are remotely settled and do not have access to the formal water supply network that are available in other parts of the sub-basin. Clean water is direly needed by these communities for consumption and to improve their hygienic and sanitary situation.

In this study, it was hypothetically alleged that there are desalination techniques and schemes of capacity that is 100m^3 per day or less, which are operated utilizing renewable energy and have been successfully piloted or implemented around the world. In accordance with this, desalination technologies exist that can be applied at small scale, supplying daily demand for human consumption, up-to 20l per person per day according to WHO per capita recommendation for informal settlements. From the world experience of various climatic conditions that is studied in this report, desalination technology can be devised technically robust and secure, to endure the harsh environmental and social conditions as the one of Olushandja sub-basin.

The area profile outlined states that the area is a newly established water management unit within the larger Cuvelai-Etosha Basin. The Northern block of the sub-basin is highly populated and most service networks and centers are established in that part of the sub-basin. Meanwhile the Southern block has one third of its land portion covered by the Etosha wild life national resort and a number of villages that are clustered in isolation of several kilometers from each other.

The hydrological situation shows that the first rainfall of the season in the area is soaked up rapidly due to the sandy-calcrete soil type that is often desiccated due to high temperature conditions in the area. The surplus rainwater builds up after the soaking, of which part of it stagnates in the undulating depressions named Iishana in the region, and the rest flows from the Northwesterly direction towards the Southern end of the sub-basin. A huge amount of the stagnating water is evaporated soon after the rainy season, while only a portion is taken up by the vegetation via evapotranspiration.

The topography of the area appears relatively flat with the lowest point at 1,075m amsl at the western-end side of the sub-basin and has a bit of rise to 1,350m amsl in-between before it falls back to 1,280m amsl towards the eastern-end side of the sub-basin, with a relieve of $0.2^{o}/_{oo}$.

The soils and geology is predominantly sands and fragmented rock of the Kalahari sequence and of the Aeolian and fluviatile origin. It is in earlier literature of up-to year 2004 reported to have low water holding capacity and to be high in salt content. While areas in the sub-basin that were drilled later from year 2008 in the Southern block of Olushandja sub-basin, have shown a profile that is layered with clayey sand, sandy clay and silty clay, with transmissivity ranging from $1.0x10^{-6}$m/s to $7.1x10^{-7}$m/s.

The reported yields in the area are from $1m^3/h$ to $30m^3/h$ with at-rest water level starting at a depth of 41m below the surface to 204m deep. The hydrochemistry of the area have shown thick evaporitic deposits of gypsum and Epsom salts that is mainly causing the high brackish content of mainly sulphate contamination, and elements of hardness, chloride and sodium.

In consideration of using renewable energy for desalinating the brackish water of Olushandja sub-basin, the potential energy options of solar and wind in the area are reviewed. Olushandja sub-basin has 300days of sunshine, with potential solar energy of 5-6kWh/m^2.day, based on the temperature variations that range from 5 to 39^{o}C. The wind velocity in the area is estimated at 4-5m/s according to world wind speed map. Typically, most wind turbines built utilizes 7m/s wind speed, but it's further reported that in recent years turbines that run on 4-5m/s have also been manufactured and have been operational.

The other possible energy source could be geothermal, as this is generated from the hot dry rock resources at depths of 4 to 5 miles everywhere beneath the earth surface it is stated in literature. Geothermal is drawn from the subsurface at any point below the earth surface -+or from below the sea floor level. At deeper level down the earth surface, the magma geological profile is the naturally occurring geothermal resource from which hot fluid can be generated for electricity power production.

Before selecting the criteria on which a suitable desalination technology can be sought and evaluated, the conditions of Olushandja sub-basin are outlined, so that the technique and infrastructure to be brought to the sub-basin can withstand the social and environmental conditions and constraints. Among the listed conditions, the highlights shows that the demand of at least 20liters per person per day in any given village should be met, the water quality should meet at least the A or B-class level of Namibia water guidelines and it should be accessible in proximity of 0.5km to everyone in the village according to standing directive of the Ministry of Agriculture, Water and Forestry (MAWF). Other important conditions are that the technology should be simple, robust and sustainable whilst appropriate training is to be provided to local residents to take care of the simple monitoring and maintenance tasks of the infrastructure.

According to obtained results from schemes around the world, all desalination technologies reviewed can treat the water well to excellent potable level as required for human consumption and can use solar energy. Olushandja sub-basin has abundant sun exposure that can be harnessed as an energy source to supply the operations of desalination facilities in the remote rural villages, generating up-to 6.2kWh/(m^2.day).

It is further noted that, the selection of a suitable desalination technology may be driven by the available resources, as financial investments and operating skills. This is because the other elements as energy, operating pressure, pre and post treatment requirements, permeate quality, recovery rate and brine disposal for evaluations are a trade-off between the different technologies. Where the membrane option do not use or need allot of energy, they need a higher investment for pretreatment systems, and where the thermal processes need allot of energy for their operations, the energy can be free since its renewable, but it may need more investment for harnessing and storing.

In addition, to plan or establish desalination technology in any given area, there are conditions that need to be met or resources to be acquired. The conditions are; at the identified location there should be a highly reliable source of water, the source water quantity and quality has to be known for planning and the type and consistent availability of energy to be used should be assessed well in advance. It is also necessary that an environmental assessment is done on the area, and the options of brine disposal are well investigated and a suitable option is identified. The options for small scale desalination brine disposal currently utilized in the market are: deep well injection, evaporation ponds, discharge to sewers and surface waters, use for irrigation or crops or landscaping and land application of aquifer recharge. The choice for an appropriate disposal of the brine concentrate in Olushandja sub-basin can be considered based on the environmental condition, both from upper surface to underground. This is specifically with regard to the possibility of re-infiltration and artificial recharge as options for disposal. The high temperatures in the sub-basin provide an opportunity for faster evaporation, in an event where evaporation ponds may be the option of choice for concentrate disposal. The option of re-infiltration can also be considered due to the clayey layers that are in the geological profile. Having desalination infrastructure in an area, potential impacts are expected on the area where it is located. Impacts include the size of land needed for use, energy consumption required, the safe storage and use of pretreatment chemicals and disposal of desalination brine.

Most of the technologies are built to meet the environmental and social conditions of durability and adaptability, as most technologies are tested or are being researched and adapted according to the prevailing conditions where they are piloted. The technologies are in most cases automated and are provided with conditioning for the electronics, to prevent impact by severe weather conditions. With automation, the systems of operation are built to minimize complexities of allot of isolated technical activities to be learned and understood. These minimal operations on the technologies can therefore be taught to a reasonably literate person for daily caretaking of the infrastructure. Due to global marketing and enhanced accessibility and logistics, allot of spares for all technologies can be sourced wherever they may be and imported to Namibia. The suitable market for the chosen technology need to be sought and then partnership with an identified agent within the country can be established. In this way the technology parts can be sourced and stocked ahead of scheduled and unscheduled maintenance and breakdown. Most of the manufacturers of technologies provide a list of parts that are likely to be replaced or can wear out before the estimated time of scheduled maintenance. This makes planning for ad-hoc maintenance controllable.

Most of the desalination technology that were tested in rural set ups were compact and pre-packed compilation, providing for mobility and flexibility associated with source water availability and nomadic and spread-out rural homesteads. The technology can be moved closer for the consumers for them to be able to collect the water in the rural villages' set-up and to be in a ratio of about 500m away as required by the Namibian government directive on rural water supply. Although the closer proximity where applicable, will lessen the burden for collecting water far, especially on women and children who are mostly involved with house chores.

The social aspects of project development and community participation has to be considered and due cognizance taken care, for the successful implementation and sustainable use of the infrastructure. From a study undertaken by GWA (gender and water alliance through WASH (water, sanitation and hygiene) United Nations institutions, most of the projects that involved both gender groups of the society have proven much more successful, then projects where some members of the villages and associations were excluded and discriminated against. It is generally recognized that women uses the water much more regularly then men, for taking care of the families and house chores. This fact has proven women to be more caring for water infrastructure and availability in their areas and villages, according to a survey study undertaken on 122 projects around the world by the World Bank. The management of the water in the rural villages is best left in the hands of both gender groups, to make sure it meets the needs and the infrastructure is taken care of by everyone. The research outcome showed that projects that excluded one gender group on the basis of alienation or discrimination, or undermining the competitiveness of such a group has proven unsuccessful.

Otherwise, most of the rural villages in Olushandja sub-basin do not have electricity; the introduction of renewable energy for running the desalination infrastructure can be cost effective if the expenses can be shared with the villages' households that are interested in acquiring electricity for use in their houses.

For institutional arrangements, Namibia rural settings have a system of choosing a committee that runs a water supply point in any given village. This committee allocates water collection times in a day and also collects the money from the community members at the end of each month. Collected money is normally paid to the responsible water utility company or governmental authority in the area.

After setting the above summarized background, the selection for suitable desalination technique for Olushandja sub-basin was done through the following process:

A set of selection criteria were compiled for the purpose of acting within boundaries that aim at having potable water for the people and it's done so effectively, efficiently and in a sustainable way. The boundary criteria prescribes that the technique to be selected from the successfully implemented scheme should be treating brackish water, using renewable energy, have a capacity of $10m^3$ to $100m^3$ per day, is technically simple and proven robust against harsh environmental conditions, among others. From these criteria, the following desalination techniques were chosen from literature; multistage flashing (MSF), multi effect distillation (MED), multi effect humidification (MEH), membrane distillation (MD), reverse osmosis (RO) and electro dialysis (ED). The RO and the ED techniques use the membrane process for desalinating the water, and the MSF, MED, and MEH use the thermal process. The MD technique uses a hybrid process of thermal process and membrane barrier for desalinating the water. Apart from these techniques there were a few others that were identified to be suitable in terms of some of the criteria as scale and renewable energy. These are vapor compression and solar distillation techniques, but information on where they are implemented and/or the capacity used was outside the scope of the selected criteria. The selected techniques will be summarized as follows:

The MSF process is made up of a series of elements called stages. The water is preheated by the condensing steam before entering the first stage of the system through an orifice. The pressure is reduced when water enters a stage through an orifice. When the pressure is reduced, the water is superheated and flashes into steam. The steam is condensed to fresh water on the tubes containing the incoming feed water. This technique common impacts are scaling, corrosion and potential losses of heat energy that affect the GOR (gained output ratio) measurement. Pretreatment is applied to the make-up water that re-enter the system. This is water that is deviated from the brine outlet and recycled back into the system. The MSF needs post treatment because the permeate produced is dilute at around 10-50ppm and it needs to be conditioned with stabilization and re-mineralization to meet the statutory requirements of prescribed drinking water quality standards. Due to the operational environment of high temperatures, the MSF infrastructure is highly susceptible to corrosion and scaling if not maintained regularly. An exemplary scheme using the MSF process with renewable energy and have a capacity of $10m^3$ per day is running in Kuwait.

The MED is composed of elements called effects. At a temperature of 70^oC, steam is supplied from an external source to drive the process. Due to absorption of thermal energy by the feed water, vapors are generated and used as heating medium in the successive effects. The succeeding effect pressure is kept lower than the preceding from where the heating steam originates and the boiling in the effects produces the distillate. The MED maintenance and post treatment needs are like for the MSF process. An MED process technique using solar energy is installed in Abu Dhabi in the United Arab Emirates.

An MEH process utilizes the concept of closed-air open-water system originating from the humidification-dehumidification as the fundamental idea. The system comprises a water heater, a humidifier and the dehumidifier. The humidifier is irrigated with hot water and air from this compartment is extracted at various points and supplied to the dehumidifier for temperature stratification. The process uses energy of around 120kWh/m^3 and has a standard recovery rate of 70%. A scheme with a capacity of 5m^3 per day is installed at Jeddah in Saudi Arabia, using thermal collectors.

The MD process is a hybrid thermal-membrane technique. Thermal energy is used for phase changing of liquid into vapor. The hydrophobic membranes that are permeable to vapor only, separate the distillate from the retained solution. The process has typical desalination impacts of membrane blockages and bio-fouling when the feed water is above 30,000ppm. Pretreatment requirement for this technique is as required for a membrane technique, while post treatment requirement is similar to the thermal process technology permeate requirement. The water produced is of a quality generated from a thermal process of 10-50ppm permeate quality. A pilot scheme is successfully running at Alexandria University in Egypt, using solar energy.

The RO process operates with a pretreatment unit, high pressure pumps to drive the water through the semi permeable membranes and post treatment to adjust the pH and stabilize the water quality, as well as disinfection of the water before distribution. The common problems in the RO process are scaling, fouling and bio-fouling that have to be controlled and kept minimal through the pretreatment step. These membrane common problems compromise the integrity of the membranes impacting the effectiveness and efficiency of the technique. The typical recovery rate for the RO process is in the range of 25 to 40 percent; it uses pressure in a range of 15 to 45 Bar and operates best in the temperature environment of 15 to 40^{o}C. The RO process needs short-term routine maintenance in 3 to 6 months and long-term maintenance for replacement of worn out parts in the high pressure pumps, membranes replacement after 2 to 3 years and regular control checks of the system by the plant engineer. A plant using RO process and wind energy from Coconut Island in Hawaii is used as an example of a successfully piloted plant. Another plant comparing the use of RO and NF (nano-filtration) membrane processes is also included.

The ED process uses electrical currents to move salt ions selectively through a membrane, leaving fresh water behind. The process needs pretreatment against scaling, fouling and bio-fouling. It only treats water that has salinity up to a limit of 12,000ppm and needs post treatment, just like the RO technique. ED membranes life expectancy is 7 to 10 years. An exemplary plant implemented in Alicante, Spain.

For the evaluation of the desalination techniques, a set of criteria grouped into technical, environmental and economic objectives, alternatively assessment groups are compiled. The criteria used are; gained output ratio, recovery rate, pretreatment requirements, sensitivity to feed water quality, post treatment, operating temperature, operating pressure, scaling and fouling potential, corrosion susceptibility, brine disposal, prime energy requirement, mechanical and electrical power output, heat energy, running cost and water generation cost. The criteria performance standards are obtained from historical performance benchmarks of successfully implemented schemes from literature.

The assessment groups given above are aimed at fulfilling the objectives of technical performance, environmental sustainability and financial feasibility of the selected desalination techniques.

Meanwhile, the decision for bringing clean water to the people of Olushandja sub-basin should not be based exclusively on the economic factor, but rather on the need of the rural community and the desired health and hygienic environment of the people. The water of Olushandja sub-basin can only be desalinated because it is clear but brackish. First the technical elements of the appropriate technology for the conditions of Olushandja sub-basin should be considered and then measures on keeping the long-term expenditures down and minimal. These costs that can be controlled and kept minimal can be assessed through the use and wastage management and engage the willingness to pay concept by the consumers.

The evaluation scoring method used is the utility value analysis tool. This method is selected because it uses all variables for quantification under technical, environmental and economic, scenarios. The utility value analysis tool belongs to the umbrella approach called multi-criteria analysis (MCA) rafter. To perform a utility analysis evaluation, the following stages through an evaluation matrix have to be undertaken; decision options (or assessment groups) have to be selected, evaluation criteria have to be identified, performance measures should be available, units are to be transformed. There after the options are assigned level of importance for determining scores of weights. The target achievements and the performance rate, scored under partial utility is generated. During sensitivity analysis the level of importance for the criteria are changed, giving more weight or rate to the assessment group of interest. Within the assessment of interest, the best performing desalination technology is rated according to the outcome. Only after the sensitivity analysis is performed for all assessment groups on all criteria, the produced data is used further for ordinal ranking and cardinal discussion.

The ordinal approach taken to rank the desalination techniques according to the scores obtained could not be used as conclusion in favor of only one desalination technology. The cardinal approach is therefore used to bring rational behind the scoring and justification for the appropriate technique forth, according to source water conditions, performance of the technique in all three assessment groups and contemporary market trends. Olushandja sub-basin has a wide range of source water quality, starting from brackish level of 4,000 to 90,000ppm throughout the area. Desalination of such water requires different types of desalination processes, as all desalination techniques have limits and disadvantages, depending on the feed water quality and the resultant cost associated with the product water quality and quantity.

The evaluations methodology' results have shown that not only one single technique can be homogenously recommended for the entire area of Olushandja sub-basin. The prevailing environmental conditions have shown that some areas have lower salinity while others have much higher salinity. The distinctive conclusion from this study is the identification and capabilities between the thermal and membrane processes and their application according to the site specific needs. The sensitivity analysis is indicating that the MED process is most environmentally friendly technique, utilizing less prime energy and has lower concentrated brine for disposal. It is further; a thermal process that is insensitive to feed water quality, evading the need for pretreatment, but it's more expensive and has the need for skilled labour. The ED process has emerged to be technically suitable being among the top three techniques in this evaluation group but it's only applicable to source water of less than 12 000ppm.

The MSF process has the great technical advantages in being the longest established technique and well stable in the desalination market, with favorable thermal efficiency and it's insensitive to feed water quality. Its major setbacks are energy needs and post treatment requirements that affected its net score. The MSF process is among the oldest techniques in the desalination market and still uses allot of expensive material of steel. The MD and MSF process have scored the lowest for the technical and economic assessment groups and are concluded not to be suitable for Olushandja sub-basin. The MEH process is cheaper and technically more appropriate then the MED in the two assessment groups. Its use of non-corrosive materials for infrastructure and being insensitive to feed water quality makes it most suitable as a thermal process.

Given the outcome from the evaluation and the collection of data from the pilot plants that are under research and the established small scale desalination schemes running on renewable energy around the world, bearing conditions comparable to Olushandja sub-basin, it can be safely concluded that the water of Olushandja sub-basin can be treated and be made available to the vulnerable rural communities. Under the environmental and social conditions of Olushandja sub-basin, desalination can be implemented to meet the hygienic and aesthetic needs of the communities, as well as curb the hazards that are associated with drawing the water from the ground through hand-dug wells. The sub-basin has abundant solar radiation to meet its solar renewable energy needs, at 5 to >6.2kWh/(m^2.day), has untapped brackish groundwater that can be further exploited and desalinated and has allot of land available for establishing new infrastructure and for handling disposable waste from the waterworks. The reviewed schemes, in Abu Dhabi (MED), Egypt (MD), Ksar Ghilene (RO), Jeddah (MEH), Alicante (ED) are all tested in climatic conditions and environments of semi-arid to arid conditions with rainfall patterns that are comparable to Olushandja sub-basin.

On the outlook of events, this study concluded that Olushandja sub-basin needs more data collection on the geological profile, distinctive identification of aquifers and evidence on the interaction between the aquifers. From the best available data obtained it could not be established with certainty where the highest contamination of brackishness is in the profile, or how the geological profile is layered. More data on ground water quality for spatial overview of the trends and pattern of the sub-basin will be useful in drawing better conclusion on the specific desalination technology needed and that is suitable for a specified village or living space. This outlook could be an approach for another PhD research, sampling and data collection. However, more research work is being undertaken in the area by donor and research organizations, including CuveWaters and GIZ.

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Appendices

A: Namibia water corporation drinking water guidelines document

NAMWATER	**Namibia Water Corporation Ltd.**
GUIDELINES FOR THE EVALUATION OF DRINKING-WATER FOR HUMAN CONSUMPTION WITH REGARD TO CHEMICAL, PHYSICAL AND BACTERIOLOGICAL QUALITY	

1. INTRODUCTION

1.1 Water supplied for human consumption must comply with the officially approved guidelines for drinking-water quality.

1.2 For practical reasons the approved guidelines have been divided into three basic groups of determinants, namely:

Determinants with aesthetic or physical implications, see TABLE 1 attached.

Inorganic determinants, see TABLE 2 attached.

Bacteriological determinants, see TABLE 3 attached.

2. CLASSIFICATION OF WATER

2.1 The concentration of and limits for the aesthetic, physical and inorganic determinants define the group into which water will be classified. See TABLE 1 and TABLE 2 for these limits.

GROUP A: Water with an excellent quality

GROUP B: Water with good quality

GROUP C: Water with low health risk

GROUP D: Water with a higher health risk, or water unsuitable for human consumption

2.2 Water should ideally be of excellent quality (Group A) or good quality (Group B), however in practice many of the determinants may fall outside the limits for these groups.

2.3 If water is classified as having a low health risk (Group C), attention should be given to this problem, although the situation is not critical yet.

2.4 If water is classified as having a higher health risk (Group D), urgent and immediate attention should be given to this matter. Since the limits are defined on the basis of average lifelong consumption, short term exposure to determinants exceeding their limits is not necessarily critical, but in the case of extremely toxic substances such as cyanide, remedial procedures should immediately be taken.

2.5 The group in which the water is classified is determined by the determinant which complies the least with the guidelines for the quality of drinking-water.

2.6 The bacteriological quality of drinking-water is also divided into four groups, namely:

GROUP A: Water which is bacteriologically very safe

GROUP B: Water which is bacteriologically still suitable for human consumption

GROUP C: Water with a bacteriological risk for human consumption which requires immediate action for rectification

GROUP D: Water which is bacteriologically unsuitable for human consumption

3. FREQUENCY FOR BACTERIOLOGICAL ANALYSIS OF DRINKING-WATER SUPPLIES

The recommended frequency for bacteriological analysis of drinking-water supplies is given below in TABLE 4.

TABLE 4	**FREQUENCY FOR BACTERIOLOGICAL ANALYSIS**
More than 100 000	twice a week
50 000 - 100 000	once a week
10 000 - 50 000	once a month
Minimum analysis	once every three months

4. PROMULGATION

The Cabinet of the Transitional Government for National Unity has approved the guidelines for evaluating drinking-water for human consumption with respect to the chemical, physical and bacteriological qualities, by Cabinet's Approval 461/85 and reporting on the evaluation of drinking-water according to the new guidelines took effect as from 1 April 1988.

GENERAL MANAGER : ENGINEERING & SCIENTIFIC SERVICES

June 1998

TABLE 1	DETERMINANTS WITH AESTHETIC/PHYSICAL IMPLICATIONS

DETERMINANTS	UNITS	LIMITS FOR GROUPS			
		A	B	C	D*
Colour	mg/l Pt**	20	-	-	-
Conductivity	mS/m 25^{0}C	150	300	400	400
Total hardness	mg/l $CaCO_3$	300	650	1300	1300
Turbidity	N.T.U.***	1	5	10	10
Chloride	mg/l Cl	250	600	1200	1200
Chlorine (free)	mg/l Cl	0.1-5.0	0.1-5.0	0.1-5.0	5.0
Fluoride	mg/l F	1.5	2.0	3.0	3.0
Sulphate	mg/l SO_4	200	600	1200	1200
Copper	µg/l Cu	500	1000	2000	2000
Nitrate	mg/l N	10	20	40	40
Hydrogen Sulphide	µg/l H_2S	100	300	600	600
Iron	µg/l Fe	100	1000	2000	2000
Manganese	µg/l Mn	50	1000	2000	2000
Zinc	mg/l Zn	1	5	10	10
pH****	pH-unit	6.0-9.0	5.5-9.5	4.0-11.0	4.0-11.0

***** **All values greater than the figure indicated.**

****** **Pt = Platinum Units.**

******* **Nephelometric Turbidity Units.**

******** **The pH limits of each group exclude the limits of the previous group.**

TABLE 2		LIMITS FOR INORGANIC CONSTITUENTS IN DRINKING WATER			
Determinants	**Unit**	**Limit for Groups**			
		A	**B**	**C**	**D***
Aluminium	µg/l Al	150	500	1000	1000
Ammonia	mg/l N	1	2	4	4
Antimony	µg/l Sb	50	100	200	200
Arsenic	µg/l As	100	300	600	600
Barium	µg/l Ba	500	1000	2000	2000
Beryllium	µg/l Be	2	5	10	10
Bismuth	µg/l Bi	250	500	1000	1000
Boron	µg/l B	500	2000	4000	4000
Bromine	µg/l Br	1000	3000	6000	6000
Cadmium	µg/l Cd	10	20	40	40
Calcium	mg/l Ca mg/l $CaCO_3$	150 375	200 500	400 1000	400 1000
Cerium	µg/l Ce	1000	2000	4000	4000
Chromium	µg/l Cr	100	200	400	400
Cobalt	µg/l Co	250	500	1000	1000
Cyanide Free	µg/l CN	200	300	600	600
Gold	µg/l Au	2	5	10	10
Iodine	µg/l I	500	1000	2000	2000
Lead	µg/l Pb	50	100	200	200
Lithium	µg /l Li	2500	5000	10000	10000

Magnesium	mg/l Mg mg/l $CaCo_3$	70 290	100 420	200 840	200 840
Mercury	µg/l Hg	5	10	20	20
Molybdenum	µg/l Mo	50	100	200	200
Nickel	µg/l Ni	250	500	1000	1000
Potassium	mg/l K	200	400	800	800
Selenium	µg/l Se	20	50	100	100
Silver	µg/l Ag	20	50	100	100
Sodium	mg/l Na	100	400	800	800
Tellium	µg/l Te	2	5	10	10
Thallium	ug/l Tl	5	10	20	20
Tin	µg/l Sn	100	200	400	400
Titanium	µg/l Ti	100	500	1000	1000
Tungsten	µg/l W	100	500	1000	1000
Uranium	µg/l U	1000	4000	8000	8000
Vanadium	µg/l V	250	500	1000	1000

***	All values greater than the figure indicated.**

TABLE 3	BACTERIOLOGICAL DETERMINANTS

DETERMINANTS (COUNTS)	LIMITS FOR GROUPS			
	A**	B**	C	D*
Standard plate counts per 1 ml	100	1000	10000	10000
Total coliform counts per 100 ml	0	10	100	100
Faecal coliform counts per 100 ml	0	5	50	50
E. coli counts per 100 ml	0	0	10	10

* **All values greater than the figure indicated.**

** **In 95% of the samples.**

NB If the guidelines in Group A are exceeded, a follow-up sample should be analysed as soon as possible.

B: Technical evaluations of the desalination techniques

RO technology performance						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	53.33%	Gained Output ratio	0.00%	0%	0.00%	0
		Recovery Rate	6.67%	35%	2.30%	2
		Pretreatment Requirement	10.00%	33%	3.33%	3
		Sensitivity to feedwater quality	10.00%	34%	3.37%	3
		Post treatment	3.33%	67%	2.22%	1
		Operating pressure range	10.00%	44%	4.44%	3
		Operating temperature	3.33%	76%	2.54%	1
		scaling/ fouling potential	3.33%	0%	0.00%	1
		Corrosion susceptibility	3.33%	50%	1.67%	1
		Permeate Quality	3.33%	40%	1.34%	1
Environmental	26.67%	Brine Disposal	6.67%	33%	2.17%	2
		Mechanical/Electrical power input	6.67%	37%	2.47%	2
		Heat energy input	3.33%	0%	0.00%	1
		Prime energy consumption	10.00%	100%	10.00%	3
Economic	20.00%	Running cost	10.00%	42%	4.23%	3
		Water generation cost	10.00%	75%	7.50%	3
	100.00%		100.00%		47.60%	
		No. of important criteria	6			
		No. of medium	3			
		No. of unimportant criteria	6			
		No. irrelevant criteria	1			
		Weight	3.33%			

Electro dialysis technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	53.33%	Gained Output ratio	0.00%	0%	0.00%	0
		Recovery Rate	6.67%	95%	6.35%	2
		Pretreatment Requirement	10.00%	33%	3.33%	3
		Sensitivity to feedwater quality	10.00%	0%	0.00%	3
		Post treatment	3.33%	67%	2.22%	1
		Operating pressure range	10.00%	0%	0.00%	3
		Operating temperature	3.33%	76%	2.54%	1
		scaling/ fouling potential	3.33%	0%	0.00%	1
		Corrosion susceptibility	3.33%	100%	3.33%	1
		Permeate Quality	3.33%	63%	2.11%	1
Environmental	26.67%	Brine Disposal	6.67%	11%	0.70%	2
		Mechanical/Electrical power input	6.67%	42%	2.78%	2
		Heat energy input	3.33%	100%	3.33%	1
		Prime energy consumption	10.00%	94%	9.43%	3
Economic	20.00%	Running cost	10.00%	100%	10.00%	3
		Water generation cost	10.00%	54%	5.42%	3
	100.00%		**100.00%**		**51.55%**	

No. of important criteria	6
No. of medium	3
No. of unimportant criteria	6
No. irrelevant criteria	1
Weight	3.33%

Membrane Distillation technology performance evaluation

	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	58.82%	Gained Output ratio	8.82%	14%	1.20%	3
		Recovery Rate	5.88%	56%	3.29%	2
		Pretreatment Requirement	2.94%	33%	0.98%	1
		Sensitivity to feedwater quality	5.88%	22%	1.28%	2
		Post treatment	2.94%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	8.82%	32%	2.79%	3
		scaling/ fouling potential	5.88%	0%	0.00%	2
		Corrosion susceptibility	8.82%	100%	8.82%	3
		Permeate Quality	8.82%	99%	8.75%	3
Environmental	23.53%	Brine Disposal	5.88%	48%	2.79%	2
		Mechanical/Electrical power input	5.88%	6%	0.38%	2
		Heat energy input	2.94%	0%	0.00%	1
		Prime energy consumption	8.82%	0%	0.00%	3
Economic	17.65%	Running cost	8.82%	78%	6.90%	3
		Water generation cost	8.82%	29%	2.57%	3
	100.00%		100.00%		39.76%	

No. of important criteria	7
No. of medium	5
No. of unimportant criteria	3
No. of irrelevant criteria	1
Weight	2.94%

Multiple Effect Humidification technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	58.82%	Gained Output ratio	8.82%	36%	3.21%	3
		Recovery Rate	5.88%	74%	4.38%	2
		Pretreatment Requirement	2.94%	100%	2.94%	1
		Sensitivity to feedwater quality	8.82%	100%	8.82%	3
		Post treatment	5.88%	0%	0.00%	2
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	8.82%	21%	1.86%	3
		scaling/ fouling potential	2.94%	50%	1.47%	1
		Corrosion susceptibility	8.82%	100%	8.82%	3
		Permeate Quality	5.88%	99%	5.85%	2
Environmental	23.53%	Brine Disposal	5.88%	30%	1.76%	2
		Mechanical/Electrical power input	2.94%	51%	1.50%	1
		Heat energy input	5.88%	8%	0.46%	2
		Prime energy consumption	8.82%	26%	2.27%	3
Economic	17.65%	Running cost	8.82%	80%	7.08%	3
		Water generation cost	8.82%	92%	8.09%	3
	100.00%		100.00%		58.51%	

No. of important criteria	7
No. of medium	5
No. of unimportant criteria	3
No. of irrelevant criteria	1
Weight	2.94%

Multiple Effect Distillation technology performance evaluation						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**58.82%**	Gained Output ratio	8.82%	82%	7.22%	3
		Recovery Rate	5.88%	35%	2.03%	2
		Pretreatment Requirement	2.94%	67%	1.96%	1
		Sensitivity to feedwater quality	5.88%	100%	5.88%	2
		Post treatment	2.94%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	8.82%	32%	2.79%	3
		scaling/ fouling potential	5.88%	50%	2.94%	2
		Corrosion susceptibility	8.82%	0%	0.00%	3
		Permeate Quality	8.82%	100%	8.80%	3
Environmental	**23.53%**	Brine Disposal	5.88%	68%	3.97%	2
		Mechanical/Electrical power input	5.88%	100%	5.88%	2
		Heat energy input	2.94%	69%	2.02%	1
		Prime energy consumption	8.82%	93%	8.21%	3
Economic	**17.65%**	Running cost	8.82%	14%	1.25%	3
		Water generation cost	8.82%	57%	5.06%	3
	100.00%		**100.00%**		**58.01%**	

No. of important criteria	7
No. of medium	5
No. of unimportant criteria	3
No. of irrelevant criteria	1
Weight	2.94%

Multi Stage Flash technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	58.82%	Gained Output ratio	8.82%	64%	5.61%	3
		Recovery Rate	5.88%	40%	2.35%	2
		Pretreatment Requirement	2.94%	67%	1.96%	1
		Sensitivity to feedwater quality	5.88%	100%	5.88%	2
		Post treatment	2.94%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	8.82%	0%	0.00%	3
		scaling/ fouling potential	5.88%	50%	2.94%	2
		Corrosion susceptibility	8.82%	0%	0.00%	3
		Permeate Quality	8.82%	97%	8.60%	3
Environmental	23.53%	Brine Disposal	5.88%	38%	2.21%	2
		Mechanical/Electrical power input	5.88%	90%	5.31%	2
		Heat energy input	2.94%	25%	0.74%	1
		Prime energy consumption	8.82%	48%	4.24%	3
Economic	17.65%	Running cost	8.82%	35%	3.06%	3
		Water generation cost	8.82%	21%	1.84%	3
	100.00%		100.00%		44.73%	

No. of important criteria	7
No. of medium	5
No. of unimportant criteria	3
No. of irrelevant criteria	1
Weight	2.94%

C: Economic evaluations of the desalination techniques

RO technology performance						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**26.73%**	Gained Output ratio	0.00%	0%	0.00%	0
		Recovery Rate	2.97%	35%	1.03%	0.75
		Pretreatment Requirement	2.97%	33%	0.99%	0.75
		Sensitivity to feedwater quality	2.97%	34%	1.00%	0.75
		Post treatment	2.97%	67%	1.98%	0.75
		Operating pressure range	2.97%	44%	1.32%	0.75
		Operating temperature	2.97%	76%	2.27%	0.75
		scaling/ fouling potential	2.97%	0%	0.00%	0.75
		Corrosion susceptibility	2.97%	50%	1.49%	0.75
		Permeate Quality	2.97%	40%	1.19%	0.75
Environmental	**23.76%**	Brine Disposal	5.94%	33%	1.93%	1.5
		Mechanical/Electrical power input	5.94%	37%	2.20%	1.5
		Heat energy input	5.94%	0%	0.00%	1.5
		Prime energy consumption	5.94%	100%	5.94%	1.5
Economic	**49.50%**	Running cost	24.75%	42%	10.48%	6.25
		Water generation cost	24.75%	75%	18.56%	6.25
	100.00%		**100.00%**		**50.38%**	

No. of important criteria	2
No. of medium	4
No. of unimportant criteria	9
No. irrelevant criteria	1
Weight	3.96%

Electro dialysis technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	26.73%	Gained Output ratio	0.00%	0%	0.00%	0
		Recovery Rate	2.97%	95%	2.83%	0.75
		Pretreatment Requirement	2.97%	33%	0.99%	0.75
		Sensitivity to feedwater quality	2.97%	0%	0.00%	0.75
		Post treatment	2.97%	67%	1.98%	0.75
		Operating pressure range	2.97%	0%	0.00%	0.75
		Operating temperature	2.97%	76%	2.27%	0.75
		scaling/ fouling potential	2.97%	0%	0.00%	0.75
		Corrosion susceptibility	2.97%	100%	2.97%	0.75
		Permeate Quality	2.97%	63%	1.88%	0.75
Environmental	23.76%	Brine Disposal	5.94%	11%	0.62%	1.5
		Mechanical/Electrical power input	5.94%	42%	2.48%	1.5
		Heat energy input	5.94%	0%	0.00%	1.5
		Prime energy consumption	5.94%	94%	5.60%	1.5
Economic	49.50%	Running cost	24.75%	100%	24.75%	6.25
		Water generation cost	24.75%	54%	13.41%	6.25
	100.00%		100.00%		59.78%	
		No. of important criteria	2			
		No. of medium	4			
		No. of unimportant criteria	9			
		No. irrelevant criteria	1			
		Weight	3.96%			

Membrane Distillation technology performance evaluation						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**26.73%**	Gained Output ratio	2.97%	14%	0.41%	0.75
		Recovery Rate	2.97%	56%	1.66%	0.75
		Pretreatment Requirement	2.97%	33%	0.99%	0.75
		Sensitivity to feedwater quality	2.97%	22%	0.64%	0.75
		Post treatment	2.97%	0%	0.00%	0.75
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	2.97%	32%	0.94%	0.75
		scaling/ fouling potential	2.97%	0%	0.00%	0.75
		Corrosion susceptibility	2.97%	100%	2.97%	0.75
		Permeate Quality	2.97%	99%	2.95%	0.75
Environmental	**23.76%**	Brine Disposal	5.94%	48%	2.82%	1.5
		Mechanical/Electrical power input	5.94%	6%	0.39%	1.5
		Heat energy input	5.94%	0%	0.00%	1.5
		Prime energy consumption	5.94%	0%	0.00%	1.5
Economic	**49.50%**	Running cost	24.75%	78%	19.36%	6.25
		Water generation cost	24.75%	29%	7.22%	6.25
	100.00%		**100.00%**		**40.34%**	
		No. of important criteria	2			
		No. of medium	4			
		No. of unimportant criteria	9			
		No. of irrelevant criteria	1			
		Weight	3.96%			

Multiple Effect Humidification technology performance evaluation						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**26.73%**	Gained Output ratio	2.97%	36%	1.08%	0.75
		Recovery Rate	2.97%	74%	2.21%	0.75
		Pretreatment Requirement	2.97%	100%	2.97%	0.75
		Sensitivity to feedwater quality	2.97%	100%	2.97%	0.75
		Post treatment	2.97%	0%	0.00%	0.75
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	2.97%	21%	0.63%	0.75
		scaling/ fouling potential	2.97%	50%	1.49%	0.75
		Corrosion susceptibility	2.97%	100%	2.97%	0.75
		Permeate Quality	2.97%	99%	2.96%	0.75
Environmental	**23.76%**	Brine Disposal	5.94%	30%	1.78%	1.5
		Mechanical/Electrical power input	5.94%	51%	3.03%	1.5
		Heat energy input	5.94%	8%	0.46%	1.5
		Prime energy consumption	5.94%	26%	1.53%	1.5
Economic	**49.50%**	Running cost	24.75%	80%	19.86%	6.25
		Water generation cost	24.75%	92%	22.69%	6.25
	100.00%		**100.00%**		**66.62%**	

No. of important criteria	2
No. of medium	4
No. of unimportant criteria	9
No. of irrelevant criteria	1
Weight	3.96%

Multiple Effect Distillation technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	26.73%	Gained Output ratio	2.97%	82%	2.43%	0.75
		Recovery Rate	2.97%	35%	1.03%	0.75
		Pretreatment Requirement	2.97%	67%	1.98%	0.75
		Sensitivity to feedwater quality	2.97%	100%	2.97%	0.75
		Post treatment	2.97%	0%	0.00%	0.75
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	2.97%	32%	0.94%	0.75
		scaling/ fouling potential	2.97%	50%	1.49%	0.75
		Corrosion susceptibility	2.97%	0%	0.00%	0.75
		Permeate Quality	2.97%	100%	2.96%	0.75
Environmental	23.76%	Brine Disposal	5.94%	68%	4.01%	1.5
		Mechanical/Electrical power input	5.94%	100%	5.94%	1.5
		Heat energy input	5.94%	69%	4.08%	1.5
		Prime energy consumption	5.94%	93%	5.52%	1.5
Economic	49.50%	Running cost	24.75%	14%	3.49%	6.25
		Water generation cost	24.75%	57%	14.19%	6.25
	100.00%		100.00%		51.03%	

No. of important criteria	2
No. of medium	4
No. of unimportant criteria	9
No. of irrelevant criteria	1
Weight	3.96%

Multi Stage Flash technology performance evaluation						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**26.73%**	Gained Output ratio	2.97%	64%	1.89%	0.75
		Recovery Rate	2.97%	40%	1.18%	0.75
		Pretreatment Requirement	2.97%	67%	1.98%	0.75
		Sensitivity to feedwater quality	2.97%	100%	2.97%	0.75
		Post treatment	2.97%	0%	0.00%	0.75
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	2.97%	0%	0.00%	0.75
		scaling/ fouling potential	2.97%	50%	1.49%	0.75
		Corrosion susceptibility	2.97%	0%	0.00%	0.75
		Permeate Quality	2.97%	97%	2.90%	0.75
Environmental	**23.76%**	Brine Disposal	5.94%	38%	2.23%	1.5
		Mechanical/Electrical power input	5.94%	90%	5.36%	1.5
		Heat energy input	5.94%	25%	1.49%	1.5
		Prime energy consumption	5.94%	48%	2.85%	1.5
Economic	**49.50%**	Running cost	24.75%	35%	8.58%	6.25
		Water generation cost	24.75%	21%	5.16%	6.25
	100.00%		**100.00%**		**38.08%**	

No. of important criteria	2
No. of medium	4
No. of unimportant criteria	9
No. of irrelevant criteria	1
Weight	3.96%

D: Environmental evaluations of the desalination techniques

RO technology performance						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	31.03%	Gained Output ratio	0.00%	0%	0.00%	0
		Recovery Rate	3.45%	35%	1.19%	1
		Pretreatment Requirement	3.45%	33%	1.15%	1
		Sensitivity to feedwater quality	3.45%	34%	1.16%	1
		Post treatment	3.45%	67%	2.30%	1
		Operating pressure range	3.45%	44%	1.53%	1
		Operating temperature	3.45%	76%	2.63%	1
		scaling/ fouling potential	3.45%	0%	0.00%	1
		Corrosion susceptibility	3.45%	50%	1.72%	1
		Permeate Quality	3.45%	40%	1.39%	1
Environmental	55.17%	Brine Disposal	13.79%	33%	4.48%	4
		Mechanical/Electrical power input	13.79%	37%	5.11%	4
		Heat energy input	13.79%	0%	0.00%	4
		Prime energy consumption	13.79%	100%	13.79%	4
Economic	13.79%	Running cost	6.90%	42%	2.92%	2
		Water generation cost	6.90%	75%	5.17%	2
	100.00%		100.00%		44.56%	

No. of important criteria	4
No. of medium	2
No. of unimportant criteria	9
No. irrelevant criteria	1
Weight	3.45%

Electro dialysis technology performance evaluation						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**31.03%**	Gained Output ratio	0.00%	0%	0.00%	0
		Recovery Rate	3.45%	95%	3.28%	1
		Pretreatment Requirement	3.45%	33%	1.15%	1
		Sensitivity to feedwater quality	3.45%	0%	0.00%	1
		Post treatment	3.45%	67%	2.30%	1
		Operating pressure range	3.45%	0%	0.00%	1
		Operating temperature	3.45%	76%	2.63%	1
		scaling/ fouling potential	3.45%	0%	0.00%	1
		Corrosion susceptibility	3.45%	100%	3.45%	1
		Permeate Quality	3.45%	63%	2.18%	1
Environmental	**55.17%**	Brine Disposal	13.79%	11%	1.45%	4
		Mechanical/Electrical power input	13.79%	42%	5.75%	4
		Heat energy input	13.79%	0%	0.00%	4
		Prime energy consumption	13.79%	94%	13.00%	4
Economic	**13.79%**	Running cost	6.90%	100%	6.90%	2
		Water generation cost	6.90%	54%	3.74%	2
	100.00%		**100.00%**		**45.83%**	

No. of important criteria	4
No. of medium	2
No. of unimportant criteria	9
No. irrelevant criteria	1
Weight	3.45%

Membrane Distillation technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	31.03%	Gained Output ratio	3.45%	14%	0.47%	1
		Recovery Rate	3.45%	56%	1.93%	1
		Pretreatment Requirement	3.45%	33%	1.15%	1
		Sensitivity to feedwater quality	3.45%	22%	0.75%	1
		Post treatment	3.45%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	3.45%	32%	1.09%	1
		scaling/ fouling potential	3.45%	0%	0.00%	1
		Corrosion susceptibility	3.45%	100%	3.45%	1
		Permeate Quality	3.45%	99%	3.42%	1
Environmental	55.17%	Brine Disposal	13.79%	48%	6.55%	4
		Mechanical/Electrical power input	13.79%	6%	0.89%	4
		Heat energy input	13.79%	0%	0.00%	4
		Prime energy consumption	13.79%	0%	0.00%	4
Economic	13.79%	Running cost	6.90%	78%	5.39%	2
		Water generation cost	6.90%	29%	2.01%	2
	100.00%		100.00%		27.10%	

No. of important criteria	4
No. of medium	2
No. of unimportant criteria	9
No. of irrelevant criteria	1
Weight	3.45%

Multiple Effect Humidification technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	31.03%	Gained Output ratio	3.45%	36%	1.25%	1
		Recovery Rate	3.45%	74%	2.57%	1
		Pretreatment Requirement	3.45%	100%	3.45%	1
		Sensitivity to feedwater quality	3.45%	100%	3.45%	1
		Post treatment	3.45%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	3.45%	21%	0.73%	1
		scaling/ fouling potential	3.45%	50%	1.72%	1
		Corrosion susceptibility	3.45%	100%	3.45%	1
		Permeate Quality	3.45%	99%	3.43%	1
Environmental	55.17%	Brine Disposal	13.79%	30%	4.14%	4
		Mechanical/Electrical power input	13.79%	51%	7.02%	4
		Heat energy input	13.79%	8%	1.07%	4
		Prime energy consumption	13.79%	26%	3.55%	4
Economic	13.79%	Running cost	6.90%	80%	5.53%	2
		Water generation cost	6.90%	92%	6.32%	2
	100.00%		100.00%		47.68%	

No. of important criteria	4
No. of medium	2
No. of unimportant criteria	9
No. of irrelevant criteria	1
Weight	3.45%

Multiple Effect Distillation technology performance evaluation						
	Weight of Assessment	**Criteria**	**Weight of target**	**Target achievement**	**Partial utility**	**Level of importance**
Technical Assessment	**31.03%**	Gained Output ratio	3.45%	82%	2.82%	1
		Recovery Rate	3.45%	35%	1.19%	1
		Pretreatment Requirement	3.45%	67%	2.30%	1
		Sensitivity to feedwater quality	3.45%	100%	3.45%	1
		Post treatment	3.45%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	3.45%	32%	1.09%	1
		scaling/ fouling potential	3.45%	50%	1.72%	1
		Corrosion susceptibility	3.45%	0%	0.00%	1
		Permeate Quality	3.45%	100%	3.44%	1
Environmental	**55.17%**	Brine Disposal	13.79%	68%	9.31%	4
		Mechanical/Electrical power input	13.79%	100%	13.79%	4
		Heat energy input	13.79%	69%	9.47%	4
		Prime energy consumption	13.79%	93%	12.83%	4
Economic	**13.79%**	Running cost	6.90%	14%	0.97%	2
		Water generation cost	6.90%	57%	3.95%	2
	100.00%		**100.00%**		**66.34%**	

No. of important criteria	4
No. of medium	2
No. of unimportant criteria	9
No. of irrelevant criteria	1
Weight	3.45%

Multi Stage Flash technology performance evaluation						
	Weight of Assessment	Criteria	Weight of target	Target achievement	Partial utility	Level of importance
Technical Assessment	31.03%	Gained Output ratio	3.45%	64%	2.19%	1
		Recovery Rate	3.45%	40%	1.38%	1
		Pretreatment Requirement	3.45%	67%	2.30%	1
		Sensitivity to feedwater quality	3.45%	100%	3.45%	1
		Post treatment	3.45%	0%	0.00%	1
		Operating pressure range	0.00%	0%	0.00%	0
		Operating temperature	3.45%	0%	0.00%	1
		scaling/ fouling potential	3.45%	50%	1.72%	1
		Corrosion susceptibility	3.45%	0%	0.00%	1
		Permeate Quality	3.45%	97%	3.36%	1
Environmental	55.17%	Brine Disposal	13.79%	38%	5.17%	4
		Mechanical/Electrical power input	13.79%	90%	12.45%	4
		Heat energy input	13.79%	25%	3.46%	4
		Prime energy consumption	13.79%	48%	6.62%	4
Economic	13.79%	Running cost	6.90%	35%	2.39%	2
		Water generation cost	6.90%	21%	1.44%	2
	100.00%		100.00%		45.94%	
		No. of important criteria	4			
		No. of medium	2			
		No. of unimportant criteria	9			
		No. of irrelevant criteria	1			
		Weight	3.45%			

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A. PERSONAL INFORMATION	
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Nationality	Namibian
Languages spoken	English, Oshiwambo, Otjiherero, Afrikaans
Date of birth	26. Mai 69
B. ACADEMIC ACHIEVEMENTS	
PhD candidate	University of Trier, Trier, Germany. 2008 - 2013
	Doctorate dissertation Supervisors: Prof. W. Symader (Univ. of Trier), Prof. W. Urban (Univ. of Darmstadt, Germany).
	Topic: Evaluation of desalination techniques for treating the brackish water of Olushandja sub-basin.
Master of Science Degree	Royal Institute of Technology, Stockholm, Sweden. MSc: Environmental Engineering, November 1997
	Thesis topic: "Groundwater Modelling Between Gobabeb and Rooibank Gauging Stations".
Bachelor of Arts Degree	Wartburg College, Waverly, Iowa, USA.
Associate in Management Practice	UCT, Graduate School of Business, 2007
C. CURRENT POSITION:	
Senior Scientist	Infrastructure Planning, NamWater, Windhoek, August 2005 – Present
D. PREVIOUS POSITION	
Area Manager	Namwater, Oshakati, July. 2001 to July 2005
H. OTHER EXPERIENCE	
Board of Trustees' member	NamWater Retirement Fund board member, August 2006 – September 2011
Main function	Ensuring that the fund is managed in a responsible and prudent manner.
NamWater Strategic Committee member	Team leader for PESTEL macro environmental analysis of NamWater, June 2014 to date
Main function	Responsible for the compilation of NamWater new stratetgy and alignment of approved structure.

DECLARATION

I, Kaliki Kambanda, the undersigned hereby declare that the work contained in this dissertation is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Signature *Date*

28/06/2012