Field testing to determine the evaporation rate of brine solutions formed during the membrane treatment of mine-water

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by

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EXECUTIVE SUMMARY

Improvements in membrane processes have made it economically feasible to treat mine-water to a drinking water quality and to sell it to municipalities. Reverse osmosis is often selected for the treatment of water from coal mines. This treatment results in a brine, or concentrated salt stream, which has to be managed as a waste. Current projects being investigated and implemented result in a brine with total dissolved solids (TDS) concentrations of between 17 500 mg/ℓ and 51 000 mg/ℓ.

Disposal options for brine include: treatment and/or authorisation for disposal to surface water resources; authorisation to discharge to sewer; deep well injection; spray irrigation; mechanical or thermal evaporation; or evaporation ponds. Evaporation ponds have been the preferred disposal option to date for the coal mining operations being considered in this project. One of the key factors influencing the design of evaporation ponds is the evaporation rate. The evaporation rates for water are readily available for most areas in South Africa. The high salinity in the brine however will reduce this evaporation rate.

The aim of the study is to conduct a literature survey to obtain reported evaporation rates on saline solutions and to carry out field investigations to measure the evaporation rate of brine solutions and compare this against that of a standard water sample.

The correct sizing of an evaporation pond depends on the accurate calculation of the evaporation rate. Typically the larger the surface area, the greater the rate of evaporation from the pond, however the relationship is not linear and a number of other factors also play a role.

The climatic factors affecting the rate of evaporation include:

- Temperature – heating the water molecules to the required temperature,
- Humidity – if the humidity levels are high, less evaporation occurs,
- Solar radiation – providing heat to enable evaporation,
- Wind – to blow away the saturated air in order to allow further evaporation to occur.

Dissolved salt in the water results in a lower saturation vapour pressure, due to the decreased chemical potential of the water, and thus results in a lower evaporation rate. The second Law of Thermodynamics implies that an increase in ion activity as a result of the presence of a solute reduces the chemical potential of a liquid solvent and also the rate of spontaneous transformation of a liquid phase into a vapour phase (Kokya and Kokya, 2006).

Procedures for calculating evaporation indicate that evaporation rate is directly proportional to vapour pressure. The vapour pressure of saline water is lower than that of fresh water resulting in a reduction in evaporation (Mickley, 2001). Cohesive forces between the dissolved ions and water may also inhibit evaporation, as it will be more difficult for the water molecules to vaporise (Miller, 1989)

Leaney and Christen (2000) indicated that the evaporation rate decreases exponentially with increasing salinity. Evaporation rates of fresh water are easily available from hydrological databases. The evaporation rates of saline solutions are normally calculated by multiplying the rate of evaporation of water by a salinity factor (Mickley, 2001).

The type of salt dissolved has an effect on the humidity at which evaporation will stop, for example there will be no evaporation from a water body saturated with sodium chloride during periods when the humidity is above 70%. With other salts, evaporation may cease at lower humidity levels (Leaney and Christen, 2000).

Field investigations were carried out in order to obtain a comparison between evaporation on synthetic solutions made-up to represent various brine concentrations and potable water. Evaporation on an actual brine sample was compared to the synthetic solution at the eMalahleni Water Reclamation Plant

in order to verify that the synthetic solutions are a reasonable representation of the evaporation rate on actual brines.

A Davis Pro2 weather station was purchased In order to understand the impact of climatic conditions on evaporation rates. The weather station has the ability to monitor temperature, humidity, rainfall, wind speed, wind direction, and solar intensity. In order to be able to replicate data at various sites requiring evaporation ponds, it was necessary to use standard equipment, thus standard A-Pans were used to measure the evaporation rates. Due to the risk of corrosion, the pans were coated with a grey corrosion proofing paint. Level readings were taken daily, except on public holidays and weekends.

Initial results indicated that stratification occurred in the evaporation pans, impacting on the results obtained. The experimental procedure was modified to include daily mixing in the pans. Results obtained are presented in Table ES1.

Table ES1: Statistical analyses excluding out of range data points of salinity factors calculated at GAA Offices and EWRP.

	GAA Offices			eMalahleni Water Reclamation Plant	
	eMalahleni	**Kilbarchan**	**Optimum**	**Actual Brine**	**Synthetic Brine**
5 Percentile	35	40	34	56	56
25 Percentile	50	57	51	66	67
50 Percentile	82	79	63	77	75
75 Percentile	96	97	75	88	86
95 Percentile	100	100	100	93	90
Average	74	74	65	77	75

An average salinity factor of 74% was calculated for eMalahleni and Kilbarchan synthetic solutions and 65% for the Optimum synthetic solution. This indicated that the salinity factor is influenced by both the concentration and the composition of the brine.

The actual and synthetic brine solution set up at eMalahleni displayed similar results, as shown in Table ES1. This confirmed that synthetic solutions can be used during the design phase of a project in order to determine a salinity factor, prior to the construction of a brine pond.

The following recommendations were made:

- Undertake investigations in a controlled environment in order to better understand the impact of various climatic conditions on the evaporation rate and salinity factor.
- Use a sensitive automated level indication on the pans and record data at more regular intervals (hourly or every 30 minutes) in order to enable a better comparison with climatic data.
- Investigate specific salts in order to improve the understanding of the composition of brine on the salinity factor.

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LIST OF ABBREVIATIONS

DWA	Department of Water Affairs
ED	Electrodialysis
EWRP	eMalahleni Water Reclamation Plant
MF	Microfiltration
mg/ℓ	milligrams per litre
NF	Nanofiltration
RO	Reverse osmosis
SF	Salinity factor
TDS	Total dissolved solids
UF	Ultrafiltration

1 INTRODUCTION AND OBJECTIVES

Historically, mine-water was considered to be unavailable water, but it is now considered a valuable resource. In several mining impacted catchments, substantial water resources are stored in old or active mine workings. These mine-water bodies are typically continuously recharged by surface water (Van Niekerk, 2009). If not utilised, the mining voids fill up and the excess mine-water decants into rivers and streams, resulting in surface water contamination.

Improvements in membrane processes have made it practical to treat mine-water to drinking water quality and supply it to municipalities. Current projects being investigated and implemented typically produce brines as a treatment waste product, with Total Dissolved Solids (TDS) concentrations between 17 500 mg/ℓ and 51 000 mg/ℓ. The brine produced typically also has high concentrations of metal ions, such as manganese, thus requiring a lined disposal facility, according to the National Waste Act.

One of the factors influencing the design and sizing of lined brine disposal facilities is the expected evaporation rate. The evaporation rates for water are readily available for most areas in South Africa. The high salinity in the brine however, can potentially reduce this evaporation rate.

The aim of the study was to carry out field investigations to measure the evaporation rate of brine solutions and compare it against the evaporation rate of a potable water sample.

The objectives of the field studies were:

- Determination of a correlation between the evaporation rate of a saline solution compared to potable water.
- Establishment of evaporation rate trends at different concentrations of salinity, i.e. TDS concentrations of 20 000, 30 000 and 40 000 mg/ℓ.
- Plotting of curves depicting evaporation against temperature, humidity and wind speed.
- Comparison of observed evaporation rates to calculated rates based on evaporation equations available.
- Comparison between different water sources, i.e. mine-water with high sulphate concentrations *vs.* water with high chloride concentrations.

The project was divided into three phases:

- Phase 1 – literature survey
- Phase 2 – field investigations
- Phase 3 – field investigations with amended methodology

2 PHASE 1: LITERATURE SURVEY

A literature survey was conducted to:

- understand the membrane desalination treatment process for acid mine-water,
- investigate methods of disposal for brine produced during the membrane treatment of mine-water,
- determine whether evaporation studies were conducted on brine produced during membrane treatment of mine-water.

2.1 Membrane treatment options

The membrane water treatment industry has grown dramatically since the 1980s (Mickley, 2001). Membrane processes include reverse osmosis (RO), Nanofiltration (NF), electrodialysis (ED), ultrafiltration (UF) and microfiltration (MF) (American Water Works Association, 1999).

The selection of the treatment process and type of membrane required is dependent on the feed water quality and the desired end use of the water (Baker, 2000).

Reverse osmosis (RO) is a pressure driven process which makes use of membranes that are permeable to water, but essentially impermeable to salt (Baker, 2000). Reverse osmosis membranes are continuous membranes, in the sense that they do not have physical pores. The smallest size of dissolved ions and organics that can be removed by RO is 0.1 nm. Reverse osmosis thus removes all particulate matter, including all bacteria and viruses, all organic macromolecules and most organic molecules with a molecular mass larger than 150 Daltons. The main application for RO is the removal of salinity, including monovalent ions, such as sodium and chloride from a water solution (Schutte, 2006).

Reverse osmosis treatment plants typically produce brine, or a concentrated salt stream, which needs to be managed as a waste. The concentration of the brine is dependent on several factors, including the feed water quality, pre-treatment processes used, the membrane selected, water recovery achieved and options for post treatment and concentration blending being employed. The waste stream's composition is dependent on the salt and other impurities found in the feed water being treated (du Plessis *et al.,* 2006).

Nanofiltration (NF) is also a pressure driven desalination process. Nanofiltration membranes have very small pores. These pores allow certain substances to pass through the NF membrane that would be contained by RO membrane treatment. Monovalent ions readily pass through the NF membranes, while divalent ions are mostly rejected by NF membranes (Schutte, 2006). Nanofiltration is often used in combination with RO treatment and the reject from the NF is combined with the reject from the RO process, or it may be recycled back to the feed stream. This is the case at the eMalahleni Water Reclamation Facility.

Ultrafiltration (UF) is another pressure driven membrane process using porous membranes. It cannot be used to remove dissolved ions or small dissolved organic molecules, but can remove bacteria, viruses and larger organic substances, such as trihalomethanes (THMs) (Schutte, 2006).

Microfiltration (MF) is similar to UF, except that the pore sizes are larger. Only particulate matter, most bacteria and protozoa can be removed using MF (Schutte, 2006).

Electrodialysis differs from RO, NF, UF and MF as the driving force in the case of electrodialysis is the electrical potential across the membrane. Charged ion groups are attached to ion exchange membrane material. These fixed charged particles partially, or completely, exclude like-charged ions from the membrane, allowing ions of the opposite charge to pass through. An electrodialysis unit is set up of alternately charged cation and anion membranes (Baker, 2000). An electrodialysis unit will have no effect on uncharged compounds and particulates, including bacteria and viruses (Schutte, 2006).

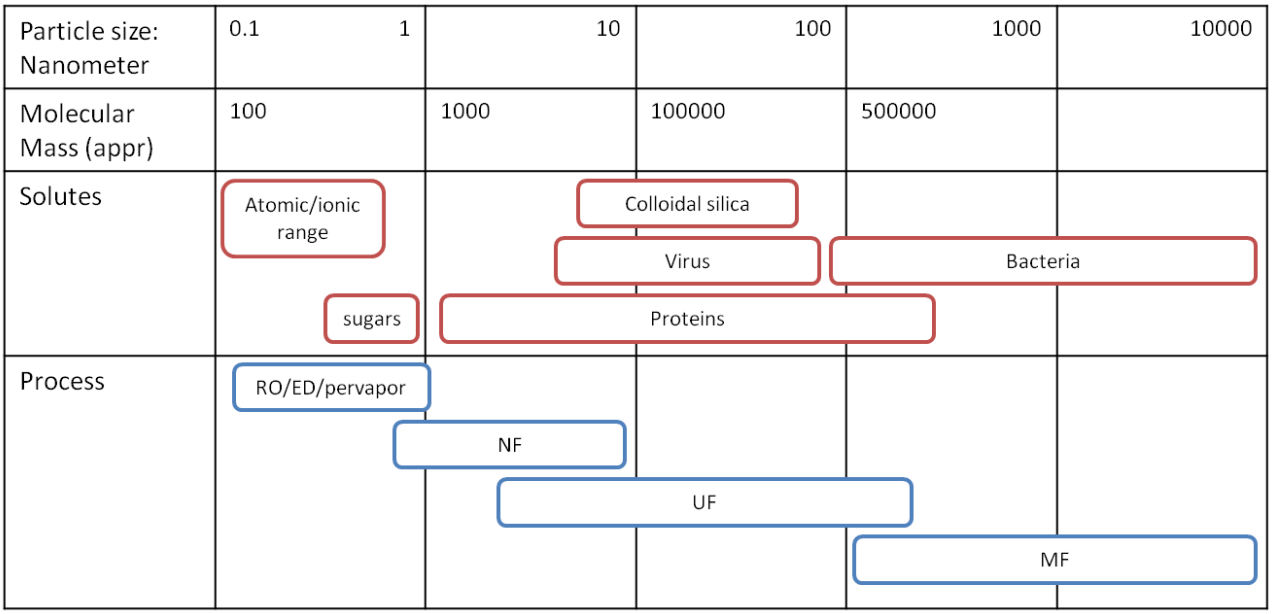

Figure 1: Size and range application for various membrane processes (Schutte, 2009)

For the purpose of this study, the focus is on brine produced at RO plants treating mine-water from the coal industry to potable water standards. The reject (concentrated saline solution, or brine) resulting from the treatment of mine-water is the waste stream from the NF/RO membrane treatment processes. The characteristics of the reject concentrate are directly related to the type of water being treated, the desalination technology used, the percentage recovery and chemical additives used (Ahmed *et alet al*., 2000).

2.2 Brine produced in mine-water treatment

As indicated in Figure 1, waste produced from RO processes will consist of dissolved ions, sugars, proteins, viruses and bacteria. In the case of mine-water, sugars, proteins, viruses and bacteria are unlikely to be present and the waste will mainly contain dissolved ions.

Existing mine-water treatment to drinking water standards projects implemented, or new projects being investigated, were considered In order to gain an understanding of typical brine concentrations. Information was obtained from:

- eMalahleni Water Reclamation Plant, which is currently treating water from various Witbank mines to potable standards,
- Optimum Project, where a pilot plant was in operation to investigate the mine-water reclamation process and requirements, and
- Kilbarchan Project, where bench scale testing was carried out for treating water from old defunct mines in Northern KwaZulu-Natal.

2.2.1 Volume of brine

The volume of brine or reject produced in the membrane treatment plant is dependent on the quality of the water being treated and the process selected (Schutte, 2009). Typically, mine-water treatment plants are designed to have 85 to 99% water recovery, hence the volume of brine remaining is 1 to 15% of the total volume of water treated.

2.2.2 Composition of brine

Mine-water from coal mines typically contains high concentrations of metals (iron, aluminium and manganese), divalent ions (calcium, magnesium and sulphate) and monovalent ions (sodium and chloride). In most plants, pre-treatment is carried out to remove the metals, typically as metal

hydroxides, as well as to precipitate some of the divalent ions, such as calcium sulphate (gypsum), magnesium hydroxide and calcium carbonate (typically for neutral mine-water). It should be noted that the brine composition is not directly proportional to the composition of the feed water as different salt rejections rates are applicable to different salts. A typical mine-water treatment process train is presented in Figure 2. A large portion of contaminants are removed in the pre-treatment process unit and wasted to the sludge dams.

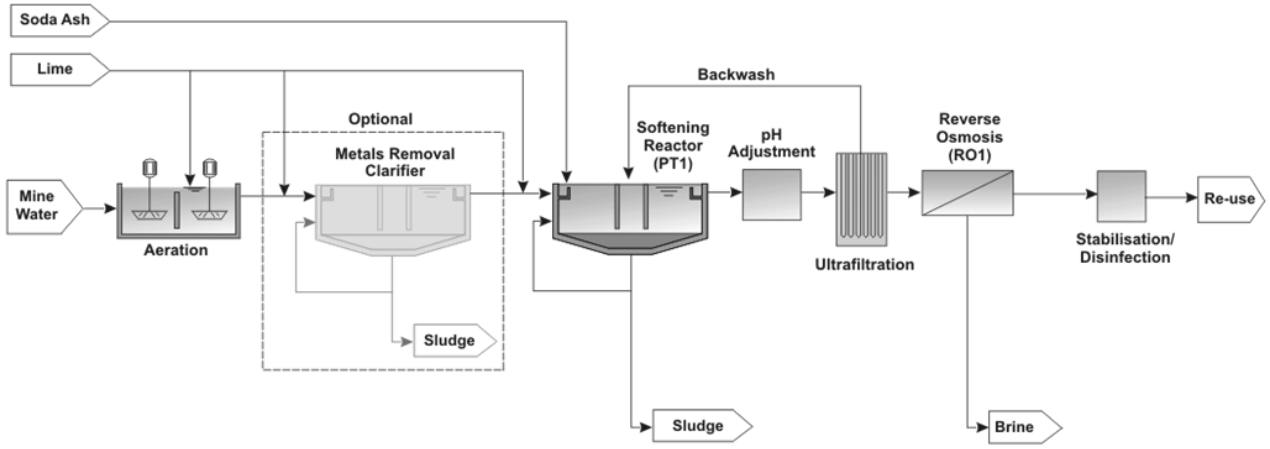

Figure 2: Typical water treatment process including RO treatment

The brine reject from the membrane process is characterised by the high TDS concentration and has low concentrations of process-related chemicals. The degree of salt concentration, also called the concentration factor, is related to the water recovery as indicated in equation 1 (Ahmed *et al.,* 2000). The relationship between the concentration factor and the rate of recovery is demonstrated in Figure 1 (du Plessis *et al.,* 2006).

$$CF = \frac{1}{1-R} \quad \textbf{[1]}$$

Where: *CF* = Concentration factor
R = Fractional treated water recovery (fraction of the total water treated that reports to the treated water stream)

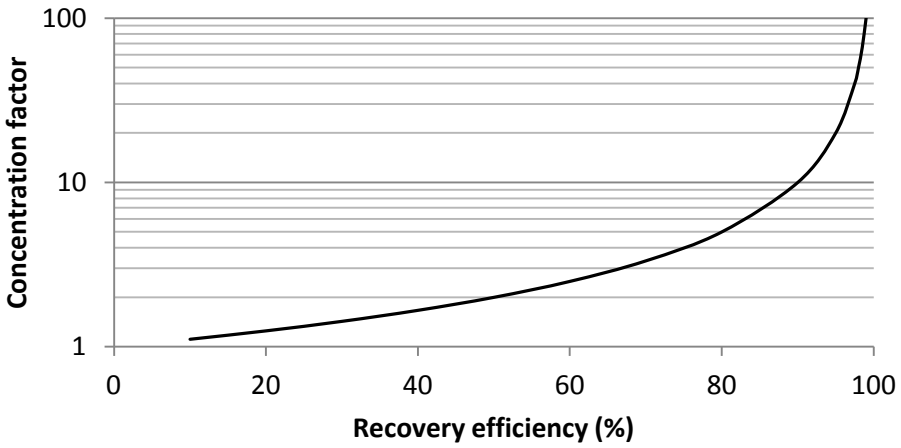

Figure 3: Chart indicating the relation between the recovery efficiency (%) and the concentration factor

2.3 Brine management

The overall mine-water management plan incorporating a water treatment plant must include a plan for the responsible management of the waste produced. Typical management options used for brine produced from membrane treatment operations include the following (Mickley, 2001):

- Disposal to surface water resources:
  - The brine salinity, discharge depth, brine density, current velocity and distance from the shore to the discharge point are important parameters that must be taken into consideration when considering this option.
  - Coal mines being considered in this study are generally located inland and the possibility of brine discharge to the ocean is not feasible, due to the long pipelines, exorbitant pumping costs and risk of environmental contamination due to leakages along the pipeline route.
- Discharge to sewer
  - Permission must be obtained from the local wastewater treatment plant owner before discharge can be considered.
  - Usually only allowed for small flows in sewer systems where sufficient assimilation/dilution capacity is available.
  - Highly site dependent.
  - Unlikely to be acceptable for RO treatment of mine-water, due to the high concentrations of dissolved salts present.
- Deep well disposal
  - Liquid waste is injected into porous subsurface rock formations, possessing the natural ability to contain and isolate it.
  - Risks of wastewater migration and contamination of groundwater must be taken into consideration during the site selection and design.
  - Deep well injection is not extensively used in South Africa. In general the geological, and more importantly the geohydrological conditions, do not lend themselves to this practise. The risk associated with wastewater migration under favourable conditions and contamination of groundwater resources is high.
- Spray irrigation
  - Higher TDS concentrations from RO and ED make this option unfeasible unless brine is diluted. South Africa is a water scarce country and dilution is not feasible.
  - Spray irrigation may be considered in the case of MF reject streams, provided that the waste meets the irrigation standards specified by the Department of Water Affairs (DWA).
- Zero liquid discharge
  - Mechanical/thermal evaporation is used to process brine to dry salts.
  - Commercially available evaporators have high energy consumptions.
  - Cost estimates indicate that capital cost is approximately R1.6 million per 1m^3/h capacity for plants of a treatment capacity in the range of 100 to 200 m^3/h (confidential quotation).
  - Typically considered only in special circumstances when no other disposal option is available.
- Disposal into isolated underground workings
  - The long term risks of contamination of ground water must be taken into account.
  - The possibility of re-mining of the workings to remove the board and pillars must be taken into consideration .
- Evaporation ponds
  - Appropriate for relatively warm, dry climates with high evaporation rates, level terrain and low land costs,
  - Depending on the composition of the brine, it often requires an expensive lining system,
  - Proper sizing of ponds depends on achievable evaporation rate.

The following aspects influence the selection of the final disposal method:

- Volume of the concentrate,

- Quality of the concentrate,
- Physical and geographic location of the treatment process,
- Space constraints,
- Regulatory approval of option – dependent on environmental legislation,
- Public acceptance,
- Capital and operating costs,
- Possibility for expansion.

2.3.1 Evaporation ponds

Evaporation ponds have been the preferred option for brine disposal for the coal mining operations being considered in this project, for the following reasons:

- The brines produced have high TDS concentrations with high sulphate and metal content and are not suitable for discharge to surrounding surface/ground water sources, sewer or irrigation,
- Obtaining regulatory approval for deep well injection is unlikely due to the risk of groundwater contamination,
- The mines are a long distance away from the sea, thus discharge to sea is not feasible even if permitted,
- The relatively low rainfall, high temperatures and relatively dry and windy climate makes evaporation ponds a viable option,
- Operational costs of forced thermal evaporation systems are exorbitant, and many projects will not be financially viable if this option is required.

The aspects that need to be taken into consideration when designing an evaporation pond include:

- Climatic conditions, including rainfall, average temperatures, wind, humidity and cloud cover,
- Topography of land,
- Land availability,
- Level of groundwater table,
- Life of project,
- Legislative requirements for surge capacity, and
- Permit or licence requirements for the storage and disposal of waste.

The evaporation rate is crucial to the design of a brine evaporation pond. The area-specific reported evaporation rate is multiplied by a factor to account for the high salinity. A salinity factor of 0.7, as suggested by Mickley (2001) has most commonly been used in the design of evaporation ponds in South Africa.

2.4 Factors affecting evaporation

The proper sizing of a brine evaporation pond depends on the accurate calculation of the evaporation rate. Evaporation ponds function by transferring water in the pond to water vapour in the atmosphere above the pond. (Ahmed *et al.,* 2000). Typically the larger the surface area, the greater the rate of evaporation from the pond, however the relationship is not linear and a number of other factors also play a role.

2.4.1 Climatic effects

In order for evaporation to occur, sufficient energy is required to change the water from a liquid phase to its vapour phase. The air above the evaporation pond becomes saturated with water vapour and this moist air must be removed in order to allow the evaporation process to continue. The climatic factors affecting the rate of evaporation include:

- *Temperature* determines the saturation vapour pressure and thereby the amount of moisture that air can hold, heat exchange from the fresh air to the water also provides some of the required heat of vaporisation to allow for the phase change from liquid to vapour to occur,
- *Humidity* if the humidity levels are high, less evaporation occurs as the difference between the actual humidity and the saturation humidity provides the driving force for further evaporation,
- *Solar radiation* helps to maintain temperatures favourable to evaporation by providing some of the required heat of vaporisation to allow for the phase change from liquid to vapour to occur,
- *Wind* to remove the saturated air in order to allow further evaporation to occur.

2.4.2 Properties of liquid being disposed of

The factors related to the brine which will have an impact on the evaporation rate include:

- Concentration of brine – the higher the TDS concentration, the lower the evaporation rate,
- Composition of brine – the type of salt dissolved will have an effect on the humidity at which evaporation will stop, for example a water body saturated with sodium chloride, will have no evaporation when the ambient humidity is above 70%. With other dissolved salts, evaporation may cease at lower humidity levels (Leaney and Christen, 2000).
- Salt precipitates – the salt precipitate is typically white, thus reflecting more heat. This will have a greater effect on shallow dams.
- Rate of disposal – The brine salinity increases with time due to evaporation, as the water evaporated leaving the salts behind. The rate of brine disposal results in a mixing and dilution effect.

2.4.2.1 Salinity

Dissolved salts in the water result in a lower saturation vapour pressure, due to the decreased chemical potential of the water, and cause a lower evaporation rate. The second Law of Thermodynamics implies that an increase in ion activity, as a result of the presence of a solute, reduces the chemical potential of a liquid solvent and also the rate of spontaneous transformation of the liquid phase into the vapour phase (Kokya and Kokya, 2006). This would be another factor leading to a brine solution having a low evaporation rate.

Procedures for calculating evaporation rate indicate that evaporation rate is directly proportional to vapour pressure. The vapour pressure of saline water is lower than that of fresh water resulting in a reduction in evaporation (Mickley, 2001). Cohesive forces between the dissolved ions and water may also inhibit evaporation, making it more difficult for the water molecules to vaporise (Miller, 1989). Leaney and Christen (2000) indicated that the evaporation rate decreases exponentially with increasing salinity.

Combining the above factors shows that as the salinity increases the vapour pressure of a solution lowers and in turn a lower vapour pressure results in a lower air saturation water vapour concentration relative to the air saturation water vapour concentration achievable over a fresh water body at the same temperature and pressure conditions. Hence the observation that the evaporation rate decreases with increasing salinity and eventually stops even when the humidity is not yet at 100% (based on clean water), although it is already at 100% for that salt solution. The difference in evaporation rates between various salt compositions is probably dependent on that specific salt solution's solubility limits and the resulting saturated salt solution concentration and its impact on the vapour pressure.

Evaporation rates of fresh water are easily available from hydrological databases. The evaporation rates of saline solutions are calculated by multiplying the rate of evaporation of water by a salinity factor (Mickley, 2001).

The effect of the salinity factor on the footprint of an evaporation pond is shown in Figure 4. The pond area increases exponentially with reduced evaporation rates. This leads to exorbitant costs associated with expensive liner systems and land requirements. Project cost estimates carried out indicate that the cost for the disposal of brine can be in the order of 15% of the capital cost of a mine-water desalination project in the case of inland locations (Gilron *et al.,* 2003). It is thus important to have a reliable value for the salinity factor. Since this factor is influenced by both concentration and composition, it is advisable to determine the salinity factor using a synthetic solution prior to designing and constructing an evaporation pond.

2.4.2.2 The Oasis Effect

Another important effect to be considered on the evaporation rates of areas with similar climates is the surface area of the water body. The evaporation rate from a water body is reduced from a maximum value for small water bodies, as determined for a standard evaporation pan, to a fraction of that value for larger bodies (Leaney and Christen, 2000). This fraction is often referred to as the pan factor. For larger water bodies the area specific evaporation rate is multiplied by the pan factor. Equation 2 (Leaney and Christen, 2000) can be used for determining the pan factor:

$$F_{pan} = 1 - 0.029 \ln A \qquad [2]$$

Where: A = surface area of water body (ha)

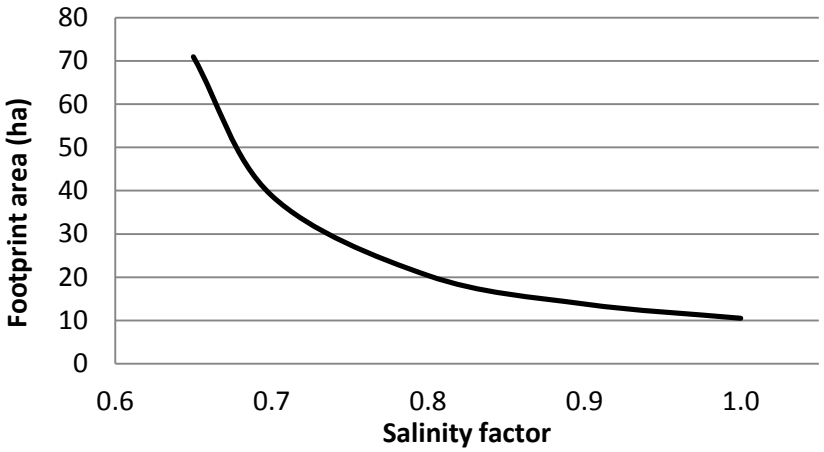

Figure 4: Effect of salinity factor on the footprint area of a pond

2.5 Methods of determining evaporation rates

Several equations and field testing methods exist for determining evaporation rates.

2.5.1 Penman equation

The Penman equation is used by hydrologists to determine evaporation rates from open water sources. This equation is suitable for natural water resources with relatively low TDS concentrations. For saline waters, the Penman equation was modified to reflect the reduced vapour pressure of the saline solution (Akridge, 2008). The modified Penman equation is presented as Equation 3.

$$E_{mass} = \frac{mR_n + \rho_a c_p (\delta e) g_a}{\lambda_v (m + \gamma)} \quad [3]$$

Where:
E = evaporation (mm/day)
m = slope
R_n = net solar radiation (W/m^2)
ρ_a = density of air (kg/m^3)
c_p = heat capacity of air (J/kgK
g_a = momentum surface aerodynamic conductance (m/s)
δ_e = vapour pressure deficit (Pa)
λ = latent heat of vaporisation (J/kg)
γ = psychometric constant (J/kg)

2.5.2 Turk and Byonton

As discussed, the rate of evaporation is negatively impacted upon by TDS. In South Africa, a data base of evaporation rates is available for various quaternary catchments. These rates are however measured and reported for low TDS waters. This rate is multiplied by a salinity factor by design engineers. Equation 4 can be used for determining the salinity factor (Leaney and Christen, 2000):

$$F_{salinity} = 1.025 - 0.0246e^{(0.00879 * S)} \quad [4]$$

Where:
Fsalinity = salinity factor
S = salinity (g/ℓ)

Historically, a salinity factor of 0.7 was recommended when designing brine evaporation ponds (Mickley, 2001).

2.6 Reported salinity factors

Limited information was obtained from literature on typical salinity factors for brine produced from RO treatment.

- Ahmed *et al*. (2000) cited a paper (USDI, 1970) stating that brine evaporation, compared to distilled water, decreased by 1% per 0.01 increase in specific gravity.
- Kokya and Kokya (2006) observed a reduction in evaporation rate to 0.94 times that of fresh water, for sea water at a TDS concentration of approximately 40 g/ℓ.
- Sartori (2000) stated that salinity alone (considering salinities of up to 3.5%, the average sea water concentration) has a minor effect on the evaporation rate, where the reduction in evaporation is equivalent to the salt concentration value, i.e. for a salt concentration of 3.5%, the reduction in evaporation rate would be 3.5%.
- Mickley (2006) cited various studies which indicate that the salinity factors for 2%, 5%, 10% and 20% NaCl solutions are 98%, 97%, 93% and 78% respectively.

The quoted studies were not carried out on brines produced from the treatment of mine-water. Mine-water from South African coal fields produces waste products typically containing metals, specifically iron, aluminium, manganese, calcium, magnesium, chloride and sulphate salts and other compounds (Van Niekerk, 2009). Past research has indicated that the composition of the waste will have an effect on salinity (Leaney and Christen, 2000). This highlighted the need for a field study, investigating evaporation rates on brine solutions specifically produced from the treatment of mine-water.

Mickley (2006) concluded that there is no simple relationship between salinity and evaporation, as there are always complex interactions among site-specific variables, such as temperature, wind speed, relative humidity, pressure, water surface temperature, heat exchange rate with atmosphere, incident solar absorption and reflection, thermal currents and depth of pond.

2.7 Conclusions

The survey indicated that very little information is available on evaporation rates on brines generated during the desalination process on mine-water. The salinity factor and thus evaporation rate of the brine has a significant impact on the size of brine evaporation ponds required as well as the cost associated with managing the waste brine stream. A decision was thus made to continue with phase 2 of the project which included field investigations.

3 FIELD TRIALS

The literature survey presented in Chapter 0 showed that insufficient information was available on evaporation rates on brine solutions and prompted the project team to continue with Phase 2. The methodology was selected to try to understand the important factors influencing evaporation rates including climatic conditions, brine composition and brine concentration.

3.1 Methodology

Phase 2 of the project involved field investigations carried out at the offices of Golder Associates Africa (GAA) in Midrand. It was unfortunate that whilst evaporation pans were set-up at EWRP, due to technical reasons, we were unable to gather sufficient experimental data from the EWRP pans during this phase.

3.1.1 Climatic conditions

In order to understand the impact of climatic conditions on evaporation rates, a Vantage Pro2 weather station was purchased. The weather station has the ability to monitor the following:

- Temperature,
- Humidity,
- Rainfall,
- Wind speed,
- Wind direction,
- Solar intensity.

A data logger and software that enable data collection and reporting from the Vantage Pro Weather Station was purchased for the project. A photograph of the weather station is presented in Figure 5.

Figure 5: Vantage Pro2 weather station at the GAA offices

3.1.2 Evaporation pans

Standard A-Pans were used to measure the evaporation rates. In order to be able to replicate data at various sites with evaporation ponds, it was necessary to use standard equipment. Due to the risk of corrosion, the pans were coated with a grey corrosion proofing paint.

3.1.3 Synthetic brine solutions

Synthetic solutions were prepared for the study. The brine produced at the eMalahleni Water Reclamation Plant (EWRP) was analysed and used to prepare the synthetic solution. Brine from Optimum Mine and Kilbarchan Mine was not available, as these plants were not constructed, or commissioned, at the time of the study. The brine produced during bench scale testing of the Kilbarchan mine-water was analysed and used. The calculated brine composition obtained for Optimum Mine was used.

The following chemicals were selected to produce solutions containing the major cations and anions found in the brines being investigated:

- Sodium Chloride,
- Sodium Sulphate,
- Calcium Sulphate,
- Potassium Chloride,
- Sodium Nitrate,
- Magnesium Sulphate.

3.1.3.1 eMalahleni Water Reclamation Plant brine

The eMalahleni mine-water is in essence a high calcium and magnesium sulphate based water. High concentrations of potassium, sodium and chloride are also present. The brine produced from treating this type of mine-water also contains high concentrations of sodium, calcium, potassium, sulphate and chloride. Brine concentration data was obtained from the EWRP. A brine sample from the facility was analysed and the results presented in Table 1. The typical distribution of the major ions is shown in Figure 6.

Table 1: Typical concentrations in brine produced at the eMalahleni Water Reclamation Plant

Parameter	Concentration (mg/ℓ)
Sodium	4862
Calcium	928
Magnesium	67
Potassium	1144
Chloride	1360
Sulphate	11680
Nitrate	96
Aluminium	0.01
Fluoride	0.2
Iron	0.01
Manganese	0.04
Silica	2.1
TDS	17058

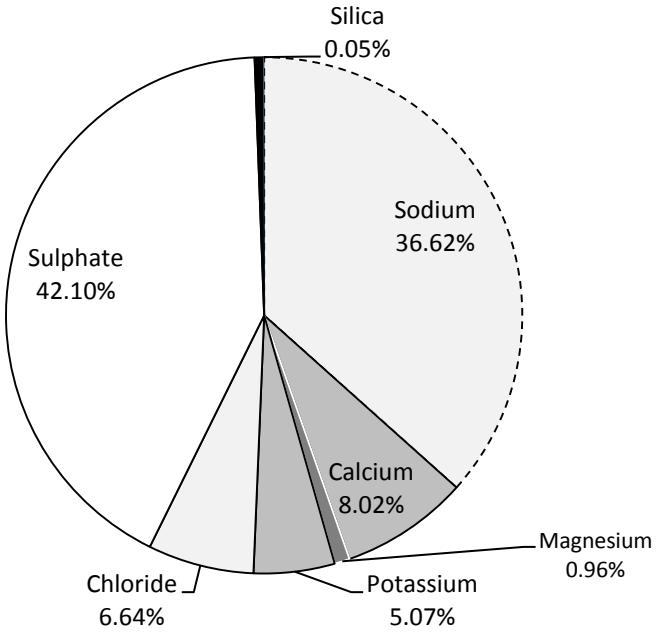

Figure 6: eMalahleni brine composition demonstrated in milli-equivalents per litre

3.1.3.2 Optimum Mine-water

The brine produced during the treatment of Optimum Mine-water is typified by high concentrations of sodium, potassium and sulphate, with calcium, magnesium and chloride also present in significant concentrations. The concentrations presented Table 2 and Figure 7 are based on modelled data for the proposed treatment processes at Optimum Mine.

Table 2: Simulated concentration of brine obtained from the treatment of Optimum Mine-water

Parameter	Concentration (mg/ℓ)
Sodium	7302
Calcium	1177
Magnesium	1423
Potassium	3052
Chloride	1913
Sulphate	19898
Nitrate	39
Aluminium	0.3
Fluoride	31
Iron	0.3
Manganese	0.3
Silica	25
TDS	34977

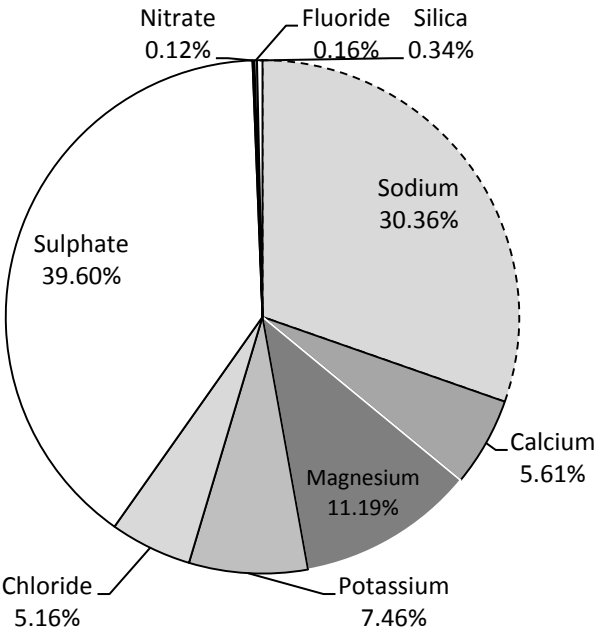

Figure 7: Optimum brine composition demonstrated in milli-equivalents per litre

3.1.3.3 Kilbarchan Mine-water

The Kilbarchan mine-water is a sodium sulphate type water, with calcium, magnesium and chloride present in high concentrations. The resulting brine is of a much higher concentration than the brine from Optimum and eMalahleni mine-waters. The concentrations presented in Table 3 and Figure 8 were obtained from bench scale testing carried out on Kilbarchan water. This was potentially the worst case scenario and the concentration of brine produced in the treatment plant is expected to be lower than this concentration.

Table 3: Typical concentration of brine obtained from bench scale testing on Kilbarchan water

Parameter	Concentration (mg/ℓ)
Sodium	12260
Calcium	353
Magnesium	802
Potassium	175
Chloride	13490
Sulphate	14923
Nitrate	3.9
Aluminium	0.1
Fluoride	1.46
Iron	0.18
Manganese	802
Silica	58
TDS	46300

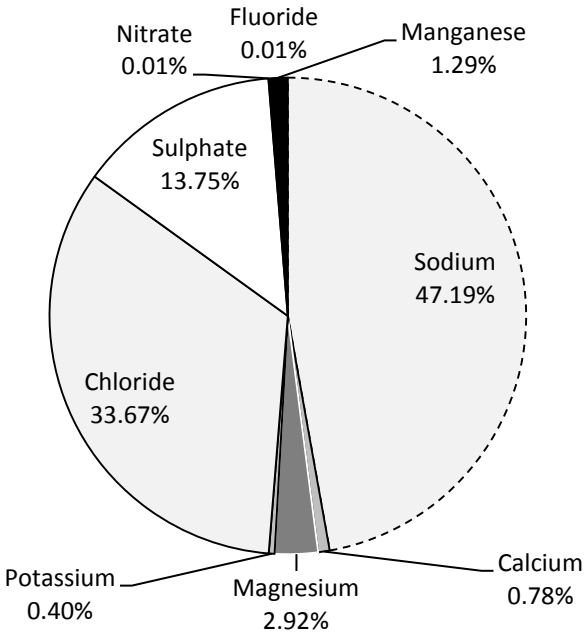

Figure 8: Kilbarchen brine composition demonstrated as milli-equivalents per litre

3.1.3.4 Brine solutions used in this study

As expected, the composition of the brine depends on the feed water. Figure 9 provides a comparison of the three brine solutions being investigated. In order to investigate the effect of the composition on the evaporation rate, synthetic solutions for all three brines were prepared.

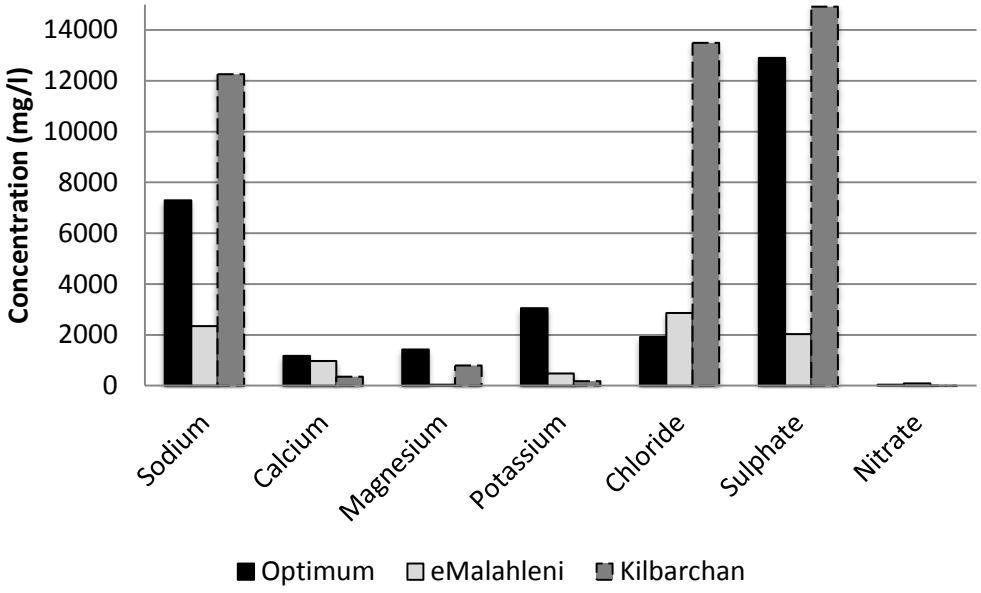

Figure 9: Composition of brine resulting from RO treatment of different mine-waters

Only the major constituents were taken into account in the preparation of the synthetic solutions. The synthetic solutions were made-up as presented in Table 4.

Table 4: Salts added to synthetic brine solutions

Salt Added (g/ℓ)	eMalahleni	Optimum	Kilbarchan
Sodium Sulphate	14.204	18.457	14.204
Calcium Sulphate	3.145	3.989	1.225
Potassium Chloride	2.177	5.218	0.373
Magnesium Sulphate	0.325	7.041	3.972
Sodium Nitrate	0.136	0.425	0
Sodium Chloride	0.584	2.922	21.917
Total	20.571	37.992	41.691

3.2 Experimental set-up

For Phase 2 of the project field studies were carried out only at the GAA offices in Midrand. The following aspects were taken into consideration in selecting the site for the installation of the evaporation pans and weather station:

- Ease of access – levels had to be read manually on a daily basis. It was therefore necessary to select an area that was easily accessible.
- A reasonable distance away from buildings, trees or other structures that may impact on the results.
- A level surface.
- Away from garden irrigation systems.

The weather station with data logger and four evaporation pans were installed on a paved area at one of the office blocks. The evaporation pans contained the following:

- Pan 1 – blank sample (control) – potable water
- Pan 2 – synthetic eMalahleni brine
- Pan 3 – synthetic Optimum brine
- Pan 4 – synthetic Kilbarchan brine

The pans were placed on wooden slats to limit heat transfer between the paving and the evaporation pan (Figure 10). Chicken mesh was fitted onto the pans to prevent birds from drinking the brine and using the pans as a bird bath.

3.3 Experimental procedure

The following information was recorded:

- Hourly climate data,
- Daily levels (Monday to Friday) in the evaporation pans.

The pans were calibrated at a depth of 138 mm at the commencement of the experiment. A steel ruler was used for the level readings and was secured in place for the duration of Phase 2.

A top-up and emptying procedure was implemented in order to maintain a level in the pan of between 20 mm and 130 mm (from the top).

When levels in the pans were above 20 mm as the result of heavy rainfall, 25 ℓ of the solution in the pan was removed. Levels were recorded both prior to and post the removal of the 25 ℓ of water.

When levels in the pans were below 130 mm, 25 ℓ of the synthetic solution was made-up and added to the pans. Levels were recorded both prior to and post the addition of the solution.

Figure 10: Evaporation pans at Golder offices in Midrand

Figure 11: Experimental set-up at the eMalahleni Water Reclamation Plant

3.4 Phase 3

Phase 3 included field investigations, but a few modifications were implemented based on Phase 2 experiences. Monitoring was conducted at both the Midrand office and at the eMalahleni Water Reclamation Plant.

3.4.1 eMalahleni Water Reclamation Plant

A separate weather station, data logger and three evaporation pans were installed at the EWRP. The facility has access to the actual brine produced during treatment and this enabled a comparison

between the actual brine produced and the synthetic solution prepared. The evaporation pans contained the following:

- Pan 1 – synthetic eMalahleni brine (same concentration as synthetic brine used at GAA)
- Pan 2 – actual eMalahleni brine
- Pan 3 – blank – potable water

Unlike at the Golder offices, the pans were placed on natural ground and there was no need for wooden support sheets (Figure 11). Chicken mesh was fitted onto the pans to prevent birds and small animals from drinking the water.

3.4.2 Modified experimental procedure

The climatic data and levels in the pans were recorded in the same way as during Phase 2.

A mixer was used to mix the solution in the pans on a daily basis. Each solution was mixed for a minute. This procedure was added to the initial experimental procedure in order to reduce the effect of stratification observed in the pans.

The levels in the pans were maintained between 20 mm and 130 mm from the top. Once the level in the pan dropped below 130 mm, it was topped up to 20 mm with potable water. The initial procedure of topping up with a synthetic solution resulted in an increase in the salt concentration in the pans. As the water evaporates, the salts remain behind. By adding potable water it was possible to ensure that the concentration in the pans remained similar to the concentrations at the commencement of the investigation.

4 PHASE 2 RESULTS

4.1 Calculations

Daily evaporation rates were calculated using the level readings in the pans and the daily rainfall measurements. The rainfall was subtracted from the level difference to determine the actual evaporation. Pan 1, which contained municipal water, was used as the reference. Salinity factors were calculated by dividing the cumulative evaporation rates in the brine containing pans by the evaporation rates measured in the reference pan.

4.2 Daily evaporation

The daily observed evaporation at the GAA office, is presented in Table A1 (Appendix A) and Figure 12. As indicated on the chart, in many instances, the observed evaporation in the pans containing saline solutions was greater than that in the pan containing potable water. As indicated in the literature investigations, a lower evaporation rate is expected for saline solutions. The data was further interrogated in order to investigate the reasons for unusual results.

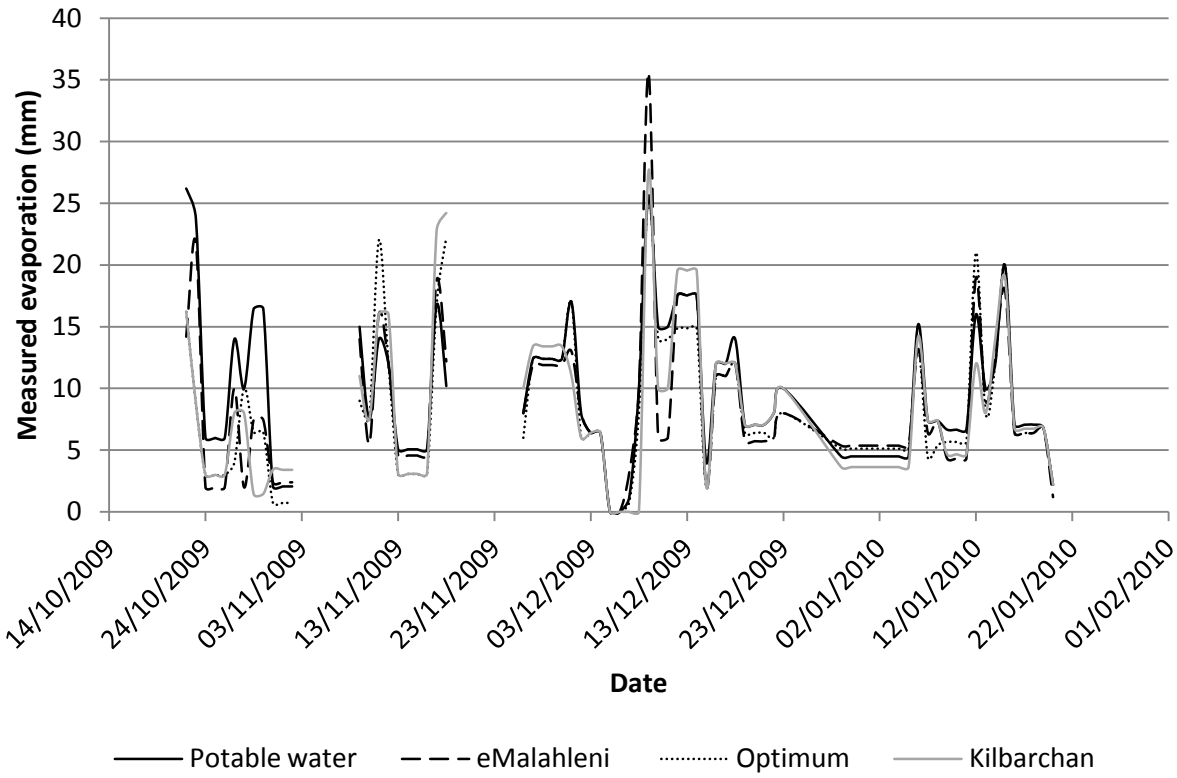

Figure 12: Daily evaporation at GAA offices in Midrand

4.3 Salinity factors

One of the objectives of the study was to determine the salinity factor for brine produced during the membrane treatment of mine-water. Calculated salinity factors are presented in Table 5. The 5, 25, 50, 75, 95 percentile and average values were calculated (Table 6). Several data points showed salinity factors exceeding 100%. As indicated in Figure 12, the observed evaporation rates of the saline solutions appeared greater than that of the potable water on several occasions. It was also observed that some negative evaporation rates were measured. This is possibly due to errors when reading the levels (parallax), or due to the effect of the nearby buildings or trees. A decision was made to exclude all factors below 20% and above 100%. These values are shaded in grey in Table 5. Once again, the 5, 25, 50, 75 and 95 percentile and averages were calculated. The results are presented in Table 7.

Table 5: Salinity factors calculated from the experiments carried out at GAA offices

Date	Salinity factor (%)		
	eMalahleni	Kilbarchan	Optimum
2009/10/22	54.20	61.83	61.83
2009/10/23	91.60	36.97	36.97
2009/10/26	33.33	50.00	50.00
2009/10/27	71.43	28.57	57.14
2009/10/28	20.00	100.00	80.00
2009/10/30	45.29	39.21	**8.81**
2009/11/02	**116.13**	35.48	**164.52**
2009/11/09	93.33	60.00	73.33
2009/11/10	73.33	100.00	100.00
2009/11/11	**114.29**	**157.14**	**114.29**
2009/11/12	100.00	100.00	**133.33**
2009/11/16	90.15	60.59	60.59
2009/11/17	111.90	100.00	**135.71**
2009/11/18	**119.61**	**217.65**	**237.25**
2009/11/26	100.00	75.00	**125.00**
2009/11/30	95.97	100.00	**108.06**
2009/12/01	76.47	100.00	64.71
2009/12/02	100.00	75.00	75.00
2009/12/04	100.00	100.00	100.00
2009/12/07	**266.67**	66.67	**-66.67**
2009/12/08	100.00	80.00	**-20.00**
2009/12/09	**139.06**	100.00	**107.81**
2009/12/11	40.00	93.33	66.67
2009/12/14	100.00	84.79	**111.41**
2009/12/15	50.00	50.00	50.00
2009/12/17	91.67	91.67	100.00
2009/12/18	85.71	85.71	85.71
2009/12/21	81.13	90.57	100.00
2009/12/22	75.00	75.00	100.00
2009/12/23	80.00	80.00	100.00
2010/01/05	**119.44**	**113.89**	52.78
2010/01/06	53.95	53.95	67.11
2010/01/07	72.97	45.95	72.97
2010/01/08	100.00	**114.93**	100.00
2010/01/11	92.86	92.86	100.00
2010/01/12	**118.75**	**131.25**	**137.50**
2010/01/13	90.00	80.00	80.00
2010/01/14	**108.33**	100.00	**116.67**
2010/01/15	90.00	100.00	95.00
2010/01/18	90.57	90.57	95.28
2010/01/19	100.00	100.00	**2.94**
2010/01/20	54.55	100.00	100.00

Table 6: Statistical analyses of calculated salinity factors

Date	Salinity factor		
	eMalahleni	Kilbarchan	Optimum
2009/10/22	40	37	3
2009/10/23	75	68	63
2009/10/26	91	86	95
2009/10/27	100	100	105
2009/10/28	120	130	137
2009/10/30	91	86	85

Table 7: Statistical calculations of salinity factors after excluding factors above 100% and below 20%

Date	Salinity factor		
	eMalahleni	Kilbarchan	Optimum
2009/10/22	37	37	42
2009/10/23	71	63	62
2009/10/26	87	85	80
2009/10/27	96	100	100
2009/10/28	100	100	100
2009/10/30	80	79	77

The results are also presented graphically in Figure 13, which indicates that the salinity factor increased with time and approached 100%. Midrand, Gauteng has had a total of 394 mm of rain between 14 October 2009 and 25 January 2010. The initial assumption was that the saline solutions in the pans were diluted due to the rainfall, hence resulting in a reduction in the salinity factor. Samples were sent to an external laboratory for analyses and the results obtained (Table 8) indicate that while the eMalahleni samples showed signs of dilution, the Golder samples appeared to have concentrated over time.

Upon further investigation, it was found that while the Golder samples were mixed samples, the eMalahleni sample was taken from the upper portion of the pan. This prompted an investigation to determine the conductivity profile, and possible stratification, in the pans. The conductivity profile confirmed that stratification took place in the pans and the surface layer had a TDS concentration similar to water. Refer to Table 9 and Figure 14 for the conductivity profile. Unfortunately, it was not possible to obtain a conductivity reading from the upper 4 cm in the pan without taking a sample. It is postulated that the upper layer is mainly rain water, and hence evaporating at a similar rate to that of Pan 1.

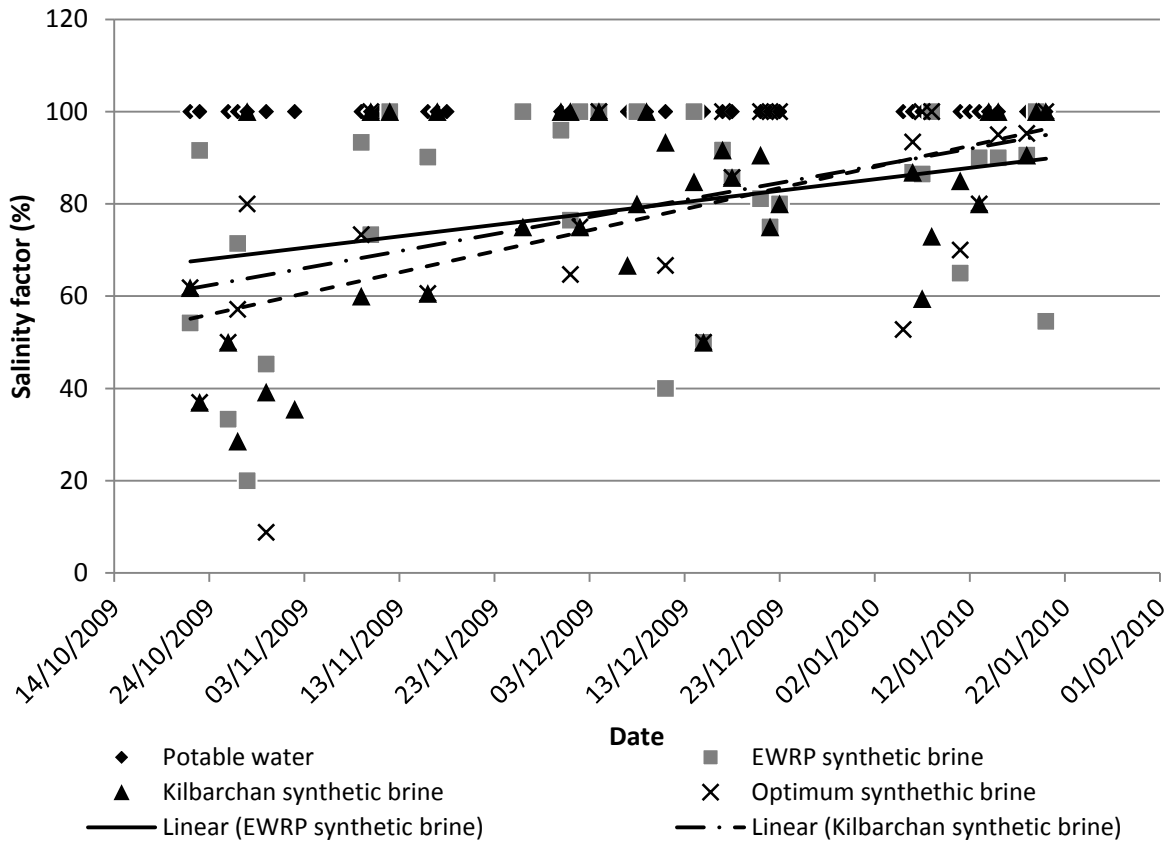

Figure 13: Salinity factors

Table 8: Water quality results

Sample	October 2009			January 2010		
	pH	EC (mS/m)	TDS (mg/ℓ)	pH	EC (mS/m)	TDS (mg/ℓ)
GAA potable water	7.7	24.4	104	7.8	32.4	226
GAA synthetic EWRP	7.9	2 130	18 930	8.9	2 718	25 638
GAA synthetic Optimum	8.4	4 950	40 284	8.6	8 960	55 366
GAA synthetic Kilbarchan	8.2	3 456	32 536	8.4	4 400	44 674
EWRP Synthetic Brine	8.4	2 141	18 902	7.4	1 466	12 726
EWRP Actual Brine	7.1	2 544	24 010	6.3	1 437	12 666
EWRP Potable Water	6.9	27	106	6.6	22.7	152

Table 9: Conductivity profile in the pans

Depth (cm)	Conductivity (mS/cm)			
	Potable Water	EWRP synthetic brine	Kilbarchan synthetic brine	Optimum synthetic brine
4	0.146	0.874	2.058	1.426
6	0.28	17.51	31.51	24.16
8	0.27	17.58	31.49	26.99
10	0.267	17.88	33.01	26.7
12	0.268	19.46	44.61	33.58
14	0.268	20.01	54.19	39.83
16	0.267	20.45	54.63	40.04
18	0.266	20.07	54.05	39.69

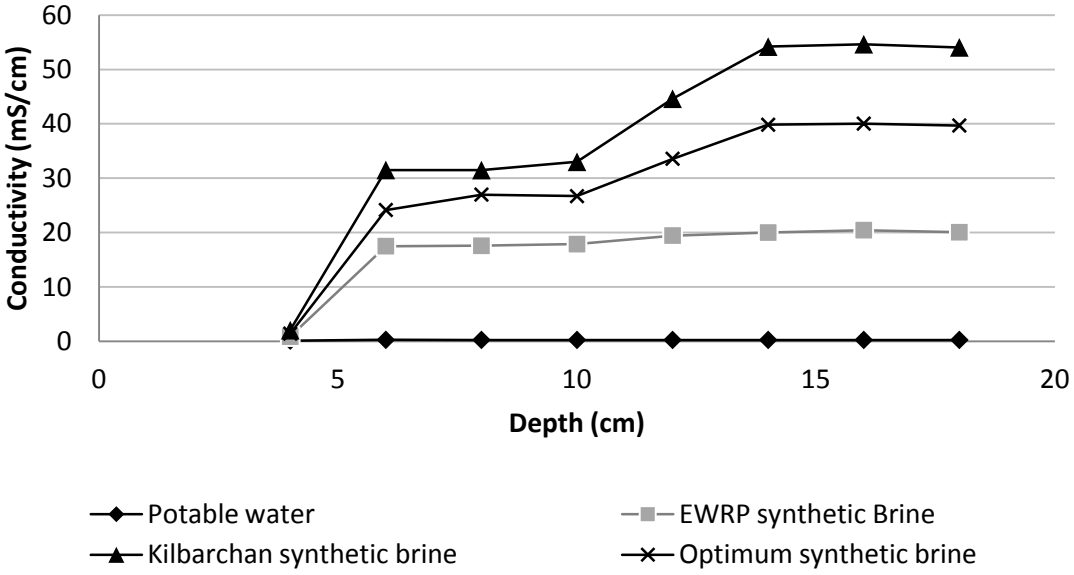

Figure 14: Conductivity profile in the pans

The concentration of the samples in the GAA pans was attributed to the fact that the pans were topped-up by a saline solution. Since only water evaporates and the salts remain behind in the pan, topping-up with a saline solution resulted in the concentration increasing over time. This prompted a modification in the experimental procedure for Phase 3 as discussed in Section 3.4.

Stratification is not expected in an actual full-scale brine pond as the result of the larger surface area and wind action. A mixing step was included in the experimental procedure in order to reduce the effect of stratification.

5 PHASE 3 RESULTS

5.1 Daily evaporation

Evaporation data obtained from the field investigations at the Golder offices and eMalahleni Water Reclamation Plant is included in Appendix A, Tables A2 and A3. Data between May and June had to be excluded from the analysis, as a floating biofilm had formed on the pans at the GAA, Midrand office. This impacted on the evaporation from the pans and on the ability to accurately measure levels in the pans. Initially a swimming pool leaf catcher was used to remove the biofilm, but the film grew back within a week. On the 6th of July, the pans were emptied, cleaned and refilled. This reduced the biofilm growth and monitoring continued for a further two months.

As with Phase 2, levels were not measured over the weekends. In order to account for this, the total evaporation measured between Friday and Monday was divided equally to represent the evaporation on Saturday, Sunday and Monday. This appears as horizontal lines on Figure 15 and Figure 16.

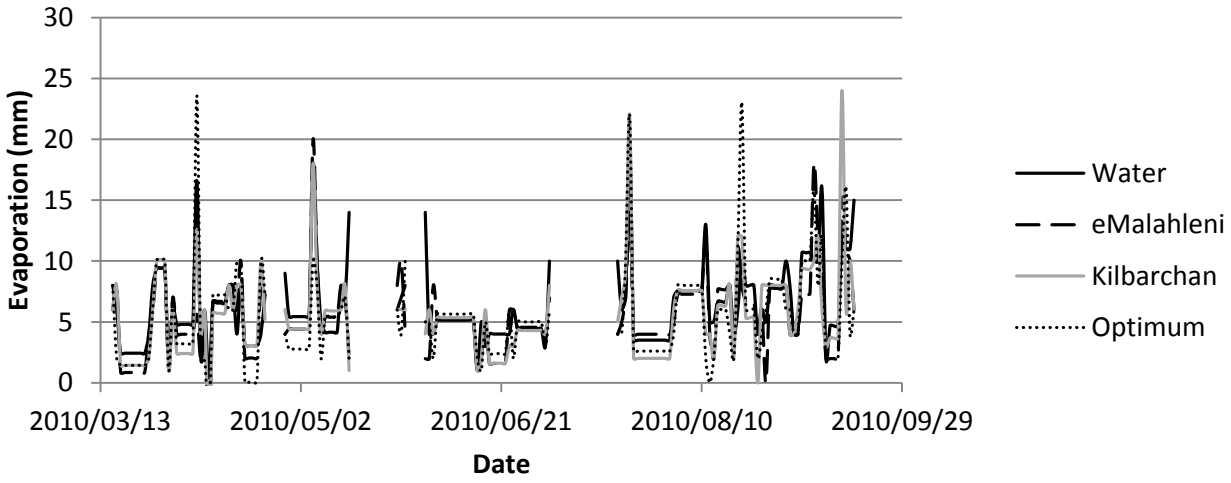

Figure 15: Daily evaporation levels for Phase 3 field investigations at GAA offices

The cumulative evaporation rates were plotted for both the GAA and eMalahleni data sets and are represented in Figure 17 and Figure 18. There is a distinct difference in evaporation for the saline solutions. It can be noted from Figure 18 that the synthetic and actual brine solutions followed a similar trend. This is a positive finding, indicating that synthetic solutions can be used to determine evaporation rates prior to the construction of brine ponds for future projects.

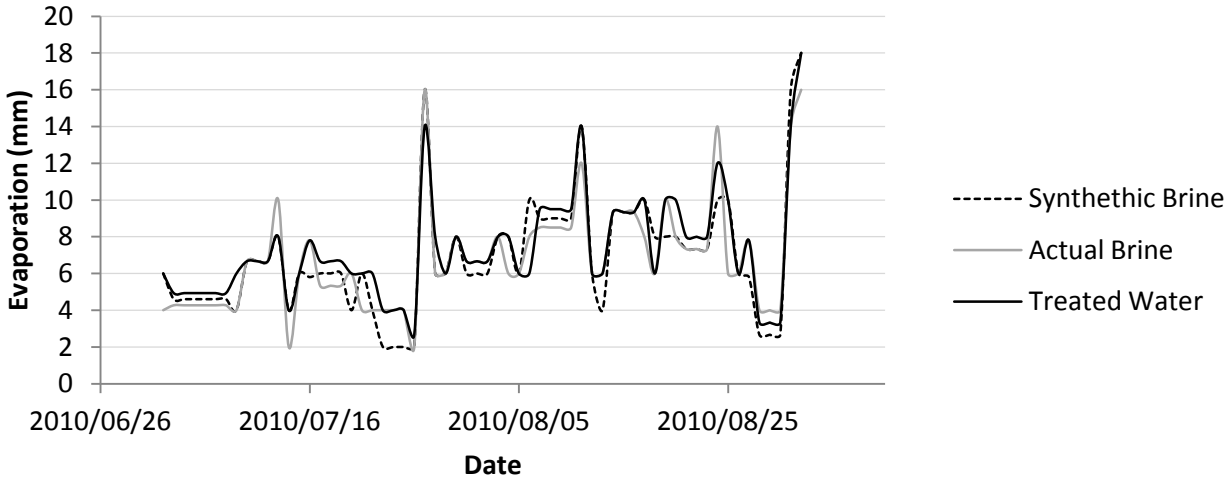

Figure 16: Daily evaporation levels for Phase 3 field investigations at eMalahleni

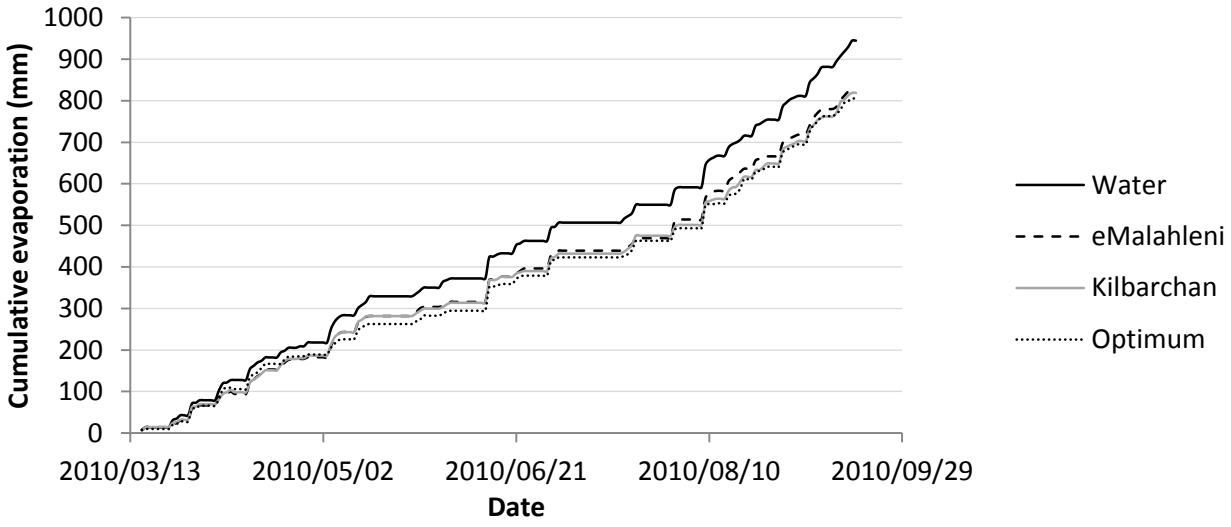

Figure 17: Cumulative evaporation measured during Phase 3 at GAA offices

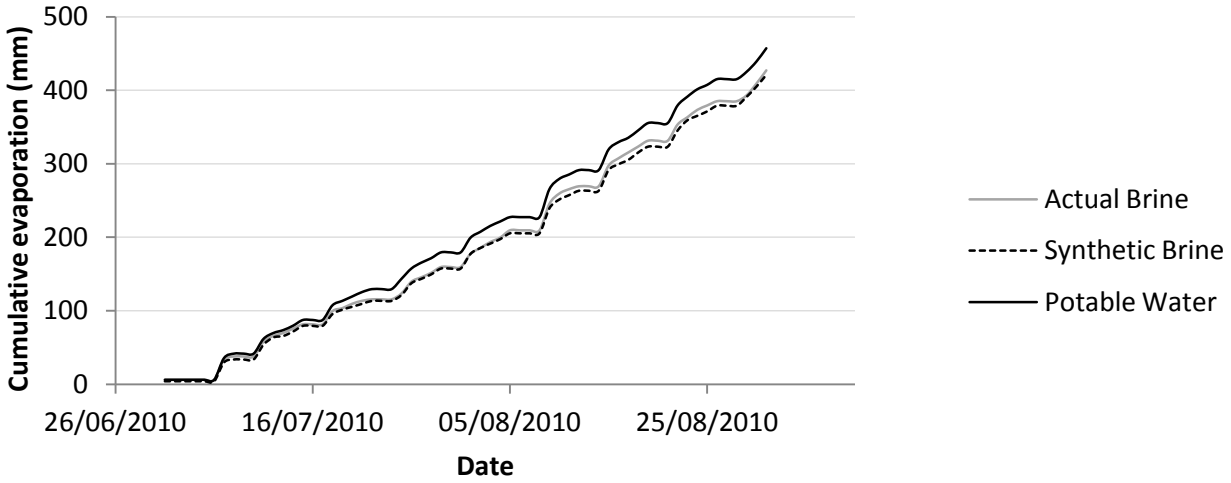

Figure 18: Cumulative evaporation measured at eMalahleni

5.2 Salinity factors

Salinity Factors were calculated and shown in Tables 10 (p. 24) and 11 (p. 25). Values greater than 100% and less than 20% were excluded from the data sets when determining the trends in salinity factors. The values excluded from the statistical analyses are shaded in grey in the tables. The statistical analyses are presented in Table 12 (p. 25).

From Figure 19 and Figure 20 it is clear the mixing of the synthetic solutions on a daily basis has improved the experimental results. Although the calculated salinity factors were still scattered over a wide range, the trend of salinity factors approaching 100%, which was noted in Figure 13 was not noted in Figure 19 and Figure 20.

An average salinity factor of 74% was calculated for the eMalahleni and Kilbarchan synthetic brine solutions, whilst a 65% average was calculated for the Optimum synthetic brine solution. The Optimum synthetic solution had a higher concentration of magnesium and potassium ions than the other two synthetic solutions and this can be a possible contributing factor. Further testing on individual salt solutions will be required for a better understanding of the effect of the composition of the brine on the salinity factor. An average salinity factor of 77% was measured on the eMalahleni actual brine and 75% on the synthetic brine.

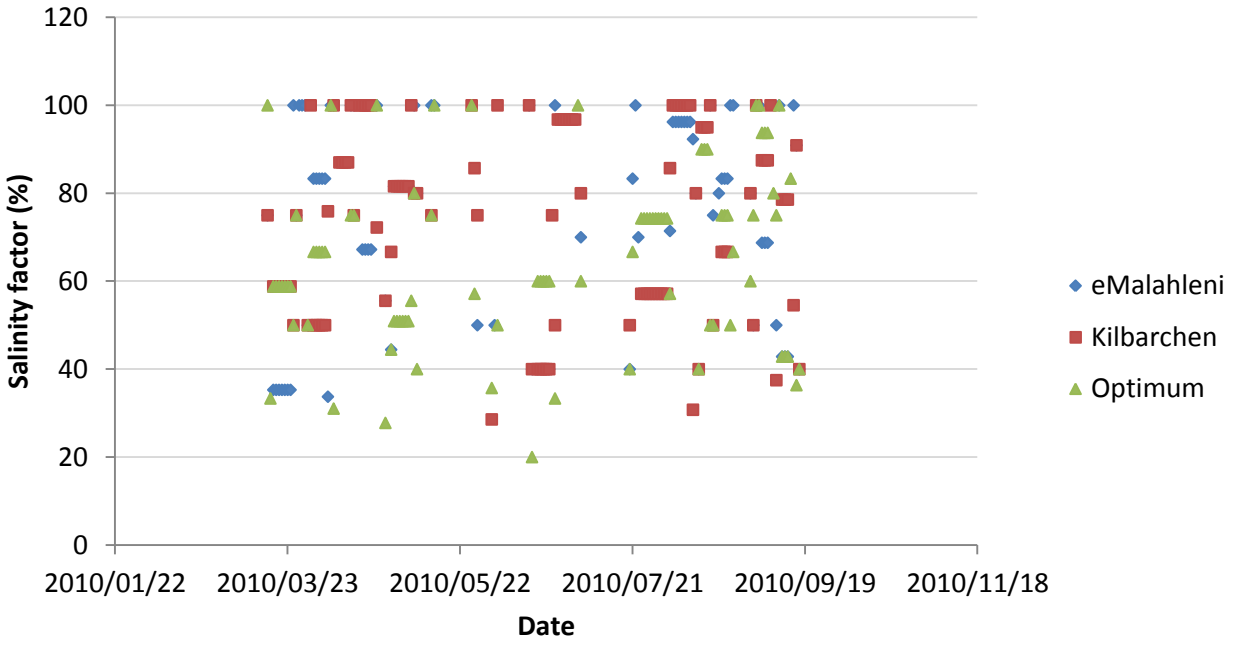

Figure 19: Chart indicating calculated salinity factors over time

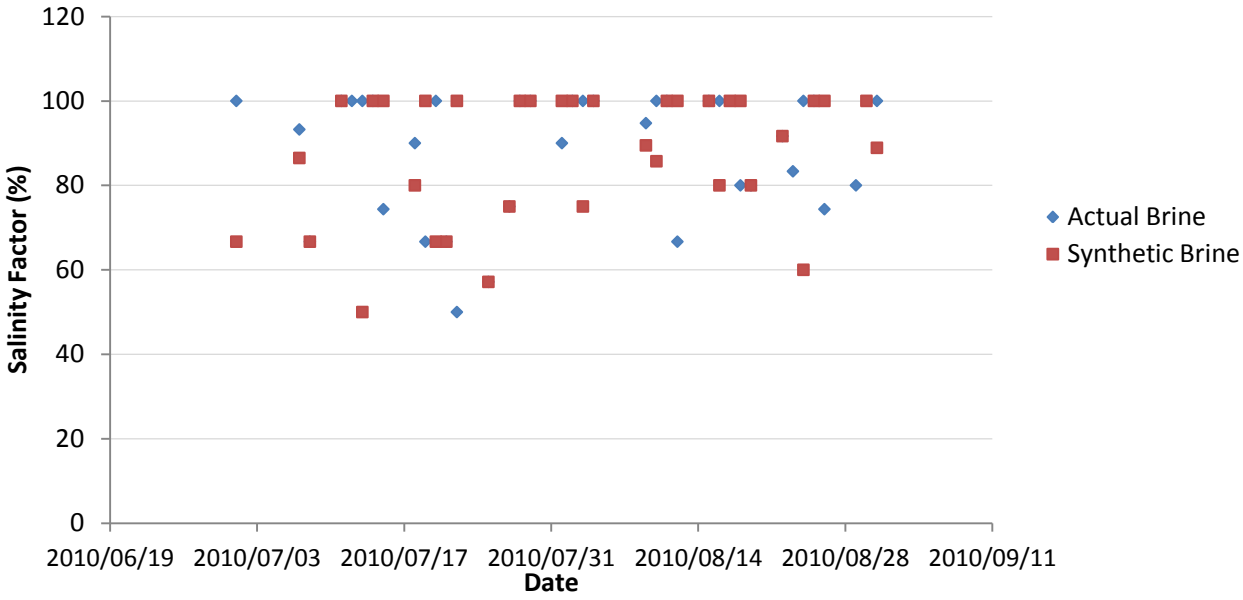

Figure 20: Chart indicating calculated salinity factors for the eMalahleni brine

Table 10: Salinity factors calculated for the evaporation rates measured in Phase 3 at GAA offices.

	Salinity Factor (%)		
Date	eMalahleni	Kilbarchan	Optimum
2010-03-16	75	75	100
2010-03-17	133	133	33
2010-03-18	35	59	59
2010-03-19	35	59	59
2010-03-20	35	59	59
2010-03-21	35	59	59
2010-03-22	35	59	59
2010-03-23	35	59	59
2010-03-24	35	59	59
2010-03-25	100	50	50
2010-03-26	75	75	75
2010-03-27	100	107	107
2010-03-28	100	107	107
2010-03-29	100	107	107
2010-03-30	50	50	50
2010-03-31	117	100	117
2010-04-01	83	50	67
2010-04-02	83	50	67
2010-04-03	83	50	67
2010-04-04	83	50	67
2010-04-05	83	50	67
2010-04-06	34	76	142
2010-04-07	100	200	100
2010-04-08	100	100	31
2010-04-10	102	87	110
2010-04-11	102	87	110
2010-04-12	102	87	110
2010-04-13	102	87	110
2010-04-14	100	100	75
2010-04-15	100	75	75
2010-04-16	150	200	250
2010-04-17	125	100	125
2010-04-18	67	100	2
2010-04-19	67	100	2
2010-04-20	67	100	2
2010-04-21	67	100	2
2010-04-22	200	250	250
2010-04-23	100	72	100
2010-04-26	56	56	28
2010-04-28	44	67	44
2010-04-29	82	82	51
2010-04-30	82	82	51
2010-05-01	82	82	51
2010-05-02	82	82	51
2010-05-03	82	82	51
2010-05-04	82	82	51
2010-05-05	111	100	56
2010-05-06	100	80	80
2010-05-07	80	80	40
2010-05-08	130	142	131
2010-05-09	130	142	131
2010-05-10	130	142	131
2010-05-11	130	142	131
2010-05-12	100	75	75
2010-05-13	100	114	100
2010-05-14	14	7	14
2010-05-26	133	100	100
2010-05-27	143	86	57
2010-05-28	50	75	125
2010-06-02	14	29	36
2010-06-03	50	150	125
2010-06-04	200	100	50
2010-06-05	102	104	110
2010-06-06	102	104	110
2010-06-07	102	104	110
2010-06-08	102	104	110
2010-06-09	102	104	110
2010-06-10	102	104	110
2010-06-11	102	104	110
2010-06-12	102	104	110
2010-06-13	102	104	110
2010-06-14	102	104	110
2010-06-15	100	100	200
2010-06-16	40	40	20
2010-06-17	167	200	167
2010-06-18	40	40	60

	Salinity Factor (%)		
Date	eMalahleni	Kilbarchan	Optimum
2010-06-19	40	40	60
2010-06-20	40	40	60
2010-06-21	40	40	60
2010-06-22	40	40	60
2010-06-23	150	75	150
2010-06-24	100	50	33
2010-06-25	103	97	113
2010-06-26	103	97	113
2010-06-27	103	97	113
2010-06-28	103	97	113
2010-06-29	103	97	113
2010-06-30	103	97	113
2010-07-01	103	97	113
2010-07-02	133	133	100
2010-07-03	70	80	60
2010-07-20	40	50	40
2010-07-21	83	117	67
2010-07-22	100	129	143
2010-07-23	70	110	110
2010-07-24	114	57	74
2010-07-25	114	57	74
2010-07-26	114	57	74
2010-07-27	114	57	74
2010-07-28	114	57	74
2010-07-29	114	57	74
2010-07-30	114	57	74
2010-07-31	114	57	74
2010-08-01	114	57	74
2010-08-02	114	57	74
2010-08-03	71	86	57
2010-08-04	96	100	106
2010-08-05	96	100	106
2010-08-06	96	100	106
2010-08-07	96	100	106
2010-08-08	96	100	106
2010-08-09	96	100	106
2010-08-10	96	100	106
2010-08-11	92	31	15
2010-08-12	80	80	0
2010-08-13	40	40	40
2010-08-14	115	95	90
2010-08-15	115	95	90
2010-08-16	115	95	90
2010-08-17	100	100	50
2010-08-18	75	50	50
2010-08-19	183	200	183
2010-08-20	80	120	230
2010-08-21	83	67	75
2010-08-22	83	67	75
2010-08-23	83	67	75
2010-08-24	100	0	50
2010-08-25	100	133	67
2010-08-26	0	160	120
2010-08-27	103	103	110
2010-08-28	103	103	110
2010-08-29	103	103	110
2010-08-30	103	103	110
2010-08-31	80	80	60
2010-09-01	50	50	75
2010-09-02	100	100	100
2010-09-03	100	150	100
2010-09-04	69	88	94
2010-09-05	69	88	94
2010-09-06	69	88	94
2010-09-07	180	100	160
2010-09-08	120	120	80
2010-09-09	50	38	75
2010-09-10	100	150	100
2010-09-11	43	79	43
2010-09-12	43	79	43
2010-09-13	43	79	43
2010-09-14	125	200	83
2010-09-15	100	55	145
2010-09-16	91	91	36
2010-09-17	40	40	40

Table 11: Salinity factors calculated for the evaporation rates measured during Phase 3 at the eMalahleni Water Reclamation Plant

	Salinity factors	
Date	**Actual Brine**	**Synthetic Brine**
2010-07-01	100	67
2010-07-07	93	86
2010-07-08	67	67
2010-07-11	100	100
2010-07-12	100	125
2010-07-13	100	50
2010-07-14	100	100
2010-07-15	74	100
2010-07-18	90	80
2010-07-19	67	100
2010-07-20	100	67
2010-07-21	67	67
2010-07-22	50	100
2010-07-25	57	57
2010-07-26	114	114
2010-07-27	75	75
2010-07-28	100	100
2010-07-29	100	100
2010-08-01	90	100
2010-08-02	100	100
2010-08-03	100	75
2010-08-04	100	100
2010-08-05	167	133
2010-08-09	95	89
2010-08-10	100	86
2010-08-11	100	100
2010-08-12	67	100
2010-08-15	100	100
2010-08-16	100	80
2010-08-17	133	100
2010-08-18	80	100
2010-08-19	80	80
2010-08-22	92	92
2010-08-23	83	117
2010-08-24	100	60
2010-08-25	100	100
2010-08-26	74	100
2010-08-29	80	120
2010-08-30	114	100
2010-08-31	100	89

Table 12: Statistical analyses excluding out of range data points of Salinity factors calculated in Phase 3

	GAA Offices			eMalahleni	
	eMalahleni	**Kilbarchan**	**Optimum**	**Actual Brine**	**Synthetic Brine**
5 Percentile	35	40	34	56	56
25 Percentile	50	57	51	66	67
50 Percentile	82	79	63	77	75
75 Percentile	96	97	75	88	86
95 Percentile	100	100	100	93	90
Average	74	74	65	77	75

6 CONCLUSIONS

The field investigations confirmed a decrease in evaporation as the result of salinity. The results obtained compared favourably to the recommended design salinity factor of 70%.

One of the key lessons learnt during the field investigations was that whilst taking manual daily readings of levels on the evaporation pans was sufficient to provide a comparison between evaporation rates on saline solutions and potable water, the large number of factors influencing the evaporation rates made it difficult to assess the impact of the various factors.

An investigation under controlled conditions is recommended to understand the effect of climatic conditions on the rate of evaporation of saline solutions. It is further recommended that a sensitive level detection probe is used in order to record level measurements more frequently and accurately.

Results indicated that although the Kilbarchan Mine synthetic brine solution had a higher salt concentration, the Optimum Mine synthetic brine solution had the lowest evaporation rate. This indicates that the composition, as well as the concentration of the brine will have an impact on the salinity factor. As with the climate data, the large number of variables made it impossible to identify the specific ions responsible for the variation in results. Further experimental work on specific solutions is recommended in order to understand the effect of composition on the rate of evaporation.

It is recommended that regular level measurements, together with climatic data and disposal rates on existing brine ponds are recorded in order to accumulate a database of observed evaporation rates in brine ponds. At present, a pan factor of 70% and a salinity factor of 70% are used in the design of these ponds. The data will enable a comparison with the theoretical pan factor and salinity factor used in design calculations. Data collected can also be built into a brine pond volume prediction model that can be used for long term forecasts in terms of pond capacities.

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APPENDIX A: DATA

Table 13: Observed evaporation in the various pans during Phase 2.

Date	Measured evaporation			
	Water	eMalahleni	Kilbarchan	Optimum
2009/10/22	26.2	14.2	16.2	16.2
2009/10/23	23.8	21.8	8.8	8.8
2009/10/26	18	6	9	9
2009/10/27	14	10	4	8
2009/10/28	10	2	10	8
2009/10/30	32.9	14.9	12.9	2.9
2009/11/02	6.2	7.2	2.2	10.2
2009/11/09	15	14	9	11
2009/11/10	7.5	5.5	7.5	7.5
2009/11/11	14	16	22	16
2009/11/12	12	12	12	16
2009/11/16	20.3	18.3	12.3	12.3
2009/11/17	16.8	18.8	16.8	22.8
2009/11/18	10.2	12.2	22.2	24.2
2009/11/30	49.6	47.6	49.6	53.6
2009/12/01	17	13	17	11
2009/12/02	8	8	6	6
2009/12/04	12.8	12.8	12.8	12.8
2009/12/07	1.2	3.2	0.8	0.8
2009/12/08	10	10	8	2
2009/12/09	25.6	35.6	25.6	27.6
2009/12/11	30	12	28	20
2009/12/14	52.6	52.6	44.6	58.6
2009/12/15	4	2	2	2
2009/12/17	24	22	22	24
2009/12/18	14	12	12	12
2009/12/21	21.2	17.2	19.2	21.2
2009/12/22	8	6	6	8
2009/12/23	10	8	8	10
2010/01/05	36	43	41	19
2010/01/06	15.2	13.2	13.2	14.2
2010/01/07	7.4	6.4	4.4	7.4
2010/01/08	7.4	7.4	5.4	7.4
2010/01/11	20	13	17	14
2010/01/12	16	19	21	22
2010/01/13	10	9	8	8
2010/01/14	12	13	12	14
2010/01/15	20	18	20	19
2010/01/18	21.2	19.2	19.2	20.2
2010/01/19	6.8	6.8	6.8	0.2
2010/01/20	2.2	1.2	2.2	2.2

Table 14: Observed evaporation in the various pans at Golder Office during Phase 3

Date	Water	eMalahleni	Kilbarchan	Optimum
2010-03-16	8	6	6	8
2010-03-17	6	8	8	2
2010-03-24	17	6	10	10
2010-03-25	4	4	2	2
2010-03-26	8	6	6	6
2010-03-29	28.2	28.2	30.2	30.2
2010-03-30	2	1	1	1
2010-03-31	6	7	6	7
2010-04-05	24	20	12	16
2010-04-06	16.6	5.6	18.6	27.6
2010-04-07	2	2	-2	-2
2010-04-08	5.8	5.8	5.8	1.8
2010-04-13	26.2	26.8	22.8	28.8
2010-04-14	8	8	8	6
2010-04-15	8	8	6	6
2010-04-16	4	6	8	10
2010-04-17	8	10	8	10
2010-04-21	12.2	8.2	12.2	0.2
2010-04-22	4	8	10	10
2010-04-23	7.2	7.2	5.2	7.2
2010-04-26	3.6	2	2	1
2010-04-28	9	4	6	4
2010-05-04	32.6	26.6	26.6	16.6
2010-05-05	18	20	18	30
2010-05-06	10	10	8	8
2010-05-07	5	4	4	2
2010-05-11	16.6	21.6	23.6	25.6
2010-05-12	8	8	6	6
2010-05-13	7	7	8	7
2010-05-14	14	2	1	2
2010-05-26	6	8	6	6
2010-05-27	7	10	6	4
2010-05-28	8	4	6	10
2010-06-02	14	2	4	5
2010-06-03	4	2	6	5
2010-06-04	4	8	4	2
2010-06-14	51.4	52.4	53.4	56.4
2010-06-15	1	1	1	2
2010-06-16	5	2	2	1
2010-06-17	3	5	6	5
2010-06-22	20	8	8	12
2010-06-23	4	6	3	6
2010-06-24	6	6	3	2
2010-07-01	31	32	30	35
2010-07-02	3	4	4	3
2010-07-03	10	7	8	6
2010-07-20	10	4	5	4
2010-07-21	6	5	7	4
2010-07-22	7	7	9	10
2010-07-23	20	14	22	22
2010-08-02	35	40	20	26
2010-08-03	7	5	6	4
2010-08-10	53	63	53	56
2010-08-11	1	0	0	0
2010-08-12	4	2	2	2
2010-08-13	5	2	2	2
2010-08-16	20	23	19	18
2010-08-17	8	8	8	14
2010-08-18	4	3	2	2
2010-08-19	6	11	12	1
2010-08-20	10	8	12	23
2010-08-23	24	20	16	18
2010-08-24	4	4	0	2
2010-08-25	6	6	8	4
2010-08-26	5	0	8	6
2010-08-30	31	32	32	34
2010-08-31	10	8	8	6
2010-09-01	8	4	4	6
2010-09-02	4	4	4	4
2010-09-03	4	4	6	4
2010-09-06	22	22	34	30
2010-09-07	10	18	10	16
2010-09-08	10	12	12	8
2010-09-09	16	8	6	12
2010-09-10	2	2	3	2
2010-09-13	4	6	11	6
2010-09-14	8	15	24	10
2010-09-15	8	11	6	16
2010-09-16	14	10	10	4
2010-09-17	12	6	6	6

Table 15: Observed evaporation in the various pans at eMalahleni during Phase 3

Date	Synthetic Brine	Actual Brine	Treated water
2010-07-02	6	4	6
2010-07-08	27.6	25.6	29.6
2010-07-09	4	4	6
2010-07-12	20	20	20
2010-07-13	8	10	8
2010-07-14	4	2	4
2010-07-15	6	6	6
2010-07-16	5.8	7.8	7.8
2010-07-19	18	16	20
2010-07-20	4	6	6
2010-07-21	6	4	6
2010-07-22	4	4	6
2010-07-23	2	4	4
2010-07-26	8	8	14
2010-07-27	16	16	14
2010-07-28	6	6	8
2010-07-29	6	6	6
2010-07-30	8	8	8
2010-08-02	18	20	20
2010-08-03	8	8	8
2010-08-04	8	6	8
2010-08-05	6	6	6
2010-08-06	10	8	6
2010-08-10	36	34	38
2010-08-11	14	12	14
2010-08-12	6	6	6
2010-08-13	4	6	6
2010-08-16	28	28	28
2010-08-17	10	8	10
2010-08-18	8	6	6
2010-08-19	8	10	10
2010-08-20	8	8	10
2010-08-23	22	22	24
2010-08-24	10	14	12
2010-08-25	10	6	10
2010-08-26	6	6	6
2010-08-27	5.8	7.8	7.8
2010-08-30	8	12	10
2010-08-31	16	14	14
2010-09-01	18	16	18

APPENDIX B: Trends with climate data

The project team investigated possible trends with evaporation and climate data. However, climate data was available for hourly intervals whilst level readings in the pans were only taken daily. As indicated in the figures below, the large number of variable factors influencing the evaporation rates made it difficult to identify definite trends. More controlled studies are recommended in order to understand the climatic effects on the evaporation of saline solutions.

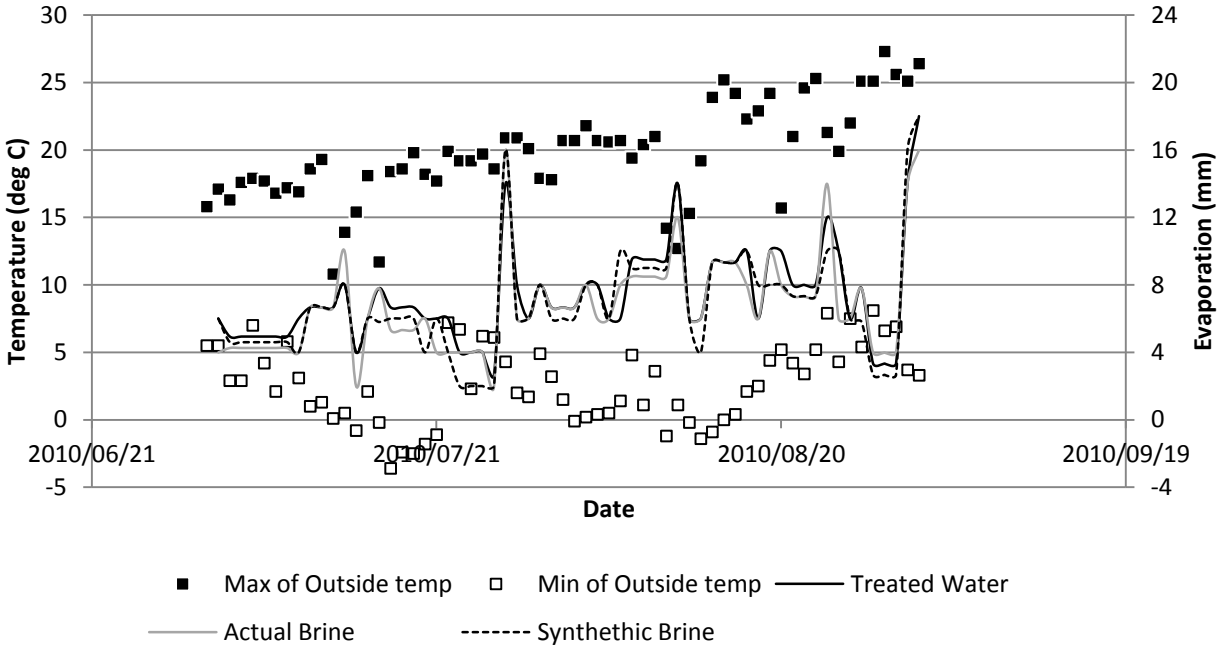

Figure 21: Atmospheric and pan temperatures.

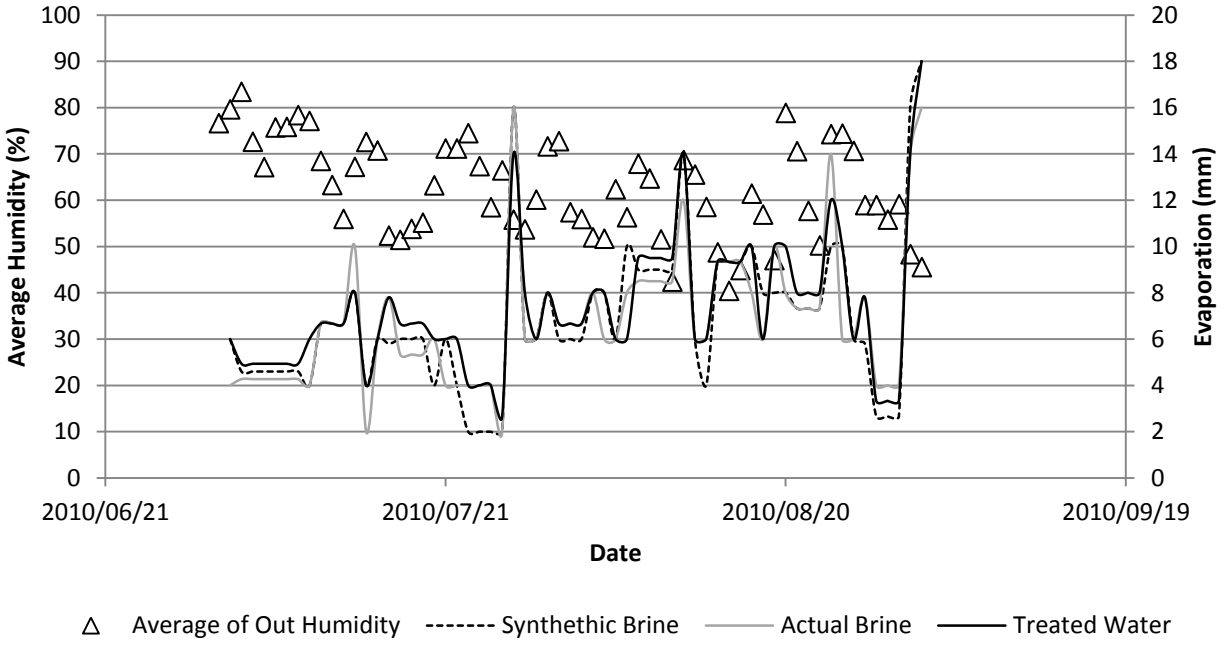

Figure 22: Atmospheric humidity and evaporation rates.