Groundwater Modelling to Predict Management Options for Kayts in Northern Sri Lanka

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Abstract Kayts is one of several islands which lie off the western end of the Jaffna Peninsula in the northern-most part of Sri Lanka. A low salinity groundwater lens is the only promising source of fresh water on the island. The return of refugees in the post conflict period has raised concerns for the quantity and quality of groundwater available for drinking and agriculture and on increased risk of seawater intrusion and upconing from unsustainably high extraction rates. The groundwater flow model MODFLOW, mass transport model MT3DMS, and salinity intrusion model SEAWAT were used to model the regional flow system and the interface separating the freshwater and saltwater flow systems, and for pumping and rainfall recharge scenarios. The water balance for the sand dune area in Kayts, found the available water from this region is 266 m^3/d. Preserving the sand dunes which are the only reliable source of potable water for Kayts remains a priority.

Keywords: Seawater intrusion, SEAWAT, modelling, water supply,

1. Introduction

Kayts is one of several islands which lies off the western end of the Jaffna Peninsula in the northern-most part of Sri Lanka. Like the Jaffna peninsula, Kayts and other surrounding islands have no streams or reservoirs of a perennial nature. Most of the islands in this region have very limited groundwater potential. A thin fresh water lens is present in the sand dune area on Kayts, which occupies a small area of the south-eastern part of the island (Fig. 1.). This low salinity groundwater lens that constitutes the Kayts aquifer system is the only promising source of potable water available for Kayts.

In most of the islands a thin fresh water lens accumulates water during the wet season, but these are exploited only for domestic use by shallow dug wells. The fresh water lens typically develops in limestone or coral reef formation and as such the storage potential is low.

During the 1990’s there was a decrease in population due to people being displaced due to the continuing conflict in the region. However with the prospect of peace and refugees returning back to the peninsula and the islands the population is projected to increase. An increase in land development and projected population growth in this region has raised concerns for the quantity and quality of groundwater available for drinking and agriculture and on increased risk of seawater intrusion and upconing from unsustainable high extraction rates.

These concerns include the effects of increased groundwater pumping on the position of the freshwater – saltwater interface and the interaction of groundwater with ponds and lagoons. Groundwater discharge from springs along the coast plays an important role in the maintenance of ecologically sensitive areas. Declines in water levels due to increased groundwater withdrawals could have a detrimental impact on the environment and natural resources of this region. Particularly on islands, depletion of the fresh water lens can result in increased salinity rendering limited freshwater supplies unusable.

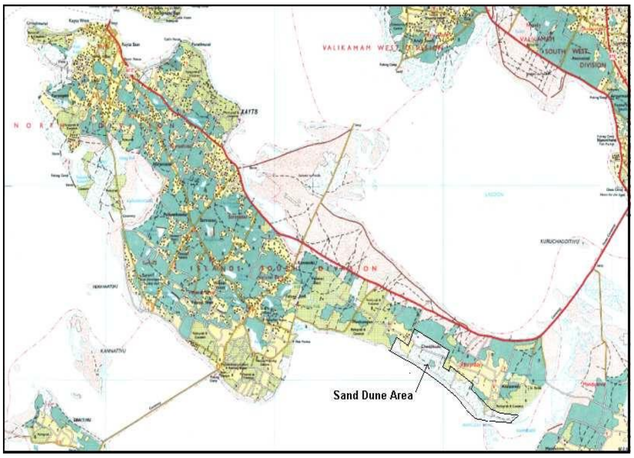

Fig.1. Island of Kayts showing sand dune area.

The intention of this study is to examine the behaviour of groundwater flow in this aquifer and come out with an appropriate management strategy to ensure sustainability in groundwater management for this region.

Studies were undertaken to develop sustainable management strategies for groundwater supplies for Kayts (Shanmuhananthan and Punthakey 2006). The objectives of the study are to develop groundwater flow and salinity transport models for the island of Kayts, estimate water balance for the freshwater lens, assess the potential for seawater intrusion and upconing for pumping and recharge scenarios, and the impact on fresh groundwater resources.

2. STUDY SITE

2.1 Location

Kayts is one of several islands which lie off the western end of the Jaffna Peninsula in the northern-most part of Sri Lanka. This island is narrow and elongated in shape and has a maximum elevation of about 4m. Like Jaffna Peninsula, Kayts has no streams or reservoirs of a perennial nature.

The extent of the Island's area is 64 km^2 and it has a coastline of approximately 69 km. Agriculture and built-up land covers 70% of the land area and 20% of the land is covered by sand or beach. The remaining 10% is covered by scrublands.

2.1.1 Sources of data

Geological data, type of aquifer and aquifer thickness details are collected from the driller's logs obtained from the Engineering Science report (Engineering Science, 1982) and from the Geology and soil maps published by the Survey Department.

The ground elevation of 220 dug wells on Kayts where water levels and chlorides were monitored monthly from 1979 to 1982 were extracted from the Water Resources Board's records and this was complemented by the findings of the topographical survey carried out under this study. The topographical survey covered 90 locations on Kayts.

Monthly water levels from 220 observation wells from 1979 tob1982 were obtained from records held by the Water Resources Board.
Possible range for the Hydraulic conductivity of the sand aquifer was determined based on the pumping data obtained from the pumping tests conducted by the Foundation and Water well Engineering (Pvt) Ltd under this study and from previous work undertaken on Kayts and described in the Engineering Science report.

Land use details were collected from the map prepared by the Survey Department.

Monthly rainfall data for the period from 1960 to 2004 were collected from Metrological Department records. Monthly evapotranspiration data were extracted from the Engineering Science report (Engineering Science, 1982).

Details of inland water bodies were collected from Agrarian Development Department's records.

Groundwater extraction related data such as human population, domestic water supply details, lift irrigation details and number of wells were collected from the Census, Water Supply and Drainage Board records, Department of Agriculture and Divisional Secretaries.

2.2 Hydrogeology & groundwater resources

The geology of islands to the west of the Peninsula has had the same origin as the Jaffna Peninsula. The Jaffna limestone formation in Sri Lanka is an important local aquifer and, together with thin sand layers that form an extensive cover for the limestone, provides a source of water for drinking and for irrigation. The bulk of the island of Kayts is covered by silt and clay overlying limestone. The clay is up to 3 meters thick with low permeability and does not serve as an aquifer. Dug wells have to penetrate the clay to reach the limestone before yielding water. Where the island narrows as it changes direction to the east, the clay is replaced by fine sand to form a two layer aquifer, sand over limestone. Because of the low permeability of these sands, a fresh water lens is able to form in this area. The area of exploitable aquifer system on Kayts extends eastward from Mankumpan to Allaipitty a distance of about 4 km, and southward from Jaffna road to the coast, a distance of about one and a third km (refer to the sand dune area outlined in Fig. 1). The rate of withdrawal from the aquifer is constrained by the permeability of the sand and thickness of the freshwater lens.

2.3 Aquifer Properties

Considering the importance of having a fairly accurate range of hydraulic conductivity and transmissivity for this study, at least for the sand aquifer, which seems to be the only promising source for additional developments, pumping tests in two test bores were conducted by the Foundation and Water Well Engineering (Pvt) Ltd. The data collected from this test was analyzed using the method derived from Darcy's law recommended by the Foundation and Water Well Engineering (Pvt) Ltd in its report. The results are given in Table 1.

Table 1 - Aquifer properties

Well No	Kay - 2	Kay - 1
Transmissivity m^2/d	28	35
Hydraulic conductivity m/d.	7	10
Aquifer thickness m	2	6

The area was demarcated into zones corresponding to the geology and each zone assigned appropriate values of hydraulic conductivities (Kh) and storage (S).

2.4 Zone division

Because recharge is a non–linear process, it is not possible to use average values of each controlling factor to derive an average recharge. Recharge should be estimated separately for each homogeneous zone; the spatially varying values are of course essential for groundwater modeling studies (Lerner, 1990). For this study, the total project area is divided into 7 groundwater extraction zones based on the availability of spatial coverage of groundwater withdrawal data and 9 recharging zones based on the geology, soil types and aquifer properties.

2.5 Land usage

The land use pattern plays a vital role in determining recharge and withdrawal of groundwater from the aquifer. Especially the type of vegetation cover decides the rate of actual evapotranspiration depending on its root constant and that ultimately decides the rate of recharge. Further percolation from irrigated lands may contribute significantly to the recharge of the aquifer. The map showing land use of Kayts is presented in Figure2.

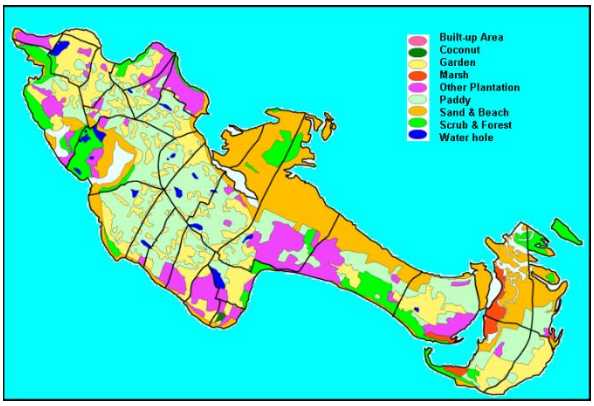

Fig.2. Map showing land use of Kayts.

2.6 Water-table & Salinity fluctuation

Rainfall is highest during the rainy season which extends from September to December. A minor monsoonal period extends from April to May. The aquifer in this region mainly gets recharged during September to December. From January onwards the groundwater table drops and in August the water level reaches its minimum. The Water Resources Board commenced measuring water levels in a network of 220 shallow wells on Kayts in early 1979 and extends to 1982. The data from this observation network constitute an exceptionally useful tool in assessing the current status of the groundwater system in the Kayts area.

Since Kayts is a small island, the coastal aquifers are usually in hydraulic continuity with marine water. Moreover the fresh water lens overlies progressively saline groundwater with depth. Excessive rates of abstraction with a consequent lowering of the water table may induce seawater intrusion and upconing, and thus contamination of the fresh water. Chlorides were monitored monthly by the Water Resources Board from 220 wells from April 1979 to December 1982.

2.7 Rainfall recharge

Runoff and infiltration due to precipitation events depend upon the amount and the intensity of the rainfall as well as the antecedent moisture condition of the soil profile (Athavale and Rangarajan, 1990)

Apart from these factors, the storage capacity of the aquifer also plays an important role in determining the recharge quantity. Even though the rainfall during Sept ‘80 to Dec ‘80 is 40% less compared to the rainfall during Sept ‘81 to Dec ‘81, there is no significant difference in the depth of water table gain. This clearly reveals that once the storage has reached its optimum level, there will be less recharge and the portion of runoff will be more.

However, most of the formulas do not consider these factors and as a result, the runoff is either overestimated or underestimated and in turn it affects the recharge. In this exercise, during the course of calibration, an attempt was made to establish a relationship between the rainfall quantity and percentage of recharge by taking the above factors into consideration.

2.8 Evapotranspiration

Water is held in a soil moisture store. Precipitation adds to the store, evapotranspiration depletes it. When full, excess precipitation is routed to groundwater as recharge. The most difficult item to measure is actual evapotranspiration, and in general a conceptual quantity called ‘potential evapotranspiration’ is defined. Good data on actual evapotranspiration is equally important as good precipitation data. Unfortunately actual evapotranspiration is rarely measured except in research projects. The average potential evapotranspiration values of various methods described in the Engineering Science report is used in this exercise.

2.9 Water Bodies - Groundwater Interaction

Recharge from Surface Water Bodies is sometimes underestimated because it is neglected. On the other hand, once irrigation has been recognized as a recharge source, the quantities are often overestimated because all losses are assumed to become recharge. Losses from irrigation occur in two overlapping areas (a) canals (b) fields. (Lerner, 1990).

According to the statistics given in the Jaffna District Statistical Hand Book, there are 50 ponds irrigating less than 400 ha of cultivable lands on Kayts. The total water holding capacity of these ponds is around 2200 ac.ft (2.7 million m^3 of storage). Most of them are small limestone sinkholes covered with clay beds. The average irrigable area and storage capacity of these ponds are 8 ha and 44 ac.ft (0.05 million m3 of storage) respectively. These statistics clearly indicate how small these ponds are.

A surface water body such as a lake or pond contributes water to the groundwater system or drains water from it depending on the head gradient between them. Such water exchange affects pond levels and groundwater heads. The seepage losses from reservoirs depend on the permeability of the reservoir bed and the flanks and are mostly a loss due to deep percolation. The methods of estimation of irrigation storage losses differ from region to region and depend on the principal factors such as head gradient, permeability of reservoir bed, thickness of accumulated silt and volume of storage which governs the percolation.

It is stated in the Engineering Science report that in the northwestern part of the Kayts, the limestone sinkholes covered with grey–brown clay create numerous ponds, some of which provide irrigation water during the dry season when the actual water table is below the bottom of the ponds. This implies that the water table and surface water bodies have less interaction due to the less impervious clay bed.

The method of estimation of recharge from surface water bodies and irrigated fields described by Ponrajah (1984) is one of well-tested method and is being practiced for several years by the Irrigation Department. This method has been adopted to estimate recharge from surface water bodies and irrigated fields in this exercise.

2.10 Groundwater withdrawals

The basic details required for the computation of Groundwater withdrawal such as human population, domestic water supply details, cultivation details, numbers of wells, extent of forest area are collected for each GN division. Using this basic data, groundwater withdrawals for each season were calculated separately for each zone. For the scope of this study, the total project area falling within the 25 GN Divisions are clustered into 7 water usage zones as shown in Figure3.

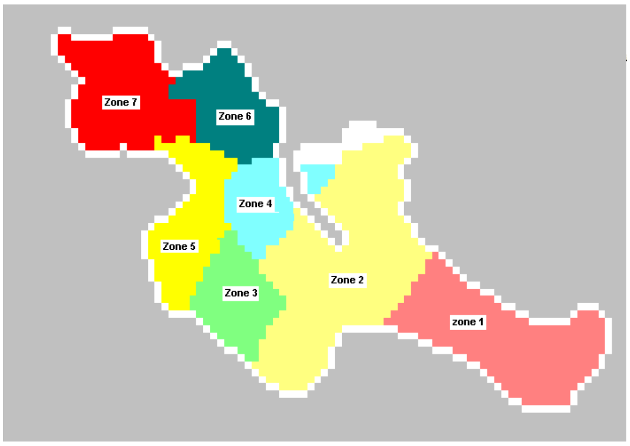

Fig.3. Map showing water use zones.

3. CONCEPTUAL MODEL

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 seawater intrusion (Guo and Langevin, 2002).

A 200 x 200 m grid was used to model the island of Kayts and the grid covered the main sand dune aquifer in the southeast of the island. 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.

The gridded area is between 96000 East and 114000 m East and between 488000 m North and 500000 m North. The model consists of 60 rows and 90 columns and 7 layers. The model was run for four years from January 1979 to December 1982 using 48 monthly stress periods, as data sets were available to aid in model calibration.

3.1 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 either of the heads whichever is the greater. The conductance term is the other parameter that controls the rate of flow across the boundary.

4. 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.

4.1. Steady state calibration

Aquifer parameters, hydraulic conductivity and storage were adjusted by trial and error so that the head simulated contours generated by the model matched the observed head contours at the end of a recharging season. MODFLOW was used for this simulation. The main purpose of the steady state model was to generate initial heads for the transient state model in addition to calibrating aquifer parameters, recharge and ET.

The performance of the calibrated steady state model is quantified by spatial calibration of heads in December 1979 and comparison of measured and predicted heads at selected bores in December 1979. The observed and predicted head contours for the steady state model is shown in Fig. 4, and the observed versus modeled heads is shown in Fig. 5. The match is found to be reasonably good. This confirms that the steady state model has been well calibrated and it can generate fairly accurate initial heads for the transient model.

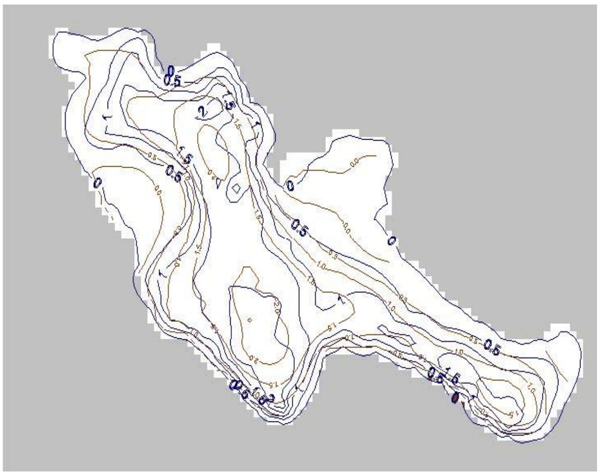

Fig 4. Steady state model calibration

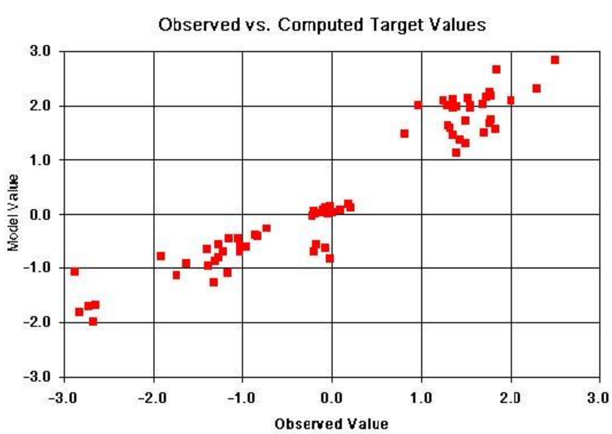

Fig 5. Observed vs. simulated head for the steady state simulation

4.2. Transient model calibration

The boundary conditions were the same as for the steady state model. Initial heads were imported from the steady state model. This model was calibrated with the data available for the four year period from January 1979 to December 1982.

Estimated values of recharge, evapotranspiration and pumping were used in this simulation run. Transient simulation allows comparison of temporal head changes in the aquifer.

The performance of the calibrated transient model is quantified by calibration of bore hydrographs from April 1979 to December 1982. The model computed head and salinity values are compared with the measured values in ten locations. The model predicted head hydrograph showed close match with the measured values although there are instances where the modelled salinities deviate from that observed.

Fig. 6, 7 for wells 13 and 89 shows a good match between observed and modelled heads. Analysis of measured and computed water levels showed a regular pattern with peak in water levels reached at the end of the wet season in January and lowest water levels at the end of the dry season in September. The seasonal variation in heads is pronounced and is simulated accurately by the model, and trends are predicted very well.

In Fig. 8, well 13 shows the model is able to simulate salinity trends with reasonable accuracy however the salinities are under predicted at times. The most probable cause for the deviation is that well 13 is in the area of the groundwater supply zone and the uncertainty of pumping records was the most likely contributing fact.

For well 89 the salinity trends are predicted with much greater accuracy as this well was far outside any zone of pumping influence. Given the high degree of both spatial and temporal variability that one encounters in the field, the match between modeled and simulated salinities is remarkably good.

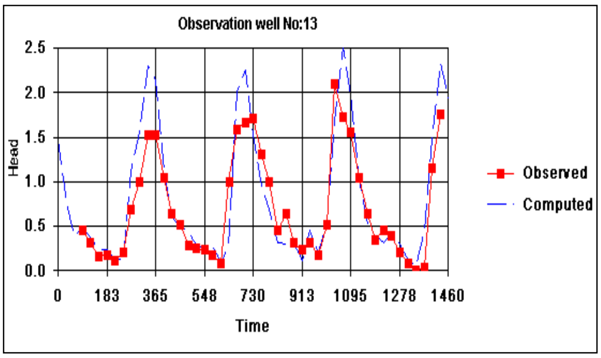

Fig 6. Observed and simulated heads for bore 13.

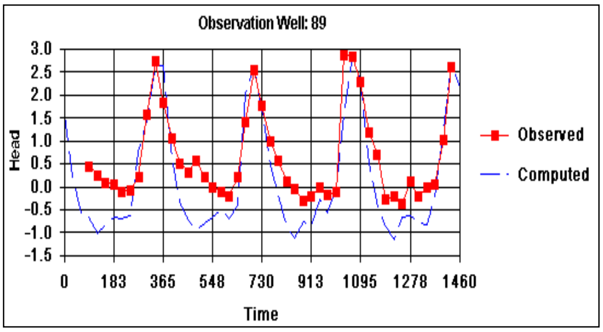

Fig 7. Observed and simulated heads for bore 89.

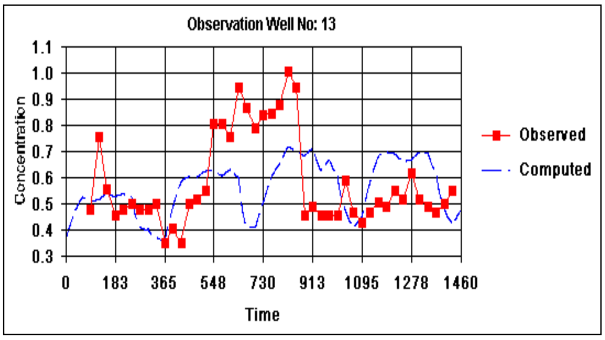

Fig 8. Observed and simulated salinity for bore 13.

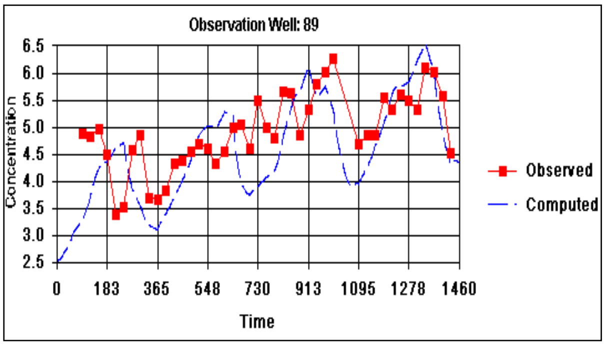

Fig 9. Observed and simulated salinity for bore 13.

The salinity distribution of groundwater during December 1982 for the wet period and in August 1982 during the dry period are shown in Fig. 10. This figure reveal that the water quality is beyond the permissible limit (2000 mg/l) in most parts of Kayts even at the end of recharging period except in the sand dune area and a small area near Naranthani.

This situation becomes worse during the dry period and at the end of the dry period a narrow stretch of freshwater lens is available only in sand dune areas. Fig. 7 shows that the area of fresh water lens with less than 2000 mg/l salinity only covers the sand dune areas. Therefore utmost care should be taken to limit groundwater extraction in all areas except in the sand dune area where some additional extraction is possible.

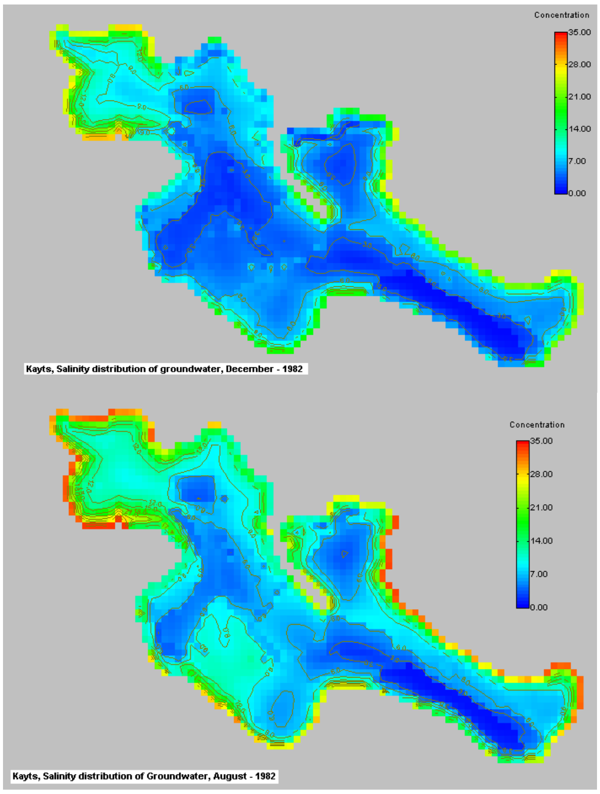

Fig 10. Salinity distribution (kg/m^3) during the wet season (Dec 82) and the dry season (Aug 82)

A small zone of fresh water found at the end of the recharge period near Naranthani area does not exists at the end of discharging period. In view of this simulation it is strongly recommended not to increase extraction during the discharging period.

5. WATER BALANCE FOR MODEL

The water balance for the regional model is presented in Table 2.

Table 2 - Annual average water balance			
Components	**Value**		**%**
Surface			
Rainfall	+	1,185	100.0
Evaporation above WT	-	459	38.8
Surface runoff	-	356	30.0
Infiltration (recharge)	-	370	31.2
Aquifer			
Infiltration (recharge)	+	370	100.0
Pumping (Domestic)	-	23	6.1
Pumping (Agro)	-	100	27.1
Pumping (Garden)	-	49	13.3
Deep rooted tree	-	17	4.6
Evapotranspiration	-	130	35.1
Net flow out to sea	-	49	13.4
Change in Storage	-	2	0.4

6. SCENARIO ANALYSIS

The Kayts regional model was simulated using the data set available for the four year period from January 1979 to December 1982. The model results reveal that additional quantity of groundwater is available only for the sand dune area of Kayts. The water balance for the sand dune area indicated that available water from this region is 265 m^3/d. Fifteen year scenarios starting from January 1983 were carried out to determine sustainable groundwater extraction rates and the most suitable method of pumping for the region.

7. RECOMMENDATIONS

Based on the results of the studies following recommendations are made for the sustainable management of groundwater resources in Kayts.

Maintaining the source

The sand dune area in Kayts is the only promising water source for Kayts island. Because of the relatively low permeability and high storage potential of these sands, a fresh water lens is able to form in this area. Following actions are recommended for the sustainable management of this water source.

- No sand mining be allowed.
- Limit development in this area which can reduce recharge to the aquifer.
- Agriculture activities have to be in limited scale to reduce the likelihood of pollution.
- Controlling the agriculture extent during dry season

Controlling the agriculture during dry season

The groundwater withdrawal for domestic consumption is less compared to agriculture consumption and domestic consumption can not be curtailed as it is an essential basic need. The cultivable extent for the recharging period need not be curtailed, since the main source of irrigation is rainfall during this period and lift

irrigation is a supplementary source of irrigation.
Therefore it is recommended to set a ceiling for the cultivable area for the dry season according to the available groundwater potential at the end of recharging period.

Introducing modern water saving technologies

It is recommended to introduce modern water saving technologies such as sprinkler irrigation and drip irrigation, by which evaporation losses can be reduced. This will require a farmer education and technology transfer program.

Conducting research to identify suitable crops

It is also recommended to extend research to identify alternative high value crops that can give satisfactory yield with comparatively less water consumption.

Appointing empowered regulatory committees.

The major groundwater issues are related to the fact that groundwater is essentially an unregulated resource. Therefore it is recommended to appoint a groundwater management authority consisting of the relevant sector representatives to ensure the sustainable management.

Rehabilitation of abandoned irrigation schemes

It is recommended to restore the abandoned small ponds for irrigation schemes in this region to tap more surface runoff for groundwater irrigation which would not only substitute a part of groundwater irrigation but also would enhance the groundwater potential through recharge of storage losses and irrigation losses.

Rehabilitation of salt water exclusion schemes

Salt water exclusion schemes can play a vital role in controlling sea water intrusion along the coastline if they are properly designed, constructed and maintained. Salt water exclusion schemes not only prevent seawater intrusion but also help to harvest rainwater which in turn influences the ground water recharge. Therefore it is highly recommended to rehabilitate salt water exclusion schemes and to allocate sufficient funds for their operation and maintenance.

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