Three Dimensional Simulation of the Home Island Freshwater Lens: Preliminary Results

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Abstract: Home Island is one of the two main inhabited islands of the Cocos (Keeling) Islands, situated about 2800 km north-west of Perth. The island has an average elevation of approximately 2 m above MSL and supports a population of about 450. The geology of the island consists of coral sediments overlying a volcanic seamount. The upper sediments are of primary importance from a hydrogeological viewpoint. These sediments consist of unconsolidated coral sands and other fragments and coral limestone. An unconformity between the younger (Holocene) unconsolidated sediments and older (Pleistocene) coral limestone was found at depths between 10 m to more than 17 m. The island has a long term average annual rainfall of 1950 mm. Water supply is based primarily on groundwater extraction from a local freshwater lens and supplementary rainwater is collected from roofs. Groundwater is currently extracted via seven galleries. In 1987 the sustainable yield of the lens was estimated to be in the range from 70 to 130 m^3 day^{-1}. However, a recent study determined the sustainable yield as 140 m^3 day^{-1}. This paper describes progress regarding the development of a three dimensional model of the freshwater lens using the SALTFLOW package followed by a steady-state calibration of the model and estimation of the parameters affecting the system.

1. INTRODUCTION

The Cocos (Keeling) Islands are situated in the Indian Ocean, approximately 2800 km northwest of Perth. The Islands consist of two atolls, South Keeling and North Keeling atolls (Figure 1). South Keeling Atoll consists of 26 small islands around a lagoon. North Keeling Atoll is a single island situated 24 km north of the South Keeling Atoll. The total area of the islands is about 14 km^2.

As with many other coral atolls in the Indian and Pacific Oceans, the islands are low-lying. Typical elevations on the South Keeling islands are between 1 m and 3 m above mean sea level (MSL) except on the ocean beach side where higher elevations are found. The maximum elevation above MSL is about 9 m on South Island. Where clearing has not occurred, coconut trees and other vegetation form a dense cover over the islands. The only inhabited islands in the Cocos (Keeling) Islands are Home and West Islands (Figure 1). Present population estimates are about 450 on Home Island and 150 on West Island. This paper describes relevant studies of the Home Island freshwater lens and the development of a three dimensional numerical model in order to gain insight into the major processes affecting the freshwater lens.

It is anticipated that the outcomes of this research will assist in the management of freshwater lenses in similar islands in the Pacific and Indian oceans, where surface water is totally absent and groundwater is the major source of water supply.

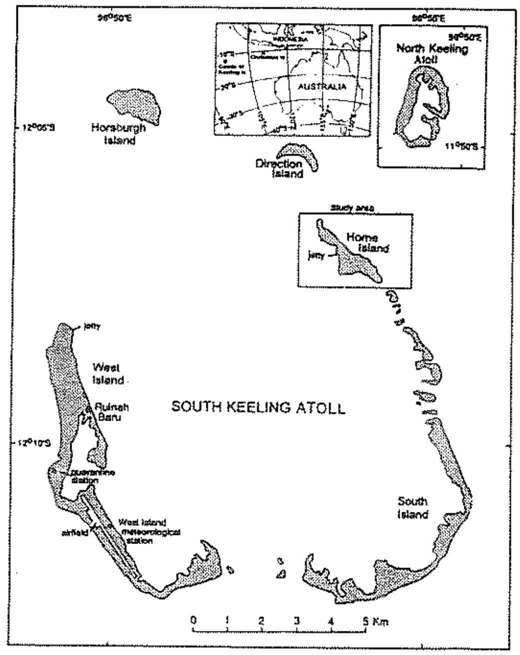


Figure 1: Location map of Cocos (Keeling) Islands in the Indian Ocean.

2. CLIMATE

Climate data is available for West Island on a continuous basis since 1952 [Falkland, 1988]. As climatic variations across the atoll are small, these data can be used to estimate key climate features for Home Island [Falkland, 1994a & b] as follows:

- annual rainfall ranging between 850 mm to 3300 mm with a mean value of 1950 mm.
- mean annual potential evaporation of 2000 mm.
- temperature ranges between 18 to 32° C with the mean monthly values of 26 to 27 ° C.

3. GROUNDWATER INVESTIGATIONS

3.1 Geology and Hydrogeology

The geology of the islands consists of coral sediments, several hundreds of meters thick, overlying a volcanic seamount. The thickness of the coral sediments is unknown at this location but Jacobson [1976] estimated it to be about 1000 m. Deep drilling on similar atolls has identified thicknesses of this order. For example, a thickness of about 1300 m was determined on Enewetak in the Marshall Islands [Schlanger, 1963], and 500 m in Nauru [Hill and Jacobson, 1989].

In order to explore the hydrogeology of Home Island, 9 boreholes (HI1 to HI9) were drilled in 1987 (Figure 2) to depths ranging from about 12 m to 21 m and in each borehole (except HI9) a multi-level water sampling system was installed. This drilling program was accompanied by a geophysical investigation using geoelectrical and seismic refraction methods [Creighton, 1988]. In 1990, four boreholes (HI9 to HI12 with HI9 relocated) were drilled and equipped with multi-level water sampling system similar to previous boreholes. Finally, in 1996 two additional boreholes (HI13 and HI14) were drilled and equipped with salinity monitoring facilities. The upper coral sediments are of primary importance from a hydrogeological viewpoint [Falkland, 1994a & b]. An unconformity between the younger (Holocene) unconsolidated sediments and the older (Pleistocene) harder coral limestone was found from drilling [Murphy, 1988] below ground surface of 9.6 m (HI4) to more than 17 m (HI6). In some boreholes the unconformity was not intersected before termination (e.g. at a depth of 17 m below ground surface at HI6). These depths are similar to those found elsewhere on similar coral atolls.

The unconformity between the Holocene and the Pleistocene sediments was formed by solution and erosion during a period of emergence in the Last Interglacial period about 120,000 years ago. The Holocene sediments were deposited in the last 10,000 years [Woodroffe et al., 1991].

During the 1987 geophysical investigation, 27 electrical soundings and five seismic traverses of 60 m length were completed [Creighton, 1988]. Results of the geophysical investigations were found to be consistent with the results of drilling and groundwater salinity data [Falkland, 1988].

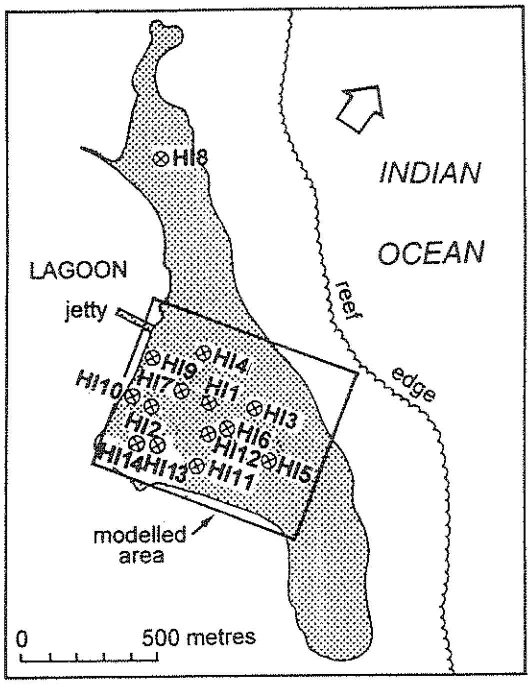


Figure 2: Location of monitoring boreholes in Home Island.

3.2 Porosity and Hydraulic Conductivity

During this study no direct measurement of the Holocene sediment's porosity was available. However, Underwood et al. [1992] have reported values ranging from 0.1 to 0.4 for the effective porosity of similar sediments. In situ measurement of hydraulic conductivity conducted at the depths of 3 to 12 m in monitoring boreholes ranged from 1.6 to 26 m day^{-1}, while below 12 m the hydraulic conductivity tends to increase sharply with measured values ranging between 20 and 650 m day^{-1} [Murphy, 1988].

3.3 Groundwater Salinity Monitoring

Permanent monitoring systems were installed at each borehole. The monitoring system consists of a set of up to 8 nylon tubes terminated at selected depths, between which bentonite layers were installed. Selected gravel was used to fill the spaces between the bentonite layers [Falkland, 1988]. Water samples can be pumped to the surface for salinity measurement using a small electric or hand operated pump. This monitoring system is preferable to permanently installed electrical conductivity (EC) probes at different depths because of the potential problem of breakdown in equipment requiring subsequent redrilling. It is noted that open boreholes (perforated or not) were not used as these lead to erroneous data on small islands, by enhancing mixing of freshwater and underlying seawater due to tidal effects.

Salinity profiles at the boreholes have been obtained since drilling at intervals of one to three months.

3.4 Tides and Groundwater Response

Automatic water level recorders were installed at selected sites including pump sites PS1 to PS4 (Figure 3a). Based on measurements at 15 minute intervals between 20 October and 19 November 1987, mean watertable elevations were between 0.2 and 0.25 m, with maximum tidal fluctuations of 0.2-0.3 m.

Tidal data on Home Island have been recorded at Jetty since 1984. Currently, the National Tidal Facility, (Flinders University of South Australia) is in charge of collecting, processing and archiving of the data. Recorded data for the period of observation (20 October to 19 November 1987) indicates tidal amplitudes ranging from 0.4 m (15 November) to 1.1 m (7 November) with an average value of 0.8 m.

Tidal influence on the groundwater level has been evaluated in terms of both tidal lag and efficiency. By definition the tidal lag for a particular site is the time difference between the tidal movement and the corresponding movement of the watertable at the site. It can be determined by calculating time differences between sets of peaks or troughs in the water movement plots. The tidal efficiency at a site is the ratio of the amplitude of the watertable movement to that of the tidal movement. For the four sites on Home Island, the mean values of tidal lags (in hours) and efficiencies, determined from four tidal cycles are respectively as follows; PS1 (2.5 h and 0.25); PS2 (2.1 h and 0.25); PS3 (2.1 h and 0.2); and PS4 (1.5 h and 0.3).

4. RECHARGE ESTIMATION

Recharge was estimated using a water balance equation for upper zone of the island (top of vegetation to watertable). This equation can be described as:

$$R = P - E + dV$$

Where:

- R = recharge,
- P = rainfall,
- E = evaporation, and
- dV = change in storage within the soil moisture zone

Some notes regarding the above equation are:

- Surface runoff is not considered as the high infiltration capacity of the soils on the atoll leads to little if any runoff.
- The evaporation term includes: interception by trees and other vegetation; evapotranspiration from the soil zone; and transpiration by deep rooted trees directly from groundwater.

A water balance model using daily rainfall, monthly estimates of potential evapotranspiration was used to make monthly and annual estimates of recharge. Details of the model are provided in Falkland [1988 and 1994b]. For Home Island, with an estimated tree cover of 15%, the mean annual recharge was 855 mm or approximately 44% of mean annual rainfall for the period 1953-1987.

5. WATER SUPPLY

The Home Island water supply is primarily based on groundwater extracted from the freshwater lens with supplementary rainwater collected from roofs [Falkland, 1988 and 1994a & b].

Fresh groundwater is supplied by pumping from seven infiltration galleries. In 1983, water was pumped from three pump wells which were dug approximately 1 m below watertable and fitted with very short lateral pipes. In 1984, two additional pump wells of similar construction were commissioned. In 1991, five infiltration galleries were constructed at the sites of the former pump wells. Two additional galleries of similar construction were commissioned, respectively, in 1992 and 1997. Each gallery consists of approximately 300 m of horizontal slotted pipe laid below the watertable and connected to a sealed pump well. Based on salinity readings taken at the pump wells before and after gallery construction, the galleries have led to a marked lowering of salinity of the water supply. This indicates that the galleries are an effective means of extracting water from the thin Home Island freshwater lens.

Total average pumping from the freshwater lens has increased from about 100-115 m^3 day^{-1} in the period from 1983-1988 [Falkland, 1988] to higher values in recent years, namely, 128, 137, 166 and 223 m^3 day^{-1} in the years 1993-1996 [Alam and Falkland, 1997]. Individual gallery pump rates have also increased. In 1987, the average pumping rates from the five wells varied between 17 and 27 m^3 day^{-1} [Falkland, 1988]. In 1996, the average pumping rates at six galleries varied from 15 to 37 m^3 day^{-1} [Alam and Falkland, 1997].

The sustainable yield of the Home Island freshwater lens was estimated to be in the range of 70 to 130 m^3 day^{-1} [Falkland, 1988]. A recent two-dimensional modelling study [Alam and Falkland, 1997] provided a revised sustainable yield estimate of 140 m^3 day^{-1}.

6. NUMERICAL MODELLING OF SEAWATER INTRUSION

6.1 Introduction

During the past few decades, a large volume of literature has been published dealing with various aspects of seawater intrusion and its numerical modelling. Reily and Goodman [1985 & 1987] provide a historical perspective of quantitative analysis of the relationship between saltwater and freshwater in groundwater systems. Huyakorn et al. [1987] provide a literature review of models developed for the simulation of seawater intrusion. Underwood et al. [1992] provide an overview of models that have been applied to the study of island groundwater systems.

Currently, several density dependent solute transport models suitable for the simulation of seawater intrusion are commercially available. These include SUTRA [Voss, 1984], which is a two-dimensional model, while HST3D [Kipp, 1987], VTT [Jacob, 1993] and SALTFLOW [Molson and Frind, 1994] are examples of three-dimensional models. These models provide solutions of two simultaneous, non-linear partial differential equations that describe the "conservation of mass of fluid" and "conservation of mass of solute" in porous media. Ghassemi et al. [1996a & b] describe applications of SUTRA and other models for simulation of a number of case studies. Recently, Alam and Falkland [1997] used SUTRA to revise the sustainable yield estimate for the Home Island freshwater lens.

6.2 Numerical simulation of the Home Island aquifer

6.2.1 Model description

The three dimensional simulation of the Home Island aquifer system described in this paper is based on the application of the SALTFLOW model [Molson and Frind, 1994]. SALTFLOW is a numerical model for solving complex density-dependent groundwater flow and mass transport problems. The model can be used to solve one, two, or three-dimensional mass transport problems within a variety of hydrogeological systems. Finite elements are employed for high accuracy and to allow deformable domain geometry. The model includes an efficient preconditioned conjugate gradient solver to solve the matrix equations.

In this model the equation of conservation of mass of fluid is expressed as:

$$\frac{\partial}{\partial x_i}\left[K_{ij}\left(\frac{\partial \psi}{\partial x_j}+\gamma c \bar{n}_j\right)\right] - \sum_{k=1}^{N} Q_k(t) = S_s \frac{\partial \psi}{\partial t}$$

where x_i are the 3D spatial coordinates, K_{ij} is the hydraulic conductivity tensor (L T^{-1}), ψ is the equivalent freshwater head (L), γ is a constant defined by $\gamma = (\rho_{max} / \rho_o - 1)$ where ρ_{max} (ML^{-3}) is the maximum density of the fluid and ρ_o (ML^{-3}) is the reference freshwater density, c is the relative concentration, $\bar{n}_j$ is the unit vector, $Q_k(t)$ is the volume flux for the sources/ sinks located at (x_k, y_k, z_k) and at the time t ($L^3 T^{-1}$), N is the number of sources/sinks at (x_k, y_k, z_k), S_s is the specific storage coefficient (L^{-1}), and t is time (T).

The equation of conservation of mass of salt is represented by:

$$\frac{\partial}{\partial x_i}\left[\left(\frac{D_{ij}}{R}\right)\frac{\partial c}{\partial x_j}\right] - \frac{\partial}{\partial x_i}\left(\frac{v_i}{R}c\right) - \lambda c + \sum_{k=1}^{N}\frac{Q_k(t)c_k(t)}{R\theta} = \frac{\partial c}{\partial t}$$

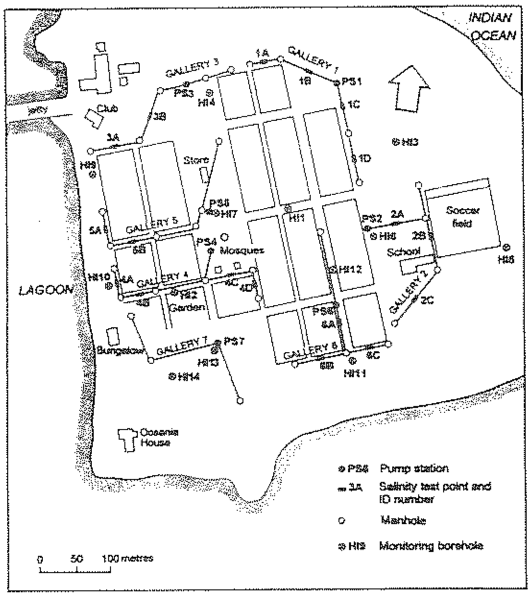
Where D_{ij} is the hydrodynamic dispersion tensor ($L^2 T^{-1}$), v_i is the average linear groundwater velocity (L T^{-1}), R is the retardation factor (dimensionless), λ is the first order decay term (T^{-1}) and θ is the porosity of the saturated media (dimensionless).

Further details regarding the theoretical basis of the SALTFLOW model, spatial and temporal discretisation criteria, and example applications are available in Molson and Frind [1994].

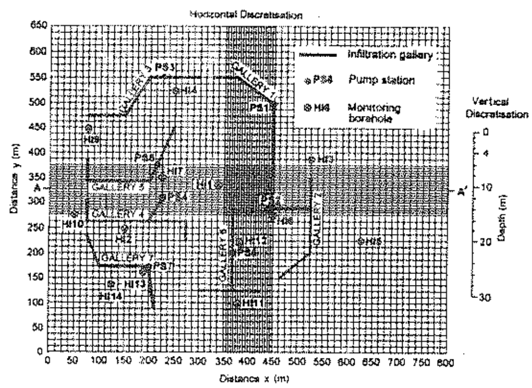
6.2.2 Discretisation

Salinity records are available for the central part of the island which is wide enough to sustain a freshwater lens. Therefore, in this modelling exercise only this part of the island has been simulated (Figures. 2 & 3). The simulated area is 800 m long, 650 m wide and 30 m deep. Various uniform and variable grids have been tested in search of the best results in terms of: best match between the measured and computed salinity profiles at various monitoring boreholes; three dimensional distribution of the computed salinity values; and the stability of the computed concentration solution. Uniform horizontal grids of 25 m and 12.5 m generated a major cusp towards the centre of the aquifer. This is due to relatively high vertical velocities caused by recharge from rainfall, and can be overcome with a finer grid and/or shorter time steps. This behaviour was also observed with other similar models.

To rectify the cusp problem the aquifer has been discretised with a variable spacing horizontal (12.5 m and 5 m) and vertical (Δ_z = 1 m from MSL to 4 m depth and Δ_z = 2 m from 4 m to 30 m depth) grid (Figure 3b). This type of discretisation has generated 90,090 (77 x 65 x 18) nodes and 82688 (76 x 64 x 17) elements. The simulated period has been 1500 days (in order to reach a steady-state) discretised to short time steps of one day.



(a)



(b)

Figure 3: (a) Home Island infiltration gallery layout and observation boreholes; (b) Horizontal and vertical discretisation of the aquifer.

It should be noted that the aquifer system is much deeper than 30 m. However, because at this depth the aquifer system contains only saline water and the deeper part of the aquifer has no major impact on the distribution of salinity at the shallow depth of the lens, it was justified to limit the simulated depth to 30 m. The other reason was the computational constraints. Increasing the simulated depth and using Δ_z = 2 m would increase number of nodes and subsequently computation time. Increasing the simulated depth and using larger grid size in the vertical direction would decrease the accuracy and would introduce numerical dispersion errors. Although for the current simulations the aquifer has been simulated to the depth of 30 m, attempts will be made to investigate the impact of increasing the simulated depth on the computed salinities.

6.2.3 Boundary conditions

Flow boundary conditions consist of: a flux boundary due to recharge from rainfall at the top surface; a no-flow boundary at the bottom surface (at the depth of 30 m); and the fixed heads of 0 m at the four lateral sides. SALTFLOW converts these heads to their equivalent freshwater heads in depth, considering a density of 1.0245 kg per litre for seawater.

Solute boundary conditions consist of: zero concentration for the rainwater recharging the aquifer from the top; zero concentration gradient at the bottom; and fixed concentration of 1.0 (relative to seawater) on the four lateral sides from MSL to the depth of 30 m.

6.2.4 Stresses

The aquifer system is affected by various natural and human-induced stresses. Major natural stresses are tidal forces and variable recharge due to climatic variations, while human-induced stresses are due to extractions from wells or infiltration galleries installed at a depth of less than 1 m below MSL.

Extractions from wells and galleries from 1983-1996 are given in Falkland [1988], Alam and Falkland [1997] and regular monitoring reports [e.g. Pink and Falkland, 1997]. In the simulations to date, the 1987 extractions used to simulate a quasi steady-state were assumed to be: 27.4 m^3 day^{-1} (PS1); 21.6 m^3 day^{-1} (PS2); 27.4 m^3 day^{-1} (PS3); 23.0 m^3 day^{-1} (PS4); and 17.3 m^3 day^{-1} (PS5). Therefore, the total extraction rate was about 117 m^3 day^{-1}. Extractions from each gallery was uniformly distributed over the nodes representing the gallery at the depths of 0 to 1 m.

6.2.5 Parameter estimation

Parameters have been estimated by trial and error using limited measurements undertaken on the island and values adopted by Underwood et al. [1992, Table 4] for their generalised atoll island model which is a two dimensional vertical model simulated with SUTRA [Voss, 1984]. The unconformity between the Holocene and the Pleistocene sediments has been simulated at a depth of 12 m below MSL. The parameter values resulting from model calibration are listed in Table 1 (except for the specific storage coefficient which has been 0.001 m^{-1}). The calibrated values are close to the measured values on the island and compare favourably with values used by Alam and Falkand [1997] and Underwood et al.[1992].

Table 1: Parameter values used to describe the Home Island aquifer system and their comparison with Alam and Falkand [1997] and Underwood et al. [1992] values.

Parameters and their units	Calibrated Values	Alam Values	Underwood values
Porosity	0.30	0.30	0.25
Holocene sediments thickness (m)	12	12	15
Holocene sediments, horizontal hydraulic conductivity (m day^{-1})	10	5	50
Holocene sediments, vertical hydraulic conductivity (m day^{-1})	2	1	10
Pleistocene sediments, horizontal hydraulic conductivity (m day^{-1})	500	500	500
Pleistocene sediments, vertical hydraulic conductivity (m day^{-1})	100	100	100
Longitudinal dispersivity (m)	5	10	6-12
Transverse dispersivity (m)	1	1	0.01
Vertical dispersivity (m)	0.01	1	0.01-0.05
Average annual recharge (mm)	855	855	500-2000

6.2.6 Calibration results

Although in 1987 the system was not in steady-state equilibrium it was found useful to calibrate the model in quasi steady-state to estimate major parameters affecting the system before calibrating the aquifer in transient in order to fine tune the parameters.

Figure 4 compares the 1987 measured and computed salinity profiles at the monitoring borehole HI2. Minor discrepancies at HI2 and HI4 and larger discrepancies at other monitoring boreholes operating in 1987 (HI1, HI3, HI5 to HI7) are due to: lack of knowledge about model parameters and their three dimensional distributions; differences between the real and simulated boundaries of the aquifer; and the fact that the aquifer system is not in a steady-state equilibrium. Further simulations have indicated that the model behave more accurately by considering the top layer as heterogeneous and considering a higher hydraulic conductivity for the ocean side of the aquifer (these results are not presented here).

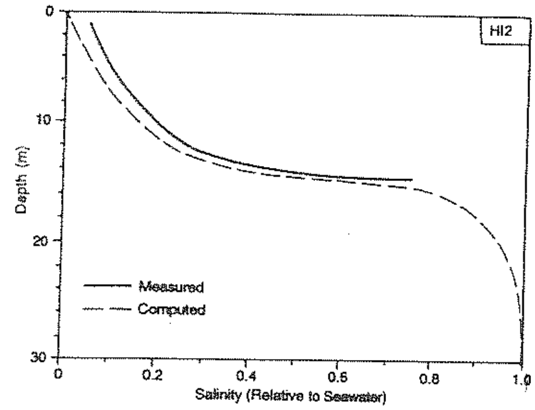


Figure 4: The 1987 measured and computed groundwater salinity at the monitoring borehole HI2.

Figure 5 shows the computed salinities within a longitudinal vertical cross-section of the aquifer system. Generally speaking, the computed salinity values within the top 5 m of the aquifer are slightly less than the observed values in the monitoring boreholes.

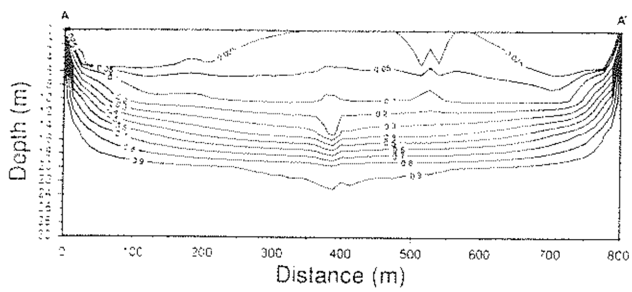


Figure 5: Computed longitudinal groundwater salinity at profile A-A' (Figure 3b).

It should be noted that the computations have been performed on a *Sun UltraSPARC Workstation Model 170E*. In terms of computation time, each run of the model required approximately 65 hours CPU time to simulate a period of 1500 days with time steps of one day. In other words each time step of one day required 2.6 minutes. This gives an excellent indication of the efficiency of the conjugate gradient method used by the model to solve the large matrix system of over 90,000 nodes.

It is useful to note that compiling the SALTFLOW code with the Fujitsu FORTRAN 90 compiler has accelerated the computations by a factor of 2.5 compared with FORTRAN 77 compiler. In other words computation time for each time step has reduced from 2.6 minutes to about one minute.

6.2.7 Sensitivity analysis

Sensitivity analysis indicated the sensitivity of the model outputs with respect to major parameters, in particular hydraulic conductivity of the Holocene sediments, dispersivity values and the recharge rates.

6.3 Simulation of Extraction Options

Alam and Falkland [1997] simulated the impact of various levels of pumping up to 200 m^3 day^{-1} using the 2D model. Based on that modelling, the sustainable yield was estimated to be 140 m^3 day^{-1}. Higher pump rates (up to 200 m^3 day^{-1}) were found to be acceptable for short periods during average or better than average recharge conditions. In the case of 200 m^3 day^{-1} extraction, simulated rates were 20 m^3 day^{-1} for Gallery 1 and 30 m^3 day^{-1} for each one of the 6 remaining galleries. Although the 3D model is not yet calibrated in transient mode, it would be useful to simulate this option and to compare the results.

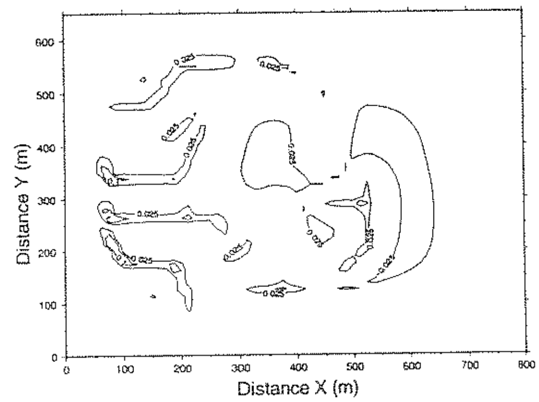


Figure 6: Computed salinities with the 3D model at the depth of 1 m for 200 m^3 day^{-1} extraction.

Figure 6 shows the distribution of computed salinities at the depth of 1 m for 200 m^3 day^{-1} extraction. It demonstrates clearly that in the areas representing the extraction galleries, computed salinities will rise within the range on 0.025 to 0.1 (relative to seawater), or about 1000 to 3500 mg L^{-1} total dissolved solids (TDS). These results suggest that an extraction rate of 200 m^3 day^{-1} is not sustainable, which is consistent with the results of the 2D modelling. However, it is important to note that 2D modelling is unable to provide details such as those provided in Figure 6. Future 3D modelling will examine different levels of pumping and compare them with 2D model results.

7. CONCLUSIONS

Since the release of SUTRA [Voss, 1984], this 2D density dependent solute transport model has played a major role in providing insight into the processes involved in seawater intrusion in coastal aquifers, upconing of the freshwater-saline water interface, and analysing the effects of various processes on freshwater lenses and their management. In spite of its 2D nature and limitations, this model, which can be run on PCs is able to provide useful results, if used properly. However, over the past decade significant progress has been made towards the three dimensional simulation of seawater intrusion using density dependent solute transport models. The development of powerful workstations has facilitated this task. In spite of all these improvements more powerful computing facilities are required in order to simulate efficiently a three dimensional seawater intrusion problem with consideration of all parameters and processes affecting the aquifer system including tidal forces.

Despite the above comments, and considering that research is continuing towards the transient calibration of the model, the following conclusions and remarks can be made based on the current results:

- Due to the three dimensional nature of the model it was possible to specify three-dimensional boundary conditions for the aquifer system as well as pumping stresses. These important factors cannot be treated adequately by two dimensional models.
- Discretisation of the model started with a uniform grid of 25 m x 25 m in X and Y directions and 2m in the vertical direction generating approximately 16,000 nodes. However, in order to reduce the numerical dispersion, grid size was gradually reduced and the number of nodes increased to 90,000. In spite of these refinements, results show some numerical dispersion which required finer discretisation toward the centre of the aquifer.
- In spite of field data limitations, the model has been calibrated in quasi steady-state and parameters affecting the system have been quantified. Simulation results not presented here indicate that the model behaved more accurately by considering the top layer as heterogeneous and considering a higher hydraulic conductivity for the ocean side of the aquifer.
- With respect to the estimation of the sustainable freshwater yield of the aquifer, preliminary results of the 3D modelling suggest that extraction of 200 m^3 day^{-1} is not sustainable. This result is consistent with the results of recent 2D modelling. However, this issue needs to be re-examined after calibrating the 3D model in transient mode.
- In terms of the computation time, compiling the SALTFLOW code with the Fujitsu FORTRAN 90 compiler has accelerated the computations by a

factor of 2.5 compared with FORTRAN 77 compiler.

- Finally, it should be emphasised that 2D and particularly 3D modelling of seawater intrusion requires a sound spatial knowledge of all parameters involved. Therefore, reasonably detailed field studies are required prior to simulation of any specific case, rather than using data measured elsewhere or trying to find suitable parameters via the lengthy calibration procedure.

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