Desalination and the Environment: Options and considerations for brine disposal in inland and coastal locations

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AQUALYNG

FOREWORD

The initiatiors of this project are Yara International and Aqualyng. The original idea for the study was focused on desalination for irrigation, however it was put aside because the brine disposal issues were identified as an absolute prerequisite for adaptation of desalination within the agricultural and tourism sectors.

I would like to thank Per Kosberg (Aqualyng) and Terje Knutsen (Yara International). Also thanks to Fernando Perez (Aqualyng), Per-Anders Hansson (Swedish University of Agricultural Sciences), Hallvard Ödegaard and Tor-Ove Leiknes (Norwegian University of Science and Technology) and Mushtaque Ahmed (Sultan Qaboos University) for assisting me with my study.

Special thanks to Assem Doss (Assem Doss & Co) for arranging my visit to Egypt and Khaled Hegazy (Assem Doss & Co) for organizing my visit.

Last but not least, I would like to thank Yara International and Aqualyng for giving me this opportunity.

SAMMANFATTNING

Studien handlar om vad som kan göras med saltrejektet från revers osmos avsaltningsanläggningar, både för platser vid kusten och platser i inlandet, för att förebygga miljöskador som okontrollerat utsläpp kan ge upphov till. Studien är uppdelad i två sektioner, en litteraturstudie och en fallstudie.

I litteraturstudien beskrivs tänkbara metoder för att ta hand om/göra sig av med saltrejektet. Dessa metoder är antingen redan i användning runt om i världen, är på idéstadie eller under utveckling.

I fallstudien tillämpas kunskaperna från litteraturstudien ur praktisk synpunkt på ett fall i Egypten. De bästa och mest optimala lösningarna bestäms utifrån förhållandena på platsen och betygsätts huvudsakligen enligt två huvudkriterier: den förväntade kostnaden och miljöeffekten.

Slutsatsen blev att det finns ingen universell lösning, utan den mest optimala metoden måste bestämmas från plats till plats och utifrån nyttan av varje metod jämfört med kostnaden. Gemensamt är att det är dyrt att vara miljövänlig och det kommer krävas lagstiftning i varje region om vad som ska göras med saltrejektet för att miljövänliga alternativ skall tillämpas.

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1. INTRODUCTION

Water scarcity is becoming a major problem in many regions of the world. Explosive population growth, increased urbanization, global warming, excessive usage and changing water resource usage patterns are mainly to blame for this. In many cases, water shortage is the limiting factor to economic and social development.

As much as 98% of the water in the world is saline water (seawater, saline groundwater and saline seas) and is therefore not suitable for drinking water or for other uses such as agriculture. Thermal technologies for the production of potable water from these water sources have been available for over half a century, however the high cost of desalination highly limited the applicability of this option. *"If we could ever competitively, at a cheap rate, get freshwater from saltwater, that would be in the long-range interests of humanity and would dwarf any other scientific accomplishments"* John F. Kennedy, 1961.

Due to the introduction of membrane desalination and the major technological advancements that has been made the last 10-15 years within the field, desalination is becoming more and more commercialised and increasing the spectrum of suitable and possible applications for it.

The only aspect of desalination which has been relatively neglected is the environment. Desalination and the environment, with the main issue being solutions for brine disposal, should be in more focus than it is today.

However, the basic concept is that it is a human right to have clean, fresh water available and in order to restrict predicted future water stress situations in the world, desalination have to be embraced and further technological progressions regarding energy consumption and ultimately the cost of desalinized water, in combination with environmental strategies, must be made. *"Let us acknowledge, that clean water is a universal human right, and in so doing let us accept that we have a corresponding responsibility to ensure that the forecast of a world where, in 25 years time, two out of every three people face water stress is proven wrong"*. Mikhail Gorbachev, 2000.

2. BACKGROUND INFORMATION

The project is divided in two sections, one theoretical part and one application study. The literature study was focused on collection of information and is written on a general level. The information comes from the internet, the library at my university and from contacts with various people. The topics in the general study include environmental effects of increasing salinity, natural and unnatural sources of salinity with focus on the problem of coastal saline intrusion and options and considerations for brine disposal in inland and coastal locations. The main focus is on inland brine disposal as this is considered to have a greater economical and environmental impact on a desalination plant since the brine cannot be disposed of into the sea.

The application study is a practical continuation of the theoretical study where previous acquired knowledge regarding inland brine disposal will be implemented on a local basis. Therefore, a case study of Samarina farm, located appr. 90 km northeast of Cairo in Egypt, was performed.

2.1 Aim

The aim of the study is, first and foremost, to highlight what kind of brine disposal methods are being used around the world, especially for inland applications, and new methods that theoretically could be applied based on new technologies and researches. The advantages and disadvantages of each method will be discussed.

This information will then be applied on a specific case study, where each method will be weighed against each other using two main criteria, the cost and the environmental impact.

I

LITERATURE STUDY

3. SALINITY IN WATER AND SOIL

Saline water can be derived from many different sources. Some of them are natural sources and others are caused by human intervention.

3.1 Connate water

Many unconsolidated sedimentary aquifers have underlying connate water. This is water which has been entrapped in the interstices of sedimentary rocks at the time of its deposition and has become naturally saline. Also called ancient water. Saline intrusion of connate water to overlying fresh water aquifers can happen in case of pumping [a].

3.2 Dissolution of evaporites

Evaporites are sediments that has been derived mainly from the evaporation of seawater. Groundwaters may become saline due to dissolution of the evaporite rocks they are circulating through [a].

Figure 1: Evaporites formed on a playa lake surface [b].

3.3 Industry

Discharge and leaching from industry as well as from municipal usage (road deicing salts etc).

3.4 Climatic factors

Global warming causing outspread of arid areas and raising the sealevel increasing the problems of saline intrusion.

3.5 Soil salinization

Soil salinization is mainly caused by the continuous accumulation of salts in the soil due to quick evapotranspiration of incoming rain and/or irrigation water. It can also be caused by the capillary rise of shallow saline groundwater as is the case in parts of southern Spain.

This continuously increasing concentration of salts in the soil will cause salinization of underlying groundwater aquifers as well. This effect will be most evident in soils where soil saturation is high and there is a shallow groundwater. Groundwater salinization can be minimised by run off control systems.

In addition to causing salinization of groundwaters, soil salinization has adverse effects on soil properties and plant growth.

3.5.1 Effects on soil properties

High solute concentrations in the soil solution are conducive to good physical properties in the soil. However, low solute concentrations and high concentrations of sodium has adverse effects on the permeability and tilth of the soil [c]. High sodium levels in clayey soils decrease soil permeability, which in turn reduces aeration, and causes dispersion of the soil particles. There is an index called sodium adsorption ratio (SAR) which determine the sodium limit in the soil [g].

When the water has high salt concentration, calcium and magnesium salts form precipitates with carbonates creating insoluble “walls” blocking soil water movement [g].

3.5.2 Effects on plant growth

Salinity in the soil generally reduces crop growth and this is dictated by the salt tolerance of the specific plant. The salt tolerance of a plant may be represented by two factors; the threshold tolerance and the gradient of yield decline [d]. The threshold tolerance is the level of salt concentration in the soil after which it is expected that the maximum expected yield will start to be affected in a negative manner. The gradient of yield decline is simply the rate at which the yield is expected to be decreased for each added unit of salinity beyond the threshold salinity.

However, for crops such as sugar beet, sugar cane, cotton, dates, barley etc which are classified as the most salttolerant crops, low salinity levels may actually increase production due to the fact that the water use efficiency is improved. The least salttolerant crops are beans, onions, strawberries, carrots and almonds [d].

The first symptoms of overexposure to salinity is a reduction in plant growth and a slight darkening in the colour of the leaves. As salinity levels reach toxic levels, visible symptoms such as tip or edge burning of leaves and shoots as well as scorching will appear. This is due to high internal salt concentrations [d]. Other visible symptoms may be connected to nutrient deficiencies caused by nutrient imbalances due to competition between nutrient ions such as Na, Ca and K. Depending on the type of plant and the salinity concentration in the root zone, symptoms may as well be increased or decreased time for the plant to reach maturity [d].

3.6 Coastal saline intrusion

Coastal saline intrusion is described as the phenomenon where seawater displaces or mixes with fresh water in an aquifer due to hydrogeological changes. It is a humanly induced problem caused by excessive drainage of low lying regions along the coast or overpumping of groundwaters that are in hydraulic connection with seawater disrupting the hydraulic equilibrium due to lowering of the groundwater level thus making the seawater displace the freshwater and the saline water/fresh water interface moves inland [a].

This interface is where the two fluids of different salinities meet and across this wedge, molecular diffusion occur which causes mixing of the fluids. The diffusion rate is relatively high in unconsolidated aquifers [a]. Movement of the fluids decreases the diffusion rate but causes dispersion to happen, due to the intergranular structure of the formation, which also causes mixing. Due to the processes of diffusion and dispersion there exists a transition zone between the fluids where there is a concentration gradient [a]. The thickness of this mixing zone is determined by the rate of diffusion and dispersion that occurs in the specified aquifer. External influences which cause movement in the fluids, such as tides and groundwater pumping, will increase the dispersion and thus increase the thickness of the transition zone. In extreme cases, where heavy groundwater abstraction occurs, this zone can be up to 100 m thick [a].

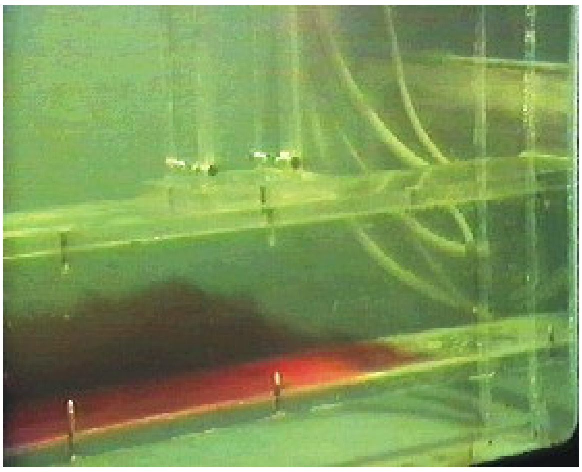

Figure 2: Experimental laboratory test depicting saline intrusion (red colour) [e].

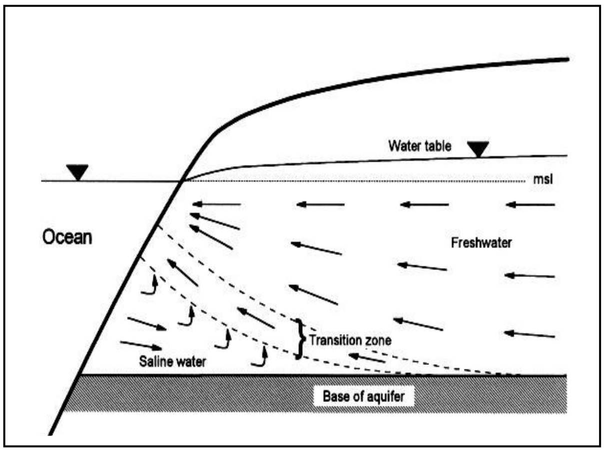

Figure 3: Illustration of transition zone in an unconfined aquifer [a].

However, saline intrusion is not just a problem for coastal areas, it occurs in inland areas as well. In U.S.A., saline intrusion has been reported for all but three states [f]. The problem of coastal saline intrusion is defined as due to horizontal movement of water and for inland locations it is due to vertical movement of water caused by pumping [f], i.e. upconing of connate water to overlying fresh water aquifers.

The increased usage of water resources together with the population growth and the widespread phenomenon of urbanisation to coastal cities, especially in the developing world where many of the groundwater aquifers are unconsolidated, increases the stress of water supply and increased groundwater abstraction enhance the problems of saline intrusion.

3.6.1 The Ghyben-Herzberg equation

The hydraulic equilibrium which exists between two fluids of different densities in a homogeneous, unconfined coastal aquifer is described by the Ghyben-Herzberg equation. Under hydrostatic conditions, there is a balance between the weight of the freshwater and the weight of the saline water at their interface [a]:

$$\rho_s g h_s = \rho_f g(h_s+h_f) \;\rightarrow\; \rho_f = \rho_s/(1+h_f/h_s) \;\rightarrow\; h_s = h_f\, \rho_f/(\rho_s-1) \;\rightarrow\; \mathbf{h_s = 40h_f}$$

h_s = depth to freshwater/seawater interface below sea level
h_f = height of water table above sea level
ρ_f = density of freshwater (1)
ρ_s = density of saline water (1.025)
g = gravitational acceleration

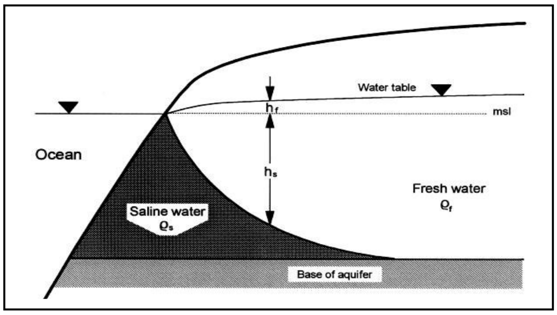

Figure 4: Illustration of Ghyben-Herzberg equation [a].

The ratio of 40:1 from this equation means that lowering the water table in an unconfined aquifer by 1 m will induce a 40 m rise in the saline water interface. Hence, small changes in groundwater levels has large effects on saline intrusion into the same aquifer.

This fact, combined with the fact that as little as 2 % of seawater mix with freshwater can render the water unpotable [a], makes it an alarming problem for coastal communities.

4. MITIGATION MEASURES

4.1 Management of saline intrusion

The first step towards managing saline intrusion is determining the presence and the extent of the problem. The presence of saline water can be determined by measurements of conductivity and chemical analysis of groundwater samples. However, specifying the extent of the problem is more complex. This is typically accomplished by establishing monitoring wells where the position of the transition zone can be observed [a].

Theoretical methods are also used where mathematical formulaes describe the position and elevation of the interface during steady state conditions [a]. The Ghyben-Herzberg equation is a simple way of describing the position of the interface, once there is a fixed position established, by measuring the height of the water table. However, this method does not take into account a transition zone and is therefore applicable mainly where the zone of mixing is minimal. There are other theoretical methods which takes into account a diffuse interface. Modeling is used for predictions of future conditions and for evaluation of alternatives for remediation [a].

Methods for controlling saline intrusion depends on a number of factors such as geology, extent of the problem and economics. The methods are:

4.1.1 Injection barrier wells

A well-known technique used today is the salt water intrusion barrier wells. These wells are used to inject water into aquifers to prevent saline intrusion by creating and maintaining a fresh water wedge. There may be numerous wells paralelling the coastline [f].

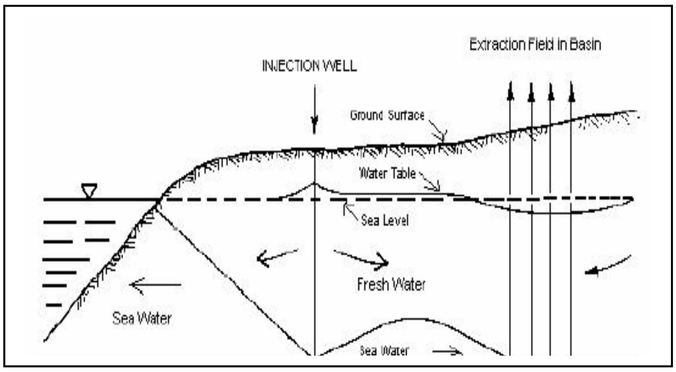

Figure 5: Barrier wells in an unconfined aquifer [f].

4.1.2 Extraction barrier wells

A line of wells along the coast abstracts saline water creating a trough where the height of the water table of the intrusive seawater is lowered in comparison to the water table of the fresh water. The abstracted water is brackish water and is normally disposed of into the sea [f]. This presents interesting possibilities for BWRO desalination. Injection wells and extraction wells can also be combined [f].

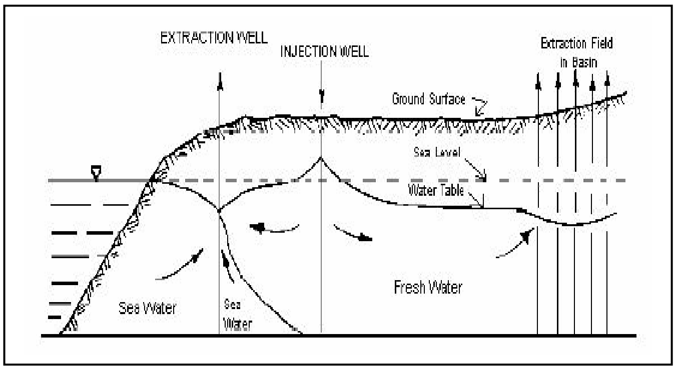

Figure 6: Combination of injection wells and extraction wells in an unconfined aquifer [f].

4.1.3 Subsurface barriers

These are physical walls placed vertically to stop movements of saline water. There are three types of subsurface barriers; steel sheet piles, grout cutoffs and slurry walls [f]. Steel sheet piles are simply lengths of steel connected to each other which are driven in the ground. Grout cutoffs involves injection of a fluid (liquid or slurry) which occupies the pore spaces of the formation and creates a physical wall. Slurry walls is created by injection of a combination of water and bentonite clay into a trench [f].

4.1.4 Aquifer management

This involves control and redistribution of pumping. Control of pumping by proper design and operation of wells and redistribution of pumping by relocating wells [a]. The problems of inland saline intrusion, i.e. upconing of connate water, can be restricted with correct safety proceedures for the drilling and operation of the wells.

4.2 Mitigation by desalination

In OC county (California), numerous injection barrier wells are used to prevent saline intrusion into four different coastal aquifers. The water used for injections is a mixture of wastewater and deep well groundwater. Up to 57000 m^3/day of municipal wastewater is used for this purpose [f]. However, in order for the injectate to meet the primary and secondary standards of drinking water in the U.S., this wastewater is treated utilizing for ex. mixed media filtration, lime clarification and reverse osmosis desalination [f]. This is done to prevent deterioration of the water quality in the aquifers. There are appr. 600 barrier wells in the U.S [f].

In coastal locations with saline intrusion problems, brackish water reverse osmosis (BWRO) desalination plants can be combined with extraction barrier wells as their feed water intake to present a dual purpose installation, i.e. production of potable water and prevention of saline intrusion.

Soil salinization due to irrigation is a widespread phenomenon in semi-arid and arid regions. This is caused by high evapotranspiration and often low quality irrigation water causing salt accumulations in the soil. Using higher quality water with less concentrations of salt may reduce soil salinization and ultimately also salinization of underlying groundwater aquifers. In Israel, there is a widespread salinization of soils and groundwaters and partial desalination of wastewater is viewed as a way of reducing the total salinity load to land and water for sustainable reuse [2].

The main application for desalination as a mitigation measure to soil and water salinization is the prevention of saline intrusion by substituting groundwater abstraction with seawater desalination. In Oman, many areas along the coastline are threatened by saline intrusion due to groundwater abstraction. In order to reduce saline intrusion, seawater reverse osmosis (SWRO) plants have been constructed [3].

5. DESALINATION: BRINE DISPOSAL

The most important environmental issues for a desalination plant are the location of the plant, brine disposal and energy considerations [4].

The location of the plant is an obvious issue where selection of site should be determined by considerations of mainly energy supply available and distance in relation to feed water intake, disposal site and end-user.

Regarding energy, selection of desalination process and source of energy used are vital aspects. Energy consumption represents appr. 25-40% of the total cost of desalination [4]. Renewable energy for desalination must be considered and is in fact viable in remote areas. These include geothermal energy, wind energy, solar energy and hydropower. Hydropower is normally not available in areas suffering from water scarcity, however wind and solar energy are available. Wind energy is used in some small desalination units on islands [4]. The disadvantages are that there are great seasonal variations in wind. Solar energy is more reliable, but it requires large areas of expensive solar acceptors [4].

For brine disposal, the methods used are vital. There are two completely different scenarios regarding brine disposal which is determined by the location of the plant. They are brine disposal in inland areas and in coastal areas with the main difference being possibility for discharge to a large saltwater body, i.e. the sea. Ocean disposal is recognised as the most simple and least costly method and is therefore almost exclusively used whereever it is possible. However, in inland locations too far from the sea, alternative methods have to be used increasing both the economical and environmental impacts of brine disposal. *"For inland locations, where the rejected brine cannot be disposed economically to the sea, or reused for agriculture or other applications, the brine disposal problem is a critical drawback of exploiting of brackish water sources [5]."*

Figure 7: Brine produced at a Hilton resort in Sharm el Sheikh, Egypt. The concentration is appr. 65000 ppm.

6. DISPOSAL IN INLAND LOCATIONS

The utilization of inland brackish groundwater for desalination is increasing. However, often the limiting factor for a plant is brine disposal. There are numerous disposal alternatives recognised today which are being used or being investigated, but the availability of the disposal alternatives is mostly site-specific. Therefore, the most suitable disposal methods from an environmental and economical perspective have to be evaluated site-specifically.

6.1 Deep aquifer injection

This involves injecting the reject water through drilled wells to deep, consolidated aquifers containing non-drinkable water [c]. This is only possible where these deep aquifers occur and the possibilities to monitor the discharges are inadequate resulting in an uncertainty of environmental impacts. It is also a very expensive procedure [c]. This method is used extensively in Florida due to the good hydrogeological conditions of the region [g].

6.2 Aquifer reinjection

This involves reinjection of the brine into the same aquifer used as feed. This will gradually increase the salt concentration in the feed water. Therefore, this method is mainly applicable to smaller plants. However, the impact of the salinity increase expected from full reinjection can be reduced by diverting part of the brine volume for various other disposal alternatives. Important considerations are the size of the aquifer, the salt concentration in the aquifer and the predicted total salt load that is returned. The intake well and the reinjection well should have adequate distance between them in order to restrict feed water quality deterioration.

6.3 Discharge to wastewater treatment plants

This can be a viable option if the desalination plant is located near a wastewater treatment plant. However, there are some considerations to be done before: the volume and composition of the brine in relation to the treatment capacity of the wastewater treatment plant, possible impacts of brine on equipment, piping or processes and what charges might be imposed [8]. In the U.K., the brine is classified as a trade effluent when disposal is carried out via a wastewater system and permission for this must be granted by the local water company [8]. The adverse effects that discharge of brine can have on a wastewater treatment plant can be for ex. calcium carbonate precipitation on filters [8].

6.4 Discharge to sewage system

Many smaller membrane plants discharge the brine to a sewage system. This has the advantage of having a dual purpose dilution. However, this may make the mixed wastewater unuseful in terms of irrigation and considerations have to be made concerning the capacity of the sewage system [6].

6.5 Discharge to open land

This method is used in two RO desalination plants in Saudi Arabia. The reject water is simply discharged to a “natural pond”, the desert [9]. This method will cause salinization of groundwater.

6.6 Reuse for agriculture or landscaping

Water reuse for landscape, ornamental and agricultural applications is an alternative. In Florida this was considered due to the potential for applying this to the very salt-tolerant turf grass that is common in that region [c]. Important considerations are that the salt concentrations as well as the chemical concentrations in the water are appropriate in order to avoid soil and groundwater contamination. These concentration levels should be dictated by vegetation tolerance and underlying groundwater salinity [7].

An important factor regarding irrigation of plants with brine is that there must be an alternative usage or disposal method available for periods of heavy rainfall (where this occurs) [8]. In San Diego County, there exists the possibility for discharge of brine to a brackish water wetland area for a beneficial wetland habitat development [10].

The criteria for using brinewater for irrigation should be site selection, preapplication treatment, hydraulic loading rates, land requirements, selection of vegetation and surface runoff control [6].

6.7 Discharge to inland surface water

Discharge to any surrounding inland surface water (lake, river) is not an environmentally viable option as these are not saltwater bodies, however if practiced it is mainly for smaller plants. The composition of groundwater varies much more than the composition of seawater. Raw groundwater may therefore contain contaminants which are toxic to aquatic organisms at certain concentration levels [7]. This is an environmental consideration for brackish groundwater plants.

Discharge of the brine to surface waters in the UK requires permission by the Environment Agency [8].

6.8 Evaporation ponds

Evaporation ponds have been used for centuries to generate salt. As a means for brine disposal, evaporation ponds can be used to concentrate the brine eventually causing precipitation of salt crystals as the solubility limit is reached.

The major factors determining the cost of an evaporation pond are land costs, earthwork, lining, miscellaneous cost (like seepage monitoring) and operation and maintenance cost [g].

Crystallization of sodium chloride (table salt) begin to happen at a concentration of 25.8% [h], leaving a mineral solution as different salts crystallize at different concentrations. The crystallization is done in crystallization beds with even bottoms as this is where the salt crystals form when they grow heavy enough to overcome the surface tension of the water.

Figure 8: Salt crystals formed [i].

It is better to build a number of smaller ponds connected to each other by pipelines than one larger pond. This will minimise wave damage on the levees and they are also easier to manage. Pond depths between 25 to 45 cm are optimal [6].

Increasing salinity decreases the evaporation rate. Comparing evaporation from brine and distilled water, the ratio is that for each increase of 0.01 in specific gravity there is a 1% decrease in evaporation [6]. A more generalised proposal to incorporate the effect of salinity on the evaporation rate is to multiply by 0.7 [6].
As evaporation ponds require large areas, this will mainly be applicable in regions with low land cost and high evaporation/precipitation ratio. High evaporation/precipitation ratio means that loss of water is quick and the pond area needed is reduced. A high recovery rate also reduces the pond area needed.

Example: The estimated evaporation pond area needed for a 500 m^3/day plant with 80 % recovery in Aswan in Egypt. The brine produced is 125 m^3/day.

Evaporation rate (annual mean): 13.6 mm/day = 0.0136 m/day
Precipitation rate (annual mean): 0-5 mm/day = 0-0.005 m/day

(0.0136-0.0025)*0.7 = 0.00777 m/day

Pond area needed: 125/0.00777 = 16087.5 m^2

The pond area needed to sustainably take care of all the brine from the above example would be appr. 1.6 hectares or about 2 soccer fields of international size. The effect of salinity on evaporation has been taken into account. This is with a recovery rate of 80 %. If a recovery rate of 70 % was used instead, the total amount of brine produced would be increased by appr. 90 m^3/day and the additional pond area needed would increase with appr. 11500 m^2 or almost 1.5 soccer fields of international size.

A major component in the construction cost of evaporations ponds are the liners. These can be made from PVC, polyethylene, butyl rubber, hypalon etc. Prices from 1992 for PVC were appr. $ 5.7/m^2 [26]. This means that the lining would cost $ 2850 for a 500 m^2 pond. Clay liners can be used and is used extensively for agricultural ponds. The cost of the lining is heavily reduced by using clay liners, however there will most likely be some leaching to the groundwater. If the leaching can be held within reasonable limits and the groundwater is brackish, then clay lining can be a viable choice. The only limitation will be availability of clay.

In the Negev region in the southern part of Israel, there is an inland brackish well water desalination plant producing appr. 5000 m^3/day of permeate and 384 m^3/day of brine with a recovery rate of 92%. The disposal method used is evaporation ponds and the total area amounts to 65000 m^2. The cost of this, including land costs, amounts to $ 8.5 cent/m^3 [5].

Evaporation ponds will, in general, most likely be competitive for relatively small plants in remote, inland locations with high evaporation rates [g].

There are a number of different synergies with income generation that can be combined with these ponds which alleviate some of the total cost of the ponds and there are also different methods for the enhancement of the evaporation stage which can be applicable.

6.8.1 Economical synergies

In order to reduce evaporation pond costs, synergies with productive activities can be established.

6.8.1.1 Fish culture

Fishes like Barramundi, Red Snapper, Black Bream, Milk fish, Mullet and Tilapia can grow and prosper in high salinity water [11].

6.8.1.2 Algae production

Algae production for the production of commercial grades of beta-carotene is possible in highly saline waters with salinity levels in excess of 200 g/l [11]. The algae production in a pilot project in Australia was exceptional with over 400000 cells/mL after only 8 weeks [11].

6.8.1.3 Brine shrimp production

Brine shrimp is sold as aquarium food for tropical fish. Synergies between fish production and shrimp production can be beneficial as the shrimps can utilise nutrients generated by the fishes and any excess shrimp can serve as a food supplement for the fishes. Brine shrimp also clean up the organic matter in the ponds and removes most of the calcium ions [11]. Brine shrimp production is ideal for evaporation ponds as the salinity levels are very high and therefore no predators or competitors to the shrimp survive resulting in a natural monoculture [1].

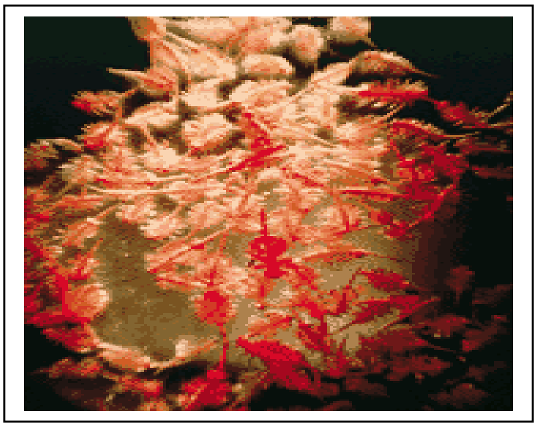

Figure 9: Brine shrimp [j].

6.8.1.4 Electricity generation

Salinity gradient solar ponds is yet another possible synergy for the evaporation ponds. These solar ponds combine collection of solar energy with long-term storage providing either thermal energy at a temperature ranging from 50 to 90 ^{0}C or electricity [12].

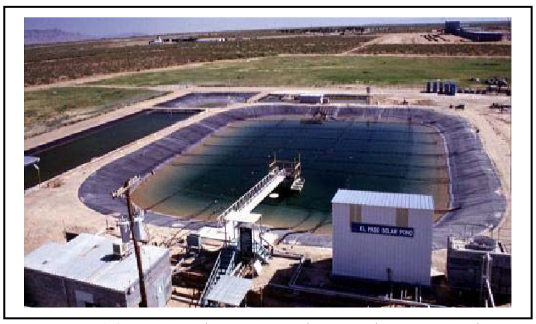

Figure10: A solar pond in El Paso [k].

The pond has three regions: the first layer at the surface of the pond is called upper convective zone (UCZ) and is comprised of water with 1-4% salt by weight [12]. The thickness of this zone is ideally appr. 30 cm as increasing the thickness reduces the ability to store heat [11]. The second layer is called the non-convective zone (NCZ) and is the insulating zone as it has a salinity gradient going from higher to lower concentration as you get closer to the surface [12]. The thickness of this layer is between 0.5-1.5 m [11]. The lower layer is called the lower convective zone (LCZ) and contains near saturated or saturated brine with appr. 26% salt by weight [12].

The sunlight energy that reaches the lower zone (LCZ) can only escape by conduction. The heat conductivity in water is low and therefore if the insulating layer is thick enough, the heat loss from the LCZ will happen very slowly. The combination of the high heat capacity of water, large volumes of water in the solar pond and the insulating properties of the non-convective layer makes it a device for energy collection and long-term storage. In order for the generator to run efficiently for generation of electricity, it is usually required that the temperature is above 85 ^{0}C [12].

The thermal efficiency of the solar pond is affected by the clarity of the brine, the thicknesses of the zones, the salt gradient and the maintenance of the vertical salt gradient and the pond area.

A 10 000 m^2 solar pond in Victoria (Australia) produced 200 000 kWh of electricity per year [11]. This means that a 500 m^3/day desalination plant with a total energy consumption of 2.5 kWh/m^3 could run 160 days a year solely dependent on the energy supply from a solar pond with this capacity and size.

One source showed that a 5000 m^2 solar pond with an impermeable liner and heat extraction system costs $ 108 000. The ORC engine which is used for electricity generation and an alternator (15 kWe) costs appr. $ 210 000 [q]. This gives a total of $ 318 000 and with amortization of 6 % over 35 years gives a cost of $ 16 000/year. With a production of 130 000 kWh/year, the power cost was $ 12 cent/kWh [q].

6.8.2 Enhanced evaporation

The evaporation rate can be enhanced by increasing water temperature, increasing exposed water surface area, increasing vapour pressure difference between the atmosphere and the surface, reducing surface tension, reducing the bond between water molecules, increasing wind velocity, increasing ground air turbulence, increasing surface roughness and stirring [6].

<u>6.8.2.1 Dyes</u>

The evaporation rate can be enhanced using dyes as this has an effect on the temperature. One source states an increase in the evaporation by 13% using Naphthol green dye at a concentration of around 2 ppm [6]. At a price of $ 44.15/100 g [r], the cost of applying Naphthol green dye at a concentration of 2 ppm (2 mg/l) in the top 20 cm of a 500 m^2 evaporation pond would be appr. $ 88/full application. The price example used here is, however, very high for this kind of application.

The algae specie that can be grown in evaporation ponds cause the colour of the pondwater to shift to a green shade [j]. This natural colour change will also increase the evaporation rate.

6.8.2.2 Rapid Spray Evaporation

A company called Aquasonics has patented a process called rapid spray evaporation. Contaminated water is ejected through nozzles at high velocities creating drops of specific shapes and sizes with evaporation happening within milliseconds. This is due to the increased surface area exposure to the atmosphere. The rate of evaporation is determined by the size and the velocity of the droplets, the general atmosperic condition and the composition of the contaminated water. During evaporation, the salts are flashed out leaving crystal flakes, and water vapour, which is condensed and collected [m]. The technology can be used in salinity concentration of up to full saturation (25 % salinity) according to test results [m].

According to Aquasonics, beneficial synergies between reverse osmosis (RO) technology and rapid spray evaporation (RSE) can be made. RSE is connected to the brine stream recovering additional potable water, creating a dry end product with possibilities for resource recovery or reducing disposal costs [27].

According to Aquasonics, using RSE as an afterstage of RO; where the RSE technology has been adapted to the installation taking advantage of prefiltration, brine pressure of appr. 5.5 MPa, water temperature of appr. 38^0 and the water infrastructure, the cost of water produced by this method is between \$ 0.198 cent/m^3 and \$ 0.33 cent/m^3 [27]. This is where waste heat is available.

According to Aquasonics, adding RSE to an existing SWRO plant with a capacity of appr. 19000 m^3/day and with an assumed water cost of \$ 0.265 cent/m^3 would give an additional 19000 m^3/day of permeate and the total cost of water would be \$ 0.46 cent/m^3 [27]. This is where waste heat is available.

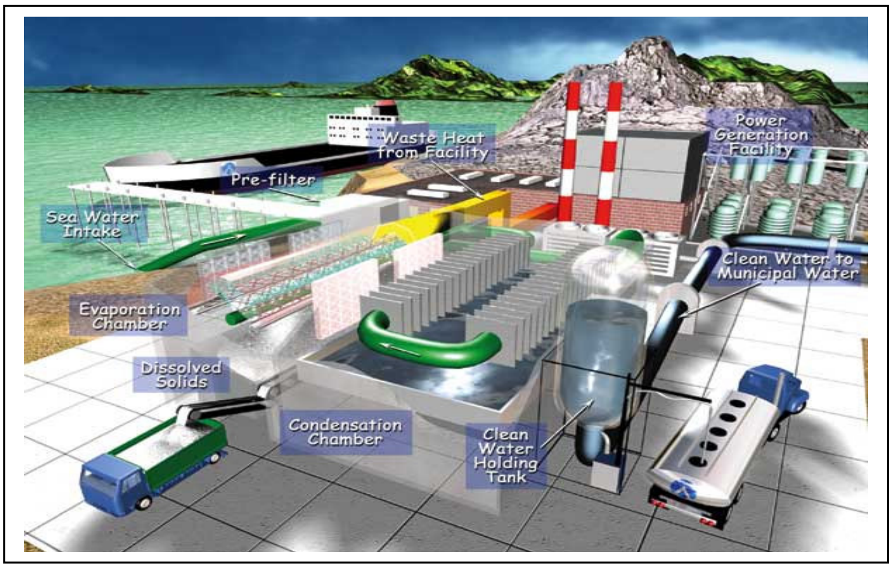

Figure 11: Illustration of the Rapid Spray Evaporation technology [27].

6.9 Zero Liquid Discharge (ZLD)

Zero liquid discharge means that a dry end product is reached and no reject water is discharged into the environment. This introduces the possibility for resource recovery.

Increasing the recovery of the desalination system is beneficial as less volume of brine is produced with higher concentrations. The main problems with high recovery RO systems is due to scaling. This is the precipitation of compounds with low solubility limits on the membranes causing gradual deterioration in the performance of the membranes. Chemicals called antiscalants are normally used to reduce the risk of scaling. However, it is never certain that scaling will not occur due to the use of antiscalants, especially for high recovery systems.

Nanofiltration can be used as pretreatment to high recovery SWRO systems as it reduces the scaling tendencies by removing most of the scale forming components, such as $CaCO_3$, $CaSO_4$ and $MgSO_4$. For ex. NF membranes generally has a rejection of 83% calcium, 87% magnesium, 93% sulphate and 10% NaCl. The RO recovery rate can be increased as well because of the simultaneous removal of some NaCl as this decreases the osmotic pressure value [13]. Using nanofiltration as pretreatment eliminates the need for antiscalants, however the cost of NF is higher. Therefore, sacrificial NF/RO units can be used in combination with antiscalants for high recovery systems in order to control scaling.

Increasing the recovery rate is beneficial in terms of saving *costs* for pretreatment and how beneficial it is depends on the feed water quality, ie what kind of pretreatment is used. Cost savings is also due to reduced feed water pumping and infrastructure.

6.9.1 SAL-PROC technology

SAL-PROC technology is based upon extraction of salts, slurries and liquid compounds by various processes. These include one or more steps of evaporation and cooling and chemical and mineral processing steps like desulphation, reaction, crystallization, washing and dewatering [11]. The economics of this processing technology can be improved with access to a cheap energy source [11].

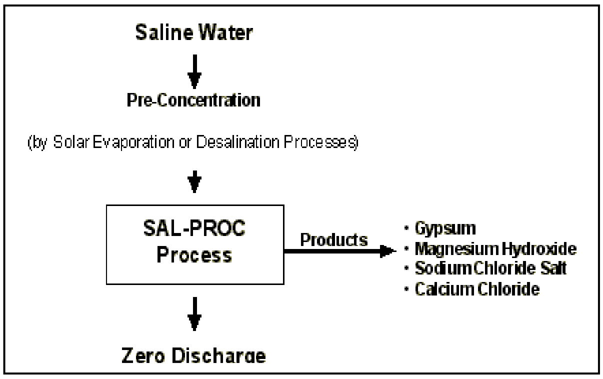

Figure 12: The SAL-PROC technology [l].

This technology is normally directed towards the principle of zero discharge by comprehensive utilization of the brine stream for resource recovery, i.e. waste minimization. The products produced is dependent on the brine composition.

Geo-Processors, a technology company based in Australia, offers standardised, complete, fixed or mobile SAL-PROC units. The process is adapted to the composition of the feed resulting in variable steps of evaporation/cooling and chemical and mineral processing [l]. Their technology is directly applicable as an afterstage of RO-desalination and can be connected to the brine stream as well as the original feed stream for the recovery of mineral and chemical products [l].

Figure 13: Mobile SAL-PROC unit [l].

Chart 1: Commercial examples of SAL-PROC units in use with approximate cost analysis [Aharon Arakel, personal communication]

	Plant Nr.1	Plant Nr. 2	Plant Nr. 3
Effluent type	Conc. seawater	Irrigation effluent	Conc. seawater
Location	South Australia	Australia, Victoria	South Australia
Plant scale	Commercial	Commercial	Commercial
Throughput volume [m^3/d]	7200	2640	5280
Feed salinity [ppm]	72 700	82 000	72 500
Product streams	1. Magnesium hydroxide 2. Magnesia 3. Gypsum 4. Halite 5. Calcium chloride solution	1. Magnesium hydroxide 2. Gypsum 3. Halite 4. Calcium chloride solution	1. Magnesium hydroxide 2. Precipitated calcium carbonate
Annual product output [tonne]	157 500	94 460	13 250
Total fixed capital cost [$]	23 063 000	15 044 008	8 605 911
Total annual operation cost [$]	8 928 000	3 810 685	3 618 404
Gross annual income from 100 % sale of products [$]	21 190 000	9 810 800	6 125 000

6.9.2 Disposal of dry end product

The main purposes for processing the brine to reach a dry end product is due to environmental considerations and resource recovery. The environment benefits from this as zero liquid discharge is met and disposal of a dry end product is much more economically feasible than liquid disposal. Resource recovery can be incorporated into the zero liquid discharge (ZLD) principle as a cost alleviation or be the main driving force for adapting the ZLD principle depending on the feasibility of the resource recovery.

In case of resource recovery without the aim of ZLD or in case no resource recovery is made, disposal of the solid or slurry brine is a must. This is normally done by transporting the effluent to approved salt deposit sites. Discharge can also happen in mines, bores or in the sea.

The cost of disposal include collecting the solids from the pond, transporting the solids and landfill disposal costs.

6.9.2.1 Resource recovery

The feasibility of resource recovery is dependent on the cost of production compared to the generated income from sales. The feasibility is therefore determined by the markets (selling possibilities) and the market values of the products. The market possibilities are often determined on a very local scale. An increased range of products that can be offered increases the chances to find markets.

Chart 2: List of commercial products that can be recovered depending on the composition of the feed water [i]

Products	Physical features	Application areas

Calcium carbonate, $CaCO_3$	Fine grain, crystalline	Paper coating pigment Filler for paper manufacturing rubber and paint
Calcium chloride, $CaCl_2$	Concentrated solution	Dust suppressants Sodic soil remediation Construction industry Cement, concrete stabilizer Road stabilizers
Caustic soda, NaOH		Many industrial applications pH buffering Feedstock for chemical processes
Gypsum, $CaSO_4$		Manufacturing of building products Sodic soil remediation Evaporation pond liners
Gypsum magnesium hydroxide, $CaSO_4.2H_20 + Mg(OH)_2$	Slurry or powder	pH buffering Soil conditioner Wastewater treatment
Halite, NaCl	Crystalline salt	Chlor-alkali production Bulk salt supply for industries Food and industrial processes
Magnesium carbonate light, $XMgCO_3.\ YMg(OH)_2.ZH_2O$	Fine grain, crystalline	Magnesium metal production Filler for paper manufacturing rubber and paint Fire retardants
Magnesium hydroxide, $Mg(OH)_2$	Slurry or powder	Animal stock feed Fire retardants Acid neutralization Magnesium metal production Water, wastewater treatment
Soda ash, Na_2CO_3		Chemical industry Water treatment
Sodium chlorate, $NaClO_4$		Paper bleaching Chemical industries
Sodium hypochlorite, NaOCl		Chemical industries Disinfection Pool chlorine
Thenardite, Na_2SO_4		Detergents, glass and surfactants manufacture

Figure 14: Magnesium Carbonate Light [i].

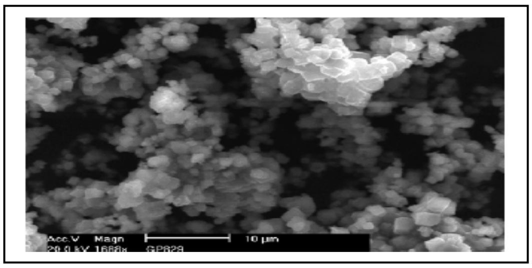

Figure 15: Precipitated Calcium Carbonate [i].

Caustic soda can be obtained from brine using a diaphragm cell [7].

It is also possible to convert NaCl in a series of chemical reactions very similar to the Solvay process into valuable products like NH_4Cl, Na_2CO_3, $NaHCO_3$ and $MgCL_2$. The highest conversion ratio of NaCl that was obtained in a study was 82.2%. However, it is uncertain whether this is economically feasible [14].

Walvis Bay Salt Refiners in Namibia has an annual production of 400 000 tonnes of salt from evaporation ponds. Most of the salt is exported to South Africa for use in the production of chlorine and caustic soda. Other exports are to West-Africa and Norway for use in the fishing industry and to other various markets for use as animal supplements and in sugar refining [n].

Nowadays, more than 30 % of the total production of sodium chloride (table salt) in the world comes from solar evaporation ponds [26].

6.9.2.2 Transportation of bulk salt products

For transportation of bulk salt products, Norsk Hydro's Portabulk bags is a beneficial choice. There is an inner and an outer bag where the inner bag keeps the product dry and clean and the outer bag is for strength. The inner bag is made from polyethylene and does not allow any moisture to enter [personal communication, Larsen]. The outer bag is made from environmentally friendly polypropylene with a high safety factor and is reused. The advantages are that it is very light material, easy pick-up possibilities due to the lift loops in the outer bag eliminating the use for pallets, stable bags giving good stacking abilities, strong and safe bags and a very low cost. The cost for 1000 kg bags are appr. 35-50 NOK/bag [personal communication, Larsen]. Due to the impermeable characteristics of the inner bag, slurries can also be transported by this method.

Figure 16: The Portabulk bag [o].

7. EXAMPLES OF INLAND BRINE DISPOSAL METHODS IN USE

- In Oman, 10 different plants with capacities ranging from 50 m^3/day to 1000 m^3/day were investigated regarding brine disposal. The majority of them used evaporation ponds mostly lined with polyethylene sheets and some plants discharged the brine into bores. Noticeable was that a lot of the evaporation ponds did not have salt build-ups probably as a result of leakage [1].

- The Petroleum Development Oman (PDO) operates 14 desalination plants in Oman and the primary disposal method is reinjection of the brine to the aquifer. Where constraints are imposed, evaporation ponds and natural depressions (lakes) are being used. In 4 of these plants, the SAL-PROC technology was investigated. The technical feasibility of treating brines from RO plants in inland locations in simple processes was confirmed. The results were that products of high quality and in demand by different industries could be derived [15].

- A survey done for nine major brackish water RO plants in the central region of Saudi Arabia showed that 3 plants disposed of their brine to sewers, 4 plants used evaporation ponds and 2 plants used open land disposal. The largest evaporation pond area was 342390 m^2 and all ponds were 1 m in depth and designed for an evaporation rate of 0.01 m/day [9].

- The Mekorot plant in Eilat in Israel directs their brine discharge to a salt production plant. It is a RO desalination plant with a capacity of appr. 12 million m^3/year where 75 % of the feed water is brackish from drilled wells and 25 % is seawater. The brine is transferred to the Salt Company ponds for resource recovery and any excess volumes due to seasonal variations is directed to a bird watching center. The brine is then mixed with wastewater from other productions and from the bird watching center, the water is directed to the sea through an open canal [16].

- A 3500 m^3/day water treatment plant in Norfolk in the U.K. with an RO membrane unit of appr. 500 m^3/day proposed to the Environmental Agency in 1995 for discharge of the brine to the nearby river. A 1-year grant was issued but with limits to the concentration of the brine and with the obligation to monitor and report the concentration of the discharge flows as well as chemical and biological monitoring of the river. The concentration limits was reached by diluting the concentrate with a total volume of 50 m^3/day with the backwash filter water from the whole plant with a total volume of 150 m^3/day [17].

- A survey done in the U.S. regarding brine disposal from 137 drinking water membrane plants with a capacity over 98 m^3/d showed that 48% discharge the brine to surface waters, 23% discharge to wastewater treatment plants, 12% uses land application, 10% uses deep well injections and 6% use evaporation ponds [6]. 73% of these plants were brackish water RO desalination plants, 11% were nanofiltration, 11% were electrodialysis and 5% were seawater RO desalination plants [8]. All the plants using deep well injections and land application were located in Florida which reflects the geological and climate conditions there. Brine discharge to wastewater treatment plants was used mainly for smaller plants which often is due to the limited capacity of the wastewater treatment plants. Land application and evaporation ponds were also used by smaller plants and required availability of land and in some cases appropriate soil and groundwater characteristics. Where the geological conditions allowed it, deep well injections were used by larger plants [8]. The cost of these disposal methods ranged from 5-33% of the total cost of desalination.

8. DISPOSAL IN COASTAL LOCATIONS

Discharge to the sea is the disposal method used almost exclusively for desalination plants at the coast or near the coast.

8.1 Ocean disposal

There are mainly four different ocean disposal alternatives.

8.1.1 Discharge by pipe far into the sea

The main factor is that there should be enough distance between the intake and the outlet as to avoid or minimize risks of feed water deterioration. The disposal of brine by pipe should therefore be sufficiently far out into the sea. The limitation is the cost.

The Dhekelia plant in Cyprus has more than 2 km distance between the inlet and outlet [16]. There are some mitigation measures that can be done in order to reduce impacts on the marine environment (see mitigation measures).

8.1.2 Direct discharge at the coastline

This is normally not a viable option. However, due to economics, it can be considered for smaller plants at insensitive shores. Even if the dilution is somewhat satisfactory, during days of calm conditions the dilution would be negligible and the impact on the shore environment would be high [16]. Brine disposal directly on the shoreline can have an effect of increasing the salinity along the coastline and therefore intensify the saline intrusion effect instead of reducing [3]. This also means deterioration of feed water quality.

8.1.3 Discharge at a power stations outlet

Main advantage is the high dilution which is achieved resulting in less density brine reducing sinking of the plume in the seawater. This is used quite extensively for thermal desalination plants as hybrid installations are common where production of water and production of energy is combined [16].

8.1.4 Discharge to a plant for salt production

This presents an environmental and economical option. However, the main limitations for this method is the presence of salt production plants in the region close to the desalination plant [16]. This is practiced in Eilat in Israel.

8.2 Environmental impacts

The environmental impacts of ocean disposal are mainly marine disturbances in the vicinity of the outlet due to the higher salinity and often chemical constituents in the brine waste.

The high specific weight of the brine creates a plume at the outlet and this prevents mixing and makes the brine plume sink to the bottom. What is created is a “salty desert” in the area near the outlet affecting the benthic environment negatively. The chemicals used are also a concern regarding the marine organisms and plants [18].

The specific impact of the brine is a function of the ecosystem in the area and conservative estimates show that benthic environments are tolerant to salinity increases of 1 ppt [7].

The following are marine disturbances in the vicinity of the outlet from ocean brine disposal caused by:

Salinity gradient: There exists an osmotic balance between the marine organisms and the surrounding environment and disruptions may have negative consequences. The main effects are on marine biota, particularly benthic and planctonic organisms [18]. Increasing salinity can have a great effect on plankton populations (mainly young individuals) as this can lead to dehydration of cells resulting in increased turgor pressure and ultimately extinction [18]. The sensitivity of crustaceans to increasing salinity varies, but generally the species with long abdomen are more sensitive than the species with short abdomen and of course younger individuals are more sensitive [18]. Some planctonic algae, especially the siliceous algae, have high tolerance towards salinity and certain species can tolerate salinity variations after some time of acclimatization. However, most of the marine species will not survive in the case of high increases in salinity [16]. Increased turbidity is also an effect of increasing salinity. The use of additives like iron further enhances this effect as some of these additives are dark in colour. This has the effect of preventing the penetration of light and therefore disrupting photosynthesis [18].

Temperature gradient: This will cause an increase in the seawater temperature resulting in a reduction of dissolved oxygen which is a necessity for the respiration of marine organisms [19].

Use of chemicals: See section on chemicals to find out the impact that the use of chemicals has on the environment.

Corrosion of equipment: This can cause heavy metals like copper, titanium and nickel to be discharged to the sea. They can be toxic towards marine organisms and humans and can accumulate in for ex. fishes posing a threat to humans [19].

Monitoring of the brine impact on marine environment is important in order to assess environmental impacts. The Dhekelia plant in Cyprus carried out monitoring every 6 months for a period of 4 years and the results showed that the marine environment within a perimeter of 200 m from the outfall point were affected [4]. This was evident by the disappearance of certain marine species [16].

Monitoring was made at the plant of Maspalomas II in Canary Islands where it was noted that the dilution at the surface of the sea was sufficient but sinking of a brine plume in a underwater river-like fashion was observed [4].

8.3 Mitigation measures

As mentioned earlier, site selection is extremely important. The most basic environmental consideration in deciding location of a plant is avoiding sensitive ecosystems. The sensitivity of different coastal subsystems to the activities of a desalination plant has been evaluated using the same model used to assess sensitivity towards oil spills. With the sensitivity going from high to low, the subsystems are [20]:

1. Mangals
2. Salt marsh
3. Coral reefs
4. Seaweed bay and shallows
5. Algal mats
6. Shallow low-energy bay and semi-enclosed lagoon
7. Fjords
8. Coastal sabkhas
9. Low energy sand-, mud- and beachrockflats
10. Estuaries and systems similar to estuaries
11. High energy soft tidal coast
12. Coastal upwelling
13. Mature shoreline
14. Exposed rocky coasts with a high water exchange rate
15. High energy oceanic coast with currents parallelling the coastline

Regarding the environmental impact in the vicinity of the outlet, the most important mitigation measure is to enhance the mixing of the two fluids with different densities, i.e. dilution.

8.3.1 Dilution

The process of dilution is a function of two things: the primary dilution and the natural dilution.

The primary dilution depends on the difference in density (salt concentration and temperature gradients) between the brine and the receiving saltbody, the momentum of the brine, the velocity at the effluent pipe, the flow rate at the effluent pipe, the diameter of the pipe and the depth at the outlet to the seafloor.

The natural dilution happens after the primary dilution mainly due to diffusion and mixing caused by waves and currents. The use of diffusers at the effluent pipe enhance the natural dilution by increasing the pressure of the brine entering the seawater and hence allows the brine to get in contact with a larger volume of seawater. The effect of the diffusers mainly depends on how many are used and how close they are to each other. The efficiency can be enhanced by using special diffusers like Red Valve diffusers [16] as well as installing the diffusers at an angle of 30-90^0 to the seafloor as this will direct the brine flow upwards increasing the volume of seawater that it gets in contact with.

Knowledge about the topography and the prevailing currents in the area are two very important considerations for selection of brine outlet point as they affect the dilution rate a lot [25].

The dilution with seawater can happen before discharge in special mixing zones or the brine can simply be mixed with other waste flows prior to ocean disposal. The dilution with a power stations cooling water has already been discussed, but dilution with municipal wastewater is also an option. This is practiced in Hollywood in Florida where the brine from desalination plants has been coupled with the infrastructure of the municipal wastewater with discharge in the sea. This presented a dual purpose dilution with improved water quality of the combined flows and the possibility to use an existing outfall [c].

However, bearing in mind that estimates show that benthic environments are tolerant to salinity increases of 1 ppt [7], it would mean that a brine concentration of 70 ppt would need to be diluted 35-40 times in order to create a brine concentration of 1 ppt above the concentration of seawater (35 ppt) [7].

Predictions for the dilution characteristics and the geometry of the mixing zone caused by the brine waste in the seawater can be made by computerised simulation systems, such as the CORMIX-GI system.

9. CHEMICALS

Chemicals are used both in inland brackish water desalination and seawater desalination, however seawater desalination use much more. Chemicals are used in pretreatment, posttreatment, membrane cleaning etc. There are uncertainties regarding the environmental impact of chemicals. Some people say that the use of chemicals does have an impact, and some people say that since the brine only contain relatively minor amounts of chemicals, it is not expected that there will be any contamination problems [4].

9.1 Chlorine

Chlorine is mainly used to prevent biofouling. Chlorine and its compounds are toxic and affect biological and enzymatic processes of living organisms [19]. It either kills the organisms or creates conditions making it difficult or impossible to settle [21]. Chlorine is a highly effective biocide which can have detrimental effects on aquatic life even in low concentrations. In U.S.A., it is classified as a pollutant and in California, discharge is not allowed [22]. In the presence of hydrocarbons in the water, like in the arabian gulf due to oil mining and oil spills, chlorine can form chlorinating byproducts (CBC), like trihalomethane (THM) which has carcinogenic properties above certain concentration levels [19].

In RO plants using polyamide membranes, there is no chlorine in the discharged brine as dechlorination must be done before the membranes as chlorine causes scaling to occur.

Chlorine has a detrimental effect on marine organisms but decays with time [23].

9.2 Antiscalants

Typical antiscalants are polyacrylic and polymaleic acids, but polyphosphates also still occur. Dosages are normally 2 ppm which means that an RO plant with an recovery of 33.3 % would have a load of 6 kg/day for every 1000 m^3 of permeate produced. The knowledge about the stability, residence times and ecotoxicity of the antiscalants is limited. Standard biodegradation tests has shown that the degradation rate of polyacrylic acid is almost three times as high as polymaleic acid with 52 % of the polyacrylic acid degraded after 35 days compared to 18%. These polymer antiscalants have similar properties as natural organic (humic) matter and the LC_{50} value is rather high indicating a low toxicity [22].
Some types of anti-scalants, like phosphate based additives will encourage red and green algae formation [19].

9.3 Acids

Membrane cleaning is done 3-4 times a year using weak acids and detergents like citric acid, sodium polyphosphate and EDTA. This rinse water is usually collected in a container and then treatment in the form of titration and neutralization is performed before discharge to authorized salt disposal sites or by releasing small quantities of the rinse water continuosly together with the brine to the sea [16].

9.4 Mitigation measures

The use of chemicals should be minimised by optimised dosing due to correct monitoring of the plant processes.

The use of chlorine can be eliminated by substituting it with ultraviolet radiation, however this is more expensive. This could also be done by changing operational practices, such as allowing some biofouling to occur in the membrane and controlling it by performing frequent membrane washing with water [personal communication, Perez].

Phosphate based antiscalants should not be used, instead organic antiscalants should be used. Polyacrylic acid is preferred compared to polymaleic acid. To eliminate or reduce the use of antiscalants, decreasing the recovery rate and/or using nanofiltration (costly proceedure) as a pretreatment can be done.

Heavy metals, due to the corrosion of equipment, can be avoided by using anticorrosive building materials.

9.4.1 Deep seawater intake

The use of chemicals can be eliminated or minimised by using deep seawater intake.

The feed water is abstracted from depths of 200-300m below sea level. The advantages are that the water has low levels of suspended matters and microorganisms optimizing the pretreatment processes like filtration and minimizing chemical injections. Other advantages are constant temperature gradient [p]. The Muroto plant in Kochi Prefecture in Japan, a brine conversion system (BCS) plant, is using deep seawater for use in bottled drinking water [24].

Figure 17: Illustration of deep seawater intake [p]

10. REGULATIONS IN THE US

The environmental concerns regarding brine disposal is focused on contamination of surface waters and groundwater resulting from salinity gradients and individual chemical components [7].

In the US, the environmental concern is reflected in the national and state regulations where policies set up for the control of discharges have evolved into policies set up for the reduction or elimination of harmful pollutants to the air, land and waters. Regarding brine disposal, permission for disposal method must be granted. In the case of discharge to surface waters, demonstration of acceptable brine chemistry (such as pH, total suspended and dissolved solids, different individual chemicals) is required. The limits are based upon the nature and use of receiving water body and human and aquatic toxicity studies. It is also required to perform a effluent toxicity test (WET test) where different organisms common to the receiving water environment are exposed to the brine during a time period and survival as well as growth and reproducibility is monitored. Periodic testing is required as well as monitoring of specified chemical concentrations [7].

Requirements for permission to use deep well injections are normally to monitor well integrity and water quality of nearby monitoring wells [7]. Regulations in Florida prohibits well injections to groundwaters which can be used as drinking water. More specifically, groundwaters with a concentration of less than 10000 mg/l is considered as possible drinking water [25].

For permits to use evaporation ponds, requirements are typically that monitoring of pond integrity must be done [7].

The land application disposal is considered to be a groundwater discharge. Therefore, a zone of discharge is established only if adequate monitoring measures of the movement of contaminants can be met. However, land application is allowed without furher notice if the aquifer has a natural salinity exceeding 1500 mg/l and it must be a non-hazardous concentrate [25].

For disposal to sewage systems, membrane concentrate is classified as industrial waste and must follow the prohibited discharge standards. A regulation within the prohibited discharge standard is that the wastewaters cannot have a pH level lower than 5 [g].

For zero liquid discharge there are requirements for disposal of the solids to approved, impervious areas posing no threat to surface and groundwaters [g].

11. DISCUSSION

There are several different origins of salinity in water and soil around the world. Soil salinization, which is becoming a widespread phenomenon mainly because of saline water irrigation practices, is destroying large agricultural areas in the world as excessive concentration of salts has negative effects on both soil structure and more importantly plant growth. This also has negative effects on the groundwater as drainage of salts from the land occurs.

However, the most important cause of water salinization is the phenomenon known as coastal saline intrusion. This is when seawater intrudes inland from the coastline replacing or mixing with freshwater in the groundwater aquifers. Coastal saline intrusion is a result of lowered groundwater levels which in turn is caused by excessive drainage of low lying coastal regions and/or overpumping the groundwater. The Ghyben-Herzberg equation shows this relationship for unconfined aquifers and the ratio reached is 40:1. This means that a 1 m fall in the groundwater level will induce a 40 m rise in the seawater/freshwater interface level and hence, small water table changes has large effects on saline intrusion. This fact, combined with the fact that as little as 2 % of seawater mix with freshwater can render the water unpotable [a], makes it an alarming problem for coastal communities around the world. Inland saline intrusion also occur and this is due to vertical movement of saline water [f], like upconing of ancient water to overlying fresh water aquifers caused by incorrect deep well drilling and safety proceedures.

There are some mitigation measures towards coastal saline intrusion. These are mainly injection barrier wells and extraction barrier wells. Injection barrier wells involves injecting high quality water into the groundwater to push the intruding seawater back towards the coast [f]. Extraction barrier wells are the opposite, the intruding seawater is extracted with these wells creating a “trough effect” which restricts the intrusion and drives the seawater back [f]. This creates interesting possibilities for combinations with desalination plants and extraction barrier wells; production of potable water and prevention of saline intrusion.

Mitigation is also possible through desalination. By substituting the water supply from groundwater abstraction with seawater desalination, the lowering of the water table can be restricted and saline intrusion halted. This has been the driving force of investing in seawater desalination in some parts of the world, like in Oman [3].

The major part of this project was to look at inland brine disposal options as this is an area of desalination which is relatively unknown but is very important. The purpose behind this is strictly informational, so the methods have not been evaluated from an environmental and/or economical perspective.

Most of the methods are site specific which means that brine disposal solutions are not universal, but have to be looked at site specifically.

Deep aquifer injection is only possible where these deep, unconsolidated aquifers occur. It is also an expensive technique. Aquifer reinjection will result in a gradual increase in salinity of the brackish aquifer used as feed water. There might exist the opportunity to inject the brine into another aquifer, if it’s not located too far away. This would mean that no quality deterioration of the feed water occurs and if the aquifer being subjected to injection of brine has higher salinity than the aquifer where the feed water is taken from, the water quality deterioration into that aquifer would be minimised or even improved.

Discharge to wastewater treatment plants and discharge to sewage system can only occur where these are available. Discharge to open land will salinize the land and the groundwater and discharge to inland surface water is definately not recommended as they are not saltwater bodies. The best solution from an environmental perspective is evaporation ponds, provided that the correct safety measures are taken to prevent leakage and correct disposal of the end product is performed. However, it requires large areas of land and is therefore an expensive option. It is mainly applicable where there is cheap land available and a dry and hot climate. The hotter the climate, the higher evaporation rate and the more water is lost through evaporation. This means a reduction in the pond area size needed.

Evaporation ponds can be combined with economical synergies that can generate income to alleviate some of the cost of this expensive disposal option. Fin fish cultivation, algae production and brine shrimp production are all productive activities that can be successfully cultivated due to their enormous tolerance towards high salinity water environments. In inland desalination plants where the water is brackish, the brine does not have as high salinity as the brine from a seawater desalination plant. Therefore, if there are several ponds in a row, the first line of evaporation ponds can have productive activities that does not have to have such high tolerance towards salinity and that possibly has a higher value on the market. Another activity is electricity generation through salinity gradient solar ponds which can supply electricity to the plant.

There are several techniques to enhance the evaporation of a pond, for example, dyes can be used to darken the colour of the water. Additional energy can be introduced for heating the pond water. There is a technology called rapid spray evaporation, which is directly applicable as an afterstage of an RO plant, that uses evaporation and condensation chambers to reach zero liquid discharge. The brine is ejected through nozzles at high velocities creating drops of specific sizes and shapes with evaporation happening in milliseconds [m]. However, it needs available waste heat in order for it to be worth the investment.

Zero liquid discharge means that a solid end product is reached. This end product is in the form of precipitated salts and/or mineral slurries that can be sold if there are any market possibilities. ZLD is normally a combination of several different disposal techniques. Evaporation ponds followed by enhanced evaporation techniques using additional energy sources to further concentrate the brine is a typical ZLD approach.

There is one technology called SAL-PROC which is based upon extraction of salts, slurries and liquid compounds by various connected evaporation/cooling and chemical processes. This technology is mostly directed towards zero discharge by comprehensive utilization of the brine stream for resource recovery, i.e. waste minimization. There are a lot of different products that can be derived from this technology and that can be commercialized and sold. The SAL-PROC technology relies on the possibility to sell these products as the cost will otherwise be too overwhelming.

Reuse of the brine for agriculture or landscaping is an easy, cheap and often productive method of brine disposal. However, mainly depending on the saline and chemical concentration of the brine, this method can cause soil and groundwater contamination. Continuous practices like this are known to destroy agricultural lands permanently due to the high total salt load applied to the same area. Therefore, the factors that should dictate if this is an appropriate disposal method at individual sites are the saline and chemical concentrations in the brine, the vegetation tolerance and the underlying groundwater salinity.

Inland brine disposal is different from coastal brine disposal in the fact that discharge to the sea is eliminated. This often increases the economical and environmental impact of brine disposal. However, brine discharge into the sea also has impacts on the environment. This is mainly due to the difference in salinity between the brine and the seawater causing the brine to sink to the bottom of the sea [18]. Most benthic environments will be harmed by this sudden increase in salinity [18].

The impact of the brine on the bottom sea environment is an effect of the dilution rate between the brine water and the seawater which in turn is dependent on natural phenomenons like seacurrents etc which enhance the natural dilution process. However, the dilution rate at the outlet can also be enhanced by using the right techniques. Diffusers enhance the mixing process dictated by how many and what types of diffusers are being used. The diffusers should as well have an angle of $30\text{-}90^0$ to the seafloor as this will direct the brine flow upwards increasing the volume of seawater that it gets in contact with.

The environmental impacts can therefore be restricted by correct considerations. This is especially important in sensitive coastal regions like mangroves or coral reefs.

Chemicals are often used in desalination. They are mainly used for SW desalination plants, but are used for BW plants as well. The main chemicals used are chlorine, antiscalants and acids with chlorine being the most harmful substance. Chlorine is a biocide and has therefore harmful effects on aquatic life [22]. The usage of chemicals is an environmental consideration and it needs to be evaluated as they can often be replaced with alternative approaches.

The regulations in the US regarding brine disposal have, in 15 years or so, evolved from almost nothing to complete control of discharges for the protection of the environment [7]. This is a good example of how the environmental concern affects the desalination industry as brine disposal is now an integral part of a plant in the U.S.A.

II

CASE STUDY

12. INTRODUCTION

I made a trip to Egypt between the 9th and the 19th of July 2004 as a part of this project. The purpose of my trip was to make a case study of a typical farm that were using desalination and observe what is being done with the brine. The idea was to see, based upon the previously acquired knowledge from the literature study, whether better solutions from an environmental point of view could be identified that still are realistic, specifically in terms of cost.

During my visit in Egypt, I also had the chance to travel to Sharm el Sheikh in the south of the Sinai desert. Therefore, I had the opportunity to witness the enormous new construction of tourist resorts all along the Red Sea. This fact, together with the fact that the water supply for the tourist resorts along the red sea has now been privatized [personal communication, Hegazy], means that there is evolving an extremely fast-growing market for desalination in Egypt and the brine disposal issue needs to be put more in focus.

12.1 Methodology

Through interviews with the manager of the farm and the head engineer at the desalination plant, I received general information about the farm, the plant and specifically what they are doing with the brine and what they have done in the past.

Then inspecting the property to identify, based upon the brine disposal alternatives described in the literature study, which methods are possible to use. Then deciding which method is the most suitable, given the cost and the environmental impact risk of each method.

13. SAMARINA FARM

The main enterprise of the farm is cattle raising. They import buffalos from Australia and raise them in order to sell them on the local market. They have a capacity of 6000-7000 buffalos at a time [personal communication, Mohamed].

The other enterprise is agriculture as they cultivate olives and dates. These are also sold on the local market. The number of workers fluctuates during the year between 20 and 100 workers [personal communication, Mohamed].

There is one existing RO plant with a capacity of 400 m^3/day which is used for drinking water for the cattles. One buffalo needs about 40 l of water per day [personal communication, Mohamed]. 7000 buffalos would then need a total of 280 000 l of water per day, or 280 m^3/day.

The plant is supplied by the Italian company Osmo Sistemi. For the pre treatment, they use sand filter with 3 sizes of sand going from the finest sand in the top to the least fine in the bottom. Then its a carbon filter to get rid of the smell and taste and then 5 micron filters. The 5 micron filters are washed every 3 months. They use a high pressure pump with 12 bar pressure. They use 4 membrane vessels with 5 membrane parts in each vessel. The recovery rate of the system is appr. 62.5 % [personal communication, Ali].

Figure 18: The 400 m^3/d plant from the outside.

Figure 19: Inside the 400 m^3/d plant.

The water is extracted from deep wells of about 130 m. The water has a salinity of appr. 3000 ppm. There are 4 different wells used [personal communication, Ali].

There is a plant of 800 m^3/day which is being built on the same premises and supplied by the same company. This plant is going to be used mainly for irrigation, and to facilitate an expansion in the cattle raising business [personal communication, Mohamed].


Figure 20: The 800 m^3/d plant.

There is no energy recovery for any of the plants.

13.1 Brine disposal

The volume of brine is about 240 m^3/day with a salinity of appr. 5000 ppm.


Figure 21: Brine salinity measurement.

There has been three different ways to deal with the brine. These are reinjection back to the aquifer, evaporation pond with fish cultivation and irrigation of halophytic trees [personal communication, Mohamed].

The only method used now is irrigation of halophytic trees. The trees were growing in small ditches surrounding an agricultural area with cultivation of dates protecting the soil from wind erosion. They were using furrow irrigation.

Figure 22: The brine outlet into furrow irrigation.

Figure 23: The brine is used for furrow irrigation of these rows of trees.

The reinjection back to the aquifer is no longer used as the pump is damaged. The evaporation pond with fish cultivation was a trial for 6-7 months where a hole was dug and some rocks placed in the bottom. This trial was stopped due to the fact that the pond was so close to the intake well [personal communication, Mohamed].

Figure 24: The leftover evaporation pond where they tried fish cultivation.

According to Mr. Heisam Mohamed, trials using the brine water to irrigate dates and olives have been going on for 3 months. It is too early to tell what the outcome will be. He was very enthusiastic about learning more about how to resolve the brine disposal issue [personal communication, Mohamed].

14. POSSIBLE BRINE DISPOSAL SOLUTIONS

The available brine disposal methods that could be used at this location, namely Samarina farm, were limited. It is an inland location with no possibility for disposal in the sea. Also there is no nearby canal or river, no nearby wastewater treatment plant and no unconfined aquifer present to be used for deep well injection.

However, the location is optimally suitable for evaporation ponds as it has a warm and dry temperature all year round and level terrain.

14.1 Evaporation pond

Usage of evaporation ponds as a means of brine disposal at this location is ideal as there is a hot and dry climate and level terrain. The limitation is the land area available. At Samarina farm, all the land area is used for either cattle raising or agriculture. There is no available land area currently that is available for the construction of evaporation ponds except the land area in the immediate vicinity of the desalination plants. A very rough estimate is that there is land area available for two evaporation ponds of 1500 m^2 each. This gives a total of 3000 m^2 of evaporation pond area.

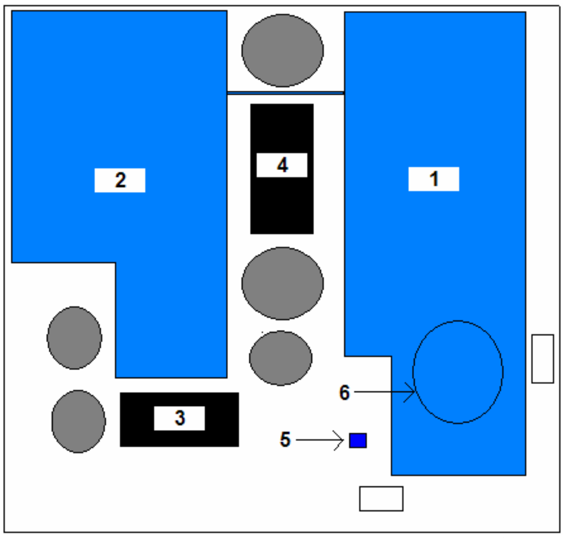

Figure 25: Sketch of evaporation ponds in the vicinity of the desalination plants at Samarina farm.

Figure 26: Picture of the des. plant under construction & showing part of the land area proposed for pond nr. 2.

1. Evaporation pond nr. 1
2. Evaporation pond nr. 2
3. Desalination plant, 400 m^3/d
4. Desalination plant under construction, 800 m^3/d
5. Intake well
6. Location of the leftover evaporation pond trial

☐ Buildings
● Storage tanks

The mean annual evaporation rate in the Cairo area in 1974 was 11.2 mm per day [s]. However, in this example 10 mm per day is used in order to have a margin:

Evaporation rate: 10 mm/d = 0.01 m/d
Evaporation pond area: 3000 m^2

Evaporated volume: 3000 x 0.01 = 30 m^3/d

The calculation above estimates that an evaporation pond area of 3000 m^2 in this geographical region can sustainably tolerate a flow rate of appr. 30 m^3/day of brine (this is only an estimate as possible leakage, precipitation and salt effect on evaporation is not included).

This means that, for the existing 400 m^3/day plant using a recovery rate of 62.5 %, a pond area of appr. 24 000 m^2 would be needed in order to sustainably take care of the 240 m^3/day brine flow. This means that either new land has to be bought or taken from existing agricultural land. However, increasing the recovery rate from 62.5 % to 93 % would mean that only 30 m^3/day of brine would be produced and the proposed 3000 m^2 pond area would be enough to sustainably take care of this brine flow.

A possible synergy is fish production, more specifically Nile Tilapia. Tilapias are widely accepted to consumers in Egypt. It is a good choice due to its significant tolerance to high salinity and environmental stresses, its high growth rate, the ease of production and the market demand [t]. It takes about 8-10 months for Nile Tilapia to reach marketable size which most commonly is around 1 kg of weight. The stocking density is normally 2 fishes/m^2 [u]. The fishes can be fed both organic fertilizers (manure from the livestock) and mineral fertilizers like ammonium nitrate for optimum growth. When added to fishponds, manure and chemical fertilizers may ultimately increase fish yields through soluble and/or particulate pathways.

Figure 27: Picture of Nile Tilapia [t].

As an example, in the West Indian whole-fish market, Nile Tilapia is sold for $ 5/kg [u]. The normal cost for producing a Tilapia fish of 1 kg in weight is about $ 2 [u]. This means a profit of $ 3/kg and with a stocking density of 2 fishes/m^2, the total annual profit would be $ 18 000 for a 3000 m^2 pond area.

Apparently, appr. 25 % of the total fish production in Egypt came from aquaculture in the year of 1998 with the main strategy being earthen pond aquaculture [t].

Earthen ponds are constructed by excavating the pond, placing fill material for insulation and compacting the soil. The fill material is normally any kind of clay soil [v]. If there is no clay soil on site, this can be imported and used. Bentonite clay or other high clay material are preferred and can be mixed with the soil on site to create a soil with acceptable clay content. The next step is compaction of the soil as it will further reduce the permeability of the soil [v]. It is expected, however, that using clay as liner will induce some leakage from the pond.

Synthetic liners can also be used, however these are more expensive. Using PVC lining for a 3000 m^2 pond has an estimated cost of $ 17100. The advantage is that no leakage is expected if the correct safety precautions, to ensure that the liner is intact, is met. Concrete can also be used as a liner. It can also be combined by using concrete on the bottom and using clay or synthetic lining on the sides [v].

The evaporation pond has to be emptied occasionally in order to remove some of the salts that has crystallized to the bottom. The brine flow to the evaporation ponds will have to be redirected for a while until the pond is adequately dry and the crystallized end products can be removed. These can either be further refined for commercial value or discharged to a approved deposit site. Norsk Hydro's Portabulk bag is a safe and cheap choice for this task of transportation.

14.2 Reuse for agriculture

Reuse of the brine for agriculture is already practiced at Samarina farm with furrow irrigation of halophytic trees. However, there are also currently trials being made to see the effect of irrigating dates and olives with the brine water. The effect of salinity on crop growth depends on the crops tolerances towards salinity. Therefore, crop selection is vital whereever salinity problems occur.

14.2.1 Crop tolerances towards irrigation water salinity

Chart 3: Guidelines for the tolerance of different crops towards irrigation water salinity [x]

Crops	Threshold limit [ppm]	Slope of yield decline [%/640 ppm]	Yield decline, 25%
Rye	7300	10.8	8800
Rapeseed *(Brass. Napus)*	7000	13	8250
Rapeseed *(Brass. Campestris)*	6200	14	7350
Guar	5600	17	6550
Kenaf	5200	11.6	6600
Barley*	5100	5	8300
Guayule	5000	10.8	6500
Cotton	4900	5.2	8000
Sugar beet**	4500	5.9	7200
Sorghum	4350	16	5350
Triticale	3900	2.5	10300
Date palm	2550	3.6	7000

* Sensitive during seedling stage, salinity should not exceed 2600 to 3200 ppm.
** Less tolerant during germination and emergence, salinity should not exceed 2000 ppm.

The threshold salinity values above should only be looked upon as guidelines as the salt tolerance of crops varies significantly depending on climatic and soil conditions as well as irrigation practices. However, these values do suggest that for ex. rye and rapeseed can be successfully cultivated using irrigation water with up to 6000-7000 ppm of salinity. This means that there should not be any significant problems using the brine from the desalination plants at Samarina farm for irrigation of these highly salt tolerant crops. Since it is also advantageous, with regards to the salt effect on crop growth, with sandy soils and drip irrigation, it increases the suitability of brine water irrigation at Samarina farm.

The soil salinization of the root zone, which has harmful effects on plant growth, can be further restricted by irrigation using higher quality water once in a while.

Date palm is considered relatively salt tolerant as it is a woody crop, whereas olive is considered moderately tolerant [x]. However, none of these are good candidates for cultivation using higher salinity irrigation water. The most appropriate crops for brine water irrigation at Samarina farm could be rye or barley.

Rye is cultivated for the grain, used to make flour, the importance of which is second only to wheat. Grains mixed with others are used for livestock feed. Rye will produce better on light, sandy soils and on soils of low fertility than other small grains. Many farmers put rye on their worst soils, since rye tends to do better than other cereals under such conditions [y].

Figure 28: Rye [z].

Barley is one of the most ancient of cultivated grains. Grains found in pits and pyramids in Egypt indicate that barley was cultivated there more than 5000 years ago. The salt and drought tolerance makes barley particularly attractive for desert scenarios [y]. It does well on light or sandy loam soil. Dry warm weather is favorable for grain ripening. Barley is ready for harvest in about 4 months after sowing and some varieties in 60 days. Plants are either pulled out or cut with sickles and sheaves stacked for about a week or more. Barley plants are fed green or as hay to livestock. Barley can be fed to cattle alone or mixed with other grains [y].

Figure 29: Barley [w].

14.2.2 Livestock tolerances towards drinking water salinity

Chart 4: Guidelines for the tolerance of livestock towards drinking water salinity [x]

Salinity [ppm]	Rating
< 1000	Excellent for all livestock and poultry
1000 - 3000	Satisfactory for all livestock. May cause temporary mild diarrhoea in livestock not accustomed to the water.
3000 - 5000	Satisfactory for livestock but may be refused by animals not accustomed to the water. If sulphate salts predominate, temporary diarrhoea may be a result.
5000 - 7000	Can be used for livestock except for the pregnant and lactating cattle. It may have laxative effect and may be refused by the livestock.
7000 - 10000	Not recommended
> 10000	Unsatisfactory for all livestock.

14.2.3 Allowable levels of toxic substances in drinking water for livestock

Chart 5: Guidelines for the limit of toxic substances in drinking water for livestock [x]

Substance	Upper limit [ppm]
Arsenic	0.025
Boron	5
Cadmium	0.05
Chromium	0.05
Copper	0.5-5
Lead	0.1
Mercury	0.01
Molybdenum	0.5

Substance	Upper limit [ppm]
Nickel	1
Nitrate	100
Nitrite	10
Selenium	0.05
Uranium	0.2
Vanadium	0.1
Zinc	24

Based upon a complete analysis of the raw well water, it can be decided whether this water is satisfactory as drinking water for the livestock without the use of desalination. It does not seem to pose a threat to the health of the animals using water with a total salinity of 3000 ppm, if the individual leves of toxic substances are approvable.

This brings up the question whether the desalination activity at Samarina farm is somewhat unnecessary.

15. REGULATIONS IN EGYPT

The agency in charge of the environmental issues in Egypt is the Egyptian Environmental Affairs Agency, EEAA. There are no national regulations for brine disposal, however, the EEAA does acknowledge the problem of brine disposal as desalination activities are growing fast [personal communication, Rabi].

There are regional regulations though, mainly for the settlements along the red sea. This is due to the sensititive nature of the coral reefs in the region.

In South Sinai, for example, there are regulations for the intake water and the disposal of the brine for coastal desalination plants. The intake water shall be extracted from beach wells or by open water intake not directly at the coastline with minimised impact on the bottom environment. The disposal options are deep well disposal, discharge by pipe far into the sea and direct discharge at the coastline. Deep well disposal is the method most commonly used. The brine is transported by pipeline appr. 3 km inland to be injected into a deep aquifer selected because of a crack in the geological structure. The well is 120 m in depth and the salinity of the water in the aquifer is appr. 35000-40000 ppm. The aquifer is very compacted [personal communication, Rabi].

For direct discharge at the coastline, the seabottom has to be insensitive in nature, hence no coral reefs. Therefore, its mainly applicable where sandy bottoms occur. Prior to discharge, it is required to have a mixing zone where the brine is diluted with seawater to a concentration of minimum 50000 ppm [personal communication, Rabi].

For discharge by pipe far into the sea, there are no regulations. However, recommendations and guidelines are that there should be holes in the effluent end of the pipe to increase dilution. Also that the pipe should cause minimal impacts on the bottom environment. Normally, the pipes are placed beneath a floating water bridgeway. Calculation methods are used to predict brine movements and dispersion [personal communication, Rabi].

Sampling of the brine at the outlet is made. The Environmental Agency also act as a consultancy agency to render help with site selection of desalination plants in order to minimize environmental impacts [personal communication, Rabi].

"All discharges of brine effluents from desalination plants are monitored. All discharge points are strictly controlled, inspected and approved by the Egyptian Environmental Affairs Agency, EEAA [28]."

No tests have been performed regarding other disposal methods. However, Mr. Medhat Rabi recognizes that as the desalination activities are increasing, they will have to do this, especially since he recognizes that deep well disposal has a limitation to the quantity of water that can be injected [personal communication, Rabi].

16. DISCUSSION AND CONCLUSIONS

Samarina farm is a cattle raising farm where 6000-7000 buffalos are raised at a time and sold on the local market. It is also a large agricultural farm with cultivation of dates and olives which are also sold on the local market [personal communication, Mohamed]. They have one 400 m^3/d desalination plant of which the desalinized water is used as drinking water for the livestock as 7000 buffalos require about 280 m^3/day of water. There is also one desalination plant under construction with a capacity of 800 m^3/day. This water is going to be used mainly for agricultural irrigation and to facilitate an expansion in the cattle raising enterprise [personal communication, Mohamed].

The brine disposal is already a problem at Samarina farm as they are producing around 240 m^3/day of brine from the existing plant. They have been trying three different ways to deal with the brine. These are reinjection back to the aquifer, evaporation pond with fish cultivation and irrigation of halophytic trees. The only method used now is furrow irrigation of halophytic trees [personal communication, Mohamed]. Although the brine salinity is low, about 5000 ppm, the flow rate is high and this induces a very high total salt load to the relatively small area being subjected to the brine water furrow irrigation directly polluting the adjacent land area and underlying groundwater. Salts move both vertically and horizontally in the soil. The cultivated land adjacent to the brine disposal ditches may also be affected in such a manner that the cultivation of dates and olives, crops which are not so tolerant to salinity, may become threatened due to root zone salinization. What is good though is that no chemicals are used in the plants at this farm.

The main objective for this study was to identify solutions to the brine disposal issue. The available brine disposal options at Samarina farm were limited due to the location of the farm. However, the geographical location is optimally suitable for evaporation ponds as it has a warm and dry temperature all year round and level terrain, i.e. desert-like features. Eventhough the evaporation pond option is at the peak of its suitability at this geographical location, it is still a relatively expensive option. The cost is mainly dependent on the cost of land and the lining used, but also earthwork and maintenance cost.

An example for the placement of evaporation ponds has been given for Samarina farm. This involves two evaporation ponds of size 1500 m^2 located in the immediate vicinity of the desalination plants as this was the only area that was available on the farm. The examples given involves either using clay or PVC as liner. It is recommended that synthetic lining is used due to the leakage factor. This is especially emphasized at Samarina farm where one of the intake wells is located very close. However, using PVC as liner for a 3000 m^2 pond is estimated to cost around $ 17 000. Clay lining is significantly lower in cost, but is not as environmentally friendly as leakage is expected to occur and the amount of leakage is dependent on how much and what type of clay material is used and how well it is compacted. If clay lining is going to be used, it would be recommended to stop using the intake well close to the ponds. This could be done by relocating it or increase the intake at the other three wells that exists at Samarina farm.

The cost of the evaporation ponds can, however, be alleviated by combinations with income bringing synergies like fish cultivation. Nile Tilapia is a good choice due to its significant tolerance towards high salinity and environmental stresses, its high growth rate, the ease of production and the good market demand in Egypt [t]. The fishes can be fed both organic fertilizers (manure from the livestock) and mineral fertilizers for optimum growth. These products are available at Samarina farm and reusing some of the manure is beneficial. An economical example of Nile Tilapia cultivation, using West Indian market prices, exhibits an approximated annual profit of $ 18 000 for a 3000 m^2 pond area. This would, in only one years time, completely cover the investment cost of using PVC as liner. Nile Tilapia cultivation is a viable cost alleviation, but will require correct management and sales possibilities.

However, the mathematical example in this study shows that a 3000 m^2 evaporation pond area can only take care of a brine flow of 30 m^3/day. The existing 400 m^3/day plant has a brine flow of 240 m^3/day which means that a pond area of appr. 24 000 m^2 would be needed in order to sustainably take care this brine flow. This means that either new land has to be bought or taken from existing agricultural land. The plant is operating with a recovery rate of 62.5 %, but if the recovery rate would be increased from 62.5 % to 93 %, it would mean that only 30 m^3/day of brine would be produced and the proposed 3000 m^2 pond area would be enough to sustainably take care of all the brine. This would of course mean that the brine would be unsuitable for irrigation, but this proposal with the increased recovery and using evaporation ponds as disposal method could be used for the 400 m^3/day plant. For the 800 m^3/day plant, the recovery could remain the same (62.5 %) or even be decreased and the brine disposal would be irrigation of productive crops. It is realistic to have a recovery rate of well over 90 % with low saline brackish water as feed water, but the desalination system would need some adjustments and therefore additional investments.

Generally, one can say that the more brine that is being discharged to an evaporation pond, the less will the total salt load to the area be and the better the environmental solution for Samarina farm.

Reuse of the brine for agriculture is already practiced at Samarina farm with furrow irrigation of non-productive halophytic trees. However, there are also currently trials being made to see the effect of irrigating dates and olives with the brine water [personal communication, Mohamed].

The effect of salinity on crop growth depends on the crops tolerances towards salinity. Therefore, crop selection is vital whereever salinity problems occur. Apparently, according to the FAO's guidelines regarding crop tolerances towards irrigation water salinity, there are some crops that can withstand irrigation water salinity levels of 6000 to 7000 ppm [x].

Whereas dates and olives are considered only moderately tolerant, they are not good candidates for brine water irrigation at Samarina farm. More valid candidates are rye and barley. These crops are well adapted to hot climates and thrive in sandy soils. Rye and barley can also serve perfectly as livestock feed which is beneficial for Samarina farm. However, the most important features are the high tolerances to salinity with rye in the lead. This means that instead of discharging the brine to irrigate trees, the brine water could be used to irrigate productive and income bringing crops, like rye and barley, and also distributing the total salt load over a much larger area than what is currently done.

Sandy soils and drip irrigation reduces the salinity effect on crops and this further increases the possibility of brine water irrigation at this farm. Another factor which is very important when discussing yields and salinity is nutrition. Correct nutritional management, like with fertigation, is vital in order to restrict the sensitivity of crops to salinity and should therefore also be incorporated.

It will be especially important for this farm to consider the brine disposal once the 2nd desalination plant will be in use.

However, it does seem like the well water, which has a salt concentration of appr. 3000 ppm, is of adequate quality for use as drinking water for the livestock. This is if the individual leves of toxic substances are approvable which can only be confirmed by a complete water analysis. This brings up the question whether the desalination activity at Samarina farm is somewhat unnecessary. The desalination activity could be due to safety precautions for the health of the cattle. Anyhow, the salt concentration of the permeate water is appr. 400 ppm and this is in any case excessive water quality and therefore not economically optimal. The permeate water can, therefore, be mixed with raw well water to get the desired water quality.

There are no national regulations currently for the brine disposal in Egypt [personal communication, Rabi]. Therefore, the private enterprises use whatever method easiest to get rid of the brine often directly polluting the soil and groundwater and without the knowledge to realize that it is doing damage and/or to what extent the damage is. Currently, the use of inland desalination is limited in Egypt. Still, these activities contribute gradually to a quality deterioration of the groundwater aquifers. This is predicted to force more and more regions to use desalination for various purposes where this was not needed before.

There is no universal solution to the brine disposal issue, solutions have to be evaluated site-specifically. The deciding factors are ultimately the environment vs economics. Private enterprises are normally not willing to invest in brine disposal as it is not an income bringing practice. In many cases, like at Samarina farm, the main enterprise is not desalination but something else. Desalination is therefore already from the beginning a secondary or third concern. Therefore, the economical aspects rule and the only way to reverse this is with increased awareness of the problem along with regulatory measures, like in the US. This will have to come hand in hand with developmental and informational approaches regarding brine disposal.

17. REFERENCES

17.1 Literature

STUDY I:

[1] Ahmed, M., Shayya, W. H., Hoey, D., Al-Handaly, J. 2001. *Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates.* Desalination 133: 135-147

[2] Rebhun, M. 2004. *Desalination of reclaimed wastewater to prevent salinization of soils and groundwater.* Desalination 160: 143-149

[3] Purnama, A., Al-Barwani, H. H., Al-Lawatia, M. 2003. *Modeling dispersion of brine waste discharges from a coastal desalination plant.* Desalination 155: 41-47

[4] Tsiourtis, N.X. 2001. *Desalination and the environment.* Desalination 141: 223-236

[5] Glueckstern, P., Priel, M. 1996. *Optimized brackish water desalination plants with minimized impact on the environment.* Desalination 108: 19-26

[6] Ahmed, M., Shayya, W. H., Hoey, D., Mahendran, A., Morris, R., Al-Handaly, J. 2000. *Use of evaporation ponds for brine disposal in desalination plants.* Desalination 130: 155-168

[7] Mickley, M. 1995. *Environmental considerations for the disposal of desalination concentrates.* IDA. Abu Dhabi Proceedings. Volume VII.

[8] Squire, D. 2000. *Reverse osmosis concentrate disposal in the UK.* Desalination 132: 47-54

[9] Alabdula'aly, A. I., Al-Saati, A. J. 1995. *Brine production, recovery and disposal in groundwater RO plants in the central region of Saudi Arabia.* IDA. Abu Dhabi Proceedings. Volume VI.

[10] Everest, W., Murphree, T. 1995. *Desalting residuals: A problem or a beneficial resource?.* Desalination 102: 107-117

[11] Ahmed, M., Arakel, A., Hoey, D., Coleman, M. 2001. *Integrated power, water and salt generation: a discussion paper.* Desalination 134: 37-45

[12] Lu, H., Walton, J. C., Swift, A. H. P. 2001. *Desalination coupled with salinity-gradient solar ponds.* Desalination 136: 13-23

[13] Turek, M. 2002. *Seawater desalination and salt production in a hybrid membrane-thermal process.* Desalination 153: 173-177

[14] El-Yakubu Jibril, B., Ibrahim, A. A. 2001. *Chemical conversions of salt concentrates from desalination plants.* Desalination 139: 287-295

[15] Ahmed, M., Arakel, A., Hoey, D., Thumarukudy, M. R., Goosen, M. F. A., Al-Haddabi, M., Al-Belushi, A. 2003. *Feasibility of salt production from inland RO desalination plant reject brine: a case study.* Desalination 158: 109-117

[16] Einav, R., Harussi, K., Perry, D. 2002. *The footprint of the desalination processes on the environment.* Desalination 152: 141-154

[17] Squire, D., Murrer, J., Holden, P., Fitzpatrick, C. 1996. *Disposal of reverse osmosis membrane concentrate.* Desalination 108: 143-147

[18] Einav, R., Lokiec, F. 2003. *Environmental aspects of a desalination plant in Ashkelon.* Desalination 156: 79-85

[19] Abu Qdais, H. A. 1999. *Environmental impacts of desalination plants on the arabian gulf.* IDA. San Diego Proceedings. Volume III.

[20] Höpner, T., Windelberg, J. 1996. *Elements of environmental impact studies on coastal desalination plants.* Desalination 108: 11-18

[21] Morton, A. J., Callister, I. K., Wade, N. M. 1996. *Environmental impacts of seawater distillation and reverse osmosis processes.* Desalination 108: 1-10

[22] Abdel-Jawad, M., Al-Tabtabaei, M. 1999. *Impact of current power generation and water desalination activities on kuwaiti marine environment.* IDA. San Diego Proceedings.

[23] Höpner, T., Lattemann, S. 2002. *Chemical impacts from seawater desalination plants - a case study of the northern Red Sea.* Desalination 152: 133-140

[24] Kihara, M., Yamamura, H., Jinno, S., Kurihara, M. 2002. *Operation and reliability of very high recovery seawater desalination technologies by brine conversion two stage RO desalination system.* IDA. Bahrain Proceedings.

[25] Kimes, J. K. 1995. *The regulation of concentrate disposal in Florida.* Desalination 102 (): 87-92

[26] Ahmed, M., Shayya, W. H., Hoey, D., Al-Handaly, J. 2002. *Brine disposal from inland desalination plants.* Water international, Volume 27, Nr 2, Pages 194-201

[27] Wright, R. 2003. *Vaporising droplets desalinate in milliseconds.* Water and wastewater international.

STUDY II:

[28] The EEAA – Department of Natural Protectorates. National parks of Egypt: South Sinai Sector. Ras Mohammed National Park Sector.

17.2 Internet sources

STUDY I:

[a] Small Island Water Information Network (SIWIN). Review – Groundwater and Salinity Management in Unconsolidated Sedimentary Aquifers. www.siwin.org/reviews/reviewlist.html 2004-05-24

[b] Evaporites. www.seis.natsci.csulb.edu/bperry/Sedimentary%20Rocks%20Tour/sedimentary%20rocks%20images/chemical%20sedimentary%20rocks/evaporites/sed_evapplaycloseup_1.jpg 2004-06-24

[c] Reimold, R. J., Loland-McLaughlin, G., Bloetscher, F. An innovative opportunity for water reuse. Florida water resources journal. 1996. www.fwrj.com/articles/9607.pdf 2004-05-05

[d] Shannon, M., Cervinka, V. Chapter 4 - Drainage water re-use. www.fao.org/docrep/W7224E/w7224e08.htm 2004-05-10

[e] Saline intrusion in marine outfalls. www.qub.ac.uk/waves/outfall/saline.htm 2004-06-24

[f] EPA. The Class V Underground Injection Control Study. Salt Water Intrusion Barrier Wells. Volume 20. 1999. www.epa.gov/safewater/uic/cl5study.html 2004-06-23

[g] Mickley, M. Membrane concentrate disposal: Practices and regulation. Desalination and Water Purification Research and Development Program Report No. 69. 2001. www.usbr.gov/pmts/water/reports.html 2004-07-02

[h] Salt Institute. Solar salt production. www.saltinstitute.org/11.html 2004-05-05

[i] Mickley, M. Desalination concentrate management and issues in the United States. www.twdb.state.tx.us/Desalination/Desal/proceedings/Mickley.pdf 2004-06-30

[j] Cargill Salt. www.cargillsalt.com/sfbay/T_solar_evap.html 2004-06-29

[k] University of Texas. Zero discharge waste brine management for desalination plants. Desalination Research and Development Program Report No. 89. 2002. www.usbr.gov/pmts/water/reports.html 2004-07-02

[l] Geo-Processors PTY. www.geo-processors.com.au/ 2004-06-30

[m] Aquasonics. Desalination & Aquasonics: An Overview. www.aquasonics.com/invest.html 2004-05-11

[n] Namport. www.namport.com/Support/dry.html 2004-05-06

[o] Ameriglobe. www.ameriglobe-fibc.com/portabulk.html 2004-07-01

[p] Fukuhara, R., Murakami, M. Utilizing deep seawater from the Gulf of Aqaba for desalination at the Dead Sea. www.medrc.org/new_content/industry_news/redsea.htm 2004-05-11

[q] Highnett, C., White, R., Rechten, H. Solar ponds – Technology and economics. 2002. www.senrac.sa.gov.au/Presentations%20Conference%202002/Highnett%20SolarPond%20Paper.pdf 2004-07-06

[r] Science Lab. Chemicals and laboratory equipment. www.sciencelab.com/page/S/PVAR/10421/SC-NA120 2004-07-06

STUDY II:

[s] Annual meteorological report (Cairo, Egypt, 1974). www.docs.lib.noaa.gov/rescue/data_rescue_egypt.html 2004-07-24

[t] Nile tilapia. www.thejump.net/id/id.htm. 2004-07-29

[u] Aquaponics. www.aquaponics.com/articlegreenwater.htm 2004-09-07

[v] Waste facility construction requirements. www.oneplan.org/Stock/wasteFac/manual3.shtml 2004-07-28

[x] Tanji, K., Kielen, N. Agricultural drainage water management in arid and semi-arid areas. FAO Irrigation and drainage paper 61. www.fao.org/DOCREP/005/Y4263E/y4263e00.htm#Contents 2004-07-27

[y] Purdue University. www.hort.purdue.edu/newcrop/default.html 2004-07-29

[z] Rye. www.oznet.ksu.edu/pr_wheat/Weeds/rye.htm 2004-09-13

[w] Barley. www.envirotest.com/feed/type_feed.htm 2004-09-13

17.3 Personal communication

STUDY I:

Smith Larsen, R. Product manager, Hydro packaging. 2004-07-01
Arakel, A. Managing director, Geo-Processing PTY. 2004-08-26
Perez, F. Technical engineer, Aqualyng AS. 2004-07-22

STUDY II:

Hegazy, K. Marketing manager, Assem Doss & Co. 2004-07-12
Rabi, M. Chief manager, Environmental Agency in South Sinai. 2004-07-13
Mohamed, H. Managing director, Samarina farm. 2004-07-17
Ali, M. Electrical engineer, Samarina farm. 2004-07-18

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