DESIGNING AN ON-FARM EVAPORATION POND FOR THE WHEATBELT, WESTERN AUSTRALIA

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DISCLAIMER

I hereby declare that this thesis is my own original work and further, I have acknowledged all sources used and have cited these in the reference section.
Executive Summary

An evaporation pond is a lined basin where wastewater is disposed to decrease the volume of water in it. Rejected brine is the by-product waste produced from water treatment technologies. The conventional evaporation pond is used to evaporate the brine solution through solar radiation and wind. It is mainly used in countries with dry and warm weather such as Saudi Arabia and it can be utilised in regions far from the seas. The rejected brine is easily dumped into the sea if the site is located near to the coast. The volume of effluent is reduced due to evaporation process making the solution more saline.

The Goldfields and Agricultural Water Supply Scheme (GAWS) is a very expensive water supply option for the Wheatbelt region in Western Australia. Therefore, Water Corporation has launched Farmland Alternative Water Supply Project to look for an alternative water supply option. Groundwater salinity is a big issue in Australia and this affects the productivity and income of farmers. Different water treatment technologies such as Reverse Osmosis/Nano Filtration (RO/NF), solar distillation and phytodesalination are used to treat groundwater and therefore, evaporation pond is constructed to manage the brine. The focus in this project is to design an evaporation pond.

Site selection is a major role before designing an evaporation pond. Salinity can be measured by using an electrical conductivity. In the project, Bakers Hill is considered and the salinity level at the site is approximately 3000-7000mg/L. The three main factors to design an evaporation pond is pond depth, pond area and pond evaporation and all the formulae are obtained from literature. The pond area depends on annual brine inflow, groundwater salinity and the Potential Net Evaporative Loss. After calculating the Potential Net Evaporative Loss, the area of basin for 100ML/year inflow can be obtained from the salinity curves and with the given information, the area of the required basin is gained.

From the results, a barchart of the monthly mean rainfall and the monthly evapotranspiration were plotted. It is noticed that there is less rain during summer than in winter season. The annual rainfall at Bakers Hill is approximately 589.4 mm and the annual evapotranspiration is about 1732.4mm. At the beginning of the year, evaporation rate is very high because the solar radiation intensity is higher during summer compared to during winter. In the months of June until August, the Potential Net Evaporative Loss is negative because rainfall records are greater than evaporation rate. An interpolation is done to
find the basin area for 100ML/year inflow at a specific Potential Net Evaporative Loss. Area of required basin is calculated by using the formula from literature. The parameters can be varying to have a proper sizing of the evaporation pond. A user manual is written for the design spreadsheet model for the farmers to follow on how to use it.

The results obtained are compared to data from literature. Two designed spreadsheets are obtained from internet resources. They are different from the one I have designed because the main parameters are not assumed but they are calculated using formula from literatures. Similar trend results were obtained from both spreadsheets.

After designing the pond, some recommendations are made to improve the designed evaporation pond. Deeper pond can be used to reduce evaporation rate. Spray evaporators is suggested to enhance evaporation rate and Wind Aided Intensified Evaporation (WAIV) can be an alternative solution for brine management instead of using conventional evaporation pond.

In this study, a Microsoft Excel spreadsheet is developed to help local people and farmers design an evaporation pond in an inland region and manage rejected brine. The formulae for each parameter are provided in the spreadsheet and farmers do not need to calculate or design them. Some factors including mean rainfall, evapotranspiration and solar radiation obtained from the Bureau of Meteorology (BOM), annual brine inflow and groundwater salinity were taken into consideration.
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List of Abbreviations & Acronyms

BOM: Bureau of Meteorology

GAWS: Goldfields and Agricultural Water Supply Scheme

RO/NF: Reverse Osmosis/Nano Filtration

WAIV: Wind Aided intensified Evaporation

TDS: Total dissolved solids
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1.0 Introduction

An evaporation pond is a shallow lined earthen basin used to dispose rejected brine from inland water treatment plants particularly from desalination plants (Voutchkov 2011, 121-134). Brine is the rejected waste by-product of water from desalination processes like RO and NF, solar distillation and phytodesalination such as investigated in the Wheatbelt project, which was discussed in the background section (Syrinx Environmental PTY Ltd 2017). The evaporation pond is a natural or artificial pond that allows water to evaporate through solar radiation and wind. They are especially useful in countries with dry and warm weather (Mushtaque Ahmed 2000). Evaporation ponds reduce the effluent volume of water from water treatment plants making it more concentrated than in non-volatile components than the influent water. Evaporation ponds are mainly utilised in the regions that are far from the sea. There are different means of brine disposal and they depend on the location of the plant. One is for inland areas and the other one is for the coastal areas. In areas close to the coast, the rejected brine is normally dumped into the ocean or sometimes used in agriculture (Mushtaque Ahmed 2000). Ocean disposal is considered simpler than inland disposal. For inland regions where no effluent is to be discharged to the environment, evaporation ponds areas are often used (Condorchem envitech 2012). Before constructing the evaporation pond, the most significant part is to design a proper pond to identify the volume of brine coming in and out as a function of time. In this study, a Microsoft Excel spreadsheet will be created to help local people and farmers design an evaporation pond.

1.1 Scope and objectives

Planning, designing, constructing, monitoring and maintenance of the evaporation pond are the main aims for disposal of water and storage of disposed salts in an inland project (Hauck and JDA Consultant Hydrologists 2004). A spreadsheet is developed for designing an evaporation pond for local people and farmers who install a small-scale water treatment system. This is especially applicable for areas far from the coast. This will be very beneficial, as an adjunct to water treatment projects which produce brines because the farmers do not need to calculate or design each parameter and the formulae for calculations will be already provided in the sheet.
The purpose of this study is the design of evaporation ponds, on-farms across the Wheatbelt. With the help of my supervisor, a set of objectives was developed to facilitate planning and evaluate performance efficiently throughout the project (Webb 2016).

The main aim of the project is to develop a friendly Microsoft Excel spreadsheet and an algorithm methodology for farmers to design an evaporation pond that can take into consideration the following parameters:

- To consider the mean monthly rainfall, evapotranspiration and solar radiation across the whole year
- To identify the mean monthly brine inflow rate into the evaporation pond
- To determine the Class A Pan evaporation
- To identify the salinity of groundwater
- To determine the Potential Net Evaporative Loss
- To design area of required basin and depth of the pond

1.2 Project management plan

A Project management plan has been developed to keep track of the tasks to be carried out throughout the project. Therefore, a Gantt chart has been made to display the starting and ending dates of the tasks in the project (Investopedia 2007) by using a Microsoft Excel spreadsheet. Another Gantt chart has been constructed to plan my weekly meetings with my supervisor and the work done till the final report submission. Gantt charts will have to be followed until the end of the project to ensure that the different milestones are completed. The chart can also be modified if the progress of the tasks is not corresponding to the timeline (Appendix A).
2.0 Background

Goldfields and Agricultural Water Supply Scheme (GAWS) supplies water from Mundaring Weir in the Perth hills to as far as Kalgoorlie in the Goldfields region as shown in Figure 1 (Water Corporation 2017). The GAWS, which includes approximately 9,600 km of pipeline, provides water for more than 100,000 customers, farm establishments, mines and other enterprises (Water Corporation 2017). This scheme water is supplied by Water Corporation at a high operational cost and through pipes, many of which are reaching their useful lifespan. Water Corporation is therefore, looking for an alternative water supply option within Wheatbelt because GAWS is a very expensive water supply option to deliver a small capacity of water to the farmland region (Murdoch University and Syrinx Environmental PTY Ltd 2017). Moreover, bursting of pipelines has been occurring frequently over recent years leading to the need to repair pipes regularly to prevent disruptions of water supply to customers (Murdoch University and Syrinx Environmental PTY Ltd 2017). The cost of maintenance and repairing the pipes is massive. Therefore, the use of local water resources such as surface water, groundwater and desalinated water could result in a reduction in scheme water provision (Murdoch University 2016).

Figure 1 GAWS distribution area (Rasheed 2017)
CSIRO has reported that soil salinity is a big issue in all parts of Australia but particularly in Western Australia, South Australia and in the Murray-Darling Basin. Australian Bureau of Statistics (2010) stated that in 2000, 5.7 million hectares of Australia have a high possibility for the development of salinity in the soil. This included 20,000 farms, and 2 million hectares of agricultural land. Loss of productivity and income from soil salinization will affect farmers and it is predicted that more regions will be affected if solutions are not found soon (Australian Bureau of Statistics 2010).

Saline groundwater consists of total dissolved solids and there are various methods to measure salinity of the water (State Water Resources Control Board 2017). Total dissolved solids (TDS) encompass of inorganic salts such as calcium, magnesium, potassium, chlorides, sulphates, and organic matter that are dissolved in water (Oram 2014). It is used for characterisation of different water resources, groundwater, rainwater and seawater. The salinity can be tested in the laboratory. Electrical conductivity (EC) is another way to measure salinity. It is the measurement of concentrated dissolved ions in water and it is tested in the laboratory where an electric current is passed through the water. The ability of current to pass through water is proportional to the amount of dissolved salts in water (State Water Resources Control Board 2017). The table below shows the approximate range of dissolved salts in fresh water to very saline water.

<table>
<thead>
<tr>
<th>Salinity status</th>
<th>Salinity(mg/L)</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>&lt; 500</td>
<td>Drinking and irrigation</td>
</tr>
<tr>
<td>Saline</td>
<td>2 000 - 10 000</td>
<td>1. Irrigation certain crops only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Useful for most stock</td>
</tr>
<tr>
<td>Highly saline</td>
<td>10 000 - 35 000</td>
<td>Very saline groundwater Limited use for certain livestock</td>
</tr>
<tr>
<td>Brine</td>
<td>&gt;35 000</td>
<td>Seawater, some mining and industrial uses</td>
</tr>
</tbody>
</table>
High salinity in groundwater will have adverse effects on crops and drinking water. Crops are damaged and plant growth is affected. Many plants can bear high saline water for a short period but it can be harmful for ecosystems later on. Moreover, it is not advisable for drinking purposes. Groundwater becomes saline due to dissolution of soil, rock and organic material process (State Water Resources Control Board 2017). Minerals dissolved in groundwater cause salinity levels to increase. Rainwater or water for irrigation passes through the soil dissolving ionic and non-ionic particles from minerals in the soil. The water passing through the soil in a particular site is saline. Salinity of groundwater can increase in several ways including evaporation processes. When groundwater is evaporated, mineral salts remain making it more salt concentrated as shown in Figure 2 (State Water Resources Control Board 2017).

![Figure 2 Increase in salinity through evaporation process (State Water Resources Control Board 2017)](image)

From Table 1, the salinity of groundwater in Australia is within a range of less than 500mg/L to more than 50,000mg/L (State Water Resources Control Board 2017). Soil salinity had an adverse effect in the town of Wickepin in the Wheatbelt. Since the salinity of groundwater was increasing, the Department of Conservation and Land Management (DCLM) decided on a salinity management plan. In the plan, bores are installed to reduce the amount of salt level. Water is pumped and furthermore, reported that approximately 300,000m$^3$ per year of saline groundwater is removed. The rejected saline groundwater is then discharged into an evaporation pond (Department of Conservation and Land Management 2003).

Engineers have found a simple solution for brine management. An evaporation pond is constructed to dump the brine produced from different water treatment technologies. The evaporation process makes the effluent more concentrated and reduces the volume of water. In the Murray-Darling Basin of
Australia, there are approximately 190 evaporation ponds with a total area of approximately 15,000 hectares. That makes each pond approximately about 80 hectares with a total capacity of 113,000ML. The annual brine disposal is about 210,000ML/yr (State Water Resources Control Board 2017).

Water Corporation has involved Syrinx Environmental PTY Ltd along with Murdoch University to evaluate the different alternative water sources available on-farm and the water treatment systems across Wheatbelt (Murdoch University and Syrinx Environmental PTY Ltd 2017). The Farmlands On-Farm Water Supply project aims to find alternative water sources to reduce the dependency on GAWS scheme for supply of water within Wheatbelt, which will ultimately lessen the cost of water supply. The use of local water will be more efficient and sustainable compared to scheme water. This project will be beneficial for the farmers because on-farm regions do not require a large amount of water (Murdoch University and Syrinx Environmental PTY Ltd 2017). The chosen water source often has to be treated, especially groundwater which is frequently very saline in that area. The main aim of the project is to identify the feasibility of local supply, in terms of performance and cost of small-scale impaired groundwater desalination as a component of an alternative water supply approach across the Wheatbelt region (Murdoch University and Syrinx Environmental PTY Ltd 2017). The major issues in the project are economic, socio-cultural and environmental for local people, farm establishments, mines and other enterprises. GAWS scheme is high cost means of providing water to the farmland region (Murdoch University and Syrinx Environmental PTY Ltd 2017). Firstly, water is supplied on a small scale that does not require a high volume of water. Secondly, there is a decrease in cost efficiency with the aged water infrastructure due to the increase of maintenance and repair of equipment. Local communities are dissatisfied with the service especially with the water provider due to the frequent occurrence of water supply failure across Wheatbelt. Moreover, according to farmers, there is limited water delivery in the area and this affects the growth of their business region (Murdoch University and Syrinx Environmental PTY Ltd 2017). Water Corporation has launched the Farmlands On-Farm Alternative Water Supply Project to reduce capital and operational costs and improve the performance of water delivery. This project will evaluate the opportunities and constraints of the alternative water supply options. Moreover, cultural indigenous connections will be established in the project to help
them gain interest and knowledge on the alternative water sources and the water treatment systems as well as collaborate in the project (Murdoch University and Syrinx Environmental PTY Ltd 2017).

The first stage of the Farmlands On-Farm Water Supply project conducted into two work packages, namely:

1. Farmlands On-Farm Alternative Water Supply Trial-Stage 1, Work Package 1
2. Farmlands On-Farm Alternative Water Supply Trial-Stage 1, Work Package 2

Work Package 1 began in 2016 with Hauck and Associates and later in the same year, there was another Work Package when Murdoch University joined the project. The Stage 1 Farmlands project evaluated the available water supply options to substitute GAWS scheme as shown in Figure 3. Unimpaired groundwater, rainwater, impaired groundwater and surface water were the main alternative water resources across Wheatbelt. Different aspects such as the volume of water that will be supplied on-farm and the technical capacity for their development were considered before selecting the proper water source (Murdoch University 2016). After evaluation, it was found out that rainwater and groundwater sources do not meet the objectives of the project (Water Corporation 2017). Therefore, desalination of impaired groundwater was chosen to be the most feasible option to the on-farm water supply because it can be used as a long-term technology and saline groundwater will be treated as well.

After Stage 1 Farmlands project, in 2017, Water Corporation has contracted Stage 2 Farmlands project directly to Syrinx Environmental PTY Ltd in collaboration with Murdoch University as shown in Figure 3. This study assessed water treatment technologies that can be used on farmland region. RO and NF are the processes that were selected as feasible technologies (Water Corporation 2017). Murdoch University was responsible for further development and testing of the RO/NF technology whereas Syrinx Environmental PTY Ltd has established a phytodesalination system for brine treatment and water treatment from wells, and groundwater springs. These technologies are suitable within Wheatbelt because the site is a small-scale region, which requires low yield but high quality water treatment (Murdoch University 2016).
Figure 4 shows the main technologies that are used to treat saline groundwater in the Farmlands On-Farm Water Supply project. The treatment technologies are:

- RO/NF
- Phytodesalination
- Solar distillation
- Evaporation pond

RO/NF is the main technology for water treatment whilst phytodesalination, solar distillation and evaporation are post treatments for brine as shown in Figure 4.
2.1 RO/NF

RO is a physical separation process, which uses a semi permeable membrane to remove suspended solids and all organic molecules from raw water, which is one of the most common desalination processes to treat saline water (Safe Drinking Water Foundation 2011). The RO process forces raw water to move from a high concentrated region to a low concentrated region through a membrane as shown in Figure 5 with operating pressure less than 30 bar (Bouguecha 2015). The pressure depends on the quality of feed water and seawater desalination can be as high as 60 bars and in this process, pressure acts as driving force for desalination, requiring energy use. The membrane has a pore of about 0.0001 micron. In this process, pressure acts as the source of energy for desalination. Raw water is separated into permeate and brine. Permeate is the water product that passes through the membrane whereas brine is the part that is rejected by the membrane. RO membranes have a high rejection of TDS of 98% to 99.5% (Bouguecha 2015).

![Figure 5 Reverse osmosis process (PR News Now 2017)](image)

NF is normally a low-pressure RO technology that removes total suspended solids, high organic content matter, and divalent ions that cause hard water (American's Authority in Membrane Treatment 2007). It has a higher water permeability than RO (Safe Drinking Water Foundation 2011). Post treatment is not required because NF can treat water that is low in salinity (<1500mg/L TDS) and it is applied in water treatment especially for water softening. It has a pore size ranging from 1 to 10nm and operates at a pressure less than 20 bars. It acts as a barrier in the same way as reverse osmosis and NF plants
operate at 85 to 95% recovery (Safe Drinking Water Foundation 2011). However, NF has high rejection on hardness, organic matter and metals especially iron. NF can be used for pre-treatment of feed to prevent fouling and scaling.

![Nanofiltration process](fumatech.jpg)

**Figure 6 Nanofiltration process (Fumatech 2017)**

RO/NF is a preferred technology for both small-scale and large scale applications. Moreover when applicable, NF can produce more permeate at a low cost (Safe Drinking Water Foundation 2011). Smaller plant required less area. The performance of membrane, its lifespan and treatment efficiency is important factors for the selection of RO/NF system (Bouguecha 2015).

Due to the depletion of fossil fuel, the price has increased and therefore, the energy required to drive the RO/NF system will have higher cost too (Bouguecha 2015). RO desalination systems can be powered by solar energy in countries with high solar radiance. Solar energy can be used as a source of power for the RO plant and therefore, an integrated photovoltaic system can be installed for a promising alternative use of using fossil fuel and improve sustainability. Operational cost is reduced too.

### 2.2 Phytodesalination

Phytoremediation is one of the technologies that were proposed for the Wheatbelt project to reduce salinity of the water. It may involve different processes, including phytostabilisation, phytodegradation, phytovolatilisation and phytoextraction that are applied for wastewater treatment, in surface water and groundwater purification (Materac, Wyrwicka and Sobiecka 2015). Phytoremediation uses some specific plants to remove contaminants such as heavy metals, chlorinated solvents and hydrocarbons
from the soil or water and concentrate them in their biomass (Manousaki and Kalogerakis 2010). Phytoextraction removes contaminants from soil, groundwater or surface water that accumulates a high level of heavy metals or organic compounds whereas in phytostabilisation process, the roots of the plants remediate the soil and prevents contaminants to groundwater and rainwater runoff. A new approach of phytoremediation is considered in the project. Phytodesalination extracts sodium chloride salts. Mickley et al. (1993) has considered a halophyte species and found that the plant is expected to extract approximately 150-800 kg/salt/ha over a period of three months. The main objective of using phytodesalination in the project is to remove salts from the brine stream after the RO/NF unit and to eliminate water from the brine to enhance evapotranspiration (Manousaki and Kalogerakis 2010). Constructed wetland is an option to treat saline water but it is a more complex system and involves many processes like bacterial oxidation, phytoremediation, filtration, nitrification, photolysis and chemical precipitation (Manousaki and Kalogerakis 2010). According to research, a 40m² phytodesalination unit can treat approximately 2kL/day of brine and 1kL/day of raw water and it has a recovery rate of 50% (Hauck and JDA Consultant Hydrologists 2004). This process may be beneficial for the project because it may be less expensive, and more environmentally and socially friendly compared to other technologies.

2.3 Solar distillation

There are many techniques for purification of saline water. Solar distillation is effective and eco-friendly. Moreover, the technology is not complex, requires low maintenance and can be repaired easily. There are two types of solar distillation systems, active type and passive type. In the active type, the process needs thermal energy to increase evaporation rate that will lead to a high productivity of pure water (Gugulothu, et al. 2015). In a passive type, only solar energy is utilised to treat the saline water. Solar radiation passes through the basin raising the temperature of water and causing evaporation to take place. The water vapour rises from the brine surface of the glass and then condenses to form pure water (Stevens 2012). It yields a low productivity of pure water. Both solar systems are commonly used to treat groundwater that has a high level of salinity (Stevens 2012).
Solar distillation is the same process as the natural water cycle. Factors that may affect solar stills are water depth of the basin, solar irradiance, inclination of the glass and ambient temperature. The temperature difference affects the yield of the treated water. Kumar et al. (2015) obtained distilled water through solar distillation and found the efficiency is about 30% (Gugulothu, et al. 2015).

![Solar distillation process](image)

**Figure 7 Solar distillation process (Tiwari and Dev 2011)**

### 2.4 Evaporation pond

An evaporation pond is used for the disposal of reject brine from inland desalination plants and other water treatment technologies. It is usually used to treat brine that has a high level of salinity. They are designed to reduce the volume of brine solution through evaporation. It is designed to reduce the volume of brine solution through evaporation and removes water from the saline solution by solar radiance. Evaporation pond can be constructed easily and require low maintenance. Areas having high evaporation rates may involve an evaporation pond that is low in cost. They are successfully utilised as a disposal method in countries like Middle East with dry and warm weather. Evaporation ponds do not need chemicals to treat water and have a long lifespan. They usually require treatments before entering the evaporation pond and they depend on the feed quality too. However, evaporation pond can also be a disadvantage. They require large area of land and odour can cause a problem for nearby towns (Condorchem envitech 2012).

An example is in Murray-Darling Basin of Australia, there are approximately 190 evaporation ponds with a total area of approximately 15,000 hectares and a total capacity of 113,000ML. O’reilly (2009)
found that the annual brine disposal is about 210,000ML/yr. Soil salinity had an adverse effect in the town of Wickepin in the Wheatbelt. Since the salinity of groundwater was increasing, the Department of Conservation and Land Management (2009) has decided to make a salinity management plan. In the salinity management plan, bores are installed under the bed to reduce the amount of salt level. Water is pumped and DCLM reported that approximately 300,000m³ per year of saline groundwater is removed. The rejected saline groundwater is then discharged into the evaporation pond (Department of Conservation and Land Management 2003) for further treatment through solar radiance.

![Evaporation pond](image)

**Figure 8 Evaporation pond (Department of Conservation and Land Management 2003)**

Various technologies have been developed to enhance the evaporation from evaporation pond. The most widely studied and used of these is WAIV. It is an alternative solution for rejected brine management and liquid waste minimisation. WAIV uses natural energy sources such as wind to enhance evaporation rate of brine resulting in lower operation and maintenance costs (Murray and McMinn 2011). However, WAIV is still being developed. Land required is reduced in comparison to evaporation pond to enhance evaporation rates (Murray and McMinn 2011).
3.0 Methodology

Evaporation is a form of vaporisation that changes from a liquid phase to a gas phase. Net evaporation can be calculated by multiplying evaporation rate by the surface area as shown in the equation,

\[ E = ER \times SA \]

Equation 1

where \( E \) is the net evaporation in m\(^3\), \( ER \) is evaporation in m and \( SA \) is the surface area in m\(^2\) (Fakir and Toerien 2009). The net evaporation can be increased by increasing the evaporation rate or the surface area.

3.1 Site selection

Site investigation plays an important role before designing an evaporation pond. It consists of an engineering field survey, soil and geology analysis and groundwater study. The investigation gathers physical data including the site description, catchment description, geology, and climate and drainage data for the construction of a pond.

For this project, the water treatment is carried out in the township of Bakers Hill. Bakers Hill township is situated 70km East Perth on the Great Eastern Highway (Addison 2001). According to the Australian Bureau of Statistics, the district has a population of 270 inhabitants and this region is mostly occupied with farmers. Bakers Hill is in the Chitty catchment, drained by Clackline Brook (Addison 2001). The catchment has an area of 3500ha from Bakers Hill to Clackline. Clackline is a locality in Wheatbelt near Baker Hill. Figure 14 illustrates the map of the site location.

The government has implemented various methods to monitor groundwater. One common option is the installation of piezometer. Piezometer is an instrument that is placed in boreholes to measure the pressure or the depth of groundwater. Firstly, drilling is done to place the piezometer in the ground and a constant pumping test is run for 24 hours. This method does not only monitor the increase or decrease in groundwater level but can also determine salinity risk of the water. Groundwater is the principal source of water in the region.
The area near to Bakers Hill has groundwater salinity issues as Bakers Hill. The salinity of groundwater level is approximately 3000-7000 mg/L TDS. Bakers Hill townsite covers partly granitoid bedrock including that the regolith consists of residual clay and some laterite (Addison 2001). Residual clay is formed from weathering of granite and doleritic bedrock (Addison 2001). The type of soil determines the permeability of the soil profile. Permeability is the capability of water to flow through the soil (SESL Australia 2015). Permeameter is an instrument to measure soil permeability.

There are two methods to test for permeability of the soil, the constant head test method and the falling head test (Reddy 2004). These experiments are conducted in the laboratory. The following equation can be used to find out permeability for constant head test,

$$K_T = \frac{QL}{Ath} \quad \text{Equation 2}$$

where $K_T$ is the coefficient of permeability (cm/s), $L$ is the length of specimen (cm), $t$ is the time (s), $Q$ is the volume of discharge (cm³), $A$ is the cross sectional area of specimen (cm²) and $h$ is the hydraulic head difference (m).

Constant head flow method is when water flows through a column under constant pressure (Geotechdata 2010). There will be a change in the head drop, $h$ and therefore, the permeability of the soil can be calculated using the above equation knowing all the parameters, column length, sample cross sectional area, constant pressure, volume of water flow and time internal as illustrates in Figure 10.
The constant head flow test is suitable for coarse-grained soils (NPTEL 2011).

The other method is the falling head test. The water from standpipe flows through the specimen and the total head $h$ does not stay constant throughout the experiment. The time difference from flowing upper to lower level is recorded. The total head changes with different time interval. The permeability can be calculated using the equation,

$$K = \frac{aA}{At} \ln \frac{h_1}{h_2}$$

Equation 3

where $A$ is a cross sectional area of soil, $a$ is the cross sectional area of the standpipe, $t$ is the time interval and other parameters like the heights and length are presented in Figure 11 (Powell 2016). This test is recommended for fine-grained soils (NPTEL 2011).
Different soils have different values of $K_T$.

**Table 2 Permeability Table (NPTEL 2009)**

<table>
<thead>
<tr>
<th>Soil</th>
<th>$K_T$ (cm/s)</th>
<th>Degree of permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>$K_T &gt; 10^{-1}$</td>
<td>Very high</td>
</tr>
<tr>
<td>Sandy, gravel, clean sand, fine sand</td>
<td>$10^{-3} &lt; K_T &lt; 10^{-1}$</td>
<td>High to medium</td>
</tr>
<tr>
<td>Sand, dirty sand, silty sand</td>
<td>$10^{-5} &lt; K_T &lt; 10^{-3}$</td>
<td>Low</td>
</tr>
<tr>
<td>Silt, silty clay</td>
<td>$10^{-7} &lt; K_T &lt; 10^{-5}$</td>
<td>Very low</td>
</tr>
<tr>
<td>Clay</td>
<td>$K_T &lt; 10^{-7}$</td>
<td>Virtually impermeable</td>
</tr>
</tbody>
</table>

The soil at Bakers Hill has very low permeability meaning it tends to leak causing the brine to flow directly to groundwater. The climate at Bakers Hill is moderate experiencing rainfall during winter months. The mean annual rainfall is approximately 605mm according to Bureau of Meteorology.

### 3.2 Overall Salt concentration

The plant discharge volume could be reduced by minimising the brine. The product of salt rejection is increased to 98.5% by reducing brine stream according to design specifications. The overall salt concentration determines the amount of salt in the feed using the formula below:

$$ CF = \frac{C_c}{C_f} \quad \text{or} \quad CF = \frac{1}{1 - R_w} \left[ 1 - R_w \left( 1 - R_s \right) \right] $$

Equation 4

where $C_c$ is the retentate concentration which is the part of the feed that is unable to pass through the membrane and $C_f$ is the feed concentration (Glater and Cohen 2003). The second equation is another way to measure the salt rejection where $R_s$ is the fractional salt rejection and $R_w$ is the fractional product water recovery.

$R_s$ can be calculated by $R_s = 1 - \frac{C_p}{C_f}$. $C_p$ and $C_f$ are permeate and feed concentrations respectively and $R_w = \frac{Q_p}{Q_f}$ is used to measure fractional product water recovery (Glater and Cohen 2003). All System recovery is examined regularly to make sure that the membranes of the technologies are operating properly. The percentage recovery is the ratio of permeate flow to feed flow,
\%

\textbf{Recovery} = \frac{\text{Permeate flow}}{\text{Feed flow}} \times 100 \ (\text{Water Treatment Guide 2007}). \ The \ higher \ the \ percentage \ rate, \ the \ less \ concentrate \ is \ the \ product \ from \ the \ system.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{schematic_diagram.png}
\caption{Schematic diagram when feed enters a system}
\end{figure}

Design parameters that can affect the performance of the membrane in a reverse osmosis system are:

- \textbf{Feed water salinity}

RO systems may undergo a lot of fluctuation on the feedwater during operation due to the level of salinity in feedwater. This may affect the efficiency of the membrane. Moreover, feed pressure as well as permeate water salinity can disturb the system. When feed salinity increases, both feed pressure and permeate salinity increase. However, permeate salinity has a greater rate of increase than the rate increase in feed pressure. The recovery ratio is reduced when the salinity of feedwater is high and scaling may occur. Scaling is the deposition of particles on the membrane causing it to block the feedwater flow. A higher energy is used to force the water through the membrane and the lifespan of the membrane decreases. Therefore, backwash needs to be done regularly (Lenntech 2015).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{feed_water_salinity_vs_product_water_salinity.png}
\caption{Feed water salinity vs. Product water salinity graph (Lenntech 2015)}
\end{figure}
From the graph, you can notice that when the salinity of feedwater increases, the product water salinity increases as well. The efficiency will therefore reduce.

- **Feed pressure**

Feed pressure can be adjusted to prevent fouling and, this will compensate for fluctuation of feedwater, salinity and, temperature. RO equipped with a high-pressure pump is needed to regulate the feed pressure.

![Figure 14 Pressure vs. Permeate flux graph](image)

Before use, the permeate flux is higher when pressure is high and permeate flux starts to decrease after the water is treated.

- **Permeate recovery ratio**

Permeate salinity and feed pressures are the main factors to affect recovery ratio.

The average feed salinity is calculated using feed salinity and average concentration factor (ACF).

\[
ACF = \ln \left( \frac{1}{(1-R)} \right) \tag{Equation 5}
\]

where R is the recovery ratio. Recovery is influenced economically because RO system is very costly (Puretec 2012).
Percentage recovery is amount of treated water that is recovered from feedwater. The water that is recovered is called permeate water or product water. Higher percentage recovery indicates that less water is wasted which saves more permeates water. Very high percentage recovery can lead to fouling and scaling (Puretec 2012).

- **Membrane fouling**

  The membrane performance is affected by membrane fouling. Membrane fouling process is the deposition of inorganic and organic material that blocks water from passing the membrane. The origin of the fouling process must be identified to manage the membrane fouling by amending pre-treatment process or operating conditions. Removal of foulant deposits from the membrane surface is done by chemical cleaning. However, it also depends on the how long foulant deposits were present (Hydraunautics 2001).

### 3.3 Sizing of evaporation pond

#### 3.3.1 Pond depth

The evaporation pond should have a suitable depth for water storage, brine disposal, freeboard for precipitation and wave action. Pond depth should be ranged within 0.02m to 0.5m (Hauck and JDA Consultant Hydrologists 2004). If the pond depth is within that, evaporation rate will decrease. Shallow evaporation pond tends to dry or crack easily and it is not durable for concentrate disposal due to an
increase in evaporation rate. When pond depth decreases, the evaporation tends to have greater area and therefore, greater surface leads to higher disposal cost. Deeper pond are most cost effective than shallow evaporation ponds. It is notice that when the pond depth is increased from 0.1m to 2.5m, evaporation rate can be reduced by 4% and the most beneficial aspect is that construction cost will be reduced too. More salts are hence accumulated at the bottom of the pond (Voutchkov 2011) . An ideal evaporation pond must be able to dispose brine under all conditions (Mushtaque, et al. 2000). Freeboard can be determined by the rainfall intensity. We have to make sure that the depth of the evaporation pond exceeds the water stored in the pond. During winter, the pond has a tendency to store reject water. Therefore, the minimum depth required to store the volume of water is calculated using the formula,

$$d_{\text{min}} = E_{\text{ave}} f_2$$

where $d_{\text{min}}$ is the minimum depth in m, $E_{\text{ave}}$ is the average evaporation rate in m/d and $f_2$ is a factor that incorporates the effect of the length of the winter.

The depth of the basin is referenced from the top of the embankment of 2.2m with life of 50years. 0.5m freeboard is included in the depth due to wind and rainfall. Freeboard depends on the monthly mean rainfall of the site and wind velocity in the pond area. The area is directly proportional to the volume of the reject water and inversely proportional to the evaporation rate. Pond depth has some effect on evaporation. Shallow ponds have faster evaporation rates than deep ponds (Voutchkov 2011). However, deep ponds are more effective in enhancing the evaporation rate (Mushtaque, et al. 2000).

There are different ways to enhance evaporation rates from concentrate disposal ponds including spray evaporation, pond aeration and use of dye from enhanced evaporation. Spray evaporation is mechanical spray evaporators that enhance evaporation rate by 20%. It scatters the concentrate over the pond surface in form of fine mist. This process consumes high amount of energy and depending on the location of the evaporation pond, it may not be as expensive. Evaporation rates depend significantly on weather conditions such as ambient temperatures, relative humidity and wind speed (Resource West 2018). At low wind velocities, the fine mist can drift away from the evaporation pond and therefore, a decline in evaporation rate will occur (Bureau of reclamation 2012).
Pond aeration is another method to enhance evaporation rate (Fakir and Toerien 2009). This is done by increasing the contact surface between the air and concentrate (Hauck and JDA Consultant Hydrologists 2004). Aeration process is a technique that produces air-bubbles. Air bubbles may increase evaporation in two ways. Firstly, evaporation is a process when water changes from liquid to gas or vapour (U.S Department of the Interior 2016). When air bubbles break up at the surface of the pond, humid air is removed from the surface making the rate of evaporation to increase. Secondly, when air is introduced into the water, bubbles are formed causing water vapour to diffuse. This water vapour contributes in an increase in loss of water. Pond aeration is an effective way in reducing evaporation (Helfer, Lemckert and Zhang 2012). It acts as a water circulating system that draws the brine from the bottom and mixes it to the water on top of the surface and this can leads to an increase of approximately 30% of evaporation rate. However, pond aeration requires high maintenance as it depends on motors to function (Hill 2013). It is not effective in deep water and water treatment occurs only on the surface of water. During cold weather, water at the surface freezes as it is exposed to the ambient air. Motors fail to operate to this condition (Hill 2013).
The use of dye can also enhance evaporation. It is found out that when 2mg/L of Naphtol is added on top of the basin, the evaporation rate is increased. For example, an area of 500m² will increase the evaporation by 13%. However, this technique is very costly especially for large pond (Hauck and JDA Consultant Hydrologists 2004).

### 3.3.2 Pond area

An evaporation pond’s purpose is to transfer brine into the pond to water vapour in the atmosphere and the size of the pond is managed by the rate at which the pond transfers water into it. Brine has a total dissolved solids concentration of approximately 20 000mg/L and 35 000mg/L. When the salts dissolved in water, the saturation vapour pressure is lowered due to a decrease in evaporation rate. Sizing of pond required the determination of both designed surface area and designed depth. The surface area relies primarily on the evaporation rate using the local climate conditions. The standard evaporation rate is typically represented in m/year and this is said that 1m/year signifies 27.4m³/day.ha. The open pond of the evaporation pond is calculated using the following formula,

\[
A_{\text{open}} = \frac{V_{\text{reject}} f_1}{E}
\]  

Equation 7

where \( A_{\text{open}} \) is the open surface area of evaporation pond (m²),

\( V_{\text{reject}} \) is the volume of reject water (m³/d), \( E \) is the evaporation rate (m/d) and \( f_1 \) is a safety factor (Glater and Cohen 2003). During winter, the reject water is stored into the evaporation pond. Freeboard also
plays an important role in the design of an evaporation basin and it is defined as the depth above the normal reject water surface (Mickley, et al. 1993). Rainfall and evaporation must be considered to avoid spillage of reject water.

\[ F_B = \sqrt{C \cdot y} \]  

Equation 8

is a simpler formula to calculate freeboard in which \( F_B \) is the freeboard in feet, \( y \) is the design depth in feet and \( C \) is a coefficient (1.5) (Thandaveswara 2008).

It can be considered to calculate freeboard and it does not require wind velocity. The table below shows the freeboard recommended for different discharge.

Table 3 Estimation of freeboard through discharge (Thandaveswara 2008).

<table>
<thead>
<tr>
<th>( Q ) (m(^3)/s)</th>
<th>Freeboard ( F_B ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.75</td>
<td>0.45</td>
</tr>
<tr>
<td>0.75 - 1.5</td>
<td>0.60</td>
</tr>
<tr>
<td>1.5 - 85.0</td>
<td>0.75</td>
</tr>
<tr>
<td>&gt;85</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The area of the pond depends also on annual brine inflow, groundwater salinity and Potential Net Evaporative Loss. The Potential Net Evaporative Loss is calculated by subtracting the annual pan evaporation and the mean annual rainfall. The area basin (ha) for a 100ML/year annual inflow can be determined based on the curves below. The curves have different groundwater salinity level.
After obtaining the area of basin (ha) for a 100ML/year annual inflow, the area of required basin is calculated using \( A_b = A_{100} \times Q_i / 100 \) assuming negligible leakage.

### 3.4 Measurement of evaporation

Evaporation can be measured using different techniques but the most common one is the standard evaporation pan, which is also called the Class A Pan. Pond evaporation can be calculated by multiplying pan evaporation (\( E_{\text{pan}} \)) and pan coefficient (\( K_{\text{pan}} \)). A small pond has a pan coefficient of 0.7 (Kean 2011). Some equation includes salinity coefficient because salinity affects evaporation rate. Evaporation rate tends to decrease due to the presence of salts in the brine. When the water is evaporated, there will be salts remaining in the pond making it to be very concentrated (INEEL 2001). Class A Pan is a cylindrical with a diameter of 1.21m and a depth of 0.254 m (MEA 2011). It has a wire mesh to prevent the access of birds and animals to the pan.
Measurements can be done manually or automatically. User needs to take measurements and refill the pan at a regular time every day for the manual pan whereas the automatic pan refills automatically by using software or recordings can be sent and saved to a PC (MEA 2011). Along with the measurement of evaporation, meteorological data such as wind velocity, humidity, temperatures and precipitation are taken into account (The Constructor Civil Engineering Home 2017). The pan is first set up in the field and filled with a known volume of water. The level of water is recorded. After the water has been evaporated, the level of the remaining water is measured. The evaporation is determined by using the formula above. $E_{\text{pan}}$ is calculated by the amount of evaporation per time (Eijkelkamp Agrisearch Equipment 2009). The amount of evaporation is the difference between the two recorded water depths (Eijkelkamp Agrisearch Equipment 2009). For class A evaporation pan, $K_{\text{pan}}$ can vary between 0.35 and 0.85 but the most efficient one is approximately 0.70 (Kean 2011). Pan coefficient usually depends on the pan used, the area where it is used and the climate. When there is high humidity and low wind speed, high $K_{\text{pan}}$ should be used and when humidity is low and wind speed is high, low $K_{\text{pan}}$ should be used (Eijkelkamp Agrisearch Equipment 2009).
Water balance is another way to balance all the inputs and outputs of the system and to determine evaporation rate (lanfax labs 2008). The evaporation pond is designed from water budgets obtained from monthly data. The water balance can be expressed from the equation below (INEEL 2001),

\[
\Delta \text{Evaporation Pond Storage} = \text{direct precipitation falling on pond} + \text{process water inputs} + \text{leachate inputs} - \text{evaporation output}
\]

Equation 9

3.5 Factors affecting evaporation rate

3.5.1 Sizing

Evaporation rate is the main key factor that influences the design of evaporation ponds and the evaporation rate can be calculated using a proper sizing of a basin. An evaporation pond removes water when brine is disposed to the pond and transfers water vapour into the atmosphere. When the rejected brine is disposed into the evaporation pond, the volume of water is reduced and it becomes more concentrated due to the evaporation process. It is said that the larger the surface area of the basin, the greater the rate of evaporation. However, a smaller pond is more easily manageable in bad weather and less maintenance is required. Therefore, to reduce the maintenance cost, local people should be trained and need to be aware about the technology.
3.5.2 Salinity

Evaporation pond is the best way to manage waste for brine production at a water treatment plant. The rate of evaporation depends on the size of the basin and it is said that salinity has an adverse impact on the rate of evaporation. Salinity factor is an indication when there is a decrease in evaporation rate. It is recommended that the salinity factor is approximately 70% (Rusydi 2018). Evaporation rate decreases exponentially with increasing salinity. Higher salinity concentrate needs a smaller volume of pond and it is less costly to evaporate. Evaporation rate of saline solution is calculated by multiplying the rate of evaporation of water by the salinity factor.

\[
\text{Evaporation rate of saline solutions} = \text{rate of evaporation of water} \times \text{salinity factor}
\]

Equation 10

![Figure 20 Salinity factor vs. footprint area graph (Fakir and Toerien 2009)](image)

Figure 20 shows a decline in salinity factor with an increasing surface area and making the pond footprint to increase exponentially with a reduction in evaporation rate. The following equation is used to determine the evaporation factor:

\[
F = 1.025 - 0.0246e^{-0.00879S}
\]

Equation 11

where \( S \) is the salinity level (mg/L) (Fakir and Toerien 2009).

3.5.3 Climatic effects

Climatic conditions such as humidity, temperature, solar irradiation intensity, wind and rainfall are another aspect that affects evaporation. The pond requires enough energy for evaporation process to occur. When there is a rise in humidity, the rate of evaporation decreases because saturation level is
reached faster. Wind speed and duration are a significant impact on the evaporation rate windier region is suitable for evaporation pond. The evaporation pond is effective when temperature and solar radiation are very high especially when it is located on the dry equatorial regions of the world for brine disposal. This is because the water molecules are heated to a required temperature for vaporisation. Solar radiation provides heat to enable evaporation. The actual design pond evaporation rate and evapotranspiration potential can be calculated as shown below:

**Actual design pond evaporation rate** = Annual evaporation rate – Actual annual rainfall rate

**Evapotranspiration potential** = standard annual evaporation rate – Annual rainfall  Equation12

The type of brine being disposed in the basin has also an effect on evaporation rate. The greater the total dissolved solids, the lower the evaporation rate.
4.0 Results and Discussion

4.1 Results

A user-friendly spreadsheet is developed for designing an evaporation pond for local people and farmers in Wheatbelt. Bakers Hill township is the site location for this project. The mean monthly rainfall at Bakers Hill is recorded from the BOM and Figure 21 demonstrates the amount of rainfall measured in each month (Australian Government Bureau of Meteorology 2018). During summer, there is less rain compared during winter season. June and July are the two months that have obtained more rainfall and November until January are mostly dry period. The annual rainfall at Bakers Hill is approximately 589.4 mm. It is estimated by adding the rainfall data in each month. The number of rain days was about 120 in 2017. However, due to climate change, rainfall is declining every year (Australian Government Bureau of Meteorology 2018).

![Annual Rainfall](image)

**Figure 21 Annual Rainfall (Australian Government Bureau of Meterology 2018)**

The Class A pan evaporation rate data is gained in a technical report from the Department of Agriculture and Food at Baker Hill (Luke, Burke and O'Brien 1987). The Bureau of Meteorology considers only Class A pan with bird guard records. The system has a wire mesh to prevent the access of birds and animals to the pan. However, it reduces the evaporation by 7% (Luke, Burke and O'Brien 1987). Class A pan evaporation rate depends mainly on the site location and solar radiation. Next, evapotranspiration
data at the site is given from the Bureau of Meteorology website. Firstly, the location of the site must be selected and data including rainfall, evapotranspiration and solar radiation are obtained from the website. The annual evapotranspiration is about 1732.4mm. Figure 22 illustrates the evapotranspiration for each month. Evapotranspiration being a vital component of water cycle is the transfer of water from land to the atmosphere by evaporation process (Natural Resources and Mines 2005). From the evapotranspiration graph, it can be seen that the trend is opposite to the rainfall graph. At the beginning of the year, evaporation rate is very high because the solar radiation intensity is higher during summer compared to during winter. Evapotranspiration is lowest in the month of July and highest in January.

![Annual Evapotranspiration](image)

**Figure 22 Annual Evapotranspiration**

In the Farmlands On-Farm Water Supply project, different technologies are used to treat saline groundwater. These technologies are RO/NF, phytodesalination and solar distillation. Treated water and brine are the two by-products after treating saline groundwater. The sum of the brine produced from all these technologies is actually the brine inflow in the evaporation pond.

The Potential Net Evaporative losses are obtained by deducting the Class A pan evaporation rate by the mean rainfall.

**Potential Net Evaporative loss = Class A pan evaporation rate – Mean rainfall**

Equation 13
For the month of January,

Potential Net Evaporative loss = 366mm – 20.8mm

Potential Net Evaporative loss = 345mm

The months of June until August show negative values because rainfall records are greater than evaporation rate. Evaporation rate is lower due to less sunlight in winter. At that location, the groundwater salinity must be found out before calculating the evaporation rate of the saline solutions. This is determined by multiplying the Class A pan evaporation rate and the salinity factor.

Evaporation rate of the saline solutions = Class A pan evaporation rate x salinity factor (0.7)

Equation 14

For the month of January,

Evaporation rate of the saline solutions = 366mm x 0.7

Evaporation rate of the saline solutions = 256mm

The salinity factor as mentioned earlier is an indication of the reduction in evaporation rate and it is recommended that the salinity factor is approximately 70% due to the site location. This will specify the amount of water being evaporated in saline solutions and it varies depending on the saline concentration of groundwater. The actual design pond evaporation rate is obtained the same way as the Potential Net Evaporative Loss, which subtracts the Class A pan evaporation rates data to the mean rainfall records.

Actual design pond evaporation rate = Potential Net Evaporative loss

Equation 15

For the month of January,

Actual design pond evaporation rate = 345mm

Later, the pond evaporation was calculated by multiplying Class A pan evaporation rates with $K_{pan}$ coefficient.
\[ \text{Pond evaporation} = \text{Class A pan evaporation rate} \times K_{\text{pan}} \quad \text{Equation 16} \]

_for the month of January,

\[ \text{Pond evaporation} = 366 \text{mm} \times 0.7 \]

\[ \text{Pond evaporation} = 256 \text{mm} \]

A small pond usually has pan coefficient of 0.7 based on research. Pond evaporation has the same trend as evapotranspiration data.

To determine the evaporation pond size, firstly, the pond depth is calculated using

\[ d_{\text{min}} = E_{\text{ave}} f_2 \quad \text{Equation 17} \]

where \( d_{\text{min}} \) is the minimum depth, \( E_{\text{ave}} \) is the calculated average pond evaporation and \( f_2 \) is the losses from length that is assumed to be one. Therefore, the designed minimum depth is 0.24m. From literature review, the suitable pond depth is approximately 0.45m (Mickley, et al. 1993). The percentage error is about 47%. Pond depth varies with increasing or decreasing pond evaporation. Embankment, spillway and pond height are not designed parameters. They are obtained from literature reviews for a proper designed evaporation pond and users do not have to change the values of these parameters. Freeboard is then determined by using

\[ F_B = \sqrt{(C \times y)} \quad \text{Equation 18} \]

where \( C \) is a coefficient that is assumed to be 1.5 and \( y \) the design depth. Knowing the design depth, \( F_B \) is about 0.6m. The lifespan of the pond varies with embankment height. From literature review, a pond with an embankment height of 2.2m will have a designed life of 50 years. It is very efficient but it has to be maintained all the time. Evaporation pond is a technique to treat brine produced through evaporation process. Before designing a pond, the salinity of the water must be taken into consideration. Normally, the salinity of groundwater is ranged within 3000 to 7000mg/L. The salinity at Bakers Hill is considered 7000mg/L. From figure 18, there are three curves and all the curves have different salinity level. A trendline is passed through each of the curve and the equation of the trendline is displayed as shown below.
The Potential Net Evaporative is calculated as shown above and its value is about 1616mm/year. From the equations below, the basin area (ha) for 100ML/year inflow is calculated.

For salinity level of 5000mg/L,

\[ y = -0.0056x + 22.652 \]  

\[ y = (-0.0056 \times 1616) + 22.652 \]

\[ y = 13.6 \text{ ha} \]

Table 5 illustrates the equations of trendline at different salinity level and from that equations, basin area (ha) for 100ML/year inflow is obtained.
Table 5 The calculated basin area for 100ML/year at Potential Net Evaporative Loss of 1616mm/year

<table>
<thead>
<tr>
<th>Salinity (mg/L)</th>
<th>Equation of trendline</th>
<th>Basin area (ha) for 100ML/year inflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>y = -0.0056x + 22.652</td>
<td>13.6</td>
</tr>
<tr>
<td>10,000</td>
<td>y = -0.0088x + 30.546</td>
<td>16.3</td>
</tr>
<tr>
<td>50,000</td>
<td>y = -0.0104x + 34.944</td>
<td>18.1</td>
</tr>
</tbody>
</table>

However, the equations are based only at salinity level 5000mg/L, 10,000mg/L and 50,000mg/L. Since the salinity level of groundwater is assumed 7000mg/L, interpolation is done to find out the basin area (ha) for 100ML/year inflow at Potential Net Evaporative loss of 1616mm/year.

For salinity level of 7000mg/L,

(5000, 13.6) (7000, y) (10000, 16.3)

The interpolation equation is

\[ y = y_1 + (x - x_1) \left( \frac{y_2 - y_1}{x_2 - x_1} \right) \]  \hspace{1cm} \text{Equation 20}

\[ y = 13.6 + (7000-5000) \left( \frac{16.3 - 13.6}{10000-5000} \right) \]

\[ y = 14.7 \text{ha} \]

It shows that at Potential net Evaporative loss = 1616mm/year, the basin area (ha) for 100ML/year inflow is approximately 14.7 ha. The area of the required basin is calculated using the formula, \( A_b = A_{100} x \frac{Q_i}{100} \) from the literature review where \( A_{100} \) is the basin area (ha) for 100ML/year inflow and \( Q_i \) is the annual design inflow which is the annual brine inflow of evaporation pond. The brine is produced from all the treatment technologies like RO/NF, solar distillation and phytodesalination and then disposed in the evaporation pond. The annual brine inflow is about 10.48ML.

\[ A_b = A_{100} x \frac{Q_i}{100} \hspace{1cm} \text{Equation 21} \]

\[ = 14.7 \times \frac{10.48}{100} \]
= 1.54 ha

~ 15 000 m$^2$

The area of the basin is approximately 15,000 m$^2$ and from the area, the volume of the basin can be obtained. The pond volume is calculated by the formula below.

\[ \text{Pond volume} = \text{Area of required basin} \times \text{pond height} \]

Equation 22

The pond height is gained from literature review and it is suitable for a designed evaporation pond.

Pond volume = 15 000 m$^3$ x 1.5 m

Pond volume ~ 23 000 m$^3$

A spreadsheet is developed and all the data from the literature reviews are placed into it. The designed parameters are calculated in the Excel sheet. This spreadsheet is mainly constructed for farmers to help designing an evaporation pond so that they are aware of the size of the basin. A user manual is written for farmers to follow the steps on how to use the designed spreadsheet.
When designing an evaporation pond, the location of the site must be taken into consideration so that they can find rainfall, evapotranspiration and solar radiation data. The Bureau of Meteorology website is opened in a new browser and WA is chosen from the map of Australia found in the front page. Under past weather, the user must select on data and graphs. A new screen is shown and the location of the site is searched to obtain monthly rainfall data. The data is from 1964 to 2018. The user is allowed to choose any year from the data and placed it in the row of mean rainfall in the database sheet. Class A pan evaporation is based on literature review at a particular site. Evapotranspiration is searched on the BOM website. Recent evapotranspiration is chosen from the website and one of the states is selected. A list of places is given and from each place, evapotranspiration and solar radiation data can be found. Evapotranspiration and solar radiation data are placed in the database sheet. The annual brine inflow is the input of evaporation pond in each month and users must add all the brine produced from the treatment technologies. Later, the records are put in the annual brine inflow row. Salinity factor and pan coefficient can be changed but they are not necessary. From the annual brine inflow, the area of the required basin can be automatically calculated using the spreadsheet.
4.2 Discussion

The spreadsheet is a simple way to design an evaporation pond and it can be used for any conditions. The main parameters that will make the spreadsheet sensitive are:

- Annual mean rainfall
- Potential Net Evaporative Loss
- Annual brine inflow
- Pond evaporation
- Salinity level

The location of the site depends on proper sizing of the evaporation pond. Evaporation pond are mainly utilised in regions that are far from the sea where brine produced can be disposed. In areas close to the coast, the rejected brine is normally dumped into the ocean or sometimes used in agriculture (Mushtaque Ahmed 2000). Ocean disposal is considered simpler than inland disposal. It is said that the treatment of saline groundwater is more effective in arid countries such as Saudi Arabia due to high solar radiation intensity. When less rainfall is collected, evaporation loss increases due to sunlight. When the mean rainfall is greater than Class A pan evaporation, there is insignificant evaporation loss. The calculated Potential Net Evaporative loss becomes negative that means the site is situated in a dry place where there is less rainfall. The curves in Figure 18 are exponential decay therefore, when evaporation loss is lower, Figure 18 demonstrates that the basin area for 100ML/year inflow is higher for all the three curves at different salinity level. Larger basin is required to dispose the rejected brine. Brine inflow is another factor that can affect the area of the evaporation pond. A larger basin needs to be designed for greater brine inflow. The average pond evaporation influences the pond depth of the evaporation pond. When the average pond evaporation has high value, there is an increase in pond depth. In the formula, $d_{\text{min}} = E_{\text{ave}} f_2$, $f_2$ being the losses is assumed to be one and the pan coefficient is 0.7. The pan coefficient may not affect the pond depth because the value is suitable for a proper designed evaporation pond obtained from literature reviews. The user can change the pan coefficient in the spreadsheet but they do not have to. When there is a decline in the salinity of groundwater, the area of basin for 100ML/year inflow decreases and therefore, the area of the basin reduce too. More water has to evaporate when the
Salinity of groundwater is low and salts remained at the bottom of the basin (State Water Resources Control Board 2017). For lower salinity, a small evaporation pond is required. The evaporation process makes the effluent more concentrated and reduces the volume of water.

Two spreadsheets were found from internet resources to compare the results that was obtained. The first spreadsheet is a bit different from my design model. In that spreadsheet, the evaporation per year and the volume of the pond are calculated. They have designed the pond by inputting the diameter of the pond and the pond depth. The slope of the pond remains constant and is assumed to be 0.5. When the pond diameter and the pond depth vary, the sizes of the pond are obtained from the spreadsheet. Therefore, the volume of the basin is determined with the designed parameters. The evaporation per year is also calculated by multiplying the average evaporation with the surface area of the pond. The spreadsheet tells the volume of water that the pond can evaporate and the pond capacity of brine it can hold. Table 6 illustrates an example of a designed evaporation pond. The first four parameters that can be changed are in blue. By changing them, a proper size of an evaporation pond will be obtained.

Table 6 An example of a designed spreadsheet for an evaporation pond

<table>
<thead>
<tr>
<th>Parameters</th>
<th>in ft/in</th>
<th>in m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pond diameter (m)</td>
<td>100</td>
<td>30.5</td>
</tr>
<tr>
<td>Pond depth (m)</td>
<td>20</td>
<td>6.10</td>
</tr>
<tr>
<td>Slope</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Average evaporation per year (m)</td>
<td>39</td>
<td>0.991</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>799079</td>
<td>3025</td>
</tr>
<tr>
<td>Evaporation by year average (m³)</td>
<td>189910</td>
<td>719</td>
</tr>
<tr>
<td>Top radius (m)</td>
<td>50</td>
<td>15.24</td>
</tr>
<tr>
<td>Bottom radius (m)</td>
<td>30</td>
<td>9.14</td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>7854</td>
<td>730</td>
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<tr>
<td>Volume (m³)</td>
<td>106814</td>
<td>3025</td>
</tr>
<tr>
<td>Area of basin (m²)</td>
<td>496</td>
<td></td>
</tr>
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</table>

My model spreadsheet is different compared the first spreadsheet that I found online. Pond depth was calculated using formula and there were parameters such as embankment and pond height were suggested from literature. From this information including salinity of rejected brine, the area of the required basin is later achieved. However, as shown in table 6, pond diameter, depth, slope and the average evaporation must be assumed to get the area and volume of the basin.
The second spreadsheet is based mainly on seepage loss and evaporation loss at a particular site. Seepage is a slow discharge of water thorough porous soil. In the spreadsheet, calculations are done to determine the seepage loss of an evaporation pond. The soil at the site and the pond depth are considered. Afterwards, the surface area of the pond will be looked at. The stability of the water inside the basin is inversely proportional to the seepage meaning that when seepage has a higher value therefore, the stability is low (Shailes 2012). Seepage is dependent on soil texture and seepage is more when water is infiltrated into the soil at different soil structure. Water loss can be affected by various factors such as soil type, permeability, depth of the pond and climate (Agri LIFE EXTENSION 2012).

Evaporation loss is another parameter that they look at in the second spreadsheet. The monthly evaporation rate was recorded and the evaporation loss was calculated by multiplying the evaporation rate and the surface area of the pond. The pond depth was estimated and next, the surface of the area and the pond capacity are calculated using pond depth. From estimated parameters, seepage loss and evaporation loss are gained.

The spreadsheets from the internet are different from my designed model spreadsheet. Mine was mainly designed for farmers. The main parameters are not assumed but they are calculated using formula from literature. From literature, it says that when there is a rise in evaporation rate, the volume of brine solution reduces making the pond smaller. Small evaporation pond has low cost and therefore, low in maintenance. With my designed model, when evaporation loss is increased, the volume of brine solution is reduced and therefore, the area of the required basin decreases.
<table>
<thead>
<tr>
<th>Purpose</th>
<th>Design model spreadsheet</th>
<th>Online spreadsheet 1</th>
<th>Online spreadsheet 2</th>
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<td>Obtaining area of basin</td>
<td>Obtaining seepage loss and evaporation loss</td>
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<td>evaporation pond</td>
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<td>Data</td>
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<tr>
<td></td>
<td>- Bureau of Meteorology</td>
<td>- Calculating volume of pond</td>
<td>- Measuring evaporation rate</td>
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<td></td>
<td>for rainfall and</td>
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<td>- Recording pond area</td>
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<td></td>
<td>evapotranspiration data</td>
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<td>User friendly</td>
<td>Especially for local</td>
<td>People who has knowledge about the topic</td>
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<td>people and farmers</td>
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<td>Assumptions</td>
<td>- Site location</td>
<td>- Pond diameter</td>
<td>- Soil Texture</td>
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<td></td>
<td>- Class A pan evaporation</td>
<td>- Pod depth</td>
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<td>- Annual brine inflow</td>
<td>- Slope</td>
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<td>- Salinity factor</td>
<td>- Average evaporation per year</td>
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<td>- Pan coefficient</td>
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</table>
5.0 Conclusion

The main objective of the project is to develop a Microsoft Excel spreadsheet helping local people and farmers design an evaporation pond. An evaporation pond is a shallow lined earthen basin for rejected brine disposal in inland region. If the site is closed to the coast, the brine produced will therefore be dumped into the ocean. Rejected brine is the waste by-product from water treatment systems. Different parameters including rainfall, evapotranspiration and solar radiation data collected from the BOM are considered. The Potential Net Evaporative Loss, the salinity of groundwater and the annual brine inflow are used to calculate the pond depth and area of required basin. Farmland Alternative Water Supply Project is launched by Water Corporation to find alternative water resources such as groundwater, rainwater and surface water. This is because GAWS is a very expensive water supply and it can reduce the dependency of scheme water too. Bursting of pipes that occur frequently and the salinity issue at the region are also the reason why Water Corporation has launched the project. Therefore, to overcome salinity issue, an evaporation pond needs to be constructed to manage rejected brine. The treatment technologies that have been used in the project are RO/NF, solar distillation and phytodesalination to treat saline groundwater. To model the spreadsheet, the pond depth was calculated by using the formula from the literature. The salinity of the groundwater at the site is measured so that the area of the required basin is calculated. All the calculations were made in the spreadsheet. The barchart of each rainfall and evapotranspiration at a specific site were plotted to see the trend monthly. The results were compared to the data obtained from literature and from the two examples of a model spreadsheet found from the internet. The area of required basin increases with decreasing evaporation loss and increasing salinity.
6.0 Recommendations

It is recommended to use deeper evaporation pond in the future for disposal of rejected brine. Shallow pond tends to dry due to an increase in evaporation rate and crack easily. Moreover, it is durable for rejected brine disposal. Deep evaporation pond is more cost effective compared to shallow pond. It also increases evaporation rate making it less dry. When pond depth is within the range 0.1m to 2.5m, there is a decline in 4% evaporation rate. Therefore, this causes a reduction in construction cost. In the designed model spreadsheet, in the months of June to August, it is noticed that the Potential Evaporative Loss has negative values. It signifies that the mean rainfall is greater than the Class A Pan evaporation. If the pond is deep, the value for the Potential Evaporative Loss will be always positive even during winter period. Brine solution will take longer time to evaporate the water and therefore, the Class A Pan evaporation will always be greater than the mean rainfall. With increasing depth of the basin, freeboard will increase as well which represents the height above the waterline and it prevents overflowing of water.

Spray evaporators is suggested to enhance evaporation rate. It scatters the concentrate over the pond surface in form of fine mist. Water temperature is increased leading to a faster evaporation process (Farnham, et al. 2015). Therefore, a smaller area of land is required to construct a small evaporation pond.

Another recommendation is using Wind Aided Intensified Evaporation (WAIV) instead of evaporation pond. It is an alternative solution for rejected brine management and liquid waste minimisation. WAIV uses natural energy sources such as wind to enhance evaporation rate of brine resulting in lower operation and maintenance costs. However, WAIV is still being developed.

Evaporation pond has a higher footprint, higher costs but a longer lifespan compared to WAIV (Murray and McMinn 2011). Moreover, land required is reduced in comparison to evaporation pond due to enhance evaporation rates.
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Appendix A: Gantt chart

Table A1 Gantt chart for the main project conducted by Water Corporation

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<td>Construction/installation of phytoremediation units</td>
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</table>

Appendix B: Rainfall Data from BOM

Figure B1 Rainfall Data. Step 1, BOM rainfall in Australia entry page; Step 2 Western Australia Weather Data; Step 3, Climate Data online at a specific area and Step 4, Rainfall Data at the site.
Appendix C: Evapotranspiration Data from BOM

Figure C1 Evapotranspiration Data. Step 1, BOM Evapotranspiration Data in Australia entry page; Step 2, Evapotranspiration Data at a specific area; Step3, Western Australia Weather Evapotranspiration Data and Step 4, Western Australia Daily Evapotranspiration Data.

Appendix D: Spreadsheet Model