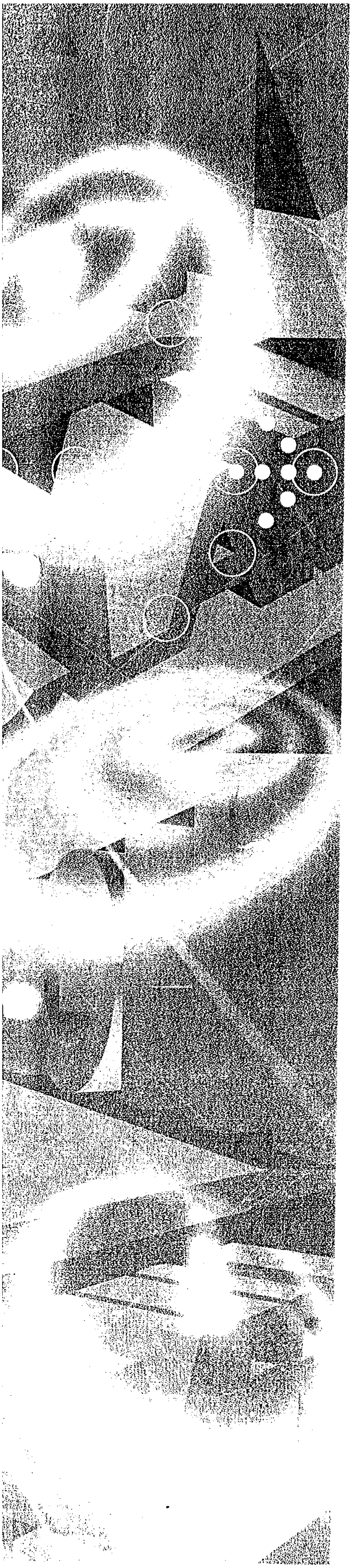

Stage V Development Proposal

Hydrogeology Experts Report - Author: Brian Barnett

Rev 4

July 2001

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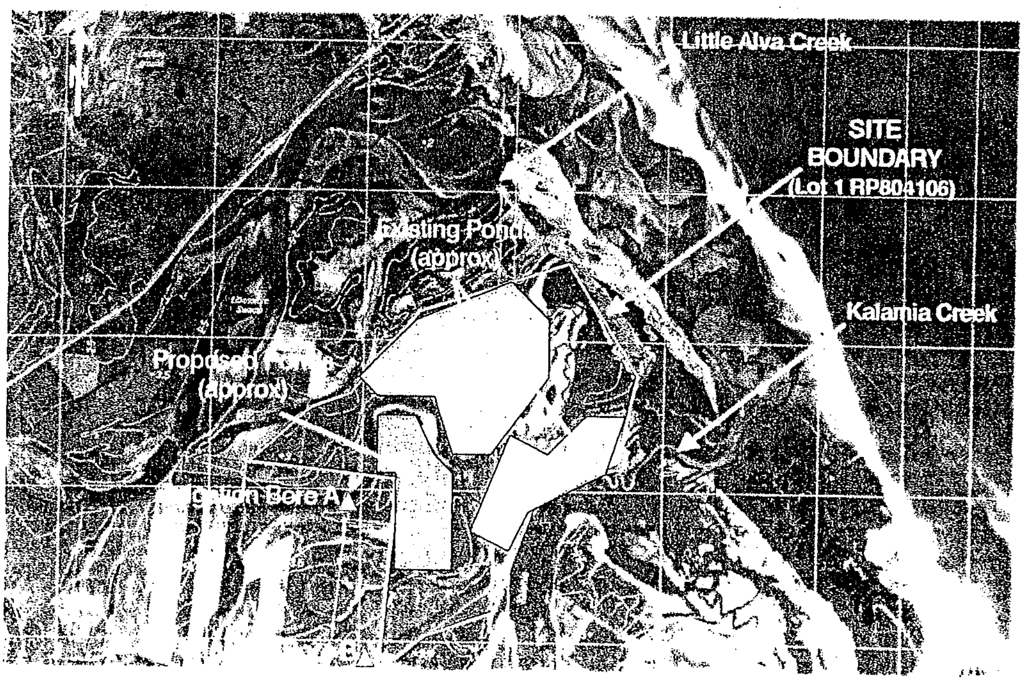
Expert Report by Brian George Barnett

1. Hydrogeological Setting

The Pacific Reef Fisheries prawn farm is located at the north western extremity of the Burdekin Delta. The fluvial and deltaic sediments and sand dunes that are found within the delta form a conductive aquifer that is used as a source of water for agricultural and domestic purposes including cane farming and potable water for the prawn farm itself.

At the Pacific Reef Fisheries property the aquifer is unconfined and consists of permeable sand and silt deposits up to 100 m thick with the water table typically 1.5 to 3.5 m below the ground surface. The hydraulic conductivity (a commonly used indicator of aquifer permeability) of the shallow sediments at the site is believed to be in the order of 5 m/day, a typical value for a medium-to-fine sand. Groundwater velocity is proportional to the hydraulic conductivity and to the local hydraulic gradient indicating local groundwater velocities of about 1.4 mm/day or 0.5 m/year in the natural state. Important hydrogeological features of the area (including approximate pond locations) are presented in **Figure 1**.

- **Figure 1 Hydrogeological Features of the Pacific Reef Fisheries Site**



In unconfined aquifers in coastal areas there is a hydrodynamic balance established between seawater and fresh groundwater systems. This balance is controlled by the density contrast of the fresh groundwater relative to the saline seawater. The lighter freshwater flows near the surface and is forced to discharge to the ground surface in the coastal margin, as it is unable to displace the denser heavier seawater. On the Pacific Reef Fisheries property, groundwater is discharged to the ground surface during times of high groundwater level through seeps and springs to adjacent

depression systems. Groundwater is also discharged in seeps found in the coastal dunes and on the shore line. The creeks and drains are of further hydrogeological significance in that they have good hydraulic connection to the aquifer and can therefore act as a portal to water entering or leaving the aquifer. In most cases they act as drains that receive discharging ground and surface water, however they may also become the source of local groundwater recharge at times of low groundwater level or when creek water levels are high (eg. at high tides).

As groundwater flows towards the coast the heavier seawater migrates inland beneath the freshwater through density driven hydrodynamic gradients. In this manner a wedge of salt water is formed that can migrate some distance inland. Extractions of fresh groundwater via pumping can promote the inland migration of the seawater wedge. Such extractions can also lead to an upwelling of the deep saline waters particularly near the pumping bores. Saline contamination of the freshwater aquifer can also arise when saline or brackish water from tidal streams, estuaries or lagoons flows into the aquifer (particularly at high tides). While this process can occur naturally it is often accelerated and magnified when groundwater is pumped from coastal areas.

Shallow bores within the Pacific Reef Fisheries property have been sampled and the analytical results indicate that the water salinity is in the range 800 to 2000 mg/l, thereby indicating that the shallow aquifer is already contaminated by saline water.

The nearest groundwater extraction bores to the proposed ponds are located on the Darwen property where it is understood that at least two bores are used for irrigating sugar cane. The approximate locations of the two irrigation bores are shown in **Figure 1**. It is understood that in order to supplement the groundwater supply and/or to reduce the water salinity, the groundwater is mixed with surface water before being applied to the crop.

2. Potential Hydrogeological Impacts of Saline Aquaculture.

The salt water ponds that have been constructed by Pacific Reef Fisheries are shown schematically in profile in **Figure 2**.

Figure 2 Schematic Cross Section Through a Pond

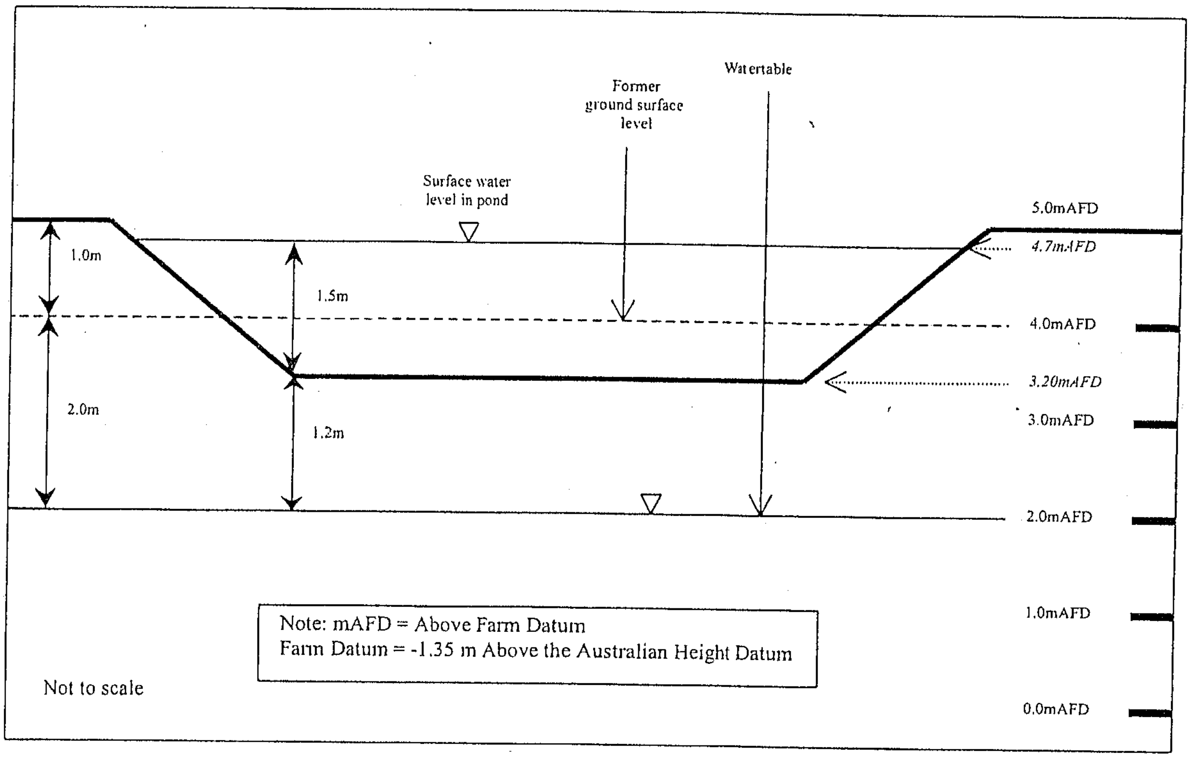


Figure 2 indicates that the saline water level in the ponds is approximately 2.7 m above the underlying groundwater head. The difference in water levels gives rise to the possibility that the saline water from inside the ponds may migrate through the pond liner and enter the shallow groundwater system.

The pond liner is constructed of compacted earth in which the natural permeability of the sediments is reduced through the reduction in pores that occurs during the compaction process. Under ideal conditions compaction of silts and clays may produce extremely small values of hydraulic conductivity in the pond liners. However the very nature of the packing of sediment particles precludes the possibility of removing all pores in the material to create a completely impervious flow barrier. While this type of liner is considered to provide effective sealing it is not possible to create a completely impervious pond liner. As such some salt water will inevitably seep from the ponds, albeit at low rates.

On entering the aquifer the salt water will tend to descend, it being heavier than the fresh groundwater, and migrate in the aquifer with the groundwater flow. Although the natural groundwater flow is generally towards the coast and away from neighbouring water users, if there is excessive seepage from the ponds, mounding of

the water table beneath the ponds may occur and may lead to minor quantities of saline water flowing in directions opposing and lateral to the natural groundwater flow direction. The nature of the groundwater flow patterns are shown schematically in **Appendix A. Figure A1** shows the relationship between the proposed ponds and the nearest bore, to scale. **Figures A2 to A6** show groundwater movement patterns for various combinations of development and groundwater use. It is important to note that **Figures A2 to A6** have exaggerated vertical scales relative to the horizontal scale.

To assess the significance of the various factors involved, numerical groundwater models have been developed to quantify the extent of seepage of saline water through the pond liners and the subsequent migration and dispersion patterns of the saline water once it enters the aquifer.

3. Numerical Modelling

Two different types of numerical models of the aquifer in the vicinity of the Pacific Reef Fisheries property have been developed.

3.1 Previous Modelling

A finite difference model was originally developed in the MODFLOW computer code. It was primarily aimed at determining leakage rates through the pond liner and subsequent fluxes of water in the aquifer across the property boundary to neighbouring farming properties. It provided a qualitative description of contaminant flow by means of flow path analyses. The results indicate that the flux through the pond liner is controlled by the thickness and hydraulic conductivity of the liner and that most of the saline water entering the aquifer will flow towards the coast. Only minor quantities of saline water are expected to travel beneath the property boundary to the surrounding sugar cane properties. The principal results of this investigation are reproduced here as Table 1.

- **Table 1 Predicted fluxes of saline water through pond liners and onto neighbouring properties**

Case	Flux Through Liner (m^3/day)	Saline Water Flux Across Western Boundary (m^3/day)
Case 0 No Ponds	0	0
Case 1 Existing ponds, liner 250mm thick, liner conductivity = $5x10^{-9}$m/s no irrigation pumping	3200	300
Case 2 Existing and proposed ponds, liner 250mm thick, liner conductivity = $5x10^{-9}$m/s with irrigation pumping	3753	485
Case 3 Existing and proposed ponds, liner 250mm thick, liner conductivity = $5x10^{-8}$m/s with irrigation pumping	4240	635
Case 4 Existing and proposed ponds, liner 250mm thick, liner conductivity = $5x10^{-10}$m/s with irrigation pumping	3265	345
Case 5 Existing and proposed ponds, liner 400mm thick, liner conductivity = $5x10^{-9}$m/s with irrigation pumping	3360	415
Case 6 Existing and proposed ponds, liner 250mm thick, liner conductivity = $5x10^{-9}$m/s no irrigation pumping	3670	395

The finite difference MODFLOW modelling package does not calculate density dependent flow and any assessment of migration and dispersion of salt water in the aquifer in this model is subject to uncertainty because of this limitation.

While SKM was reasonably satisfied that the MODFLOW modelling results indicate that widespread salt water contamination of the aquifer is unlikely, the concerns expressed by neighbouring groundwater users and by the appellants have been recognised. Accordingly, a second model was formulated utilising a more sophisticated modelling package that is capable of analysing density dependant groundwater flow and contaminant transport. This model has been developed and run in the finite element groundwater modelling code known as FEFLOW. It is a groundwater and contaminant transport model that calculates the migration and dilution of the salt water contaminant plume, taking into account the density differences between the fresh groundwater and the saline contaminant.

3.2 Density Coupled Contaminant Transport Modelling

The objective of the FEFLOW contaminant transport modelling is to calculate the leakage of salt water through the floor of the ponds and to estimate its likely travel once it has entered the aquifer.

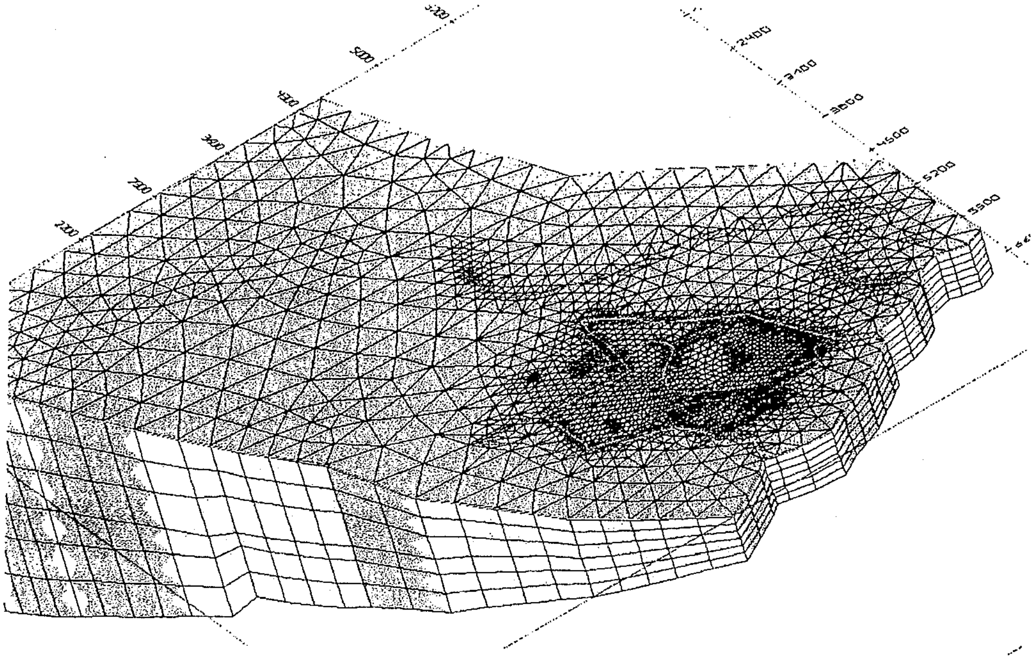
The model consists of 19192 nodes and 32963 elements in 7 layers extending from the level of the pond liner to the assumed base of the freshwater in the aquifer. The model structure is presented in **Figure 3**. The figure represents the layout of the nodes and elements included in the model in both isometric and plan views. It also shows the extent of the model and the vertical layering structure that has been adopted.

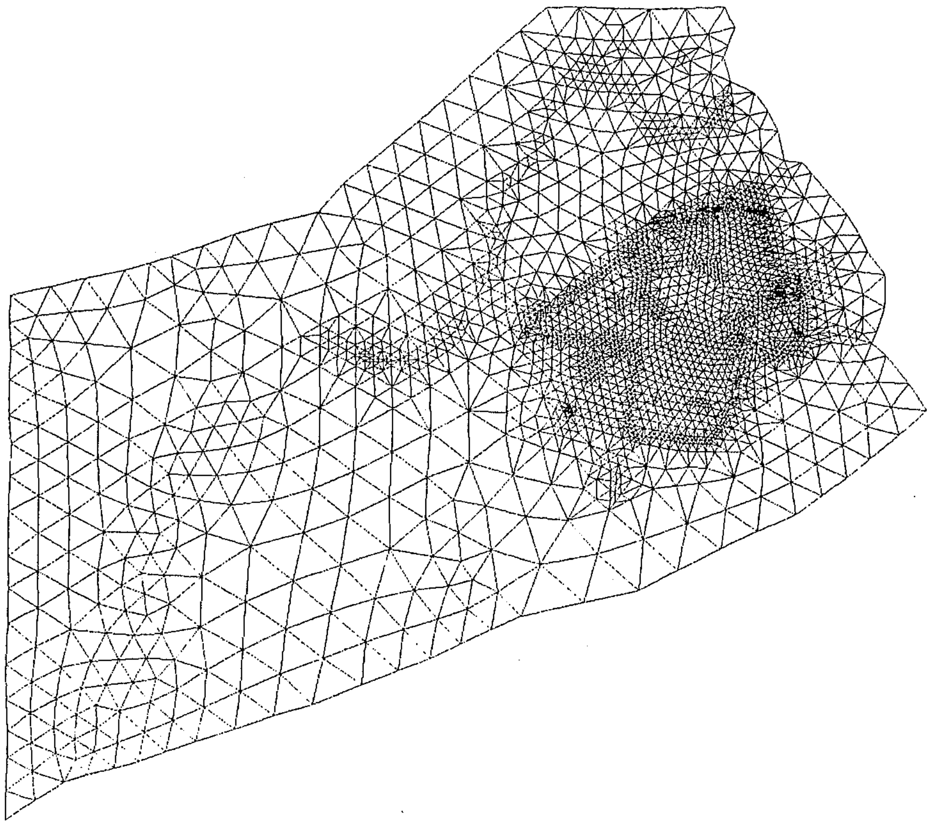
The model includes the following features:

- Constant head boundaries at the coast (equal to sea level) and at the upstream model boundary. Diurnal tidal fluctuations are not included.
- Constant head and constant concentration boundary conditions at the surface of the model to emulate salt water in the ponds.
- Density coupled flow calculation to account for the difference in density between salt and fresh waters.
- Pumping from two bores on the Darwen property to emulate typical irrigation pumping requirements. Because water extraction from the irrigation bores is not known, pumping rates for irrigation bores A and B were estimated by assuming that they irrigate 30 and 60 hectares respectively. Additional assumptions used to generate the pumping schedule for bores A and B are:
  - Sugar Cane requires an annual irrigation application of 12 megalitres per year per hectare.
  - Groundwater and surface water are used in equal proportions.
  - Irrigation is typically carried out over a ten day cycle from December to March and on a 25 day cycle for the remainder of the year.
  - The maximum possible pumping rate for each bore is 50 litres per second. The resultant pumping schedule used in the model is presented in **Figure 4**.
- Fully transient flow and transport calculations that include the effects of non-constant irrigation pumping and pond filling scenarios.
- Ponds are assumed to be full of seawater (salinity of 36,000 mg/l) for six months of the year.
- Monthly average rainfall, recharge due to excess irrigation and net evapotranspiration rates are included in the model.

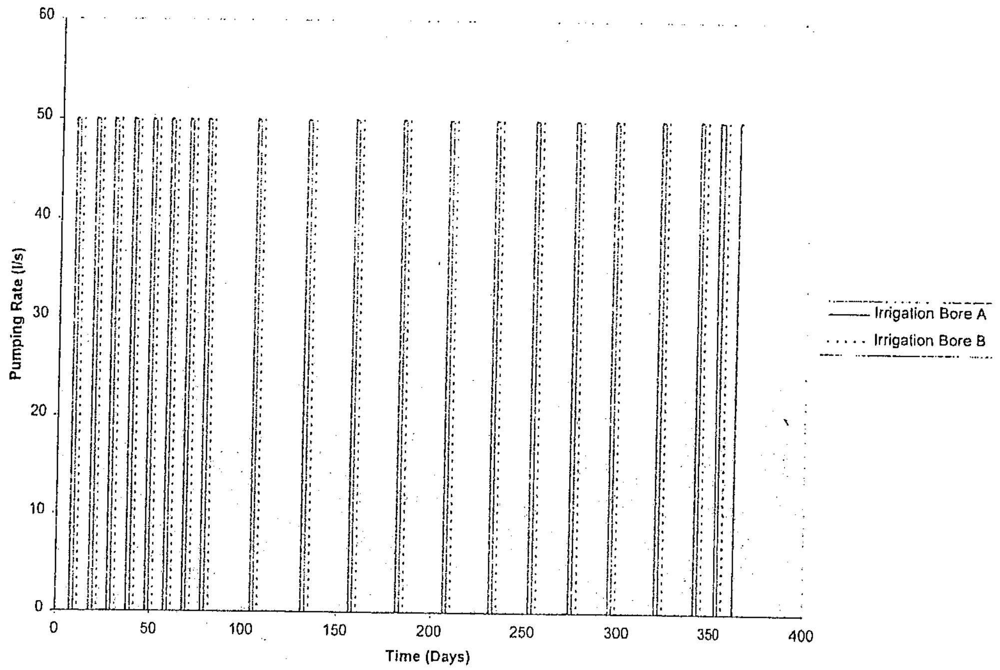
The models calculate the advection, dispersion and diffusion of contaminant in the pond liner and aquifer. Calculations are based on the boundary and initial conditions applied to the model, the hydraulic and contaminant transport properties assigned to the model nodes and elements and according to equations that describe water flow and contaminant transport in porous media.

- Figure 3 The FEFLOW Finite Element Grid





▪ Figure 4 Annual Pumping Schedule Used in All FEFLOW Models



Four separate models were run and are described below.

Scenario 1 - Existing Ponds with the Most Likely Hydrogeological Conditions
This model includes the existing ponds only with the most likely values of all hydrogeological parameters. It represents how the existing ponds have impacted on the local aquifer.

The model has the following features:

- Only existing ponds are included.
- Pond liner is 250 mm thick.
- The hydraulic conductivity of the pond liners is 5 E-9 m/s.

Scenario 2 - Existing and Proposed Ponds with the Most Likely Hydrogeological Conditions
This model includes the existing and proposed ponds with the most likely values of all hydrogeological parameters. It represents how the future ponds will impact on the local aquifer.

The model has the following features:

- Existing and new ponds are included.
- Pond liner is 250 mm thick.
- The hydraulic conductivity of the pond liners is 5 E-9 m/s. It is noted that a common environmental standard for pond liners is 1 E-9 m/s. Modelling of 5E-9 m/s as the hydraulic conductivity of the proposed pond liner therefore includes an inherent degree of conservatism in terms of the calculated rates at which salt water seeps through the pond liner.

Scenario 3 - Worst Case Scenario
This model includes the existing and proposed ponds with all hydrogeological parameters set to simulate the maximum leakage rate through the pond liner and to maximise the subsequent travel and dispersion of salt water in the aquifer. It represents the worst case of possible impacts on the local aquifer and neighbouring users.

The model has the following features:

- Existing and new ponds are included.
- Pond liner is 250 mm thick.
- The hydraulic conductivity of the pond liners is 5 E-8 m/s.
- Hydraulic conductivity of the aquifer increased by a factor of two.
- Hydrodynamic dispersion increased by a factor of three.

Scenario 4 - Worst Case Scenario with Remediation Drain
This model is the same as the worst case scenario model described above with the inclusion of a boundary drain aimed at intercepting saline water before it travels across the property boundary.

All models were run to 1000 days of simulation time with an initial groundwater salinity of 1200 mg/l reflecting the fact that the groundwater has pre-existing salinity.

3.3 Modelling Results

3.3.1 Leakage Volumes

The maximum flux of saline water through the pond liners for each of the scenarios is presented in Table2.

- **Table 2 Predicted seepage rates through pond liners for all modelling scenarios.**

Scenario	Description	Seepage Through the Pond Liner (m3/day)
1	Existing ponds	1064
2	Existing and proposed ponds	1315
3	Worst case of existing and proposed ponds	3286
4	Worst case of existing and proposed ponds with tile drain	3815

The predicted seepage rates are much less than those predicted by the MODFLOW model. The reason for the difference is that the MODFLOW models are run in steady state mode in which the ponds are continuously full and the irrigation pumping is assumed to be continuous. The FEFLOW models on the other hand are more representative of reality and are run in transient mode in which the ponds are filled for only six months of the year.

3.3.2 Contaminant Migration in the Aquifer

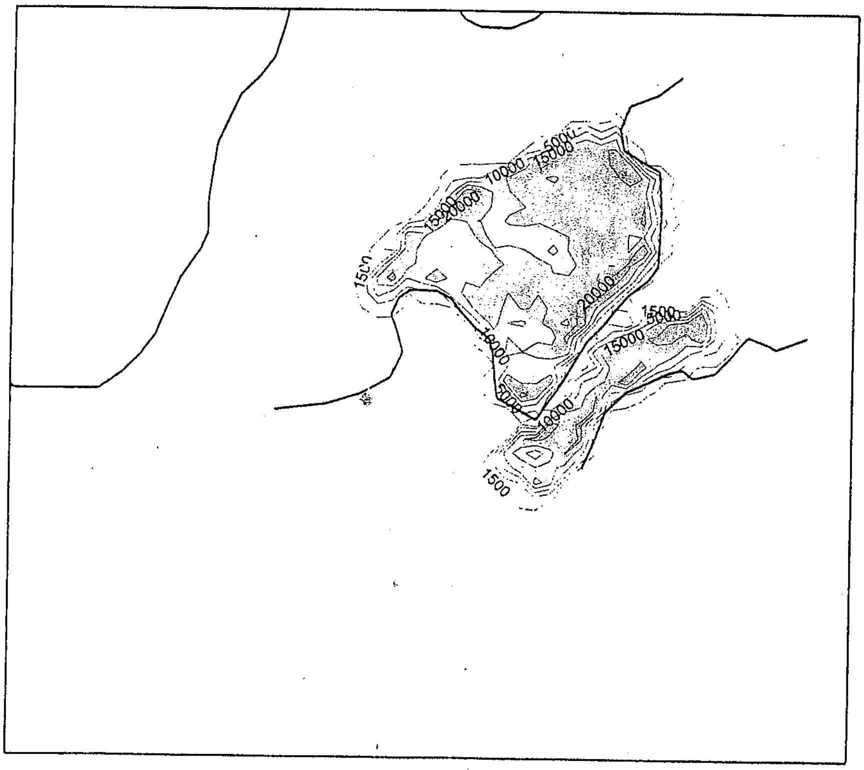
Modelling results in the form of contaminant concentration maps after 1000 days of pond operation are presented in **Figures 5 to 8**. Model Layer 4 has been chosen to display the contaminant plumes as this represents the shallowest level at which the

irrigation bores are represented in the model. It is at approximately –5 mAHD at the location of the irrigation bores.

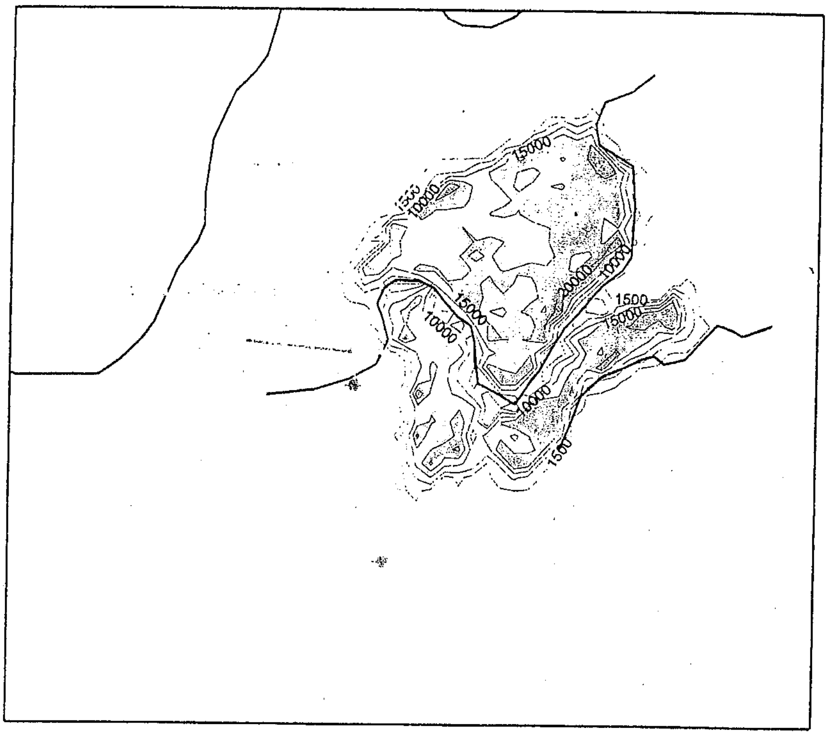
Results suggest that the principal movement of contaminant in the aquifer is vertically downward, in response to the density contrast between the fresh and saline water and then towards the coast in accordance with the natural groundwater flow direction. Very little contaminant migrates towards the irrigation bores, against the groundwater flow direction. Plume expansion towards the irrigation bores largely occurs as a result of the drawdown in groundwater level caused by the extraction of water.

Some of the saline water that leaks through the floor of the ponds is discharged to surface streams principally on the Pacific Reef Fisheries property. In general the natural hydraulic gradient towards the coast ensures that most of the discharge occurs between the ponds and the coast and that when the remedial tile drain is included, there is almost no increased discharge to surface waters in the region immediately west of the property boundary.

- **Figure 5 Scenario 1 – Existing Ponds - Salt Concentration in Layer 4 (mg/l) after 1000 Days**

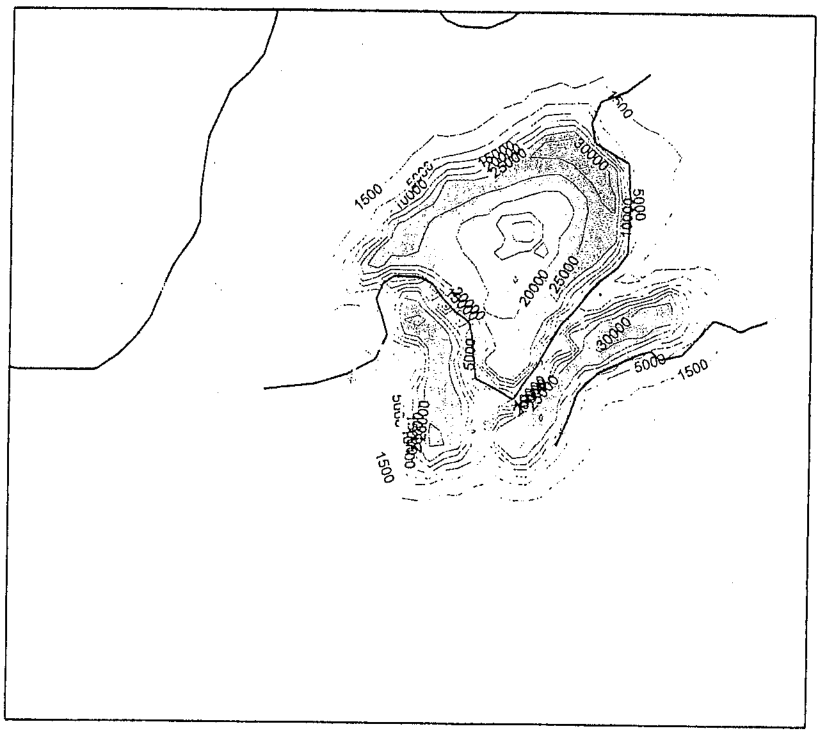


- Figure 6 Scenario 2 – Best Estimate of Existing and Proposed Ponds - Salt Concentration in Layer 4 (mg/l) after 1000 Days



- Figure 7 Scenario 3 – Worst Case Scenario - Salt Concentration in Layer 4 (mg/l) after 1000 Days

- **Figure 8 Scenario 4 – Worst Case Scenario with Remedial Tile Drain - Salt Concentration in Layer 4 (mg/l) after 1000 Days**



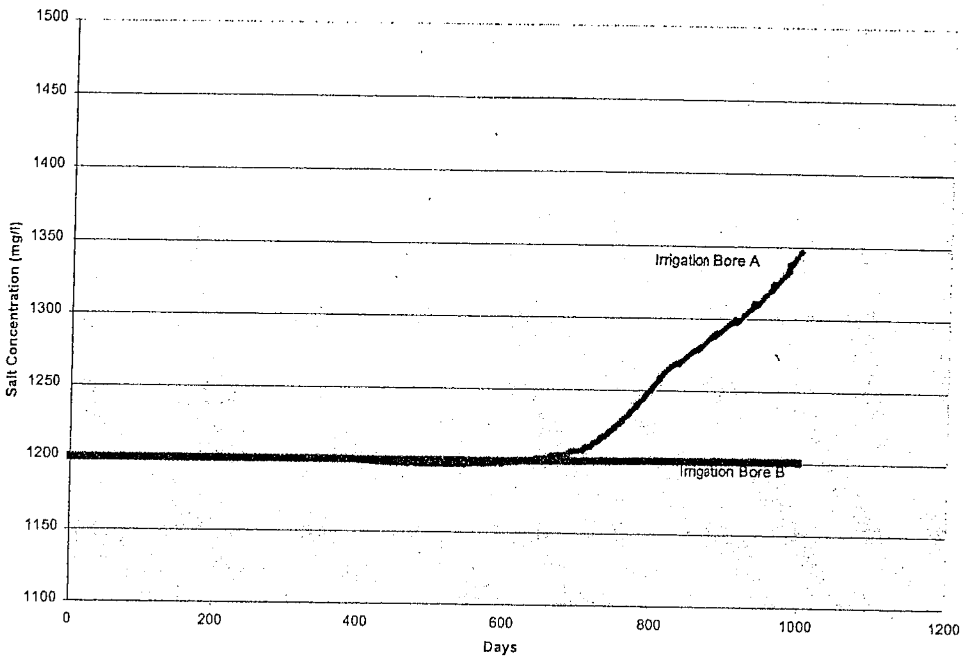
3.3.3 Impact on the Nearest Groundwater User

All scenarios result in no increase in the concentration of salt in the water discharged from the neighbouring irrigation bores except for scenario 3. In this case there is an observable impact on the salinity in irrigation Bore A. The predicted salt

concentrations in both irrigation bores for scenario 3 (the worst case model with no tile drain) are presented in **Figure 9**.

It can be seen that with no tile drain and with a combination of pessimistic physical and hydrogeological parameters an increase in salinity from 1200 to about 1350 mg/l in irrigation Bore A is expected. The increase is predicted to start after about 700 days of pond operation. No impact is observed in irrigation Bore B, it being sufficiently distant from the ponds that the salt water plume does not expand to this location. The result is important in that it demonstrates that bore location is an important consideration in potential impacts on neighbouring water users and that relocation of Bore A would be an effective means of securing a fresh water source for irrigation even in the worst case scenario.

- **Figure 9 Salinity Concentrations in Irrigation Bores for Scenario 3**



3.4 Modelling Discussion

The groundwater modelling described in this report can help address points raised in the Grounds of Appeal as follows:

Grounds of Appeal No. 3: "*...the intrusion of salt water into both ground and surface water could cause the established cane farming property to lose productivity...*" Groundwater modelling and pond operation to date provide no evidence that saline water contamination of surface water will occur on or near the neighbouring cane farms. Any potential impact on surface waters on neighbouring properties is effectively eliminated by the operation of the tile drain. The drain acts to lower the water table at the property boundary thereby reducing the chance of direct saline water discharge to surface water bodies or to the ground surface. Similarly the chance of groundwater contamination of neighbouring irrigation bores can be effectively eliminated by the operation of the drain.

Grounds of Appeal No. 7: "*The location and height of the ponds above existing surface water resources will put at risk the quality of surface water...*". Groundwater modelling and pond operation to date provide no evidence that saline water contamination of surface water bodies will occur as a result of pond construction and operation. In the model, the combined actions of the irrigation pumping and operation of the remedial tile drain ensure that discharge to surface is minimised.

Grounds of Appeal No. 11: "*...there is a potential contamination of both ground and surface waters as a result of salt water intrusion and should this occur the impact would result in many years of lost or reduced productivity by cane farmers...*" Groundwater modelling provides no evidence that there will be an increased chance of salt water contamination of surface water on the cane farming properties. The tile

drain operation will provide protection from contamination for neighbouring groundwater extractions.

In many cases the accuracy and reliability of numerical groundwater models can be demonstrated by the application of the model to recreate observed or measured trends or responses in the aquifer. In the case of the Pacific Reef Fisheries aquifer there are few suitable measurements against which to test the models. In such circumstances it is necessary to call on the modellers experience in similar hydrogeological environments. Irrespective of the modellers expertise and experience, there is always a degree of uncertainty associated with any model predictions of future aquifer and contaminant behaviour. This uncertainty is dealt with by carrying out sensitivity studies that identify a worst case scenario that corresponds to a combination of parameters that lead to the most pessimistic predictions of contaminant transport. The author has carried out the numerical aquifer modelling described in this report in accordance with this philosophy. The worst case scenario includes the worst likely combination of parameters that would promote the leakage and subsequent migration of salt water in the aquifer.

It has been shown that a simple tile drain located at the boundary of the Pacific Reef Fisheries property is able to intercept most of the salt water from the aquifer. Even under the worst case scenario further deterioration in the quality of water extracted from existing bores on neighbouring properties is prevented by installation of the remedial tile drain.

It is noted that groundwater at this location has a relatively high salinity. It is most likely that elevated salinities currently present at this site have arisen from a combination of natural salt water recharge from the tidal streams and drains that cross the property and from enhanced saline water recharge in response to groundwater withdrawals. It is important to recognise this phenomenon and to ensure that baseline water quality surveys accurately characterise the current salinity of both surface and groundwaters so that possible future impacts can be effectively distinguished from pre-existing salinity.

A layer of apparently low permeability organic material, has been observed by the author to cover the floor of the ponds after they have been drained. This material has accumulated during the operation of the ponds and its accumulation has added to the sealing of the ponds floor.

A similar phenomenon has been reported by the Co-Operative Research Centre for Catchment Hydrology in their study of salt disposal basins in the Murray-Darling Basin (CSIRO 2000)[123]. The presence of polysaccharide on the floor of salt disposal ponds is described as being indicative of algal activity in the water body. It is further

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[1] "On-farm and Community-Scale Salt Disposal Basins on the Riverine Plain – Guidelines Summary", CSIRO Land and Water Technical Report 24/00.

[2] "On-farm and Community-Scale Salt Disposal Basins on the Riverine Plain – Evaluating Basin Leakage Rate, Disposal Capacity and Plume Development", CSIRO Land and Water Technical Report 17/00, 2000.

[3] "On-farm and Community-Scale Salt Disposal Basins on the Riverine Plain – Evaluating Basin Leakage: Site Studies at Girgarre, Victoria, and Griffith NSW", CSIRO Land and Water Technical Report 16/00, 2001.

stated that high concentrations of polysaccharides may significantly reduce leakage by clogging pore spaces in the soil. Salt water disposal basins provide an ideal environment for algal activity because they provide clear, warm, nutrient rich water for algal growth (CSIRO 2000)[3].

It is the author's opinion that polysaccharide accumulation in the proposed pond (where algae growth is actively promoted) will significantly reduce rates of salt water leakage from the ponds. The associated reduction in hydraulic conductivity of the pond liners has not been included in the numerical models described in this report. It is noted that this phenomenon will tend to reduce the flux of salt water to groundwater and hence reduce the growth and migration of the subsequent contaminant plume. In this regard all scenarios described in this report are inherently conservative.

4. Mitigation Measures

In response to SKM reporting of a degree of uncertainty associated with prediction of groundwater behaviour, a series of control, monitoring and mitigation measures were incorporated into the Burdekin Shire Council approval. It must be stressed that, based on the investigations conducted to date, it is expected the mitigation measures will not be required. They have been included to provide additional confidence to all stakeholders that appropriate measures will be taken to ensure appropriate construction standards are employed, monitoring of local conditions will be undertaken, and if required, steps taken to mitigate any effects.

In particular, conditions 1) and 2) of the approval provide confidence that the pond liners will be constructed using appropriate materials, and to the standards required to minimise seepage. The groundwater modelling undertaken, and more specifically the hydraulic conductivity parameters used in the model, are based on the assumption that these controls will be employed.

Conditions 3), 4), 5) and 8) relate to monitoring arrangements that will provide confidence to stakeholders that any deleterious impacts of the proposed development will be detected early, and will trigger a pre-determined series of mitigation measures. In particular, it will ensure that "real" effects can be distinguished from naturally occurring background variations in water quality. A reporting framework has been proposed (Condition 4), that provides for independent, regular review of the monitoring results.

The remediation measures proposed in Condition 7) would involve progressively more significant mitigation measures to be undertaken. Should it be required, it is the opinion of the author that the first remediation measure, installation of additional tile drains beneath the ponds, would effectively capture all seepage from the ponds. These drains would be designed with due allowance for local ground conditions, in accordance with contemporary design practice. It is highly unlikely that the subsequent remediation measures would be required.

The measures encapsulated in the conditions to the approval provide a clear and logical framework for controlling, monitoring and, if necessary, mitigating the impacts of the proposed development. This approach is considered preferable to the adoption of arbitrary measures, such as a 100 m buffer zone between the proposed ponds and the property boundary, because they provide a much greater degree of confidence for all stakeholders.

Appendix A Groundwater Schematics

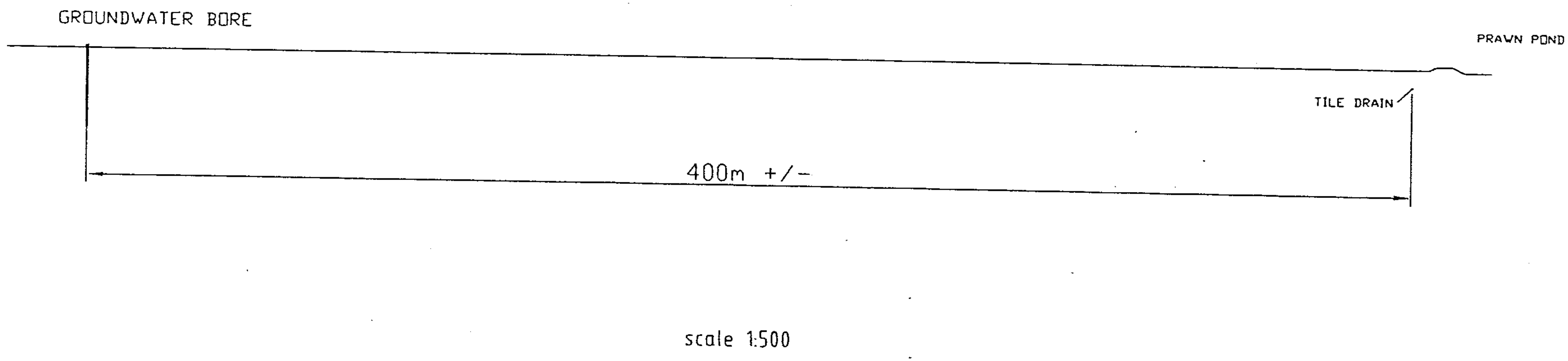

FIGURE A1 - GROUNDWATER SCHEMATIC

ALVA BEACH
GROUND WATER SCHEMATIC

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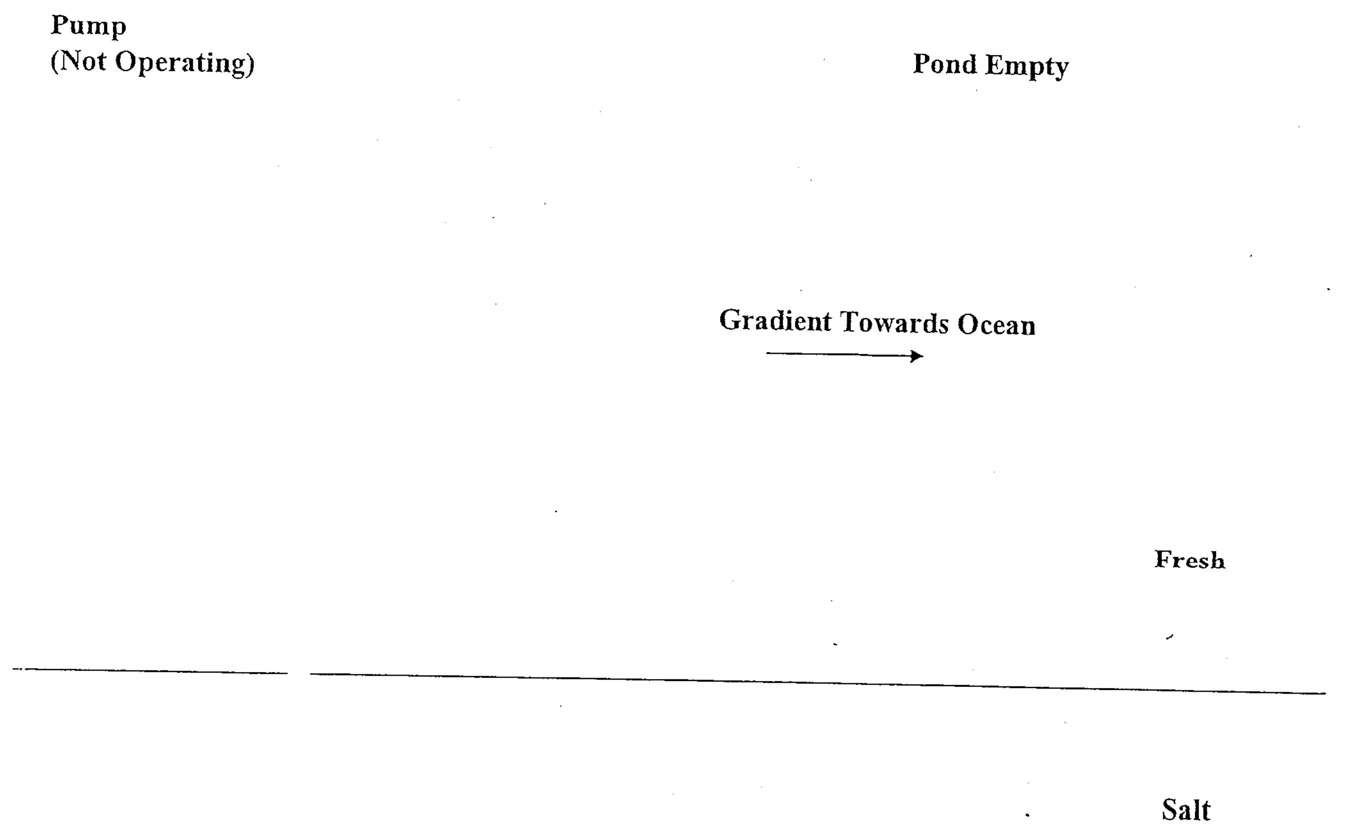
Figure A-2: Ground Water Schematic - No Development



■ Figure A-3: Groundwater Schematic – With Groundwater Pumping

Pump (Operating)

Pond Empty

Localised Groundwater Drawdown

Fresh

Salt

- Figure A-4 Groundwater Schematic - Seepage But No Impact

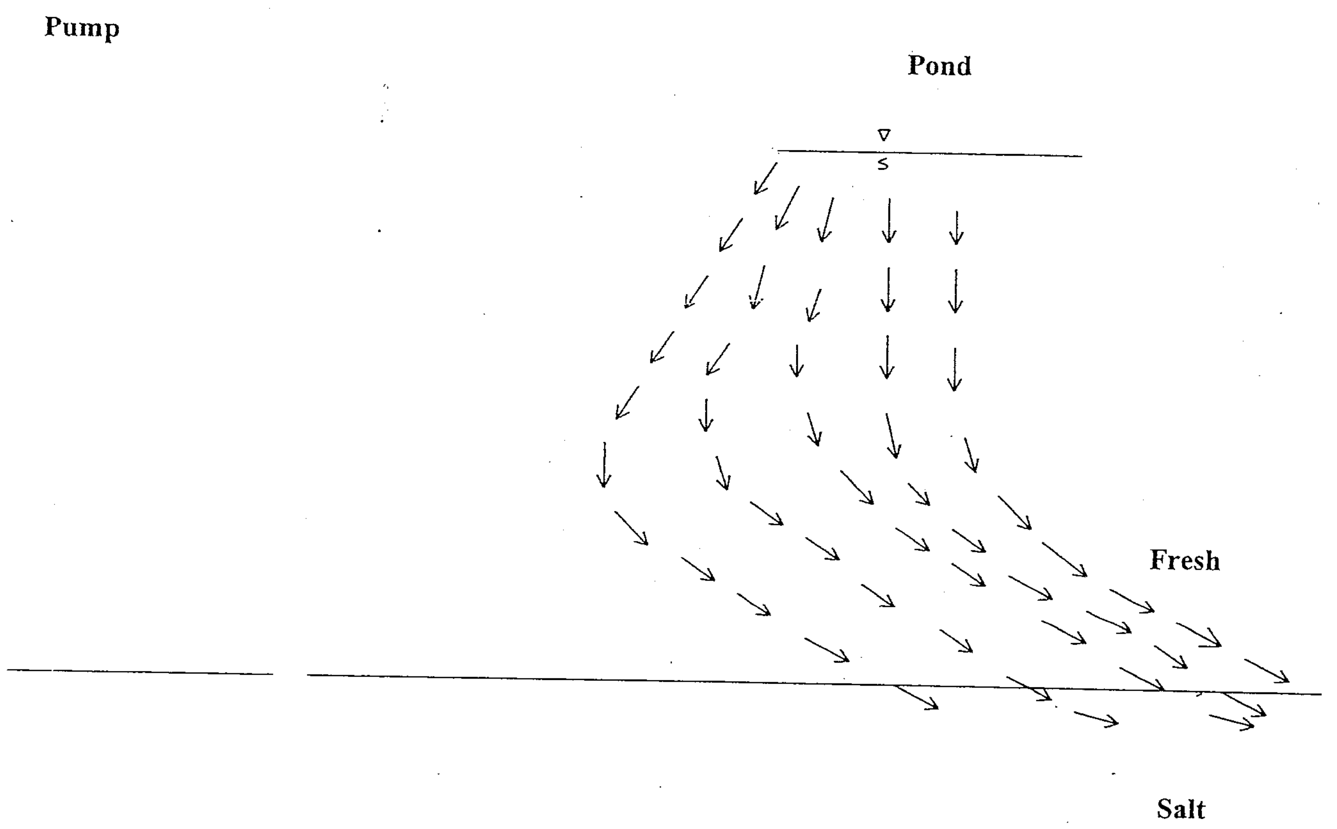
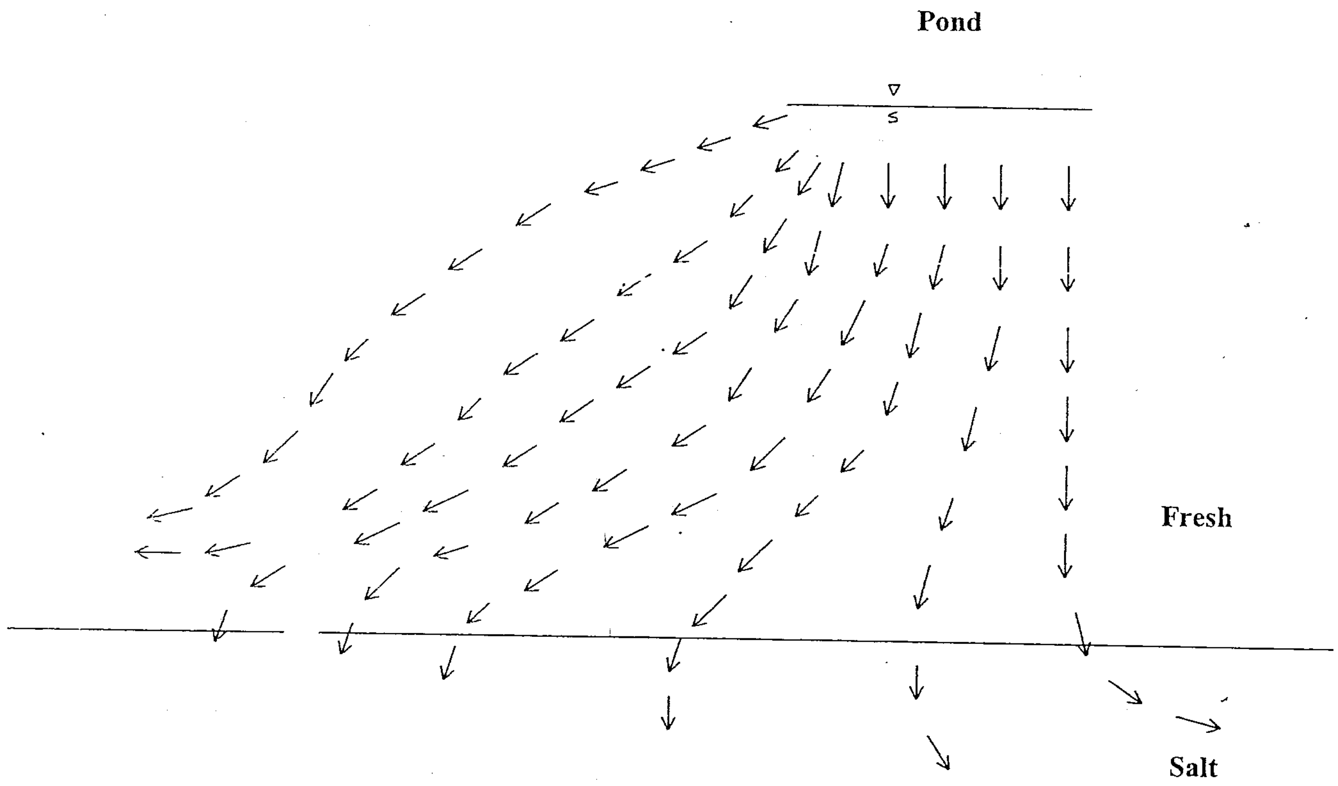


Figure A-5 Groundwater Schematic - Seepage With Impact



- **Figure A-6 Groundwater Schematic - Tile Drain**