

32nd WEDC International Conference, Colombo, Sri Lanka, 2006

SUSTAINABLE DEVELOPMENT OF WATER RESOURCES, WATER SUPPLY AND ENVIRONMENTAL SANITATION

Coupled Flow and Salinity Transport Modelling and Assessment of Groundwater Availability in the Jaffna Peninsula, Sri Lanka*J.F. Punthakey, Australia and Nimal P.D. Gamage, Sri Lanka*

The development of a groundwater management strategy is essential for the sustainable management of groundwater resources. This study describes the hydrogeology of the two main geological formations, which contain freshwater resources in the Jaffna Peninsula, Sri Lanka. A numerical groundwater flow model was developed as part of the investigation to assist in the analysis of freshwater and saltwater flow for current and changing pumping and recharge conditions. The groundwater flow model MODFLOW, mass transport model MT3DMS, and salinity intrusion model SEAWAT were used to provide additional understanding of the regional flow conditions in the aquifers, including regional movement of the interface separating the freshwater and saltwater flow systems. The calibrated model was used to estimate water balance for the Jaffna Peninsula, assess the potential for seawater intrusion and upcoming, and its impact on low salinity groundwater resources.

Introduction

THE JAFFNA PENINSULA lies in the northern-most part of Sri Lanka (Figure 1). The peninsula is dependant on groundwater for all its water requirements. The surface stream, Valukai Aru, is active only during the height of the monsoon, and there are no reservoirs of a perennial nature. The Peninsula is narrow and elongated. It has a flat terrain with a maximum elevation of about 10 m, has an area of 1000 km², and a coastline of 160 km.

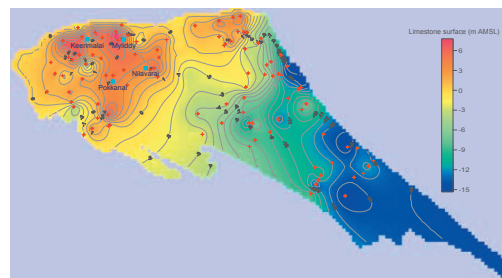
A significant number of studies carried out to assess the hydrology and hydrogeology of the Jaffna Peninsula were found in literature. Some of the key studies are Shanmugara-jah (1993); Engineering Science (1984); Balendran (1970); Arumugam (1970); Balendran (1966).

The objectives of the study are to develop groundwater flow and salinity transport model for the Jaffna Peninsula, estimate water balance for the Jaffna Peninsula, assess the potential for seawater intrusion and upcoming during pumping, and its impact on low salinity groundwater resources.

Study Area and Data**Geological setting**

Geological units exposed in the Jaffna area are part of a sequence of Tertiary aged rocks, which rests on a basement of Precambrian crystalline rocks. The total thickness is approximately 250 m made up of three main units, the Mannar Sandstone at the base, the Jaffna Limestone, and a thin discontinuous surficial cover. The basal Mannar Sandstone comprises about half this total but is not exposed in the study area. The Jaffna Limestone, which is some 50 to 90 m thick, overlies the Mannar Sandstone and is extensively exposed in the western part of the Peninsula in the Chunnakam area and in a small area to the west of Point Pedro (Figure 2). The limestone is also extensively exposed on the islands off the west coast.

On the north east side of Vadamaradchi Lagoon (right hand side of Figure 1) there is a long almost linear belt of coastal sand dunes increasing from less than 2km wide at the southern extremity to about 3 km at the northern end near

**Figure 1. Map of Jaffna Peninsula, Sri Lanka****Figure 2. Limestone surface (m MSL) for Jaffna Peninsula and bore locations**

Point Pedro. This dune area has been the target of exploration drilling as part of the study and the sand beds appear to range from about 8 m to about 17 m thick with a maximum elevation of about 10 m above sea level. They are clearly a recent coastal feature and in places are currently mobile.

The surface topography was processed using 228 bore logs (Figure 3). The catchment has generally low relief with elevations varying from -1.5 m to over 10 m AMSL.

In the Chavakachcheri – Palai area to the southwest of the Vadamaradchi Lagoon is a thin discontinuous cover of unconsolidated deposits which are mapped as un-named yellow and brown sand. The sands in this area are fine to medium grained and subrounded, with a maximum reported thickness of about 15 m. Similar sand deposits occur in limited areas on the islands off the western end of the Peninsula, and in the western part of the Chunnakam area north of Jaffna city. The lagoon soils which are of marine clay origin comprise 36 percent, followed by yellow brown sands of the Chavakachcheri – Palai area are 34.4 percent and comprise the largest geological groupings.

Hydrogeology

The altitude and configuration of the water-table mounds in the Jaffna Peninsula aquifer system are affected by factors such as surface-water bodies, the geologic framework, and changing pumping and recharge conditions. In general, groundwater flows radially from the highest point of the water table toward the coast and the inter-lens discharge areas.

Rainfall

The average monthly rainfall pattern (1960-2004) for Jaffna is shown in Figure 4. The lowest average monthly rainfall of 14.8 mm occurs in June and the highest average monthly rainfall of 363.2 mm in November. There is a pronounced wet season lasting from October to December. The average annual rainfall for the peninsula is 1284 mm/yr.

Evaporation

The monthly pattern of pan evaporation for selected stations is shown in Figure 5. The lowest average monthly evaporation of 56.3 mm occurs in November and corresponds to the highest rainfall month. The highest average evaporation of 140.4 mm is in July corresponding to the second driest

month during the dry period. Evaporation exceeds rainfall in the dry season months from February to September by a considerable margin with the largest deficits occurring in June and July with 117 mm and 114 mm respectively. The average yearly evaporation of the Peninsula is 1234 mm.

Groundwater usage from agricultural wells

There are some 100,000 dug wells in the peninsula of which 17,860 are agricultural wells and the remainder are used to meet domestic and garden demand in urban and rural areas in the Peninsula. The largest number of agricultural wells are in Valikamam East at 7,942 followed by 2,321 in Valikamam West. The highest usage also occurs in Valikamam East with dry season water use at 39,000 ML and wet season usage at 26,000 ML, with total usage in this area exceeding 65,000 ML or 44.5 percent of the total agricultural usage for the peninsula. The agricultural usage ranges from 600 ML/yr at Nallur to over 65,000 ML/yr in Valikamam East.

The total agricultural well usage is 147,000 ML/yr with dry season use at 88,000 ML and wet season usage at 59,000 ML. Of this we have assumed an average of 24 percent returns to the aquifer from excess irrigation. Thus the net agricultural well usage is 112,000 ML/yr.

Urban and rural water use

The most intensively exploited areas are the urban areas of Jaffna Chavakachcheri and Point Pedro, and to a lesser extent Valvettithurai which lies to the west of Point Pedro. For rural water use the most heavily exploited areas are

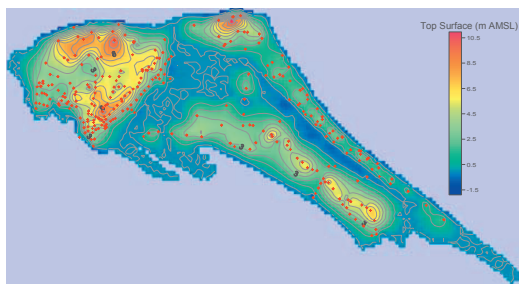


Figure 3. Surface topography contours of Jaffna Peninsula

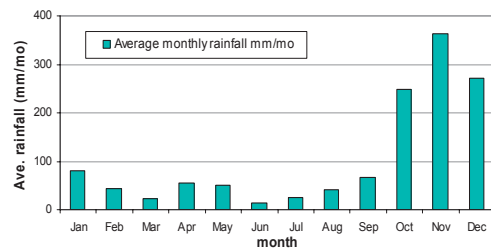


Figure 4. Average monthly rainfall (mm) for Jaffna Peninsula from 1960-2004

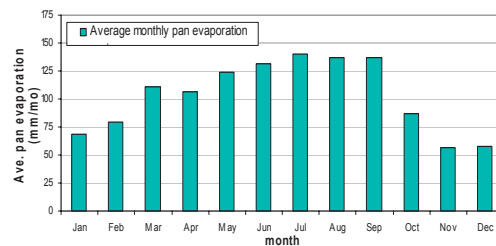


Figure 5. Average monthly pan evaporation (mm) for Jaffna Peninsula from 2000-2004

in Valikamam East and a small zone in Valikamam West. Water use for most of the area covered by the Chunnakam aquifer is in the 120 to 300 m³/d range. Similarly there are zones to the north and northeast of Chavakachcheri that use 120 to 300 m³/d of water. However, the remaining areas in Chavakachcheri and for the entire Palai area rural water use is less than 120 m³/d. West of Point Pedro there are zones where rural water use is in the 120 to 300 m³/d range, however, south of Point Pedro along the coastal sand dunes at Vadamaradchi all of the area has very low water use.

Material and Method
Model Development

The groundwater models used were MODFLOW to model the flow system (McDonald and Harbaugh, 1988), MT3DMS to model mass transport (Zheng and Wang, 1999) and, SEAWAT to model (Guo and Langevin, 2002) for seawater intrusion. A 500 x 500 m grid was used to model the Jaffna Peninsula covering the major groundwater areas of Valikamam, Chavakachcheri, Palai and Vadamaradchi East. To accommodate the horizontal component of flow, the groundwater system is considered to be formed of a series of layers, each of which is given a mathematical representation of the aquifer characteristics for that layer. The model consists of 7 active layers that correspond with the sand layer and the limestone formation as shown in Figure 6.

Construction of the land and limestone surfaces was undertaken using available bore logs and also the additional drilling undertaken as part of this study. The remaining layers were constructed by setting a bottom limit of -51 m MSL for the bottom of layer 7. From a few available logs and previous studies the thickness of the limestone has been reported to be up to 80 m. The rationale for choosing the bottom of layer 7 at -51 m MSL was to ensure that layer 7 is below the 50 percent isochlor contour. This will ensure that the saline interface is adequately accounted for by the model. The remaining model layer surfaces were constructed by taking an approximate even distance between the land surface and the bottom of layer 7.

The top sand layer is unconfined and the deeper limestone layer is treated as a confined layer. In the north central part of the Valikamam region the limestone is treated as unconfined where it is exposed at the surface. The bedrock which forms

the floor of the basin and marks the base of the limestone formation is assumed to have negligible permeability and so no flow occurs across this surface.

SEAWAT Equations

The USGS SEAWAT model combines the MODFLOW code (Harbaugh and McDonald, 1996a & 1996b) for groundwater flow and MT3DMS (Zheng and Wang, 1999) for advective-dispersive transport. The standard SEAWAT model equations assume a purely advective- dispersive salinity transport according to the following governing equation (Guo and Langevin, 2002)

$$\frac{\partial c(\bar{x}, t)}{\partial t} = \bar{u}(\bar{x})c(\bar{x}, t) + \bar{D}\bar{c}(\bar{x}, t)\sum q_i \tag{1}$$

where c is the salinity in kg/m³, u is the pore velocity in m/day, D is the dispersion tensor in m²/day and q_i are source and sink terms in kg/m³/day. Salinity transport and flow are coupled via the fluid density, which can be seen from the following continuity and Darcy’s Law equations:

$$\nabla(\rho(c)\theta\bar{u}) = \frac{\partial}{\partial t}(\rho(c)\theta) \tag{2}$$

$$\theta\bar{u} = -\frac{K}{g}\left(\nabla\left(\frac{P}{\rho(c)}\right) + \bar{g}\right) \tag{3}$$

where ρ is the density of the fluid (kg/m³), θ the porosity, K the hydraulic conductivity (m/day), P the pressure (bar) and g the gravitational acceleration in (m/day²). In case of density-dependant groundwater flow, the fluid density is no longer constant, but a function of the solute concentration, which in SEAWAT is approximated with a linear relationship (Guo and Langevin, 2002):

$$\rho = 1000 + 0.7143c\left[\frac{g}{l}\right] \tag{4}$$

Lagoon-Groundwater Interaction

The river module in MODFLOW models the interaction of the river and groundwater system by adding contributions from the lagoon to the groundwater system and also allowing for flow of groundwater back into the lagoon system. The lagoons are conceptually treated as river cells to allow for lagoon-aquifer interaction. The flow rate to or from the aquifer is controlled by the difference in head between the lagoon and the aquifer within a model cell and the conductance of the lagoon bed. The direction of flow is controlled by the head in the aquifer or the lagoon whichever being the greater at a particular point in time.

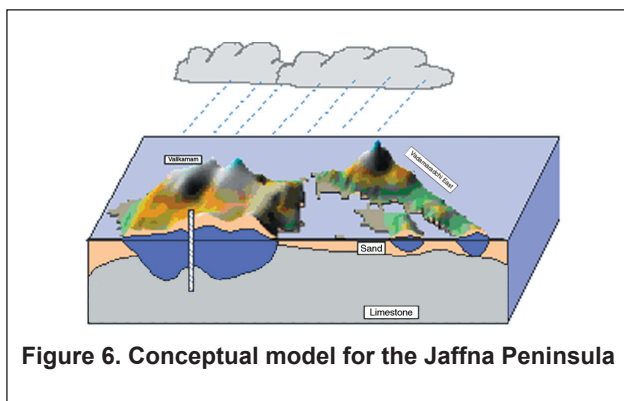


Figure 6. Conceptual model for the Jaffna Peninsula

Boundary Conditions

Two types of boundary conditions are used in the model to define the sea boundary surrounding the peninsula. General head boundaries are used for the first two layers and constant heads are used for the remaining layers. Flows across model boundaries were specified using the general head boundary package in MODFLOW. Flows are controlled by head gradients between boundary heads and model heads, and the direction of flow is controlled by the either of the heads whichever is the greater. The conductance term is the other parameter that controls the rate of flow across the boundary. The advantage of using general head boundaries is that during model simulations as heads within the model domain change so also does the flow in or out from the boundary. Initial estimates of boundary heads and conductance values were modified during model calibration.

Model Calibration

The procedure adopted in calibrating groundwater models is essentially a trial and error process involving adjustment of parameters and fluxes until model responses match field observations according to pre-set calibration targets. Adjustments in parameters are required because each parameter is associated with a level of uncertainty. The range of uncertainty influences the level of adjustment applied. Typically the procedure involves incremental changes in aquifer parameters within realistic limits such that there is a gradual improvement in the models ability to simulate field measured piezometric heads and salinities.

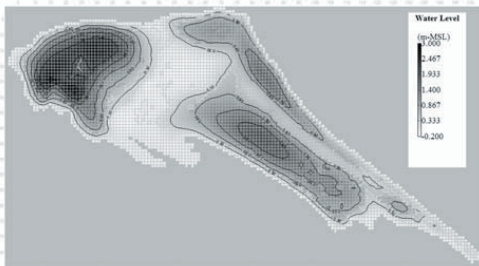


Figure 7. Steady state heads (m MSL) for the Jaffna Peninsula

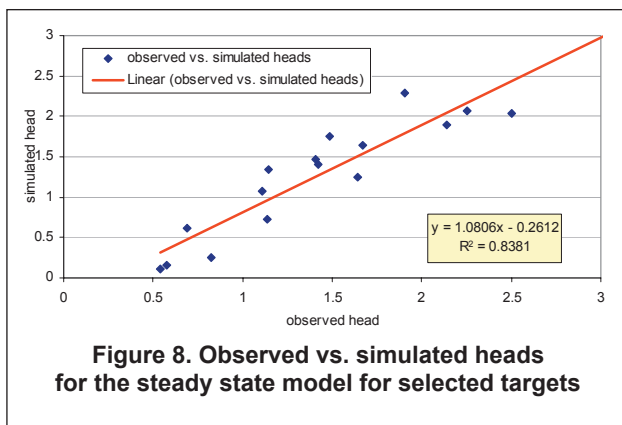


Figure 8. Observed vs. simulated heads for the steady state model for selected targets

Steady State Model Calibration for Jaffna Peninsula

A steady state model was developed to generate a water level surface that could be used to provide starting conditions for transient simulations. Average values for rainfall, evaporation and pumping were used. Figure 7 shows heads generated by the steady state model for the peninsula. Figure 8 shows the observed vs. simulated heads for selected targets for the steady state model. The simulated heads compare favourably with observed heads with an R² of 0.84. Comparison of head values were undertaken for January 1999 so that initial heads for the transient model would be reasonable. The absolute residual mean was 0.26, the residual standard deviation was 0.28, and the range in residuals was from -0.38 to 0.57. The statistics indicate that the model was well calibrated for steady state heads.

Transient Model Calibration for Jaffna Peninsula

The calibration for the transient model was undertaken to ensure the model is capable of predicting the regional flow for the Jaffna Peninsula, and the model is able to replicate temporal responses. The procedure involved adjusting aquifer hydraulic properties, storage, boundary conditions, and system stresses such as recharge, evaporation and lagoon-aquifer interaction such that the model is capable of simulating both spatial and temporal responses. It was not possible to calibrate the model to spatial responses, primarily due to the paucity of water level information for the aquifers in the catchment which did not allow the piezometric surface to be contoured with reasonable accuracy. However, a great deal of time and effort was expended to ensure calibration of temporal responses where data from observation bores was available. As stated earlier the availability of monitored wells where heads and salinity were measured monthly was restricted to the southern Valikamam region. Thus greater confidence in model results can be placed in this area.

The period of calibration for the transient model extended from 1999 to 2004. The initial conditions for the transient model were taken from the piezometric surfaces produced from the steady state model shown earlier in Figure 7. The resultant piezometric surface after a simulation period of six years from January 1999 to December 2004 is shown in Figure 9 for December 2004 at the end of the wet season, and in Figure 10 for August 2003 at the end of the dry season. There is considerable variation in heads across the Peninsula from 0 m MSL along the coastal and lagoon areas to 5.94 m MSL in the Chunnakam aquifer at the end of the wet season, and to a lesser degree in the dry season in July 2003. Dry season heads range from -0.2 m to 3.1 m MSL for the peninsula. Head gradients are higher in the Chunnakam and Point Pedro areas, particularly where the topography is relatively higher and trending towards a much more subdued pattern across the Chavakachcheri-Palai region. Figure 11 and Figure 12 show salinity variation for the freshwater zones in December 2004 and August 2003 respectively. Salinity increase is noticeable in August at the end of the dry season which is indicated by greater numbers of green, orange and red cells.

Model calibration involved the comparison of model results against key hydrographs with measured data. This part of the calibration allows the user to determine how much confidence can be placed in selected locations within the model domain. During the calibration process changes in parameter values were made within reasonable limits to ensure that values used in the model are realistic. The bore calibrations involve comparison of simulated heads and salinity with field measured heads and salinity. Some of the limitations that accompany these comparisons are that field measured heads and salinity are point measurements in space and time, and at best are an indication of the heads in proximity to the bore. Simulated heads for the Jaffna Peninsula regional model are average values for a grid cell which is 500 x 500 m. Besides being spatially averaged values modelled heads are also temporally averaged. In the case of the Jaffna Peninsula model monthly stress periods are used so that stresses and flows are constant over a single stress period. Figure 13 shows observed and simulated heads for well 296 to the east of the Jaffna Municipal Council water supply wells. The seasonal change in heads simulated by the model match observed heads reasonably well as do the trends. Figure 14 shows observed and simulated salinity values for well 296. The salinities match very well and seasonal trends are also reproduced to some extent.

Result and Discussion
Water Balance for Jaffna Peninsula

An analysis of water balance was undertaken for the cali-

brated model from 1999 to 2004. Water balance for the entire model is presented for the purpose of understanding flows for the aquifer system and its interaction with the coastal sea boundary. The water balance for the transient model is presented in Table 1. All values are in m³/d and are averaged over the 6 years of simulation.

Net recharge is approximately 21 percent of the average annual rainfall and accounts for 63 percent of all inflows. Runoff is assumed to be 30 percent of rainfall for the peninsula, this means that evapotranspiration from the soil above the watertable is approximately 49 percent of the rainfall. The remainder contributes to net recharge to the system. The largest outflow component is evapotranspiration from the watertable or 43.5 percent of total outflows. Thus the total evapotranspiration from the peninsula is approximately 62.5 percent of average annual rainfall.

Lagoons and ponds contribute 26.5 percent of total inflows, and boundary flows from the sea contribute 10.8 percent of total inflows. Boundary inflows occur along the coast and areas of high inflows are most likely to be prone to seawater intrusion. Figure 15 shows the risk of saline intrusion into coastal areas. The total outflow to the sea from the coastal boundaries accounts for 17.7 percent of all outflows. The high value of outflows to the sea is a good indication of the low storage potential of the aquifer. The high conductivity in the limestone is a contributing factor.

The second highest outflow component is evapotranspiration which accounts for 43.5 percent of all outflows. It has the most significant impact on the available water that can

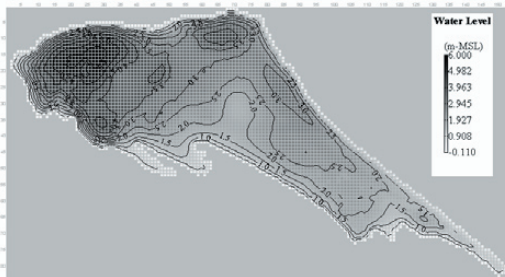


Figure 9. Wet season heads (m MSL) in December 2004 for the Jaffna Peninsula

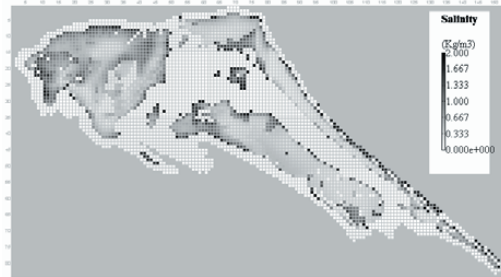


Figure 11. Salinity concentration (kg/m³) for freshwater zone during the wet season, Dec. 2004



Figure 10. Dry season heads (m MSL) in July 2003 for the Jaffna Peninsula

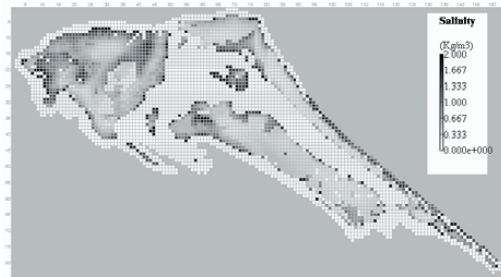


Figure 12. Salinity concentration (kg/m³) for freshwater zone during the dry season, July 2003

be extracted from the aquifers of the peninsula. A reduction in pumping brought about by an increase in irrigation efficiency by encouraging the use of sprinklers and drip irrigation and through farmer education will result in additional water available for water supply. However, this is a long term process and cannot occur overnight. Based on the pumping rates used in the model for urban and rural users and from agricultural wells the total available water for the peninsula is 83123 m³/d. However not all of this is available for extraction because of the risk of upconing, saline intrusion into coastal areas, and also because in some areas the salinity is high. In order to determine the sustainable yield a separate water balance for the freshwater zones in the peninsula has been undertaken.

Water Balance for Freshwater Zones in Jaffna Peninsula

An analysis of water balance for the freshwater zones was undertaken for the calibrated model from 1999 to 2004. Freshwater zones were defined as areas of the model with salinity less than 2300 mg/L (3500 EC). Water balance for the entire model as well as for groundwater management zones and more importantly for the freshwater zones is estimated for the purpose of understanding flows for the aquifer system. The available yield for the six year simulation is 51790 m³/d from the freshwater zones. One important point to keep in mind is that rainfall during the calibration period from 1999 to 2004 was 1490 mm/yr which was 16 percent higher than average for the Jaffna Peninsula. In addition rainfall for 2001

and 2004 was 1744 and 1869 mm/yr respectively during the calibration period. These two very high rainfall years have a large impact on groundwater recharge.

Scenario Analysis

A groundwater pumping scenario was undertaken with additional pumping from 25 wells with laterals or spears which were used to examine the impact on the groundwater system of diffuse extractions, with laterals/spears supplying between 100 to 150 m³/d. Optimum locations were selected based on the water quality of the freshwater lens.

Figure 16 shows salinity at a well in Valikamam and Figure 17 shows salinities at Chavakachcheri. Salinities show a rising trend for the first 5 years before stabilising. Salinity for the hydrograph in Figure 17 was well above the permissible limit. Thus these locations are not suitable under the proposed pumping regime.

Similarly salinity hydrographs were analysed for wells at Vadamaradchi East and Point Pedro. For the Vadamaradchi well maximum salinity was 0.4 kg/m³. For the Point Pedro wells the maximum salinity was in the 0.5 and 0.85 kg/m³.

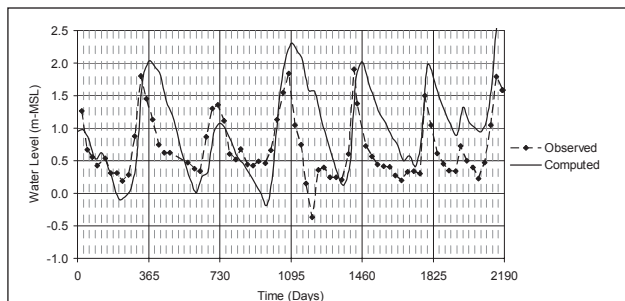


Figure 13. Observed and simulated heads for calibration target, Well No. 296 (119347 N, 496512 E)

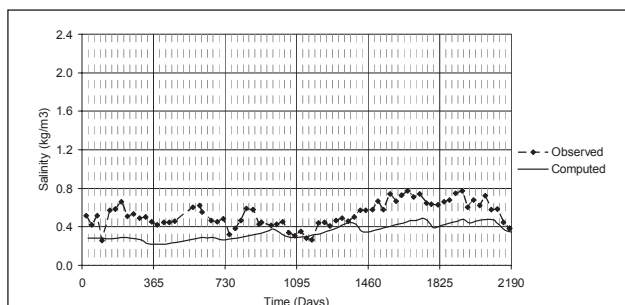


Figure 14. Observed and simulated salinity for calibration targets, Well No. 296

Table 1. Water balance for Jaffna Peninsula 1999-2004

Stresses	Inputs m ³ /d	Outputs m ³ /d	Net m ³ /d
Recharge	821037	0	821037
Lagoons	347397	9444	337953
Wells		467125	-467125
Evapotranspiration		533696	-533696
GHB flows	4	20473	-20469
Constant Head flows	142167	196744	-54577
Net Storage	1310605	1227482	83123

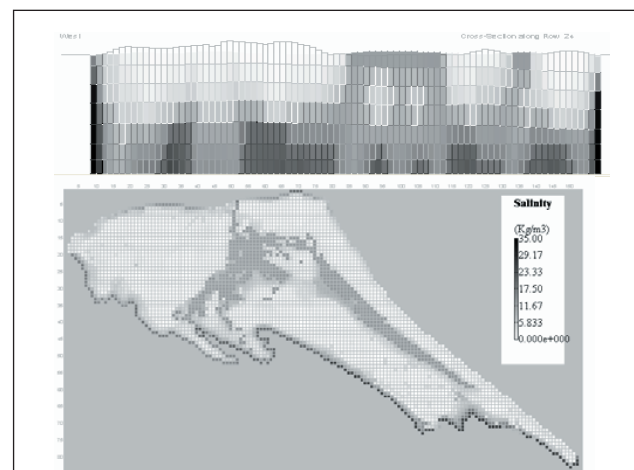


Figure 15. Risk of saline intrusion into coastal areas Cross-section of row 24 (above) and layer 1 (below) for dry season July 2003

In all wells salinity generally remain below the permissible level and only in the Point Pedro well does it exceed permissible levels for a short duration.

Figure 18 shows selected cross section for Chunnakam. Single production bores at relatively high rates of 1200 m³/d will result in upconing and will deteriorate the water quality of the freshwater lens. The upconing can be seen clearly in column 32. The scenario for wells with 8 laterals at a radius of 500 m shows no upconing as maximum extraction rates are 150 m³/d.

Conclusions

A regional numerical flow model was developed as part of this investigation to assist in the analysis of freshwater and saltwater flow for changing pumping, and recharge, conditions. The model was used to determine water budgets, flow directions, and the position and movement of the freshwater/saltwater interface throughout the study area for current conditions. The model also was used to assess potential effects of increased pumping for proposed pumping well locations on ponds, streams, coastal areas, and the position of the freshwater/saltwater interface to demonstrate how the model can serve as a tool that can be used by engineers and local managers to assess possible effects of proposed water management strategies on Jaffna Peninsula.

The availability of monitored wells where heads and salinity were measured monthly was restricted to the southern Valikamam region. Thus greater confidence in model results can be placed in this area. The available yield for

the calibration period is 51790 m³/d from the freshwater zones. Sustainable extractions of about 50000 m³/d would be sustainable if salinities do not become excessively high as a result of this extraction. However, rainfall during the calibration period from 1999 to 2004 was 1490 mm/yr which was 16 percent higher than average for the Jaffna Peninsula. In addition rainfall for 2001 and 2004 was 1744 and 1869 mm/yr respectively during the calibration period. These two very high rainfall years have a large impact on groundwater recharge. As such the estimated available water is expected to be higher than for average years.

Five zones were identified in the freshwater areas in the peninsula; these are Valikamam, Chavakachcheri, Palai, Vadamaradchi East and Point Pedro. The available yield for the 6 year simulation is 31431 m³/d from the freshwater zones in Valikamam; 4315 m³/d from the freshwater zones in Chavakachcheri; 3542 m³/d from the freshwater zones in Palai; 6907 m³/d from the freshwater zones in Vadamaradchi; and 5638 m³/d from the freshwater zones in Point Pedro.

Groundwater pumping scenarios were undertaken with additional pumping from 25 production wells and wells with 8 laterals or spears at 500 m radius. High pumping rate from production bores found to be unsuitable for the Peninsula. Use of wells with laterals or spears is suitable for the Jaffna Peninsula, as it limits the risk of upconing. The maximum sustainable pumping rates per laterals are 150 m³/day in Valikamam and 125 m³/day in Chavakachcheri, Point Pedro, and Vadamaradchi East areas. Finding suitable locations for wells in the Peninsula remain a challenging task due to the inherent complexities of the system and the fact that the thickness of the freshwater lens amongst other factors has a bearing on the quality of groundwater extracted. Thus each location needs rigorous testing and sensitivity analysis to ensure its suitability.

Acknowledgements

We thank Eng. Lal Premanath, Project Director, ADB Assisted Third Water Supply and Sanitation Project, NWS&DB for giving necessary approval to write this paper. Funding

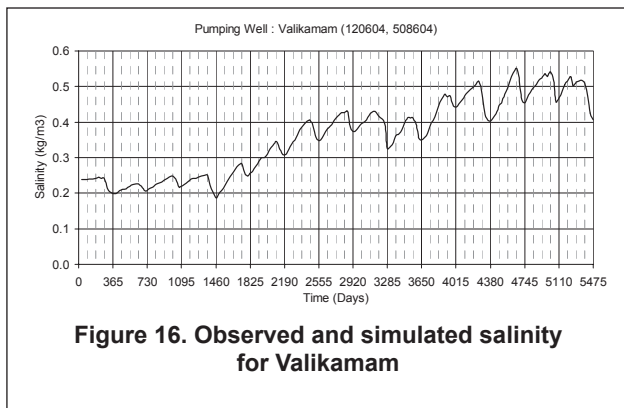


Figure 16. Observed and simulated salinity for Valikamam

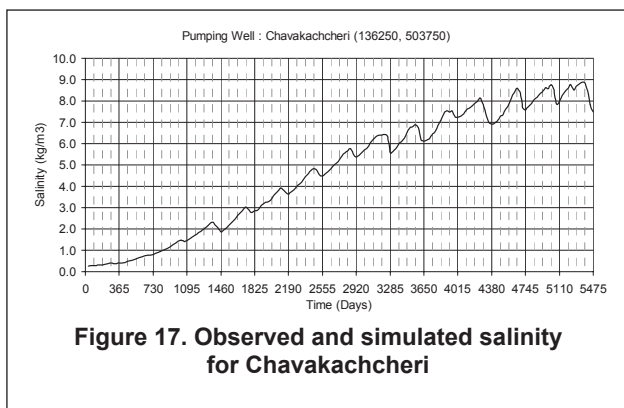


Figure 17. Observed and simulated salinity for Chavakachcheri

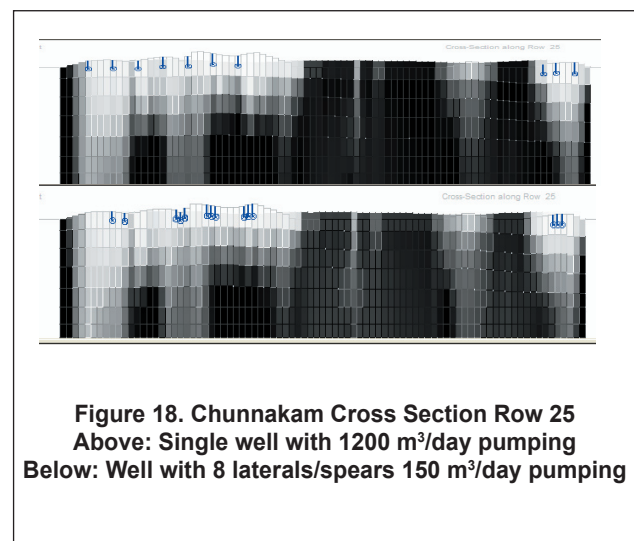


Figure 18. Chunnakam Cross Section Row 25
Above: Single well with 1200 m³/day pumping
Below: Well with 8 laterals/spears 150 m³/day pumping

for this project was provided by the ADB and the Government of Sri Lanka, Ministry of Urban Development and Water Supply through the ADB Assisted Conflict-Affected Areas Rehabilitation Project – Sri Lanka (ADB Loan No: 2043/2044, for the Jaffna Peninsula Water Supply and Sanitation Feasibility Study (Component D). The study was carried out by SMEC International Pty Ltd in association with Ceywater Consultants (Pvt) Ltd. The staff at the Jaffna project office and at SMEC and Ceywater offices in Colombo are thanked for their assistance during the study.

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