Commercial Use of Saline Groundwater

actis Environmental Services
PO Box 176
Darlington
WA 6070
Phone 08 95255806
Fax 08 95255807
1 Introduction
The extraction of groundwater has been suggested as a mechanism for solving salinity problems for several locations around Australia. The area that has received the most attention is the Murray River, as it meanders through three Australian States. The projects that come to mind are the Cooke Plains Interception Scheme, and the interception of saline groundwater at Waikerie and Wacool. A small private venture at Pyramid Hill in NSW is based on intercepting saline ground water and value adding the crystallised salt recovered from the brine.

The Cooke Plains project is managed by the Coorong District Council and pumps groundwater into tunnel houses, in which various types of aquaculture take place. Two species, *Dunaliella salina* (a type of algae) and snapper have been used in trials. The brine left over from the aquaculture is pumped into a small evaporation pond from which it is intended to harvest salt.

The Waikerie project pumps saline water from the Waikerie irrigation area to an evaporation pond in Stockyard Plains in South Australia. The project is managed by SA Water at Berri but is funded principally by the local fruit growers association. There is some intention to landscape the saline wetland but up until now there has been no integrative design. The scale of pumping is quite large and the wetland is reputed to cover an extensive area. The objective is to remove saline water and put it ‘elsewhere’.

The Wacool (Victoria/NSW border) project is similar, with saline groundwater intercepted before entering the Murray River and pumped to an evaporation pond. The project was initiated in the mid eighties by the local council and water board. No salt had been extracted from the evaporation pan by the mid 90’s although it is believed that salt has been taken from the pan since then. ‘Bitterns’ has been sold from the project as a road stabilizer.

A fourth project is a private concern at Pyramid Hill in NSW. This project is conceptually similar to the design of the current proposal but little is known about it, as it is a privately funded project. It is not known whether the project is commercially viable at this stage. Publicity releases indicate that the project intercepts saline ground water, crystallises salt from the brine, then re-dissolves the salt before re-crystallising the salt in a controlled environment. The objective of re-forming the salt crystal in a controlled environment is to improve the salt quality to be competitive in the vacuum dried table salt market.

All of these projects have in common the principal of artificially reducing the water table in order to reduce saline scalds and surface water logging. The alternative of catchment and watershed management has not been precluded but rather seen as a long-term solution that can be run in conjunction with active groundwater discharge. The Wacool and Waikerie projects could be seen as successful in the primary objective of removing saline groundwater from the area of interest. The Cooke Plains project is successful in demonstrating an integrated solution to help reduce the rising groundwater problem, but was never intended to solve an immediate environmental problem. The Pyramid Hill project is an interesting and worthwhile project as it also includes an integrative approach. The commercial viability has yet to be proven.

Relocating the groundwater to the surface is a simple engineering exercise. The problem remains of disposing of the salt and justifying the financial and environmental cost.
1.1 Disposal versus Use

The primary aim of these projects is to reduce or stop the increasing salinity presented at the surface. This implies the removal or redirection of saline groundwater. (Land use and land care are better long term alternatives for slowing the rise of saline groundwater.)

Intuitively it can be reasoned that removal means intercepting the brine, and moving it to another area either directly or in steps. The interception process can only be undertaken by pumping groundwater or encouraging groundwater discharge into a dam or holding area.

The current surface drainage system is a combined interception and redirection system. This process has been successful, by all accounts, but the deeper groundwater is still having an impact on Toolibin Lake. Only bores can successfully intercept the deeper groundwater. These bores will create a cone of depression in the groundwater aquifer. The saline water moves through the substrate towards the bore and is pumped to the surface. The effect of the depressed groundwater on the function of the Toolibin wetlands is unknown, and there are likely to be benefits and disadvantages.

Once intercepted, the saline water or brine has to be removed to be successful in the primary objective. The removal of salt can only be achieved at a cost neutral or profitable manner by removing the brine, or processing the brine on site to a value added state.

Economically, the removal of the brine is not feasible unless it is to a nearby lake or re-injected into the groundwater. The piping or transport of large quantities of brine any distance is very expensive. It is often possible to sacrifice a nearby wetland or basin. It is considered philosophically unpalatable to destroy one damaged wetland to preserve another, especially if there are other alternatives. This is especially critical when there are so few wetlands in a natural condition in the central Wheatbelt of Western Australia. Groundwater recharge will be considered further into the report. Both of these solutions could potentially cause problems for other areas and there could be legal, environmental and social implications from these actions.

Historically the best option for the removal of brines has been to reduce the volume of brine by evaporation so that either a more concentrated brine remains or a salt and brine. It is not possible to be left only with a salt, as there will always be some brine remaining. The most common salt, sodium chloride, is, as its name implies, very common and makes up a large proportion of normal brine. The evaporation process to produce sodium chloride is quite easy in most areas. The paper discusses the economic aspects of salt in some detail. The point is that saline groundwater can be made into something quite usable and with some value, and the salt is removed from the environment.

It is unlikely that salt production is going to be anything except economically marginal, as there other more cost effective ways of harvesting salt than pumping from groundwater reserves.

This leads us to the final category of users of brine. There are a number of commercial ventures that may conceivably use the brine in an economically profitable fashion, but do not dispose of the salt. Examples of these are aquaculture and solar energy production. These concurrent uses of brine may be able to cross-subsidise the cost of pumping the brine and the subsequent disposal of the salt. It is important to recognise that these ventures only indirectly help the primary objective of saline groundwater interception and hopefully final removal. Without the mechanism of removing the salt, intercepting and using the saline groundwater has no benefit.
1.2 Project Objectives
The objective of this project is to develop and test techniques for disposing of saline effluent in an environmentally safe manner that is cost neutral or profitable.

1.3 Methodology
The first task was to collect information pertaining to the proposal held at regional and central government offices.

The second task was seen as a technical review of the existing saline resource and the design of an extraction system that would be most economical. This will generate the cost of extraction and the likely salinity of the brine over the life of the project. This data is important in analysing the depreciation of capital costs and the security of the project. Recommendations were made about the potential to extract saline water and estimates made of the quantities and salinity.

A preliminary filter of the potential methods of removing the salt was made, reducing the field to a small number of potential solutions worthy of further investigation. Several novel uses of brine have been mentioned in the report, which may be worth while considering at a later date but are currently very much at the research stage.

The expectation was, and proved to be true, that there would be three main areas worthy of further investigation. Most potential solutions were permutations of salt extraction, sale of bitterns, aquaculture (Artemia, finfish, Dunaliella salina), and re-injection of some or all of the salts.

A conceptual design of an appropriately sized saltfield based on information generated in the earlier stages of the investigation was completed plus a business plan for harvesting, stockpiling, transportation and sales.

Through collaboration with Fisheries WA, AgWA and TAFE, a list of aquaculture species suitable for the conditions found at Lake Toolibin was made. A model of the costs of production and capital was designed and the species compared. Market sensitivities were investigated.

Three scenarios for removing salt were investigated. Each scenario was developed to a conceptual stage with details including marketing and construction costs. Recommendations have been made on the suitability of each scenario. Combined with the several options for aquaculture, the number of combinations is quite extensive.

It is believed that the proposed scenarios are applicable to a number of brine extraction processes.
1.3.1 Evaporation Pond Site
A prerequisite for building a solar salt field is flat land with relatively impermeable soil. The best type of soil for preventing leakage is clay.

1.3.2 Loss of Concentrated Brine from Evaporation Ponds
A major concern of the project would be the loss of concentrated brine as seepage from the ponds. There are number of methods of addressing this problem which have varying success and costs associated with them. There are two issues with seepage, namely the commercial cost of losing brine and the environmental cost of releasing high salinity brine into the environment.

Loss of fluids could be estimated with a hydraulic conductivity of 0.15 m day^{-1}, this is based on Martin (1990) which represents an average hydraulic conductivity of profile properties from one drill hole. From calibrated results from SKM (1999) a middle layer of 0.015 m day^{-1} could be used as a minimum value, although this calibrated result is also limited to that one drill hole (SKM 1999). For a better estimate of loss of brine it is recommended that the vertical hydraulic conductivities be determined at prospective sites.

The radiometric data indicated that there was a substantial depth of clayey soils on the western side of Toolibin Lake. The clay layer would reduce the level of seepage and it would be an advantage to site the ponds on a clay layer. A further advantage of locating the ponds on the western side of the Lake is that any leakage from the ponds is likely to be drained away along palaeochannel A and not impact on Toolibin Lake. The radiometric method provides information about the sub surface soil types however does not provide good information about the surface type. Before a salt field is designed, a program of detailed soil sampling should take place. Areas of high permeability, such as sand, should be identified and avoided. The normal practice when building ponds is to make the banks out of relatively impervious clay, which are keyed into the underlying clay. This involves removing the surface soil to a depth of half a metre to the width of the bank and refilling with clay borrowed from nearby.

Experience at operating salt fields has shown that the loss of brine to seepage reduces as the biology of the field deposits fine sediment on the floor of the ponds. This sediment, along with the mucilagce produced by anaerobic bacteria, creates a barrier to the loss of brine.

To minimise loss of brine into underlying aquifers and the potential damage that may result, it has been suggested that the ponds be lined with plastic. Plastic membranes are not a 100% barrier to seepage, as the membrane will be holed at various places during and after construction. The membrane layer will then provide a rapid exit path for the leaked brine. The cost of the membrane is in the region of $30 000 to $40 000 per hectare laid (Fabtech Pty Ltd pers. comm.). A more cost effective, but not as efficient, method of using plastic membrane is to lay the plastic vertically through the banks to a depth of a metre or two below ground level, effectively stopping lateral movement of brine through the subsurface but not vertical movement.

Identifying the areas of high permeability within the proposed ponds is a priority. These areas can then be mechanically compacted with rollers and with perhaps clay bought in to reduce seepage. This will not be entirely successful for a number of reasons and seepage will result.

The danger to the lake from seepage is not great because the hydraulic cone of depression caused by the main bore field will tend to draw the brine deep below the lake. Also, if the
evaporation ponds are on the western side of the lake then the interception drain will move the brine away from Toolibin Lake. The main environmental danger is to the west and south of the ponds. It is suggested that either an interception drain(s) be built on these sides to take up seepage from high velocity conduits, or alternatively another much shallower bore field (matching the seepage rate) be designed to create a hydraulic cone beneath the ponds (George pers. comm.).

It is estimated that the environmental concerns for seepage are more sensitive than the commercial problems of losing concentrated brine from the salt field. Therefore it is expected that if the seepage is reduced to a low level for environmental reasons the commercial implications will be trivial.

1.3.3 Disposal Alternatives
The most feasible alternative to disposing of the salt other than salt harvesting is to create evaporative ponds to store the pumped water and dispose the concentrated brines into/on the ground at a distance. The legal and environmental implications of disposing concentrated brines into/on the ground should be investigated.

Disposal sites could be
- On the surface in the form of evaporative ponds
- Regolith aquifers
- Palaeochannel

Before considering any of the sites the following information is necessary to make the decision.
1. The hydrogeological parameters of different aquifer systems should be understood with greater confidence.
2. The aquifer selected should be isolated from the fresh water aquifers (even at distance) and should not disturb the ecological balance in the future.
3. A detailed catchment study similar to the Toolibin catchment is necessary to understand the subsurface hydro-geological conditions south of the lake.
4. The corrosion from hypersaline brines and the impact on the materials used should be considered.

Another alternative to salt harvesting and aquifer recharge is to truck the salt or concentrated brine to an estuary or the sea for disposal. This alternative has not been considered in detail for the following reasons.

- Disposing of the salt for zero return must be less financial than receiving some monies for the item. It is true that less effort and therefore cost would be needed in harvesting the salt but the net marginal return would be in the region of -$15 per tonne, whereas the net marginal return for harvested and sold salt would be +$10 per tonne. Disposing of brine into the sea would cost as much as -$15 per tonne because the harvest cost would be minimal but the transport cost would be at least five times the cost of transporting salt. Saturated brine takes up five times the volume of the salt it produces. The cost of transporting the salt to the nearest seashore is approximately $10 per tonne. The cost of transporting saturated brine would be $50 per tonne of salt crystal and the cost of transporting sea water concentration brine would be $500 per tonne of salt crystal.
- Disposing of salt or brine into the sea is an environmental issue. Saturated brine and salt will cause salinity stratification around the disposal site. Most marine species are

---

1 This cost of transporting brine is very conservative as it only based on increased volumes needed to be transported. A tanker is needed to transport liquids and the opportunities for back loading are much lower. As a result liquid transport often has to be costed at twice the one way trip. Also tankers carry 20 tonne per load not 24 tonne as do flat top semi trailers.
very sensitive to salinity changes and will be killed, if they are unable to move away, by even a 30% increase in salinity. Transporting seawater concentration brine to the sea would be less of an environmental issue but the volume of brine would be 50 times the volume of salt. The social cost of moving 25 000 tonnes of brine would be significant.

1.3.3.1 Disposal on the Surface
A series of evaporation ponds could be constructed. The evaporation ponds would concentrate the brine and deposit salts during high evaporation. In the event of major floods most of the salts accumulated in the ponds would be washed away down stream. The environmental effects of such released salts should be studied in detail before taking this option. Evaporation basins should be located on areas where maximum vertical recharge is possible, and away from flood zones.

1.3.3.2 Reinjection into Regolith
Regolith aquifers comprise weathered sediments close to the surface, pallid zone and saprolite aquifers.

Weathered sediments close to the surface would not be a good option for re-injection due to low transmissivity. Shallow injection of brine in these soil types would possibly result in groundwater mounding. As a result the re-injection might cause extensive salinity damage to the surrounding country.

Pallid zone or weathered rock aquifers are more suitable for reinjecting concentrated brines than weathered sediments. The ideal location would be a zone bounded by dykes that would act as a groundwater compartment to hold the concentrated solution, which is presently only partially saturated. However, the vertical loss in this case would make the deeper aquifers hypersaline. Knowledge of the composition and function of the aquifers on the top and bottom of the disposal site is necessary. The advantage would be to contain concentrated brines in the place for longer periods. Long term rising groundwater may result in extensive surface salinity in the area.

Continuous re-injection of brines over 2 to 5 years could increase the salinity within the re-injection area many fold. It is extremely important to assess the hydraulic conductivity of the soils at various depths along the length and breadth of the disposal site in order to evaluate the potential of transplanting the salinity problem. Re-injection is unlikely to be a long term prospective and few sites would be suitable for re-injection. The high costs associated with selecting and monitoring a re-injection field makes re-injection an unlikely candidate for primary disposal of brines.

1.3.3.3 Reinjection into Palaeochannel
The most feasible solution for re-injection is into the palaeochannel downslope of Toolibin Lake. Concentrated brines could be reinjected into the palaeochannel, as it appears to be the most transmissive feature in the region. The site should be at a sufficient distance away from Toolibin Lake, so that the concentrated brines do not flow back towards Toolibin Lake. Care would be needed to ensure that excessive pumping did not change the local hydraulic gradients and draw back the reinjected brine into the lake.

The continuity of the Palaeochannel identified at Toolibin is not known further south. George et al, (1994) reported fresh and high yields from the sediments in the palaeochannel at Towerrinning Lake. The string of lakes southwest of Taarblin indicate that the palaeochannel could be further extended in this direction. Discharging the concentrated brines into the palaeochannel may increase the overall salinity of the channel. This discharge may pollute the unknown reservoirs down the stream such as the...
Towerrinning palaeochannel. The palaeochannel should be explored further south to at least 10 km by airborne geophysics to make the disposal environmentally and legally viable.

1.3.3.4 Future Investigation
The following information is required before taking up the re-injection models:

The hydrogeological systems that are the potential recipients of the concentrated brines should be studied in detail. Drilling should be done into different aquifers and the aquifer properties should be evaluated. Interrelations between aquifers and the leakage factors should be evaluated.

Water levels should be monitored to estimate the rate of increase in the levels per annum. Data obtained from monitoring programs would increase the confidence in building the models for future effects of the re-injection.

The amount of water and the salt loads entering the hydrogeological system south of the Toolibin Lake should be assessed.

Modelling the movements of the concentrated brines injected and monitoring of the future movements is required to assure the movements are in accordance with the model.

The required number of monitoring wells, their depths and location, depends on the aquifer system chosen for the disposal. However, the spacing of monitoring wells should be closer at the site of disposal.

With the present data it is not possible to suggest a site for re-injection of concentrated brine.

1.4 Cost of Pumping Brine to Surface
It is not possible to generate a fixed cost for pumping. The following estimated cost was based on using three phase submersible pumps, each pumping in the region of 1 to 2 litres per second. The brine would be pumped into either a PVC or poly pipe network and the electricity supplied via 3 phase power. The network would have a linear distance of 3.5 kilometres. Initial costing indicated that a submersible cable (below ground) was a much more expensive exercise than the traditional aerial power supply. The disadvantage of the aerial supply is the aesthetics and clearing required for its installation.

The submersible pumps were chosen because of the relatively low maintenance, and have less visual and audible pollution than the existing air pumps. The aquifer in the palaeochannel should be more consistent than the aquifer in the fractured rock formation that the existing air pumps are using. This means that the pumps can be sized to match the flow and should not run dry, negating the main advantage of the air pumps, which are not affected if the bore hole is dry. The increased pumping rate is shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Pump Rate for Proposed Borefield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pumps</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Proposed</td>
</tr>
<tr>
<td>Proposed</td>
</tr>
</tbody>
</table>
The cost of installing each bore and the bore field infrastructure is summarised in Table 2 and Table 3.

Table 2 Installation cost of a bore

<table>
<thead>
<tr>
<th>Bore costs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pump</td>
<td>$1,300</td>
</tr>
<tr>
<td>drilling &amp; casing</td>
<td>$2,500</td>
</tr>
<tr>
<td>transformer</td>
<td>$5,000</td>
</tr>
<tr>
<td>telemetry</td>
<td>$3,000</td>
</tr>
<tr>
<td>electrical</td>
<td>$1,000</td>
</tr>
<tr>
<td>drilling &amp; casing PVC/metre</td>
<td>$2,500</td>
</tr>
<tr>
<td>Total</td>
<td>$15,300</td>
</tr>
</tbody>
</table>

Table 3 Cost of borefield

<table>
<thead>
<tr>
<th>Km of Pipe</th>
<th>Cost of Pipe</th>
<th>Cost of HV cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$19,250</td>
<td>$150,000</td>
</tr>
</tbody>
</table>

An estimate of the operational costs was made using the assumptions in Table 4. The estimated operational costs, excluding maintenance and depreciation, are given in Table 5.

Table 4 Assumptions for power cost

<table>
<thead>
<tr>
<th>Cost KW/hr</th>
<th>Days of Operation</th>
<th># of bores</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.125</td>
<td>300</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5 summarizes the total operational and installation cost of the bore field. As indicated the total cost is only for budgeting and does not imply that a detailed design of the bore field has been made. It was anticipated that a detailed costing would be made at the time of designing the field.

Table 5 Summary of costs for expanded borefield

<table>
<thead>
<tr>
<th>Per bore</th>
<th>Five bores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>$2,014</td>
</tr>
<tr>
<td>Bore Cost</td>
<td>$15,300</td>
</tr>
<tr>
<td>Borefield</td>
<td></td>
</tr>
</tbody>
</table>

The largest cost of installing the bores is the high voltage power supply, which accounts for $150,000 of the total cost of $250,000. Suggestions of using generators and motors have been made but these alternatives become prohibitively expensive over time because of the increased operational and maintenance costs. It might be possible to locate the bores close to existing power supplies and/or share the cost of power with the stand-alone enterprises. The western palaeochannel is very close to the existing power supply to the air generator and the eastern palaeochannel branches close to the road where there is also an existing power supply. If hydrological studies show that these locations are adequate to draw down the saline aquifer then the cost of the bore field installation would be more like $30,000. The existing bore costs include a telemetry system which was thought essential but again if the bores are located near existing power supplies telemetry is not needed, although useful, and a further saving of $15,000 can be made.
1.5 Summary

Chemical analysis data supplied by CALM and George and Bennett (1995) shows that the average TSS from bores in Toolibin Lake is 50 000 mg L\(^{-1}\). Groundwater salinity in the Flats (area below 330m contour north of the lake) and in the lake ranged between 6000 – 9000 mSm\(^{-1}\).

Martin (1990) estimated hydraulic conductivity to be 0.15m day\(^{-1}\) and specific yield as 0.1 from a bore hole to the west of Toolibin Lake.

The present pumping rate from the bores in the Toolibin Lake is approximately 0.085 M m\(^3\) pa. Recharge in the Flats was estimated at 2.95 Mm\(^3\) pa. With specific yield of 0.1 (Martin, 1990) the amount of water that can be extracted was calculated to be 10% of this at 0.295 Mm\(^3\) pa. Aquifers in the Flats may not be regional and the yields are dependent on the extent of these aquifers. If the extraction of groundwater is not equal to the recharge, groundwater levels may continue to rise. Thus evaluation of aquifer properties is necessary for more accurate results. Groundwater levels will continue to rise if the excess recharge is not extracted.

Recharge in the palaeochannel amounts to 1 Mm\(^3\) pa. From the interpretation of geophysical data, if the transmissivity of the palaeochannel is high, large amounts of water can be pumped. A conservative calculation (9) yields about 0.19M m\(^3\), which is more than double of the present yields.

Potential for future pumping from the palaeochannel was estimated to be 0.14 m\(^3\) to 0.2M m\(^3\). Salt loads estimated from the present pumping and the future pumping range from 4000 to 7000 tonnes per year.

A large amount of water needs to be pumped for long periods of time to reduce water level considerably in the palaeochannel and under the lake. The time frame may be three or five years depending on the number of pumping bores and the amount that can be pumped out. Yields and salinity of brine are also expected to reduce with long term (>10 years) pumping.

Hydraulic properties of the palaeochannel and other aquifers are required for a better estimate of yield, salinity of brine and water level reductions.

Further investigations are required south of Toolibin Lake to fully assess re-injection of brine in the palaeochannel.

1.6 Recommendations

Groundwater recharge studies should be carried out for the whole Toolibin catchment. The selection of production bore sites should be based on the interpretation of the geophysical data to maximise yields of brine.

Further pumping tests are required to calculate the hydraulic properties of the palaeochannel such as specific yield, hydraulic conductivity, geological logs and groundwater salinity. These should be used to refine the calculations. Airlift pumping, which was previously used, will not accurately abstract water at a controlled rate so that yield and draw down of wells can not be accurately determined. It is recommended that long term controlled pumping tests be conducted to evaluate hydraulic properties of different aquifers.

Evenly spaced nests of piezometers monitoring the palaeochannel and all other aquifers should be located within a minimum distance of 600m around future production wells.
Continuous monitoring of the piezometers is required to study the effects of water levels from future pumping.

It is recommended that further drilling should be carried out to confirm the presence of the palaeochannel to the west of the lake. The interpretation of what is best for the Toolibin Lake system would be influenced by the presence of another channel.

The pumping area of influence should also be assessed to check if the present pumping is affecting the palaeochannel to the west.

The vertical hydraulic conductivities of prospective sites for the evaporation ponds should be determined.

Recommendations for further studies for re-injection are given in section 1.3.3.3

If re-injection is considered then further studies are required between Wyalbring and Taarblin. These areas should be surveyed with either airborne or ground geophysics for suitable sites for re-injection of brine solutions.
2 Value Adding to the Process

The objective of pumping the groundwater is to protect the wetland, Toolibin Lake. Only salt removal can achieve this objective. Salt production has been discussed in another section but it is likely to be economically marginal without considering the environmental benefit of protecting a wetland.

There are a number of ventures that can return a profit but will not remove salt from the environment (or only marginally). There is a certain amount of synergy by combining these ventures. The advantage of encouraging other ventures is that the initial infrastructure cost of pumping the brine from beneath the ground can be shared. The salt field can be the repository of the potentially nutrient enriched brine from the fish culture. The increasing salinity will sterilize the brine, killing pathogens and the like.

Aquaculture has the most potential but there are other developmental ventures that can contribute.

2.1 Aquaculture

Aquaculture is a growing industry and has popular support. This is emphasized by the large number of people that attend regional seminars, such as the one held in Narrogin in March 1999. It has the potential of rapid return for a relatively small capital investment. This is often not realized because of the vulnerability of the industry to disease and environmental fluctuations. Stock deaths happen rapidly and are costly. The industry is relatively new and the support available to the community is not comprehensive. New aquaculturists sometimes underestimate the amount of onsite research and development needed for a new venture.

There are environmental issues with aquaculture. The effluent from the farms can have high concentrations of nutrients and potentially, disease. The cultured fish can also be a risk to the environment if they are not normally found in that region. Translocation and disease issues are discussed in a Discussion Paper by the Fisheries of Western Australia (August 1996). This paper was specifically dealing with Silver Perch but similar issues arise with other fish species.

The species that are reported to grow in high salinity brine are: brine shrimp, Barramundi, Black Bream, Pink Snapper, Milk Fish, Mullet and Tilapia (see Table 6). Of these Barramundi and Milk Fish will not be successful at the low temperatures recorded during a Narrogin winter. Pink Snapper is also doubtful but has been grown at lower temperatures than that indicated in the table. Mullet and Tilapia are not sought after fish in Australia and have been excluded for this reason. For the above reasons, only Black Bream and Pink Snapper were investigated further.
Table 6 Temperature and salinity parameters for a number of species of fish crustaceans and molluscs. (modified from Lawrence 1996)

<table>
<thead>
<tr>
<th>SPECIES</th>
<th>SALINITY (ppt)</th>
<th>TEMPERATURE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRINE SHRIMP</td>
<td>31-340</td>
<td>6-35</td>
<td>Persoone &amp; Sorgeloos 1980</td>
</tr>
<tr>
<td>Artemia salina</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BARRAMUNDI</td>
<td>0-50</td>
<td>16-35</td>
<td>Shelley 1993</td>
</tr>
<tr>
<td>Lates calcarifer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RED SNAPPER</td>
<td>16-60</td>
<td>13-28</td>
<td>Aquaculture WA (1) 1995</td>
</tr>
<tr>
<td>Pagrus auratus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLACK BREAM</td>
<td>3-60</td>
<td>8-33</td>
<td>Lenanton 1976, Suderneyer et al (in press)</td>
</tr>
<tr>
<td>Acanthopagrux butcheri</td>
<td></td>
<td></td>
<td>Jenkins et al. 1999 Akatsu et al 1983</td>
</tr>
<tr>
<td>GROUPER</td>
<td>23-45</td>
<td>18-31</td>
<td>Akatsu et al 1983</td>
</tr>
<tr>
<td>Epinephelus tauvina</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARRON</td>
<td>0-6</td>
<td>0-30</td>
<td>Morrissy et al 1990 Morrissy 1992</td>
</tr>
<tr>
<td>Cherax tenuimanus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILK FISH</td>
<td>0.5-158</td>
<td>25-36</td>
<td>Schuster 1960, Brais 1988</td>
</tr>
<tr>
<td>Chanos chanos</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MULLET</td>
<td>0-75</td>
<td>3-35</td>
<td>Murashige et al 1991 Walsh et al 1991</td>
</tr>
<tr>
<td>Mugil cephalux</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIANT TIGER PRAWN</td>
<td>13-33</td>
<td>10-25</td>
<td>Tseng 1987</td>
</tr>
<tr>
<td>Penaeus monodon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAINBOW TROUT</td>
<td>0-35</td>
<td>10-22</td>
<td>Sedgwick 1985, Bromage &amp; Shepherd 1990</td>
</tr>
<tr>
<td>Oncorhynchus mykiss</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TILAPIA</td>
<td>0-60</td>
<td>8-42</td>
<td>Pullin &amp; Lowe-Connell 1982, Kueltz &amp; Onke 1993</td>
</tr>
<tr>
<td>Oreochromis mossambicus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YABBIES</td>
<td>0-8</td>
<td>0-36</td>
<td>Morrissy &amp; Cassells 1992, Mills &amp; Geddes 1980</td>
</tr>
<tr>
<td>Cherax albidus</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The only other species that may be cultured in hypersaline brines that has some commercial value is the introduced brine shrimp, *Artemia salina* or possibly its cousin, the native Parartemia. This species of Anostraca is commonly used as a fish feed for aquarium fish and fry of cultured species.
2.1.1 Parartemia
The need for Artemia biomass in aquaculture is quite well defined. The problem is that Artemia is an introduced species, and it is thought to be replacing populations of the native Parartemia species. Artemia is not common in the wheatbelt and is mostly found as a non sexual species with limited distribution characteristics. The introduction of Artemia as a vibrant species next to a class “A” reserve would be of concern. The cultivation of Parartemia is not well known but is being investigated by the Wheatbelt Development Commission. For the purposes of this study, a business plan for Artemia has been presented with the view that it should serve as a benchmark for Parartemia, of which little is known. There is some contention about the historical and current status of Artemia and Parartemia in Australia.

Basically, for a relatively small investment of $50 000 a small brine shrimp farm could be constructed. This would return a similar amount on a yearly basis before tax and labour, assuming that the enterprise would be self managed. This venture would have a lot of synergy with any proposed fin fish culture as brine shrimp would reduce nutrient outflow from the finfish culture, the nutrient being a major pollutant. Also if a hatchery was started for the finfish culture, the brine shrimp could be used as a feed for the fish fry.

The business plan is for a much bigger venture and a capital entry would be in the region of $200 000 and return a substantial amount of $150 000 pa after two years.

Brine shrimp culture seems to be a logical and relatively low cost method of increasing the value of the brine pumped from the groundwater. The current analysis has not included a cost for the supply of the brine to the brine shrimp culture.

2.1.2 Finfish culture
Two finfish have been considered, Black Bream (Acanthopagrus butcheri) and Pink Snapper (Pagrus auratus). The fish are similar in many respects in that both are suitable for the ‘plate size’ market and are sought-after eating fish. Their feed and growth requirements are similar. The methods of culturing the two species are, from the level of analysis used in this report, essentially the same. This report does not deal with the technical aspects of fish culturing and it should be clearly understood by the reader that there would be technical differences in the methods of culturing the two species.

Preliminary inquires with companies that market fish in Western Australia and readings from the literature indicate that the market for the two species is different. Both fish fetch a similar price of $6.50 per kilogram when there is a limited supply. The Pink Snapper market, however, is better buffered and the price is less elastic than for the Black Bream. The Black Bream’s price falls to $3.50 when there is an abundance of fish; this would be the case with the proposed aquaculture harvest. The Pink Snapper market is much larger domestically and is cultured extensively overseas. There is a glut during the main snapper season in which the price falls substantially but with the longer grow out time of the snapper it should be possible to harvest during times when the market is under supplied. The analysis in this report has used the conservative estimate of the price of Black Bream.

The market price for fish is governed by quality of the product. Aquaculture creates the potential for niche development in the market. With proper handling, with the appropriate equipment it should be possible to market both species at the higher price. Both the species are popular eating fish. Cultured fish should be of better quality than the wild caught fish. Black Bream cultured in saline water is likely to have a taste more readily accepted by the Australian public than the same fish caught in fresher water.

Using the assumptions described at the end of this document, the profitability of each venture has been calculated (Table 7). For greater detail see the attached business plan.
should be noted that neither of the two species has been grown commercially at the salinity found at Toolibin Lake.

Table 7 Annual Profitability and Cost for each species.

<table>
<thead>
<tr>
<th></th>
<th>Direct Cost per Kilogram</th>
<th>Operating Cost per Kilogram</th>
<th>Total Cost per Kilogram</th>
<th>Feed Rate</th>
<th>Feed Cost</th>
<th>Fingerling Cost</th>
<th>Market Price</th>
<th>Total Cost (000)</th>
<th>Profit before Tax (000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Snapper</td>
<td>$2.63</td>
<td>$1.29</td>
<td>$3.92</td>
<td>1.50%</td>
<td>$1.50</td>
<td>$0.35</td>
<td>$4.50</td>
<td>$1,465</td>
<td>$122</td>
</tr>
<tr>
<td>Black Bream</td>
<td>$2.67</td>
<td>$1.18</td>
<td>$3.86</td>
<td>1.50%</td>
<td>$1.50</td>
<td>$0.40</td>
<td>$4.50</td>
<td>$1,586</td>
<td>$168</td>
</tr>
</tbody>
</table>

There is always a high risk factor in any new enterprise, especially aquaculture. The main risks are volatile market prices for both supply and sale of goods. Lack of technical knowledge by the proprietors, and the industry in general, also increases the risk. Disease and malnutrition being the main dangers with farming fish.

In terms of the financial evaluation, the main sensitivities are variations in the price of feed and the fish fry. Feed costs can be stabilized by negotiating with feed suppliers and is not the major risk that it was in past years. Fry are a significant expense (70%) and can be difficult to obtain. The number of fry required for this venture is very large and it can not be certain that there will be a supplier of fry available for either fish species at the right time. It would be prudent of any proponent of either aquaculture projects to investigate the potential of growing their own fish fry. This has not been priced in the financial analysis.

Either fish venture is superficially profitable and has potential to contribute to the repayment of the cost of pumping the saline groundwater. On the negative side, fish farming has the ability to generate nutrient rich outflow due to the high feed rate to encourage growth. For this reason there are benefits in tying this venture to brine shrimp culture and salt mining. The nutrient rich outflow could be used as feed water for the brine shrimp and the resulting high salinity brine used as the feed into the salt field. Fish farming is very labour intensive and has social advantages in rural areas such as Narrogin and Toolibin.

2.1.3 Algae Culture
Algae is a major marine crop. About 6 million tonnes of algae is harvested per year at an unknown value. The products produced range from agar and alginates to carrageenans. A useful summary of the algae industry was compiled by Denham (1998).

The most successful saline algae aquaculture in Australia is *Dunaliella salina* for beta carotene extraction. There are two commercial ventures, one at Whyalla and another at Port Gregory in Hutt Lagoon, WA. The same company Betatene Pty Ltd, after a recent acquisition owns both. It is understood that these two ventures are the largest in the world (Borowitzka 1999). Several smaller ventures have been started at Port Hedland and Esperance but it is unknown what is the status of these two ventures. The alga grows and produces commercial grades of beta carotene at salinities greater than 200 g/L.

Another species of salt tolerant ‘algae’ but is more correctly a blue green bacteria is *Synechococcus* sp. This species produces copious amounts of extra cellular polysaccharide that might have commercial application as a viscosity modifier. This species can tolerate salinities above 180 g/L. Commercial exploitation of the species is very much at the research stage (Coleman pers. comm.).
Most other commercially grown algae species, such as *Spirulina* sp., *Ulva* sp. and *Caulerpa* sp., are not viable at the high salinities expected at Toolibin Lake (>50 g/L). The brown algae such as kelps will not grow at the high salinities found at Toolibin Lake.

2.1.4 Synergy Between Aquaculture Ventures
The finfish and Artemia/Parartemia ventures have many advantages by being joint ventures. The financial advantages are many. For instance many of the pumps and aerators can be shared, as could the laboratory, administration and marketing functions. The brine shrimp could be grown in the waste stream of the fin fish culture and oversupply of brine shrimp could be used in the feeding of fish. It has been estimated that the saving would be in the region of $50 000 per year if the ventures were joined, as well as advantages conferred by specialisation of staff.

2.2 Power Generation by Solar Pond
The following information was collected from http://www.eren.doe.gov/consumerinfo/briefs.html.

A solar pond is a body of water that collects and stores solar energy. Solar energy warms bodies of water exposed to the sun, but the water loses its heat unless some method is used to trap it. Water warmed by the sun expands and rises as it becomes less dense. Once it reaches the surface, the water loses its heat to the air through convection, or evaporates, taking heat with it. The colder water, which is heavier, moves down to replace the warm water, creating a natural convective circulation that mixes the water and dissipates the heat. The design of solar ponds reduces either convection or evaporation in order to store the heat collected by the pond. They operate in almost any climate.

2.2.1 Types of Solar Ponds
There are two main categories of solar ponds: nonconvecting ponds, which reduce heat loss by preventing convection from occurring within the pond; and convecting ponds, which reduce heat loss by hindering evaporation with a cover over the surface of the pond.

Non-convicting Ponds
There are two main types of non-convecting ponds: salt gradient ponds and membrane ponds. A salt gradient pond has three distinct layers of brine (a mixture of salt and water) of varying concentrations. Because the density of the brine increases with salt concentration, the most concentrated layer forms at the bottom. The least concentrated layer is at the surface. The salts most commonly used are sodium chloride and magnesium chloride. A dark-colored material; usually butyl rubber lines the pond. The dark lining enhances absorption of the sun's radiation and prevents the salt from contaminating the surrounding soil and groundwater.

As sunlight enters the pond, the water and the lining absorb the solar radiation. As a result, the water near the bottom of the pond becomes warm-up to 200° F (93.3°C). Although all of the layers store some heat, the bottom layer stores the most. Even when it becomes warm, the bottom layer remains denser than the upper layers, thus inhibiting convection. Pumping the brine through an external heat exchanger or an evaporator removes the heat from this bottom layer. Another method of heat removal is to extract heat with a heat transfer fluid as it is pumped through a heat exchanger placed on the bottom of the pond.
Another type of non-convecting pond, the membrane pond, inhibits convection by physically separating the layers with thin transparent membranes. As with salt gradient ponds, heat is removed from the bottom layer.

Conveeting Pond
A well-researched example of a convecting pond is the shallow solar pond. This pond consists of pure water enclosed in a large bag that allows convection but hinders evaporation. The bag has a blackened bottom, has foam insulation below, and two glazings on top. The sun heats the water in the bag during the day. At night the hot water is pumped into a large heat storage tank to minimize heat loss. Excessive heat loss when pumping the hot water to the storage tank has limited the development of shallow solar ponds.

Another type of convecting pond is the deep, saltless pond. This convecting pond differs from shallow solar ponds only in that the water need not be pumped in and out of storage. Double glazing covers deep saltless ponds. At night, or when solar energy is not available, placing insulation on top of the glazing reduces heat loss.

2.2.2 Applications
Applications for solar ponds include community, residential and commercial heating; low-temperature industrial and agricultural process heat; preheating for higher-temperature industrial process applications; and electricity generation. Heat extracted from ponds can also run absorption chillers. Several U.S. organizations, in consultation with the Israelis (the leaders in solar pond technology) built a 0.8 acre (0.32 hectare) salt gradient solar pond in El Paso, Texas, to generate electricity. This system generates 100 kilowatts (kW) on demand, while simultaneously desalinating salt water. The electricity generated by a Rankine cycle heat engine power a food cannery located on the grounds. There are several other demonstration projects in the United States. A Miamisburg, Ohio operation uses a salt gradient pond to heat a recreational building and swimming pool. The Tennessee Valley Authority built several shallow solar ponds for various purposes, and has assisted others with similar projects.

The above-mentioned solar pond in El Paso began construction in 1985. The first application of the pond was to produce heat for the canning operation. The pond has been producing heat in this manner since the summer of 1986. The system operates at about 185°F (86°C) and is delivering about 300kW thermal energy. In July 1986, the operators added the Rankine Cycle engine to the system. In September, the El Paso solar pond became the first in the United States to generate grid connected power, producing up to 70kW. In May 1987, the operators added a 24 stage, falling-film low temperature desalting unit. In June, it began producing about 4,600 gal/day (16,000 liters/day). In 1992, the facility was shut down due to a failure of its original XR-5 liner. The pond was reconstructed with a geosynthetic clay liner system and operations resumed in the spring of 1995.

2.2.3 Feasibility
Solar ponds can only be economically constructed if there is an abundance of inexpensive salt, flat land, and easy access to water. Environmental factors are also important. An example is preventing soil contamination from the brine in a solar pond. For these reasons, and because of the current availability of cheap fossil fuels, solar pond development has been limited in the United States. The greatest potential market for solar ponds in this country could be in the residential space heating and industrial process heat sectors.
An example of solar salt energy generation is given below.

GENERAL CHARACTERISTICS
Applications: Desalination; Industrial Process Heat; Space Heating; Electric Power Generation.
Typical Size: 2,000-250,000 m2; 0.02-5.0MWe.
Design Fuels: Solar Radiation.
Performance Measure: Operating Efficiency: 2-3%(electricity); (annual average) 15-20% (thermal).
Design Lifetime: 20-30 years.
Construction and Delivery Timeframe: 24-48 months for large generation systems (construction only). Construction of solar ponds requires large quantities of earth to be moved along with the installation of piping and pumps for water and brine movement. Variations in construction time are largely dependent on pond size.
Development Status: Commercial (salt-gradient).

COST INFORMATION ($US)
Capital and Installation:
* 5175/kWe (electricity) (1983 dollars).
* 9.5-42.7/m2 (thermal) (1986 dollars).
Non-fuel Operating and Maintenance: $0.064/kWhe(electricity) (1983 dollars); $0.58/m2 (thermal) (1986 dollars). Salt costs, if purchased - $0.04/kg (1986 dollars).
Fuel: None.

ENVIRONMENTAL CHARACTERISTICS
Waste Streams: Dilute brine. Salt pollution due to pond leakage is a potential hazard.
Air Pollutants: None.
Carbon Emissions: None.
Site Specific: Preparation of solar pond systems involves the disturbance of large quantities of land, which may bring negative impacts to habitats. Evaporation ponds are high in salt content and can pose a salt encrustation threat to waterfowl. There are risks of leakage, which would contaminate land and/or ground water with salt.
Emissions Retrofit Potential: None.

IMPLEMENTATION REQUIREMENTS (LABOR AND INFRASTRUCTURE)
Operating Personnel:
1 full-time operator (250,000 m2 pond);
1 part-time operator (smaller ponds).
Maintenance Personnel: Periodic maintenance crews.
Infrastructure Requirements: Salt and fresh water availability are important considerations. Land area requirements are as follows:
24-48 ha/MWe (base-load electricity generation);
4-12 ha/MWe (peaking electricity generation).

2.2.4 Resources
International Solar Energy Intelligence Report
Business Publishers, Inc.
951 Pershing Drive
Silver Spring, MD, 20910-4464
Phone: (301) 589-5103.
Internet: (E-mail); bpinews@bpinews.com;(World Wide Web)
The Solar Thermal Design Assistance Center and the National Solar Thermal Test Facility

The Solar Thermal Design Assistance Center and the National Solar Thermal Test Facility are operated by the Sandia National Laboratory for the U.S. Department of Energy to assist in the development and application of solar thermal power systems.

The Solar Thermal Design Assistance Center provides a variety of services to organizations, business, agencies, and individuals who use, develop or manufacture solar thermal technology. The Center provides assistance to manufacturers of solar thermal and/or related products to reduce the cost and/or improve the reliability of products.

The National Solar Thermal Test Facility researches, develops, and tests solar thermal components and systems. The Facility also conducts tests on other technologies where intense thermal flux is needed. The Facility's large-scale solar concentrators can also be used for optical experiments such as astronomy and laser applications.

Use of either the Solar Thermal Design Assistance Center or the National Solar Thermal Test Facility by the government or private sector is on a first-come, first-served basis. For more information, contact:

Solar Thermal Design Assistance Center
Solar Thermal Technology Department
Attn: David Menicucci
Sandia National Laboratory, Mail Stop 0703
Albuquerque, NM 87185-5800
Phone: (505) 844-3077; Fax: (505) 844-7786
Internet: (E-Mail) dfmenic@sandia.gov
(World Wide Web)
http://www.sandia.gov/Renewable_Energy/solarthermal
2.2.5 Summary
The use of solar energy and salt ponds is in its infancy. However there are enough examples of working operations to suggest that a similar project may be possible at Toolibin Lake. The advantages are that energy would be generated in an environmentally friendly way; research results generated from the project would be useful for rural communities and may provide a cost neutral method of providing local employment and community interest. The cost of generating electricity by this method is in the same region as commercial rates.
3 Disposal of Salt and Brine

3.1 Review of Salt production in Western Australia

Western Australia is a major producer of salt in the world. Most of this salt is produced by the evaporation of seawater to produce sodium chloride crystals. The major producers, based on the northwest coastal fringe, do not sell much salt into the domestic salt market although some is sold from time to time. The majority of the salt produced along the northwestern coast is shipped to Asian markets for use in chemical and manufacturing industries.

The majority of the domestic salt market in Western Australia is supplied by WA Salt. A moderate sized salt producer based in Perth, WA Salt produces salt evaporated from natural brines in two salt lakes. Lake Deborah produces 120 000 tonnes of salt while Pink Lake near Esperance produces 15 000 tonnes of salt per year. Most of this salt is sold for industrial chemical production (chlorine-caustic soda). Except for a small amount of salt brought in from the eastern states for table salt, the remaining salt producers are small agricultural enterprises taking advantage of a local salt lake to produce a low grade salt for stock feed, hide and tanning salt.

3.2 Review of Technical Issues concerning Salt Production

Salt production utilises evaporation to remove $H_2O$ from brines to concentrate the salts in solution to saturation. The composition of seawater is given in Table 8.

Table 8 Composition of Seawater (g/L) (Bassegio 1974)

<table>
<thead>
<tr>
<th>SG</th>
<th>Ca</th>
<th>SO4</th>
<th>Mg</th>
<th>Cl</th>
<th>K</th>
<th>Na</th>
<th>Br</th>
<th>Total Salts</th>
</tr>
</thead>
<tbody>
<tr>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
<td>g/l</td>
</tr>
<tr>
<td>1.0247</td>
<td>0.418</td>
<td>2.708</td>
<td>1.296</td>
<td>19.240</td>
<td>0.389</td>
<td>10.740</td>
<td>0.067</td>
<td>35.0</td>
</tr>
</tbody>
</table>

As the water is evaporated from the brine, salts start to precipitate. There are a number of minor salts that precipitate from the brine but the major salts in the range of salinity considered in this project are calcium sulphate and sodium chloride. Figure 1 shows the percentage of these salts precipitated at increasing salinity. Salt producers normally try to concentrate brine up to sodium chloride saturation in ‘concentrating’ ponds so that the specialised ponds for sodium chloride crystallisation or ‘crystallisers’ have minimal contamination from gypsum, an impurity of salt production. Sodium chloride crystallises out of concentrated seawater at a SG of 1.218 or 332 g/L. As the brine continues to concentrate and sodium chloride forms crystals on the floor of the crystalliser, the magnesium concentration increases. By the time that the brine has reached a SG of 1.25 or 360 g/L it is normally considered uneconomic to continue using the brine for ‘salt’ production. There are some notable exceptions to this rule and some fields go as high as 1.275. The problem with the high salinity is that the sodium chloride crystals become smaller and evaporation of such a high salinity brine falls rapidly. ‘Drift’ salt forms on the surface and brine retention in the product escalates the magnesium concentration. Mechanical problems in physically removing the salt from the crystallisers may also become an issue.
In a properly maintained crystalliser, the salt forms a hard pavement on the floor of the crystalliser. Specialised machinery is then used to ‘harvest’ the salt and deposits it into either a conveyor or trucks to transport to a stack; or the salt is placed in windrows that are picked up and transported by truck to a stack. This step is important, as the design of the crystallisers can determine the method of harvest and therefore the quality and cost of harvest.

Once harvested, the salt is normally washed in a saturated brine to remove impurities in a solid form and then stacked in a manner that allows the soluble impurities to drain to waste. This waste stream is potentially a pollutant source for the environment.

Even washed salt has only a limited retail market while in bulk. It is possible to sell to the wholesaler or bulk user in this form but the price is reduced. To retail the salt, it would normally have to be at least bagged into 25 kg bags.

The stock feed, hide, pool and water softener salt is normally sold as drained in a wet form with 3-5% moisture. Textile and skin salt has to be dried to less than 0.1% moisture. The salt is normally dried in a gas fired rotary kiln. Pool and water softener salt is often partially dried to facilitate screening when producing a consistent product size. Before bagging, the skin salt has 1% sodium fluoride and 1% boric acid added. The process of producing the various grades of salt is shown in Figure 2.

---

2 The section of the graph from 350 to 480 grams is represented by only one point making the curve more linear than it should be in practice. This section would be better represented by a logarithmic curve.
Figure 2 Schematic Diagram of Production of Salt (Aries 1996)
Between the salinity of 330 and 360 g/L roughly 76% of the sodium chloride is precipitated and sodium chloride represents about 80% of the total dissolved salts in brine at 330 g/L. This means that the process of salt production extracts about 61% of the total dissolved salts from seawater type brines.

The remaining brine is a byproduct known as bitterns. Most salt fields would discharge this brine under licence to either the lake that the brine was taken from or the ocean. These options do not seem viable in the case of Toolibin Lake. Bitterns has value as a road base additive or dust suppressant once it has a TDS over 480 g/L. This dust suppressant represents only two percent of the initial brine volume.

The breakdown of the salt balance from the brine is illustrated in Table 8. A small percentage of the dissolved salts will precipitate in the concentrators. The bulk of the salts will form in the crystallisers and be in the useable form of NaCl. A significant proportion of the salt in solution is in the brine after the useable sodium chloride has been crystallised. If the brine is evaporated to road base stabiliser then 16% of the salts as poor quality sodium chloride will be precipitated, preferably not in the crystallisers but a purpose built enclosure. The remaining fifth of the original dissolved salts can then be on-sold as road base or dust controller. It is important to remember that these calculations do not include seepage, which may be significant. Industrial experience has placed this at 10% of the total salt intake.

### Table 9 Salt Balance in Brine

<table>
<thead>
<tr>
<th>Salinity Range</th>
<th>Predominate Salt</th>
<th>Percentage of Total Salts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salts Precipitated between 49 and 331 g/L</td>
<td>Gypsum</td>
<td>3.6%</td>
</tr>
<tr>
<td>Salts Precipitated between 331 and 359 g/L</td>
<td>NaCl</td>
<td>60.0%</td>
</tr>
<tr>
<td>Salts Precipitated between 359 and 480 g/L</td>
<td>Impure NaCl</td>
<td>16.4%</td>
</tr>
<tr>
<td>Salts Remaining in Bitterns at 480 g/L</td>
<td>Magnesium salts</td>
<td>20.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

3 These calculations are based on a brine similar to sea water composition as reported by Baseggio (1974). Other authors have reported similar figures but there are minor variations. In practice these figures will provide useful indications of salt production within the context of natural variation. The estimates do not consider seepage which constitute a loss of brine back into the water table. Seepage may be in the region of 10 to 20 percent of total salts pumped into the system.
3.3 Production of Salt at Toolbin Lake

The conceptual production of salt has been covered in Aries Pty Ltd. (1996). The Aries Pty Ltd. (1996) report provides a useful summary of the technical issues with one important exception. actis Environmental Services and WA Salt have considerable experience in the technical aspects of salt production and it is their belief that the ‘K’ factor used to estimate the effective evaporation of saturated brine from freshwater Class ‘A’ pan evaporation underestimates the evaporation and therefore salt production for the area. Because of this discrepancy, it was decided to repeat the production estimates in this report.

Salt is deposited as a function of evaporation of saturated salt solution. There are a number of parameters such as humidity, wind velocity, ambient temperature and solar energy that influence the evaporation rate. For the same meteorological conditions, evaporation reduces with increasing salinity. The composition of the brine also has an effect, in particular the magnesium concentration of the brine. The estimation of the evaporation of brines is a very complex science but fortunately there are some industry-accepted standards that allow a reasonable estimate of the salt production from Toolbin region.

The first step is to convert the BOM Class ‘A’ evaporation pan figures for the Narrogin PO to a large water body evaporation rate. A large water body evaporation rate is roughly 70% of the evaporation rate in a Class ‘A’ evaporation pan used in all present day official meteorological stations in Australia. The reduction is due to the localised effect of a large water body increasing the local humidity. The next step is to estimate the reduction of evaporation due to salinity. The effect of salinity on the evaporation rate can be negligible in low salinity brines, to actually having a negative relative evaporation for hydroscopic magnesium rich brines. There are formulas for conversions but they are conditional on a number of factors. For brines with seawater-like composition, in the range of salt saturation to the release of the waste stream (called bitterns) an average reduction of 70% in evaporation rate is considered a reasonable estimate. Therefore the reduction in evaporation due to pond size and salinity is 49% of a standard Class ‘A’ pan evaporation rate.

According to the tables provided by Baseggio (1974) 0.355 tonnes of sodium chloride are deposited for every kilolitre of water evaporated. This can be converted to a production rate for Narrogin (Toolbin Lake). The results are presented in the following table (Table 10) showing that a hectare of crystalliser at Toolbin Lake is likely to produce 1000 tonnes per year of salt. It is estimated that the months of May, June, July and August are months of negative evaporation. September is a month of break-even evaporation while the rest have a positive evaporation. It should be emphasised that these figures are estimates using averages and should only be used as indications. For simplicity, only the saturated brines are considered. It is quite likely that the low salinity brines would still have a positive evaporation during September and some of the winter months.
The following Table 10 lists the approximate volumes of brine expected to be pumped through the salt field, and salt mass dissolved and precipitated.

### Table 10 Relative Volumes of Brine at Toolibin Lake

<table>
<thead>
<tr>
<th></th>
<th>Volume kL/year</th>
<th>Salinity g/L</th>
<th>Total Salt Pumped kg</th>
<th>NaCl Precipitated Tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake</td>
<td>134000</td>
<td>49</td>
<td>6615894</td>
<td></td>
</tr>
<tr>
<td>Maiden Brine</td>
<td>18872</td>
<td>331</td>
<td>6248413</td>
<td></td>
</tr>
<tr>
<td>Bitterns</td>
<td>6576</td>
<td>359</td>
<td>2358588</td>
<td>3890</td>
</tr>
<tr>
<td>Dust Supressant</td>
<td>2700</td>
<td>480</td>
<td>1295859</td>
<td>1063</td>
</tr>
</tbody>
</table>

3.4 Scenarios

Three scenarios have been considered for the production and disposal of salt at Toolibin Lake. The scenarios can be defined as follows.

**Scenario one**
Under this scenario a complete salt field plus refinery is built. The salt would be grown on the site, harvested, washed, dried, crushed and screened before being bagged into predominately 25 kg bags. The aim of the project would be to sell as much of the salt as a refined product as possible. Scenario one needs a very large capital injection. Salt for human consumption was not considered, as the level of quality assurance required is much higher, as is the initial capital. The production of salt for human consumption is best considered by an enterprise after it has expertise in the production of salt for other markets.

**Scenario two**
This scenario does not include value adding the salt. The salt is grown in a crystalliser and a third party harvests and buys the salt at a bulk unwashed rate. The capital for this project is minimal. The primary objective is to convert the brine into salt and then divest the disposal of the salt to a third party.

**Scenario three**
This scenario is really midway between the scenarios above. As in scenario one, the salt is harvested and washed but is not refined by drying and screening. This reduces the need for capital but also reduces the markets for the salt.

3.5 Summary

Toolibin Lake Salt Producer is located to sell salt into the wheatbelt region of Western Australia. The main salt products that Toolibin Lake Salt Producers could sell are skin salt, hide salt and stock salt with potential for water softener and pool salt. Another non-salt product that might be provided by Toolibin Lake Salt Producers is bitterns, which can be used as road base consolidator, dust control and pasture fertiliser.

3.5.1 Market Potential

After detailed discussion with existing salt producers, it was decided that scenario one has a limited market and that market share would only be gained by price cutting, which is unlikely to benefit a new producer with a high capital cost such as Toolibin Lake Salt Producer. The largest user of a refined salt not for human consumption is the skin market, which is on a downward trend. It is a relatively volatile market.
Scenario two is based on an existing offer from WA Salt, so the market is defined. The risk is that WA Salt may withdraw from, or at the end of a contract decline the option of continuing to buy the salt. Otherwise it is the most stable marketing solution.

The third scenario involves producing a partially refined salt product principally for the pool market. This market is an expanding one but tends to attract small buyers only. This creates difficulty in distribution and sales. Again the capital cost is very high and the market place is open to competition from WA Salt and others.

3.5.2 Profitability
Using the assumptions described at the end of this document, the profitability of each venture has been calculated (Table 11). For greater detail see the financial lists at the end of the document. From this analysis it can be seen that only the third scenario makes an annual profit. Scenario two is essentially break even while scenario one makes a loss.

Table 11 Annual Profitability and Unit Profit for the Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Profit before tax</td>
<td>-$105,582</td>
<td>$1,713</td>
<td>$2,834</td>
</tr>
<tr>
<td>Final Profit per tonne</td>
<td>-$26.40</td>
<td>$0.37</td>
<td>$1.11</td>
</tr>
</tbody>
</table>

3.5.3 Risk
In terms of profitability prediction, scenario two is most likely to be accurate. Both of the other two scenarios’ profitability are much more sensitive to engineering blow outs and delays. They are also much more sensitive to competition from WA Salt and other competitors, and the relative skill of the managers of the salt venture. Competition would have the effect of reducing the price even to the level of making scenario three unprofitable. Scenario two has a much lower risk factor.

The risk of not getting a mining lease over the area is real, but it is thought unlikely that a lease large enough for salt production will be refused by the holders of the exploration license.

Another unknown is the compatibility of the two objectives, namely reducing the groundwater salinity and running a profitable salt industry. There is a distinct possibility that the groundwater interception will be successful in reducing the salinity within the next ten to twenty years. In this case the production levels might fall decreasing the profitability of scenarios one and three in particular. Again scenario two is the most stable solution, as the annual production rate is not critical to selling the salt.

3.6 Residual Salt after NaCl Production
As mentioned in the preceding section, the removal of sodium chloride from brine leaves a solution commonly called ‘bitterns’. This material has a high concentration of magnesium salts and a proportion of sodium chloride salts.

Bitterns needs to be stored in a bunded area for further evaporation after being decanted from the sodium chloride crystallisers. This further evaporation can only be completed during the high evaporation months. After evaporating to a SG of 1.300, a major proportion of the remaining sodium chloride is precipitated out and the bitterns can be sold as road base stabiliser or dust suppression liquid. The product retails for anything between ten and fifty cents per litre depending on the level of product support. It is commonly used at a rate of 1 litre per metre square.
Recommended reading on the technical and environmental aspects of using magnesium chloride or bitterns as a road stabiliser, are Kirchner 1988, Bressler 1986, and Goldern 1991. The product has low toxicity to the people applying the mixture and minimal environmental impact, at least less than the dust from the roads. The road surface needs to be roughened by grading or scarifying to allow penetration of the liquid. After the surface has been compacted the road is ready to be driven on straight away. Bitterns can be applied directly by a water truck without roughing and subsequent compacting, but it is not as effective. Independent studies by various public works organisations in the USA have shown that $\text{MgCl}_2$ brine is a cost effective method of reducing dust from gravel roads and ongoing maintenance costs.

A company called Rainstorm, which has an agency in Western Australia, currently sells a small amount of bitterns trucked down from Dampier. There is little sodium chloride left in the brine and it has no harmful environmental effects. In fact, bitterns is sold as a natural fertilizer in some states (Queensland, NSW). Its main market is as a dust suppressant in mines and on dirt roads. Potential customers are rural shires and mining companies.

Alternatively a process can be undertaken to produce magnesium sulphate salts from the bitterns which have a high market value. A business plan has been produced for magnesium sulphate production but the technology is developmental.

There is no doubt that there is real potential to replace imported Magnesium Sulphate with material produced at the Toolibin Lake mine site. The annual amount of Magnesium Sulphate imported into Australia is about 2,000 tonnes whereas a conservative estimate of the production from Toolibin Lake would be in the region of 600 tonnes. The current price (if it were not compromised by a price war) would make the proposed business profitable at $82,000 before tax. Once production was started it would take a further year to break into the existing markets.

The main risk to the proposed venture is translating the researched process technology to the commercial production of a suitable grade of Magnesium Sulphate for the agricultural market. At this stage it has not been possible to produce a 99% pure Magnesium Sulphate grade, and only a 75% pure product has been made. This does not preclude the sale of this product at the present quality but it does raise some serious questions about potential markets.

The proposed venture has synergy with the current sodium chloride operation that has been operating and expanding for a number of years. The NaCl salt remaining in the bitterns pond would not be suitable for sale except as a very low grade product. An alternative is to re-dissolve the salt crystals during winter rains or pump low salinity brines onto the pan after the dust suppressant material has been harvested. The resulting brine makes very good feed brine into the crystallisers after it has reached sodium chloride saturation again.

In this manner all of the saline brine recovered from the saline groundwater has been converted to a saleable product. The return may not be substantial but is expected to be cost neutral. It should be noted that none of the analysis has taken into account the cost of the bore infrastructure or operational costs.
4 Summary

4.1 Extraction of Salt from the System
The cost of intercepting the saline ground water as proposed by this report and within
the limitations detailed, is expected to be in the region of $130 000 to $250 000. The
running cost per annum without maintenance is in the region of $10 000. This cost has
not been included in any economic analysis of the separate ventures. The reason for
this is that the benefit of reducing the water table is a public benefit. No single
business venture would want to cover this cost as the benefits extend past the
commercial regime. A business venture may be convinced to partially pay for the cost
via rent or lease. Basically if business was required to pay the relatively high cost of
pumping the brine from underground, they would seek suitable sites in other locations.

The recommended locations of the bores have been determined using the limited
hydrological knowledge and the discovery of palaeochannels beneath the Lake. In the
end, only drilling the holes and test pumping will give a good indication of the aquifer
characteristics. This would be a prerequisite before constructing a commercial
saltfield.

The brine should be pumped into a holding pond of moderate size to buffer the
downstream users from fluctuations in supply of brine. The dissolved metal ions
would have a chance of precipitating out in this holding pond, reducing the chance of
contaminating aquaculture production.

It has been noted in the process of reviewing the groundwater hydrology that there has
not been a comprehensive review of the environmental implications of drawing down
the groundwater, on the functions of Toolibin Lake, either biological or hydrological.
Since this was not an objective of this report it has not been pursued. CALM will
undoubtedly wish to monitor the effects of groundwater pumping and manage the
quantity discharged. This leads to a potential conflict between the objective of
protecting Toolibin Lake and the commercial objective of producing salt.

4.2 Removal of Salt
Three scenarios were investigated for salt recovery. Two involved value adding on
site. One scenario involved selling bulk salt to WA Salt Supply, who would truck the
salt to their Robbs Jetty refinery. None of the scenarios were commercially attractive
and were at best cost neutral. The recommendation is for the bulk sale of the salt to
WA Salt. There are a number of reasons for this recommendation.
• The capital infrastructure is much less for this option.
• The risk to the producer due to competition is much less.
• The sale will be under contract and the income assured.
• The option of selling refined salt has not been precluded at a later date.
• More salt is removed from the area (15%)
• There is no guarantee that the supply of saline brine will continue for the life of a
salt field (20 years plus) and the less capital infrastructure the less risk.

The cost of harvesting and buying price for the salt used in the business plan do not
preempt commercial discussions with WA Salt.

The option of using plastic membrane on the base of all the ponds is not a
commercially viable option. This report does not discuss the design in any detail but at
a rough cost of a dollar per square metre the construction of a 35 ha (350 000 m$^2$) salt
field with plastic membrane covering the floors adds to the already substantial cost.
Preliminary estimates place the cost of fully lining a pond at $30 000 to $40 000 per hectare. A survey by Agaria has shown that there are substantial clay deposits in the area of the proposed salt field. On site surveys indicated that the clay is not superb material but should be adequate for a saltfield. All banks should be cored with clay as a matter of course without even considering the sensitive nature of the site. If further precautions are needed the banks could be cored with plastic membrane at a later date or interception ditches dug between the saltfield and the Lake. These techniques have been used with success in other areas.

The salt field should be designed as described by the report Aries (1996). It is recommended that the concentrating ponds be divided into five ponds with a smaller number of crystallisers. The holding pond may be used as a source of brine for the aquaculture venture. The waste brine from the aquaculture ventures could be pumped into the first concentrator. The salt field should be used as a source of brine at the correct salinity for aquaculture. Once most of the salt has been precipitated, the remaining brine should be pumped into the bitterns pond for further evaporation. This product can be marketed as a separate commodity. The poor quality salt in the bitterns pond can be recycled back into the concentrators.

This concept of the salt field uses all of the saline water in a break-even manner. There is low risk. The only source of environmental pollution is seepage and this can be controlled.

4.3 Value Adding to the Process

The value adding process was seen to be principally the aquaculture ventures. All three ventures, Black Bream, Pink Snapper and Brine Shrimp are potentially commercially viable. There is a high level of risk in all of these ventures but they potentially could return much more than the salt field. All require a saltfield to provide a source of clean brine and to act as a receiver of high nutrient brine outflow. Without a salt field the environmental pollution from these ventures could be significant or at least costly. There is a significant amount of synergy between the ventures with the brine shrimp filtering the waste from the fish culture and, in turn, acting as a feed source for the smaller fish.

It is recommended that investors be encouraged to culture finfish on site using the brine stream to the saltfield. Brine shrimp could be cultured by the same venture but it is likely that it will develop as a separate venture due to the specialist expertise needed.
4.4 Social Cost/Benefit

The social cost/benefit of any venture must be balanced against not doing anything. If nothing is done to improve the situation it is expected that Toolibin Lake in particular will continue to deteriorate, as will other lakes in the region. A natural habitat that is already rare in the region will disappear. A previously undescribed species of Halosarcia was recently found in the local area and it is unknown whether further populations will be found. Farmland will increasingly be lost to salt scalds and the social amenity of the area will deteriorate.

The costs and benefits of intercepting the saline groundwater have been listed and are itemised in Table 12. It was not possible to be specific about the costs and benefits as it is unknown what ventures would be undertaken and which expenditure will be supported by private interests. It is known that it will cost about a quarter of a million dollars to install the bores listed in this report and that the operation of the bores would be in the region of $15 000pa. In return there will be a rental or lease amount for the ventures that are started and this cost should at least cover the operating cost of the bores. The other financial benefits will mainly be accrued to the community in general. For instance if a saltfield and finfish farm is started, up to ten people may be employed and the wages would be spent locally. The maintenance and service industries would also benefit from these ventures with the so-called multiplier effect generating expenditure in the local communities.

**Table 12 Cost/Benefit of recovering saline groundwater**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial Infrastructure $250,000</td>
<td>Rental/Lease Unknown</td>
</tr>
<tr>
<td>Annual operating cost $15,000</td>
<td>Large capital investment of potentially up to two million dollars</td>
</tr>
<tr>
<td></td>
<td>Large unspecified turnover of monies due to wages, maintenance and secondary investment</td>
</tr>
<tr>
<td></td>
<td>Increased tourism and indirect growth</td>
</tr>
<tr>
<td>Environmental</td>
<td>Increased bird habitat</td>
</tr>
<tr>
<td>Potential introduction of exotic species</td>
<td>Toolibin Lake Recovery</td>
</tr>
<tr>
<td>(direct/indirect)</td>
<td>Taarblin Lake Recovery?</td>
</tr>
<tr>
<td>Industrialisation next to reserve (noise,</td>
<td>Removal of salt</td>
</tr>
<tr>
<td>aesthetics, traffic)</td>
<td>Protection of wetland diversity</td>
</tr>
<tr>
<td>Possible salt leaks</td>
<td></td>
</tr>
<tr>
<td>Risk of chemical spillage</td>
<td></td>
</tr>
<tr>
<td>Social</td>
<td>Slowing loss of farmland downstream</td>
</tr>
<tr>
<td>Loss of farming land for industry</td>
<td>Reduced groundwater level and salinity in immediate area</td>
</tr>
<tr>
<td>Potential loss of agricultural production</td>
<td>Direct employment of ten plus</td>
</tr>
<tr>
<td>bores</td>
<td>Research and development initiative</td>
</tr>
<tr>
<td>Risk of fire from transmission lines</td>
<td>Local investment of a million dollars plus in a range of ventures</td>
</tr>
<tr>
<td>Risk of financial failure</td>
<td>Revitalisation of rural community</td>
</tr>
<tr>
<td>Increased heavy traffic</td>
<td>Leaders in active remediation of saline land</td>
</tr>
<tr>
<td></td>
<td>Encouraging new research and development initiatives</td>
</tr>
<tr>
<td></td>
<td>Demonstration of new rural industries</td>
</tr>
<tr>
<td></td>
<td>Focal point for salinity management</td>
</tr>
<tr>
<td></td>
<td>Community identification in ‘solving’ a problem</td>
</tr>
</tbody>
</table>
The environmental costs and benefits in Table 12 are mostly self explanatory and have been discussed elsewhere. One issue is that permanent water in the salt field will attract wading and estuarine birds to the area that may not have there in large numbers before. This may be considered a benefit and a cost.

The social costs and benefits of the new ventures are also listed in Table 12. Most of the benefits and costs are associated with the previously mentioned fiscal and environmental issues. A particular social issue is that of the community identifying with the solution to a problem that affects all of them. Being part of a solution is a positive social advantage and benefits the entire community.

The social issues described above are only meant to be an outline of the potential issues. For a more comprehensive analysis the proposed project needs to be reviewed by the community with an invitation for constructive comments.

4.5 Application to Other Areas
Most of the information generated in this report is directly applicable to other areas. Some items may be changed by distance to main regional and state centres.

In terms of market share the number of identical concurrent ventures is more important. The market for cultured fish and brine shrimp will change with a large number of producers. It will still be possible to sell the fish and shrimp but it will be at a lower price, or with more effort into overseas markets, or a combination of both. It may be possible to expand some of the fish/brine shrimp markets.

The most sensitive market however is the salt market. It is not an expanding market and in some sectors it is actually contracting. Less than 50 000 tonnes is sold within the domestic/ business sector outside of the chlor-alkali industry in Western Australia. Supplying the other states with salt would not be possible because of transport costs and more competitive producers in those states. Export salt markets are covered by the much more cost-effective salt industries in the north of the state. As a result it is easy to conceive that the domestic market would become saturated with even a small number of new producers of 5 000 tonne capacity acting in direct competition to WA Salt. It is probable that there would not be a viable niche for even one producer if there was stiff competition from WA Salt. If salt is sold to the larger users in the chlor-alkali industry, there might be potential for up to six salt producers of 5 000 tonne capacity. It is difficult to see how this would happen without the support of WA Salt.
5 Reference and Bibliography

5.1 Parartemia and Artemia

McVey, James P., CRC Handbook of Mariculture, Volume 1, Crustacean Aquaculture.


Sorgeloos, P., High density culturing of the Brine Shrimp, Artemia salina L. Aquaculture,1 (1973) 385-391


Sorgeloos, P., Tackaert, W., The Use of Brine Shrimp Artemia in Biological Management of Solar Saltworks, Seventh Symposium on Salt Volume 1, 617-622 (1993)

5.2 Fin Fish Culture


Doupe, R and J Alder (1998) “An overview of environmental management guidelines for prospective and established participants.” Centre for Ecosystem Management Edith Cowan University Joondalup, Western Australia

EPA Guidelines for Aquaculture Proposals


Morrissy, N.M.(1992) An introduction to marron and freshwater crayfish fanning in Western Australia Fisheries Department of Western Australia.


5.3 Alage


Denham, R., Market Review of seaweed derived products in Australia and overseas: Opportunities for Western Australia. AgWA Narrogin.

5.4 Hydrological


George, Richard J, personal communication


George, R.J., and Bennett D., 1995. Toolibin groundwater management Program. Drilling results, Report to CALM, Unpublished AgWA.


Sinclair Knight Merz, 1999. Groundwater model of the effects of groundwater pumping on Toolibin Lake. Unpublished draft report to CALM, WA.

Smith, Amanda CALM, personal communication

5.5 Salt


Kirchner H.W. 1988; Road Dust Suppressant Compared, December 1988.

5.6 Solar Energy


5.7 General


Clarke, J.D.A.,1994; Lake Lefroy, a paleodrainage playa in Western Australia, Australian Journal of Earth Sciences 41, 417-427.


Dell et al, 1988; The Biological Survey of the Eastern Goldfields of Western Australia, Part 5 Eujudia- Menzies Area; Western Australian Museum, Australia.


Geddes, M.C., De Deckker, P., Williams, W.D., Morton, D.W. and Topping, M., 1981; On the chemistry and biota of some saline lakes in Western Australia; Hydrobiologia 82, 201-222.


Hill, A.J., Semeniuk, C.A., Semeniuk, V. and Del Marco, A., 1996; Wetlands of the Swan Coastal Plain Volume 2a; Western Australian Waters and Rivers Commission and Department of Environment.


Timms, B.V.1992; Lake Geomorphology; Gleneagles Publishing, Australia.

Wetlands Advisory Committee, 1977; The status of reserves in system 6, Report of the wetlands Advisory Committee to the Environmental Protection Authority, Perth, WA.


Wilson P., 1980; Chenopodiaceae; Nyutsia 3(1) WA Herbarium.