Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t911751996

Feasibility of groundwater withdrawal in a coral island

V. S. Singh[a]; C. P. Gupta[a]
[a] National Geophysical Research Institute, Hyderabad, India

To cite this Article Singh, V. S. and Gupta, C. P.(1999) 'Feasibility of groundwater withdrawal in a coral island', Hydrological Sciences Journal, 44: 2, 173 — 182

To link to this Article: DOI: 10.1080/02626669909492216

URL: http://dx.doi.org/10.1080/02626669909492216

Hydrological Sciences—Journal—des Sciences Hydrologiques, 44(2) April 1999

Feasibility of groundwater withdrawal in a coral island

V. S. SINGH & C. P. GUPTA

National Geophysical Research Institute, Hyderabad 500 007, India

Abstract Groundwater on a small coral island occurs in the form of a lens floating on saline water. The freshwater lens is highly sensitive to various stresses such as pumping, sea tide, etc. Since groundwater is the only source of freshwater on the island, it is not only being utilized for various purposes but also there is growing demand for increased pumpage. In order to assess the impact of additional groundwater pumpage, various hydrogeological parameters were obtained through detailed investigations. These parameters were then used to construct a two-dimensional solute transport model and the effect of additional groundwater pumpage on quality of groundwater was studied. The model helps in arriving at a safe groundwater pumping scheme. Feasibility of groundwater augmentation by constructing a subsurface dam has also been demonstrated.

Possibilités d'exploitation de l'eau souterraine sur une île corallienne

Résumé Dans une île corallienne de petite taille, l'eau souterraine est formée d'une lentille d'eau douce flottant sur de l'eau salée. Cette lentille d'eau douce est très sensible aux sollicitations du milieu environnant telles que les pompages, les marées, etc. Dans ce type d'île, l'eau souterraine est la seule source d'eau douce. Dans le cas de l'île étudiée, l'eau souterraine est utilisée pour les besoins domestiques, industriels et agricoles et, récemment, une demande croissante pour un pompage intensif est apparue. Afin d'estimer l'impact de l'augmentation du pompage de l'eau douce, différents paramètres hydrogéologiques ont été évalués aux cours d'études détaillées. Ces paramètres ont été utilisés pour élaborer d'un code numérique 2D simulant le transport des solutés en milieu souterrain et les effets de l'accroissement des pompages sur la qualité de l'eau. Le modèle permet d'établir un schéma de pompage optimum. La possibilité d'augmenter la capacité du réservoir souterrain par la construction d'un barrage souterrain a aussi été démontrée.

INTRODUCTION

There are about 36 coral islands (called Lakshadweep) in the Arabian Sea off the western coast of India, with Kavaratti as the principal island (Fig. 1). The maximum length of this island is 5.5 km and maximum width is 1.4 km. The total population (including the floating population of visitors) on the island is about 10 000. The main sources of drinking water are shallow dug wells in individual houses. The inhabitants of these islands mostly depend upon groundwater to meet their needs, particularly for drinking purposes. With the increase in population and developmental activities, the demand for freshwater has also been growing. However, the freshwater aquifer on a small island is generally a fragile system, occurring as a thin lens floating over saline water. An unregulated exploitation of groundwater in such a condition would naturally cause an irreversible deterioration of groundwater quality due to upconing of saline

Open for discussion until 1 October 1999

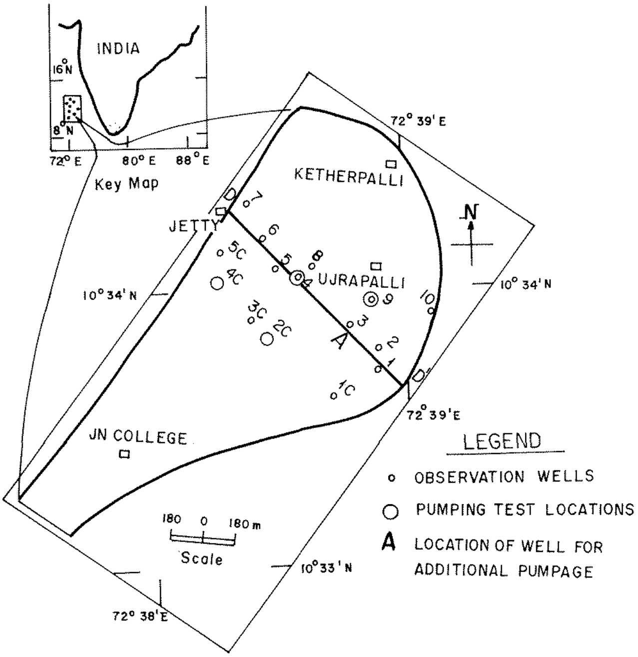

Fig. 1 Location map of study area with detailed map of Kavaratti Island, Lakshadweep.

water (Griggs & Peterson, 1993). It is therefore vital to study the impact of groundwater withdrawal and work out a technically viable, comprehensive scheme of groundwater exploitation consistent with the natural constraints existing on the island.

METHODOLOGY

Detailed investigations were carried out to evaluate various hydrogeological parameters. These parameters were then used to construct a two-dimensional solute transport model of a vertical cross section of the island using the US Geological Survey code SUTRA (Voss, 1984). The model was calibrated against the observed height of the water table above mean sea level, tidal efficiency, and the observed salinity at the water table. The calibrated model was then used to predict the effect of various pumping schemes on the salinity of the groundwater. Hence a safe pumping scheme was derived.

HYDROGEOLOGY

Details of geomorphological and hydrogeological features of the island are described by Jacob & Madhavan Pillai (1983), Jacob *et al.* (1987), and Varma *et al.* (1989). Coral sand, corals and coral limestones are the main water bearing formations. The island is encircled by a wide lagoon on the western side where hard coral limestone forms the ridge. Hard coral limestones are also exposed in various locations along the beaches. Based on the lithological data from the shallow open wells, it is concluded that coral sand of above 8 m thickness may be underlain by carbonate rocks. These carbonate rocks are about 1000 m thick (Geological Survey of India, personal communication). The topography on the island is undulating and the elevation above average sea level ranges from a few centimetres to about 6 m in some places. The average annual rainfall is about 1500 mm which occurs mostly during June–September. The natural drainage system and surface water bodies are not found on the island.

Despite a high rate of percolation through very permeable coral sands, the net recharge of fresh groundwater is meagre because a large percentage of the recharge flows out to the sea as subsurface runoff. Several shallow open wells tap fresh groundwater. The diameter of these wells varies from 1 to about 6 m and the depth

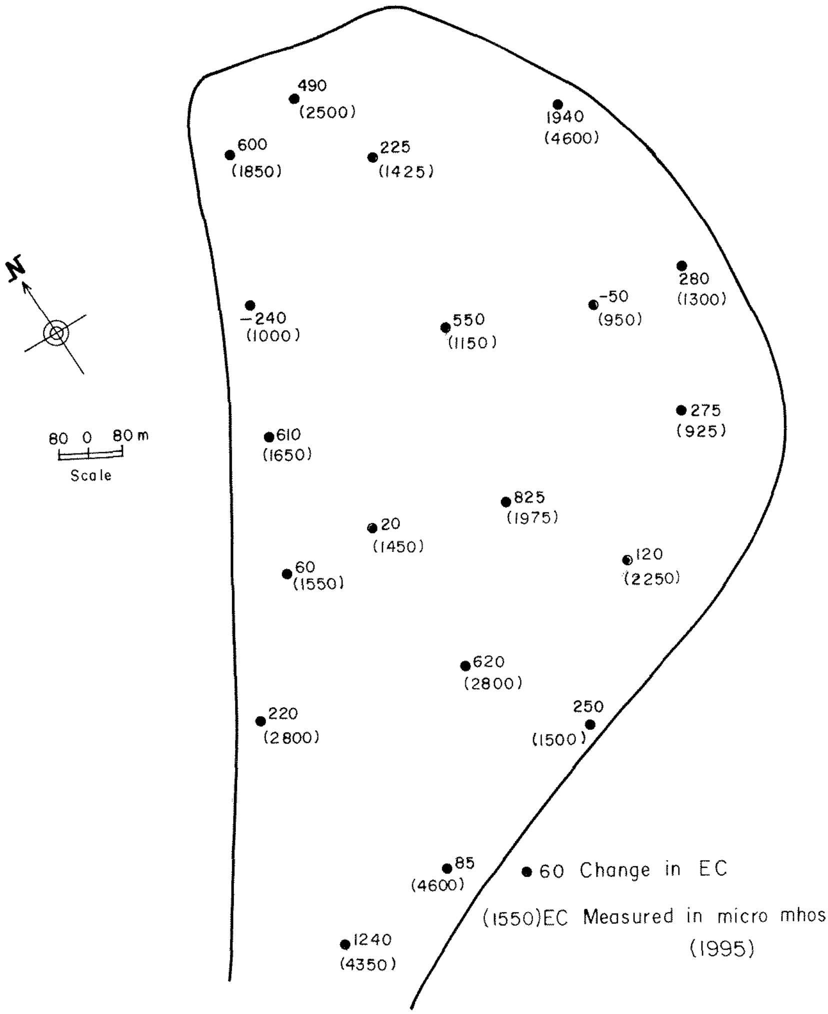

Fig. 2 Comparison of EC values of Jacob *et al.* (1987) with those measured in January 1995.

from less than a metre to about 5 m. The depth to water table is in the range of 0.5 to about 4 m below ground level.

GROUNDWATER QUALITY

The electrical conductivity (EC) of groundwater (which is a measure of salinity) from the same wells as described by Jacob *et al.* (1987) was measured during January 1995. The measured values were compared with those of Jacob *et al.* (1987) and the change in EC values and the values measured during January 1995 are shown in Fig. 2. It can be seen that the EC of groundwater in most of the wells has increased since 1987, which indicates that the salinity of the fresh groundwater zone has increased over the last decade. This is caused by pumping of fresh groundwater as well as by sea tides. The inevitable consequence has been a progressive thinning of the fresh groundwater zone.

WATER TABLE AND SEA LEVEL

The height of the water table above the average sea level has a significant bearing on the process of saline water ingress into the freshwater zone. Therefore, both the sea level (at jetty in Fig. 1) and the water table in a well on the island (well 9 in Fig. 1) were continuously monitored for about three weeks during January 1995. The sea level was monitored within a specially designed structure to avoid the interference due to sea waves. The sensor of the recorder was protected from the waves by mounting it within a cylindrical structure. The variation in sea level and water table is shown in Fig. 3. It was found that the sea level is higher than the water table during high tide, and lower during low tide.

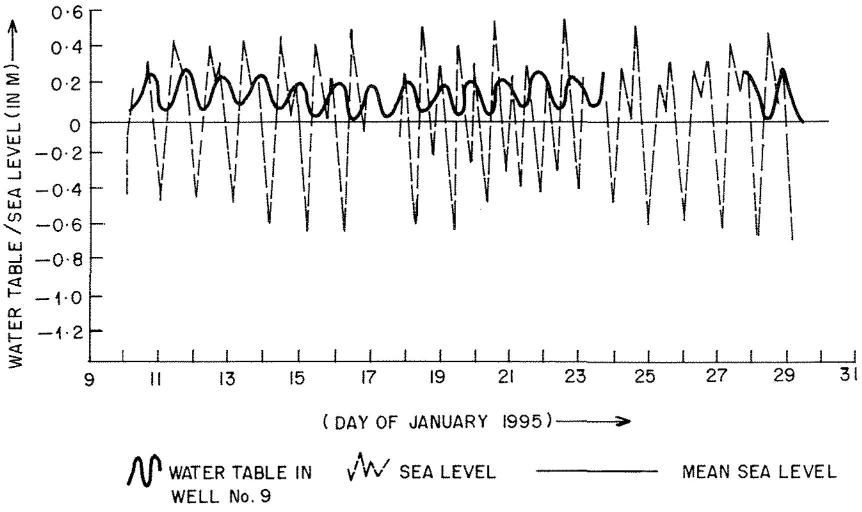

Fig. 3 Variations in sea level and water table.

The water table levels in seven wells located along a section DD′ (Fig. 1) were also monitored hourly on 11 January 1995. The water table fluctuation in all the observation wells was found to have practically the same phase difference with sea tide. Also, the magnitude of water table fluctuation in any observation well is almost independent of its distance from the sea shore. This implies that the influence of sea tides on the water table is primarily transmitted vertically, except near the sea shore where the lateral inflow may also be appreciable. The highest and lowest water table contour above average sea level, based on observed water table during May 1995, is shown in Fig. 4(a) and (b).

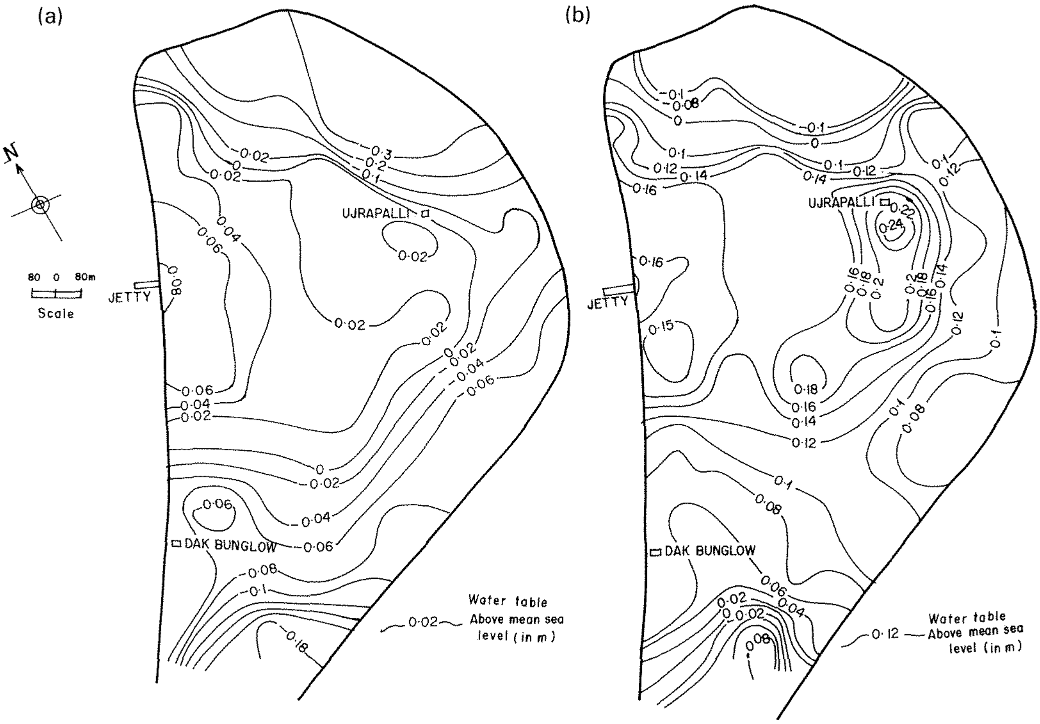

Fig. 4 (a) Highest and (b) lowest water table contours above average sea level (based on observations, May 1995).

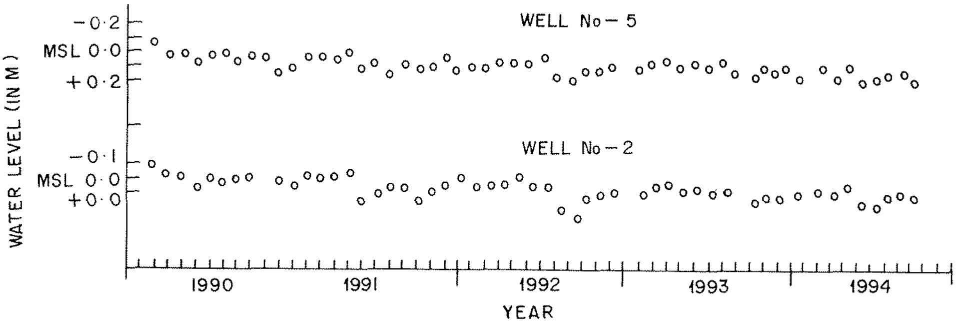

Fig. 5 Hydrographs of wells 2 and 5 over a period of five years.

The water table does not demonstrate any long term variation. This is corroborated by hydrographs of several wells on the island. Two such hydrographs for wells 2 and 5 over a period of five years are shown in Fig. 5. A similar conclusion was drawn when the water table measured by Jacob *et al.* (1987) was compared with present measurements on the same wells (Gupta *et al.*, 1996).

AQUIFER PARAMETERS

In order to estimate aquifer parameters, pumping tests were carried out on four selected existing wells. These wells tap coral sand deposits. Details of pumping tests are given in Table 1.

The pumping durations were kept small, since large drawdown in the pumping well may significantly reduce the saturated thickness of the aquifer at the well face, and cause upconing beneath the well. During monitoring of the water table, it was observed that when the water table is at the highest or lowest level due to tidal effect, it does not change significantly for at least 4–5 h. Hence, after careful study of the water table variation, short durations were selected when the change in water table is insignificant and pumping tests were carried out only during such periods to avoid tidal effect. The discharge rate and groundwater level were monitored at regular intervals. A typical time–drawdown curve at one of the locations is shown in Fig. 6.

Pumping test data were interpreted using a numerical method (Gupta & Singh, 1988) wherein the following field conditions were taken into account:

(a) initially a part of the pumped water is drawn from the well storage;

(b) wells are partially penetrating and water flows into the well horizontally through the walls of the well and also vertically upwards through the well bottom; and

Table 1 Salient features of pumping tests.

Well no.	Diameter (m)	Discharge rate (m^3 day^{-1})	Duration of test (min)
9	5.85	1296	30
2C	5.95	262	150
4	3.67	351	47
4C	1.80	36	25

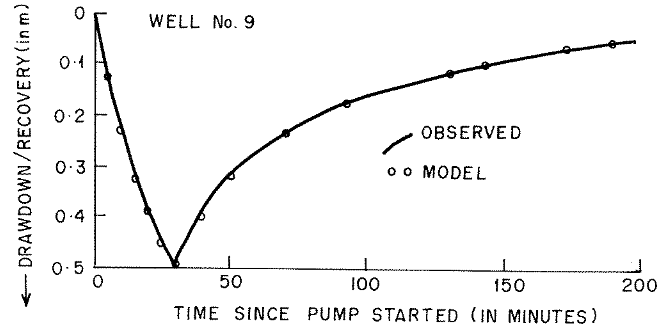

Fig. 6 Time–drawdown curve at well 9.

(c) the inflow into the well from the aquifer is caused by the decline of the water table as well as the variation of fluid density with depth (Voss, 1984).

Estimated hydrogeological parameters are given in Table 2.

Table 2 Aquifer parameters.

Well no.	Permeability (m day^{-1})	Storativity
9	245	0.01
2C	220	0.001
4	80	0.018
4C	120	0.003

GROUNDWATER MODELLING

A groundwater model of a vertical section through DD′ (cf. Fig. 1) was constructed to simulate hydraulic conditions and movement of saline water into freshwater. The section DD′ is considered to represent average hydrogeological conditions on the island. The computer code SUTRA (Voss, 1984) was used to carry out the groundwater flow study. Necessary modifications were made to incorporate the effect of tidal phenomena, variable recharge in time and water table conditions (Souza & Voss, 1987; Griggs & Peterson, 1993; Underwood *et al.*, 1992; Oberdorfer *et al.*, 1990).

Physical framework

The physical framework of the modelled aquifer broadly conformed to the geological setup described by Jacob *et al.* (1987), Oberdorfer *et al.* (1990), Underwood *et al.* (1992) and Griggs & Peterson (1993). The top layer of coral sand was assumed to be extended up to a depth of about 8 m. This layer is underlain by carbonate rocks which according to the above papers and the Geological Survey of India (personal communication), may extend up to a depth of about 1000 m above the basalt basement. Various other parameters considered for this study are as follows:

Aquifer compressibility	2.5×10^{-9} m^2 N^{-1}
Water compressibility	4.4×10^{-10} m^2 N^{-1}
Fluid viscosity	1×10^{-3} kg m^{-1} s^{-1}
Freshwater density	1000 kg m^{-3}
Sea water density	1025 kg m^{-3}
Solute mass concentration in sea water	0.0357 kg salt kg^{-1} sea water

The initial values of longitudinal and transverse dispersivities were assumed as 20 m and 0.1 m respectively, which were modified during the process of model calibration. The vertical section was divided into 24 × 24 nodes, finer at the top and coarser at the bottom.

Boundary conditions

All the nodes representing the island–sea boundary were assigned pressure fluctuating with sea tide, which was approximated by a triangular wave function having periodicity of 24 h and an amplitude of 0.9 m. Solute concentration at these nodes was assigned as 0.0357 kg kg^{-1}. The bottom of the aquifer was considered as a no-flow boundary which may be impermeable basaltic formation. The water table, the upper boundary of the model, is recharged mainly during June–September only.

Various parameters were then progressively modified until a reasonable match was obtained between the computed and observed values of (a) the water table above mean sea level, (b) the salinity of the groundwater, and (c) the tidal efficiency (Table 3).

Table 3 Height of water table and salinity as observed in the field and computed through model.

Well no.	Average water table (m)		Salinity*	
	Observed	Calculated	Observed	Calculated
6	0.12	0.18	2.1	2.0
4	0.1	0.19	1.8	1.4
3	0.16	0.19	1.5	1.4
1	0.1	0.16	2.9	2.2

* as a percentage of sea water.

RESULTS

The prognosis for the increase in salinity of groundwater due to additional pumpage at different rates was carried out using the calibrated model. Figure 7 depicts the change in salinity at the water table corresponding to various pumping rates. It was found that, if the pumping rate is less than 13 m^3 day^{-1}, the salinity at the water table stabilizes to below 2.5% of that of sea water, which is within the permissible limit for drinking purposes. The salinity profile along the vertical section after five years of additional pumpage at the rate of 13 m^3 day^{-1} is shown in Fig. 7. The effect of additional pumpage in the form of increased groundwater salinity is felt in an area of 200 m radius. It is therefore imperative that, to maintain an acceptable water quality, pumping from a single well in this situation should not exceed 13 m^3 day^{-1} and the distance between two wells should be at least 400 m. Further, such wells should be selected in the area where the water table is at least 0.15 m above average sea level.

OTHER SUGGESTIONS

Considering rainfall and local conditions, alternative suggestions have been made to augment the water supply on the island (Gupta *et al.*, 1990, 1992, 1996). Two of these include rainwater harvesting and a reduction in the outflow to the sea.

Most of the recently constructed government buildings are provided with facilities to collect the rainfall from the roof tops. Since most of the private houses also have tiled or corrugated roofs, the rainwater can also be harvested at these individual houses.

Another method to augment groundwater potential could be to construct a subsurface dam (Kawasaki *et al.*, 1993). A simple method for this purpose is to drill three rows of closely spaced bore wells of 0.05 m diameter and 8–12 m deep along selected sites at the sea shore. The bore wells may be grouted by injecting a thin

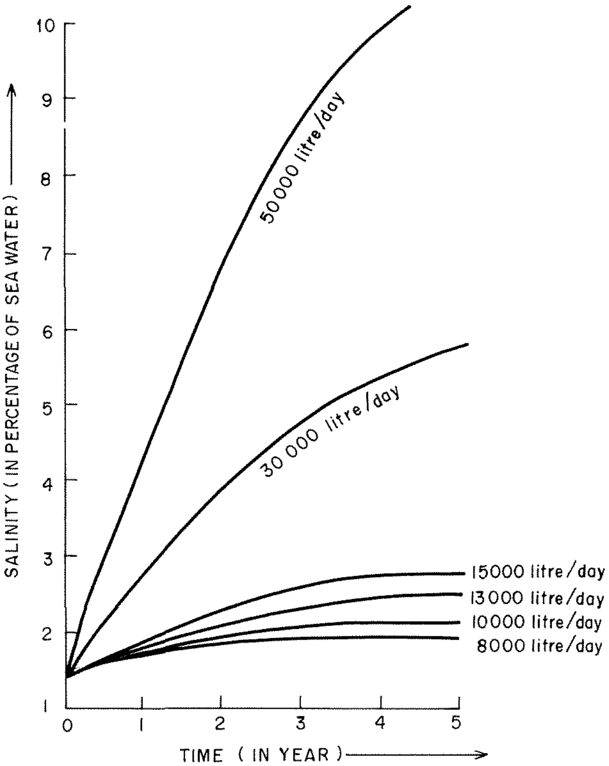

Fig. 7 Change in salinity at the water table due to groundwater pumpage.

mixture of cement and clay. This will appreciably reduce the effective permeability of the aquifer and, hence, the subsurface outflow of freshwater to the sea, resulting in a rise in the water table on the island.

An experimental prognosis of the rise in the water table due to such a subsurface dam along the coast was made using the existing vertical two-dimensional model. It was seen that, if the transmissivity of all the coastal elements is reduced, the water table will rise by 6 cm in five years. A reduction in transmissivity all along the coast will, thus, help an appreciable build-up of the water table on the island.

Acknowledgements The authors are thankful to the Director, National Geophysical Research Institute, Hyderabad, for his kind permission to publish this work. Thanks are also extended to Dr Clifford I. Voss, who has provided very useful input in modelling.

REFERENCES

Griggs, J. E. & Peterson, F. L. (1993) Groundwater flow dynamics and development strategies at the atoll scale. *Groundwater* **31**(2), 209–220.

Gupta, C. P. & Singh, V. S. (1988) Flow regime associated with partially penetrating large diameter wells in hard rocks. *J. Hydrol.* **103**, 209–217.

Gupta, C. P., Rao, V. V. S. G. & Ahmed, S. (1990) Groundwater resources of Kavaratti Island: an appraisal. *NGRI Tech. Report no. ENVIRON-87, National Geophysical Research Institute, Hyderabad, India.*

Gupta, C. P., Singh, V. S., Rao, V. V. S. G. & Ahmed, S. (1992) Drinking water supply in Kavaratti Island—some suggestions. *Tech. Report no. NGRI-92-ENVIRON-133, National Geophysical Research Institute, Hyderabad, India.*

Gupta, C. P., Singh, V. S., Dhar, R. L., Anjaneyulu, G. R., Ramachandra, Y. M., Rao, V. V. S. G., Yudhveer, K., Krishnan, V., Prakash, B. A. & Babu, G. R. (1996) Hydrogeological and geophysical investigations for safe exploitation of groundwater in Kavaratti Island, Lakshadweep. *Tech. Report no. NGRI-96-GW-201, National Geophysical Research Institute, Hyderabad, India.*

Jacob, T. V. & Madhavan Pillai, K. (1983) *Project Report of Water Supply and Sanitation to Kavaratti Island, Lakshadweep.* PHED, Kerala, India.

Jacob, V. C., Rajagopalan, K., Thambi, D. S., Najeeb, K. M. & Ramulu, K. (1987) Groundwater investigations in Kavaratti Island, UT of Lakshadweep. Unpublished report, CGWB, Trivandrum.

Kawasaki, S., Sugahara, T., Miyakita, J., Kotoku, M., Nagata, J., Nagata, S., Enami, N., Nishijima, T. & Azuma, K. (1993) Geotechnical development of subsurface dam program in Japan. *Selected Papers on Environmental Hydrogeology IAH* **4**, 215–228.

Oberdorfer, J. A., Hogan, P. J. & Buddemeier, R. W. (1990) Atoll island hydrogeology: flow and freshwater occurrence in a tidally dominated system. *J. Hydrol.* **120**, 327–340.

Souza, W. R. & Voss, C. I. (1987) Analysis of an anisotropic coastal aquifer system using variable density flow and solute transport simulation. *J. Hydrol.* **92**, 17–41.

Underwood, M. R., Peterson, F. L. & Voss, C. I. (1992) Groundwater lens dynamics of atoll island. *Wat. Resour. Res.* **28**(11), 2884–2902.

Varma, A. K. R., Unnikrishnan, K. R. & Ramchandran, K. R. (1989) Geophysical and hydrogeological studies for the assessment of groundwater resource potential in the UT of Lakshadweep, India. *Report, CESS, Trivandrum.*

Voss, C. I. (1984) A finite element simulation model for saturated–unsaturated, fluid-density-dependent groundwater flow with energy transport or chemically reactive single-species solute transport. *US Geol. Survey Wat. Resour. Invest. Report 84-4369.*

Received 18 November 1997; accepted 2 September 1998