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APPLICATION OF A NUMERICAL MODEL TO PREDICT FRESHWATER DEPTH IN ISLANDS DUE TO CLIMATE CHANGE: AGATTI ISLAND, INDIA

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Global warming could raise sea level by several tens of centimeters in the next fifty years, about one meter in the century, and several meters in the next few centuries by expanding ocean water, by melting glaciers, and by causing ice sheets to melt or slide into the ocean. Such a rise would inundate deltas, coral atoll islands, and other coastal lowlands, erode beaches, exacerbate coastal flooding and threaten water quality in estuaries and aquifers. Saltwater intrusion is a serious environmental problem to coastal subsurface water systems around the world due to climate change. In the development of subsurface water protection and rehabilitation strategies, mathematical models play an important role in coastal areas. A density dependent model is applied to predict freshwater depth in coastal areas of islands. A case history from a small island, Agatti Island, in the Laccadive Islands of India, is used to illustrate the current modeling methodology and mechanisms of saltwater intrusion due to climate change.

INTRODUCTION

With increasing population and recreational development, the supply of water in many small islands is becoming critical. Desalinization of seawater is proving feasible under certain circumstances, but frequently due to financial constraints, reliance has to be placed upon surface-water retention schemes or groundwater abstraction. Where groundwater is the major water supply, the need for reliable quantitative assessments is imperative and numerical simulation modeling is a logical approach.

In islands the main usable sources of groundwater normally occur in the form of freshwater lenses resting upon saltwater (Figure 1). Under natural conditions, islands frequently develop a body of fresh groundwater, if an adequate balance of groundwater recharge, hydraulic conductivity and land width exists. For phreatic aquifers, this freshwater assumes the form of a lens floating on the underlying seawater in accordance with the Ghyben-Herzberg principle (Ghyben, 1988, Herzberg, 1901). It is usually thickest at the central part of the landmass tapering to a thin edge at the shore margins. Steady state solutions for the size and shape of the lens assuming a fixed boundary and a sharp interface have been given by Todd (1959), Henry (1964), Fetter (1972) and Van Der Veer (1977), among others. Given the Ghyben-Herzberg assumptions it has been shown how the actual Ghyben-Herzberg ratio used in the analysis is proportional to the effective recharge rate used. This makes it extremely important to know, with some degree of certainty, either the true effective recharge rate, or the effective Ghyben-Herzberg ratio, or preferably both. The Ghyben-Herzberg ratio, based upon the difference in density between seawater and freshwater, is about 40 (Bobba, 1993). Due to a lack of historical data, temporal variations in lens shape have not been confirmed. It has been found, however, that spatial variations in recharge rate and permeability are likely to be far more significant than temporal variations in recharge in determining the theoretical lens configuration. Furthermore, this study has highlighted those parameters which are most significant in assessing lens groundwater resources.

In the islands the reference datum about which the lens tends to equilibrium is commonly taken as mean sea level (MSL) (Figure 1). Though the situation is highly dynamic, at any point in time the

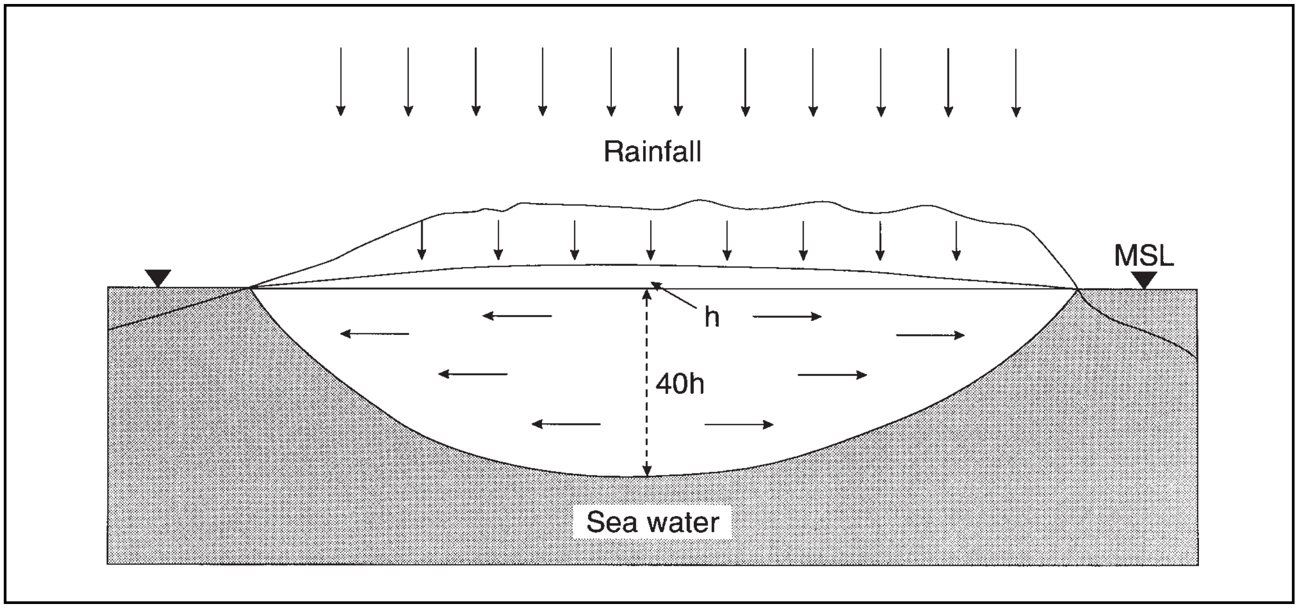

Figure 1. Ghyben-Herzberg freshwater depth approximation for an island.

freshwater lens can be envisioned as moving toward a balance with all the forces acting on it. In theory, assuming a sharp saltwater-freshwater interface, the thickness of the lens at any point in a homogeneous isotropic landmass may be determined if the freshwater head above mean sea level is known. In application of the theory to a field situation, a major problem is to determine the appropriate local elevation of mean sea level to use.

Several numerical methods (Sherif et al., 1988, Sherif and Singh, 1990), including the method of characteristics, finite difference methods, and finite element methods, have been used in sharp interface models. The objective of this research is to apply a numerical model, SUTRA (Voss, 1984), to predict freshwater depth by the finite element method for Agatti Island, in the Laccadive Islands, India, due to the effects of climatic change.

SALTWATER INTRUSION DUE TO CLIMATE CHANGE

As a result of industrial production, energy consumption and land use change, the concentration of a number of gases in the atmosphere (CO_2, CH_4, N_2O, and chlorofluorocarbons) is rapidly increasing. As a result the average global temperature is likely to rise. Figure 2 shows sea level rise as projected at the Villach conference (1987) and published by UNEP and WMO (Jaeger, 1988). In Figure 2, three scenarios of sea level change are displayed. The upper curve (III) reflects a scenario of accelerated emissions of greenhouse gases and a relatively high climate sensitivity. The middle curve (II) represents a scenario of continued present trend emissions and a moderate climate

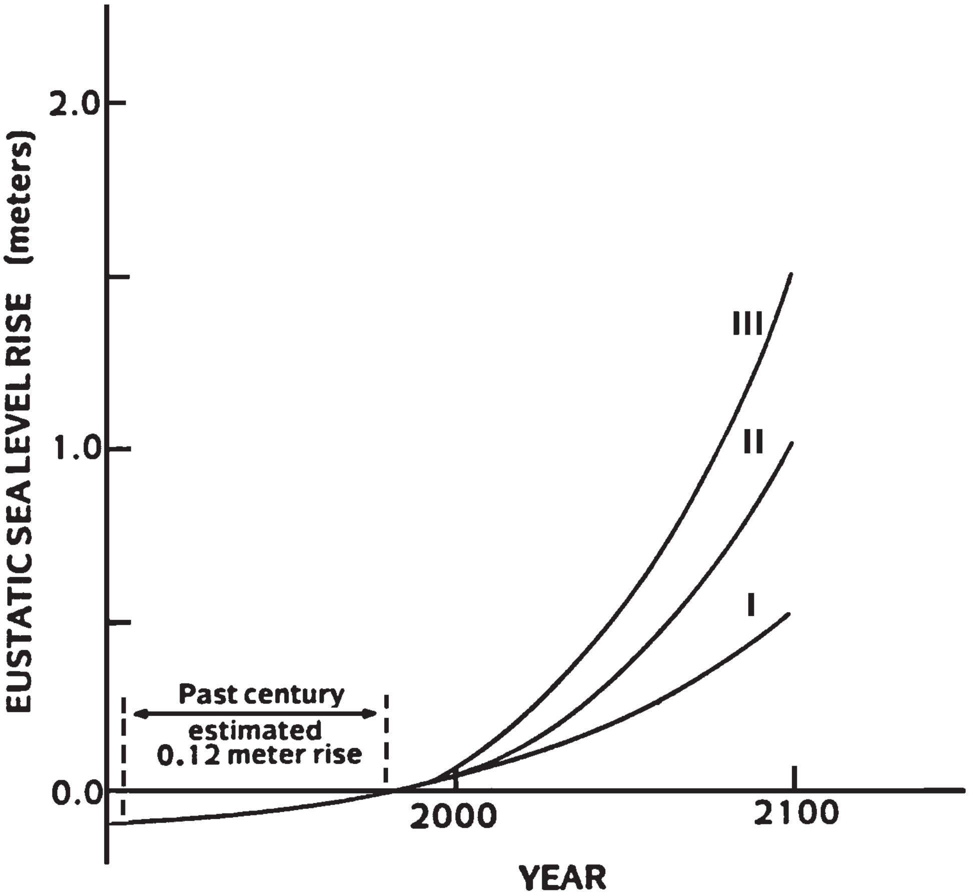

Figure 2. Sea level change with time due to climate change (Jaeger, 1988).

sensitivity. The lower curve (I) is based on a scenario of radically curtailed emissions and a low climate sensitivity. While it is theoretically possible that sea levels will drop, this is extremely unlikely. Since sea level position is largely a temperature dependent variable, it is anticipated that the historical rate of global sea level rise will be accelerated by greenhouse induced warming (NRC, 1987).

Referring to Figure 1, it can be seen that a rise in sea level would generally cause the saltwater-freshwater interface in an aquifer to advance inland and could increase groundwater salinity. Some aquifers that are pumped well below sea level are recharged by freshwater rivers. If sea level rises, it enables saltwater to advance up river during droughts, and saltwater can recharge the aquifers, and render their water unfit for human consumption.

THE SUTRA MODEL

The SUTRA (Saturated,Unsaturated,Transport) model is a finite-element groundwater flow and energy (heat) and solute (contaminant) transport code which was developed by U.S. Geological Survey (Voss,1984). This model has been applied to real field data with favorable results (Bush, 1988, Bobba, 1993, Piggott et al., 1994, Voss and Souza, 1987). The model simulates saltwater movement by means of two partial differential equations:

$$\frac{\partial(\theta\rho)}{\partial t} = -\nabla(\theta\rho v) + Q_p + T \tag{1}$$

$$\frac{\partial(\theta\rho C)}{\partial t} = -\nabla(\theta\rho v C) + \Delta\left[\theta\rho\left(D_m I + D\right)\nabla C\right] + Q_p C* \tag{2}$$

Where, θ = porosity, ρ = fluid density, Q_p = fluid mass source, v = average fluid velocity, T = solute mass source; D_m = molecular diffusivity, I = the identity tensor, D = the dispersion tensor, C = the fluid solute mass fraction, $C*$ = the solute mass fraction of fluid sources; t = time , and ∇ = a differential operator.

The first equation is written in terms of fluid pressure and is used to describe the flow of variable density fluid (mixture of freshwater and saltwater) in the aquifer. In this way the driving mechanism for flow is described by pressure differences as well as by density variations. In the second equation, the solute transport mechanism is formulated in terms of salt concentrations.

These equations are solved with the use of appropriate boundary conditions and initial conditions by following a specific numerical scheme for the distributions of pressure and concentrations throughout the aquifer. The numerical scheme is based on a hybridization of finite-element and integrated finite-difference methods used in the framework of a method of weighted residuals (Voss, 1984). The modeling analysis was accomplished in two steps: a) an areal model of groundwater flow was applied, and the head distribution in the region was calculated under steady state conditions (the most suitable boundary conditions and the physical parameters were determined during the steady-state calibration runs), and b) the results were input to a density dependent saltwater intrusion analysis. In these runs, an areal mesh was selected, and the position of the freshwater-saltwater interface was analyzed for steady state and transient conditions.

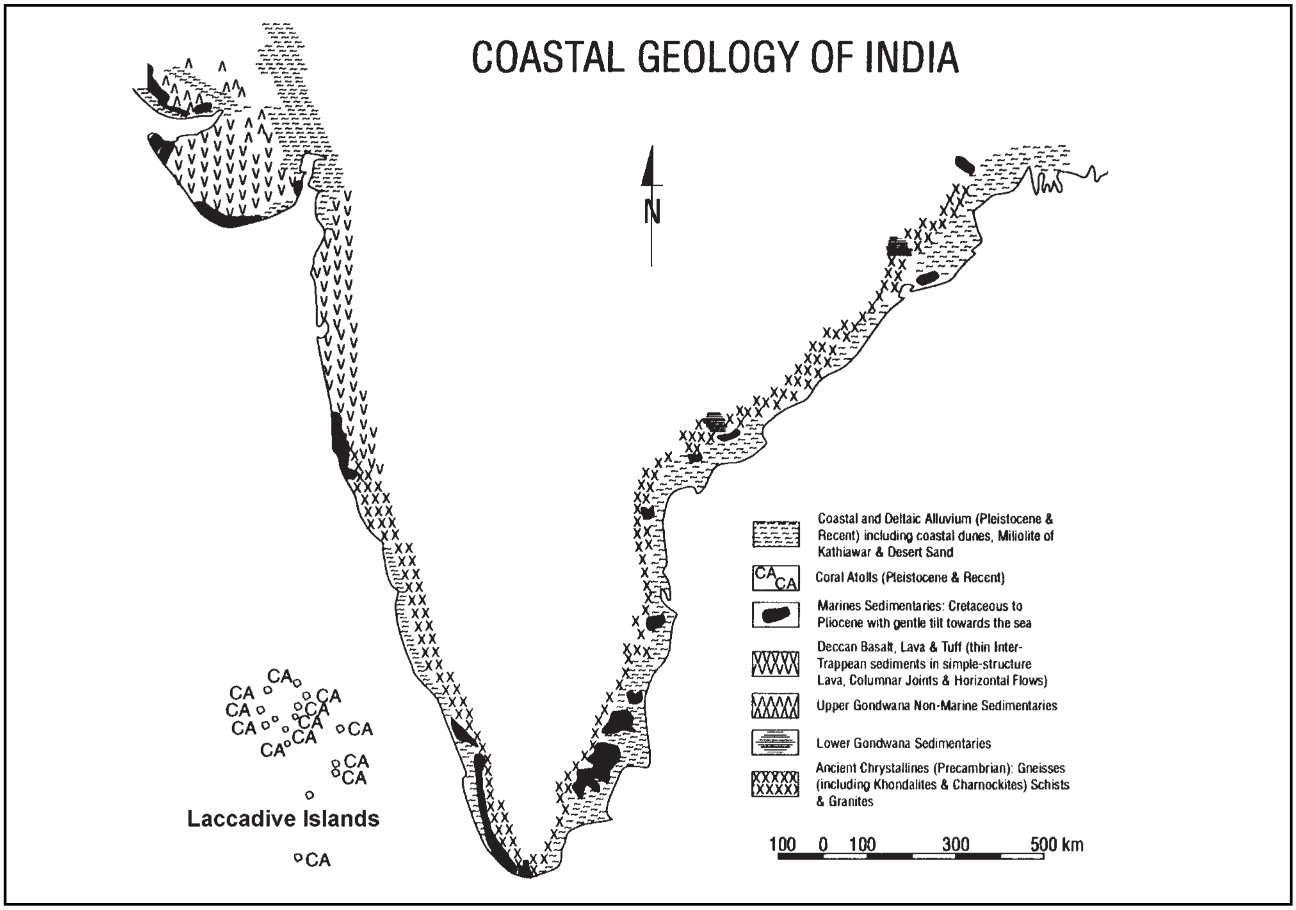

Figure 3. Location of Laccadive Islands, India.

CASE STUDY : APPLICATION OF NUMERICAL MODEL TO LACCADIVE ISLANDS, INDIA

The Laccadive Islands, located in the Arabian Sea 200 to 300 km off the coast of Kerala (India), consist of a group of 36 islands (Figure 3), comprising a number of coral atolls enclosing lagoons, submerged reefs, and banks between latitudes 8^o and 14^o N and longitudes 74^o41’ and 74^o10’E. Ten of these islands are inhabited. Kavaratti, Agatti, Minicoy, and Amini are the main islands. The capital is Kavaratti located on Kavaratti island.

The Laccadive Islands have an average elevation of 3-5 m above mean sea level with an area of 109 km^2. Hills and streams are conspicuous by their absence. In general, the lagoons are on the western (windward) side and relatively steep slopes predominate along the eastern margins except for Andrott island, which extends east-west. The climatic conditions do not show much variation. As a matter of fact, the region remains muggy throughout the year as the temperature never falls below 23.8^{o}C. The mean annual total rainfall recorded at Amini is 255 mm and at Minicoy 220 mm. Only one-fourth (28 km^2) of the total area (109 km^2) of the islands is inhabited with a total population of about 51,000 (1990).

GEOLOGY AND HYDROGEOLOGY

The islands are of coral origin which developed around volcanic peaks (Pratap, 1990). It seems that they first rose to the surface in the form of shallow oval basins, and under the protection of the reef, the eastern rim gradually developed towards the center, forming the islands. This process of development towards the center of the lagoon is still going on in some of the islands. Identical in structure and formation, the islands rise no more than 5 m above MSL and are of varied size, measuring from barely a meter to 10 km across. The islands are typical atolls, elongated reefs of organic limestone that are partly, intermittently or completely covered by water. They form a ring around a shallow basin of water, the lagoon. The reefs vary in width at their surface with a maximum width between lagoon and ocean of over 5 km. Beneath a thin layer of vegetal humus there is fine coral sand extending over the surface of all the islands. Below this is a compact crust of fine conglomerate looking like coarse oolitic limestone with embedded bits of shell, and beneath this crust, there is another layer of fine sand. Groundwater is found at a depth of about 2 m from the surface, and it is the traditional source of water for many of the islands.

The detailed hydrogeology of the islands is not available. Whether an island rises or subsides profoundly affects its hydrogeology. The most productive aquifers are composed of limestones of the fossil reef facies, the thickness of which is usually less than a hundred meters. Volcanic rocks are poorly permeable and rarely act as good aquifers in the unaltered state. Most aquifers on the high oceanic and limestone free island are weathered zones of volcanic rocks. The islands hydrogeology further depends on the extent and thickness of raised limestones, and thickness of the weathered basement or the weathered volcanic rocks. In atoll islands, coral limestone and its weathering products determine hydrogeology.

NUMERICAL SIMULATION: MODEL DESIGN

Agatti Island (Figure 4) was modeled in two dimensions as 159 nodes and 114 elements (Figure 5). 51 wells are located on the island. The data for the groundwater model are the hydrogeologic parameters, boundary conditions, transmissivity, and storage coefficient. Mesh hydraulic head is specified at each node. In addition, boundary nodes and stream nodes are specified.

The aquifer was discretized with a regular grid. The phreatic level was not imposed as a condition at the model boundaries, even at the coastal boundaries between the aquifer and the sea, which was

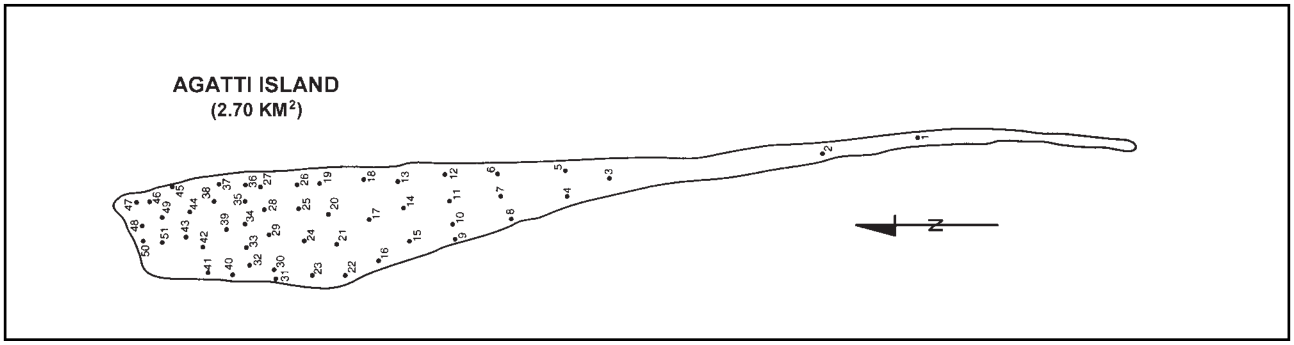

Figure 4. Agatti island showing locations of observation wells.

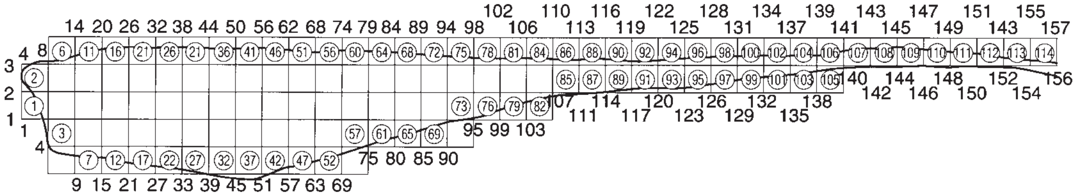

Figure 5. Finite element nodes of Agatti Island.

treated as an open boundary condition. The simulations were carried out under steady state conditions, with a view towards establishing how the aquifer reacts with the sea boundary. The aquifer porosity and permeability values used in modeling were obtained from sensitivity analysis.

Table 1a. Input Parameters Determined from Literature Values

Parameters	**Value**
Compressibility of water	4.4 x $^{-10}$m^{2}N^{-1}
Porosity	0.35
Fluid Viscosity	1.0 x 10^{-3}kgm^{-1}s^{-1}
Solute mass fraction, sea water	0.0357 kg salt kg^{-1}sea water
Density, sea water	1025 kg m^{-3}
Density, fresh water	1000 kg m^{-3}

Table 1b. Input Parameters Determined from Sensitivity Analysis

Parameters	**Value**
Upper aquifer permeability	1.2 x 10^{-11}m^2
Lower aquifer permeability	1.2 x 10^{-9}m^2
Compressibility of porous media	1.0 x 10^{-9}m^{2}N^{-1}

Some input parameters for the model were taken from standard values in the literature; others were estimated from field data and then refined with sensitivity analysis. The input values determined from literature values are given in Tables 1a and 1b.

By adjusting permeabilities, and in some cases recharge, a fairly reasonable lens configuration was obtained under essentially steady-state conditions by letting the models run for some 25 years (Figure 6). It was known that the lens configurations were measured at the end of the recharge season but the question was raised as to whether the results obtained would have varied by a large amount had the measurement been taken at the beginning of the recharge season or at some other time. If the answer to this question was in the affirmative it would make calibration more difficult. To investigate this problem the annual recharge to the model was concentrated in a three month period and made cyclic thereafter. The details of tidal variations are explained Bobba, 1998 and Bobba, et al.,1998.

RESULTS AND DISCUSSION

The results of simulation are represented according to their three main characteristics, that is, water table levels, the position of interface between salt and freshwaters and the thickness of freshwater and saltwater available in the aquifer.

Figure 7 shows the freshwater depth across nodes 33-38 on the island. The three scenarios of sea level rise 0.05, 0.075 and 0.1 m are shown in this figure. Even a very small sea level rise due to climate change affected the freshwater depth in the island. Saltwater intrusion was affected more in coastal areas than toward the of the island. The simulated hydraulic head and freshwater depth agreed very well with observed data as shown in Figure 8. These figures have been drawn by using the SURFER® computer program with a kriging method. They show the interface between freshwater and saltwater depth at different locations. If the sea level rises 0.1 m, the thickness of freshwater lens is reduced

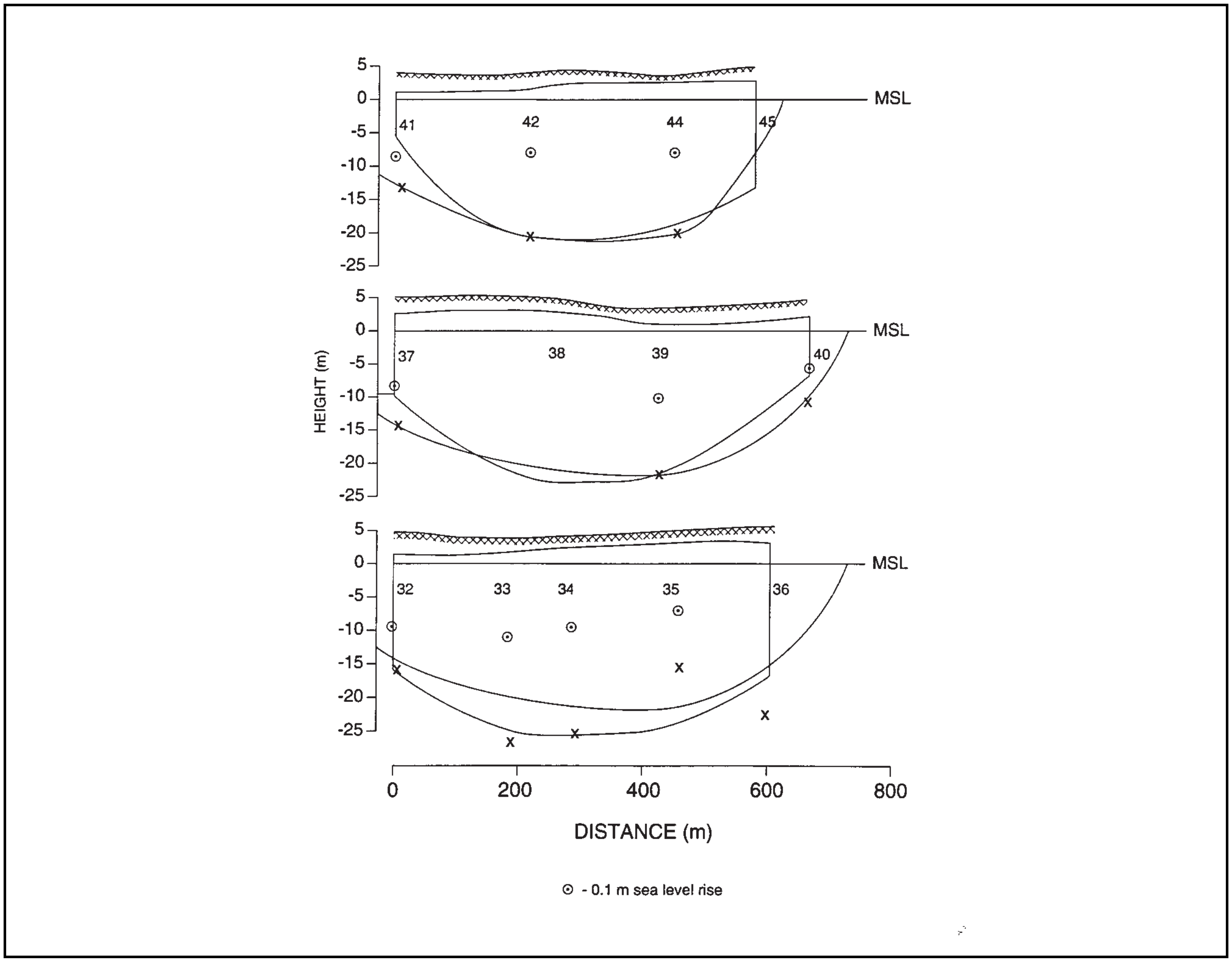

Figure 6. Comparison of freshwater depth with observed data and for 0.1 m sea level rise along Agatti island.

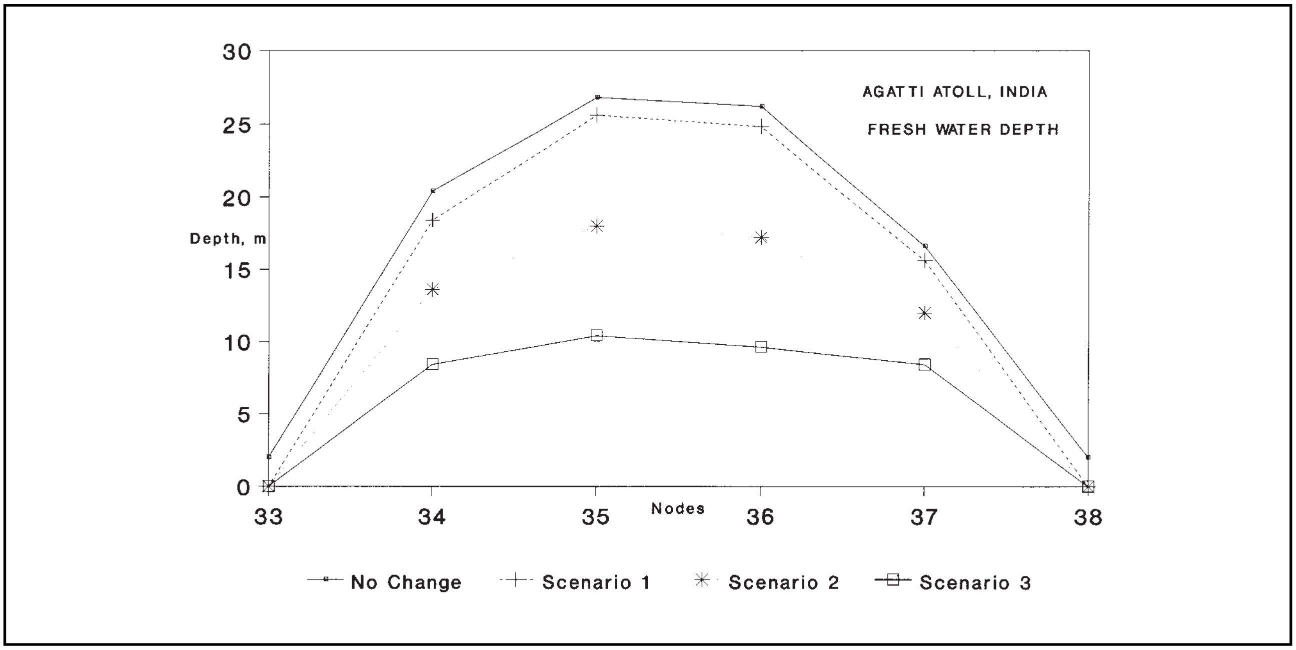

Figure 7. Simulated freshwater depth due to climate change effect from nodes 33 to 38 for different scenarios.

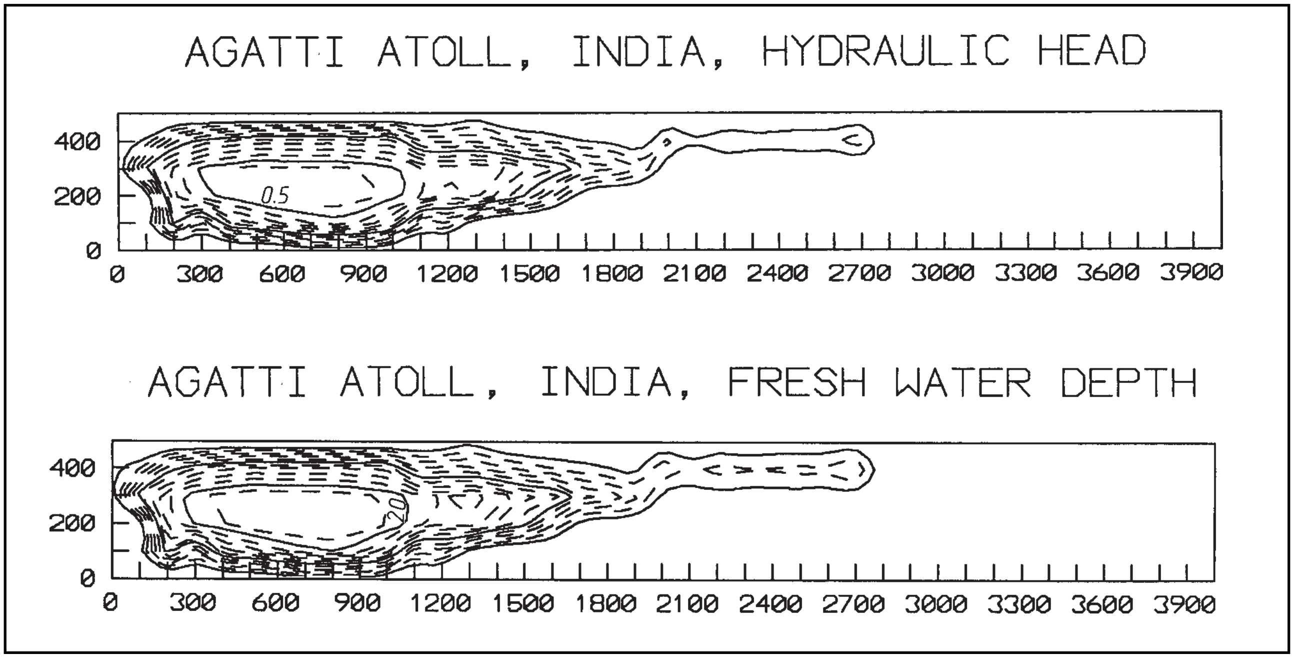

Figure 8. Simulated hydraulic head and freshwater depth of Agatti island without climate change effect in two dimensions.

in the island due to saltwater intrusion along coastal zone as shown in Figure 9.

Figure 8 shows the simulated hydraulic head and freshwater depth in the island without sea level rise. The freshwater depth is greater in the center of the island than at the coastal areas, with the available freshwater extending to a depth of 25-27 m. Figure 9 illustrates the simulated hydraulic head and freshwater depth in areal and in three dimensional form due to a sea level rise of 0.05 m. Freshwater depth was reduced from 25 m to 18 m in the center of the island.

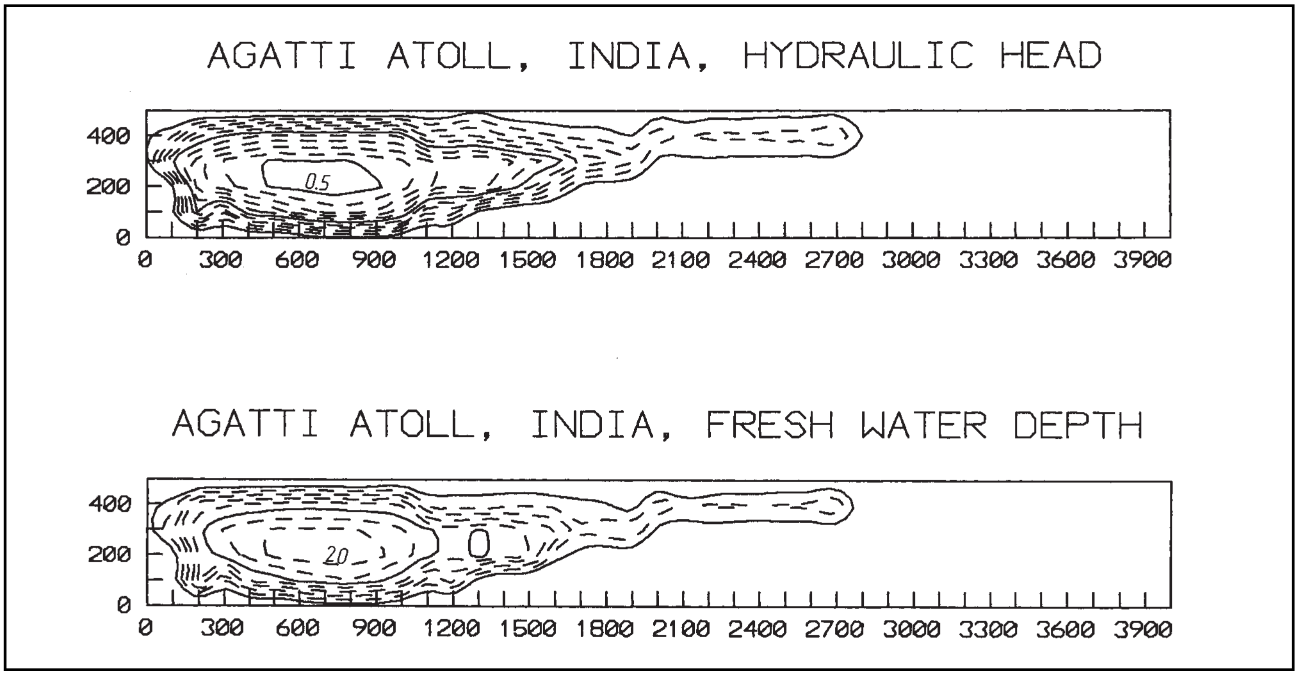

Figure 9. Simulated hydraulic head and freshwater depth of Agatti island due to 0.05 m sea level rise in two dimensions.

Figure 10 shows the hydraulic head and freshwater depth of the island in two dimensions with a 0.1 m sea level rise. The freshwater depth was distributed due to tidal action along the coastal zone of the island and freshwater depth declined from 25 m to 10 m in the center of the island. Figure 11 shows the available freshwater in the island.

In the contour maps representing the interface, Figures 8, 9, and 10 show the area occupied by the freshwater-saltwater interface and its thickness. The boundaries of the inland area allocated to the interface on the maps represent the zero saltwater thickness (interface toe); beyond these limits, the contour lines represent the thickness of freshwater only. The sector occupied by seawater intrusion

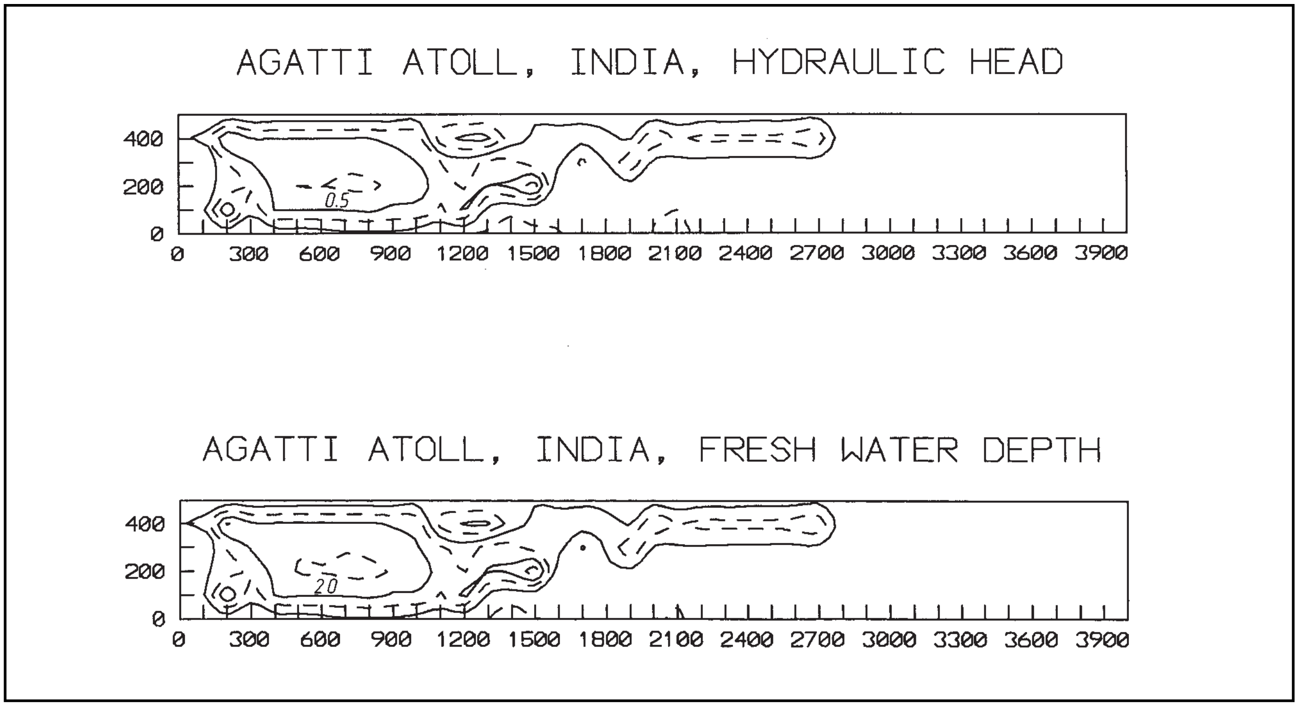

Figure 10. Simulated hydraulic head and freshwater depth of Agatti island due to 0.1 m sea level rise in two dimensions.

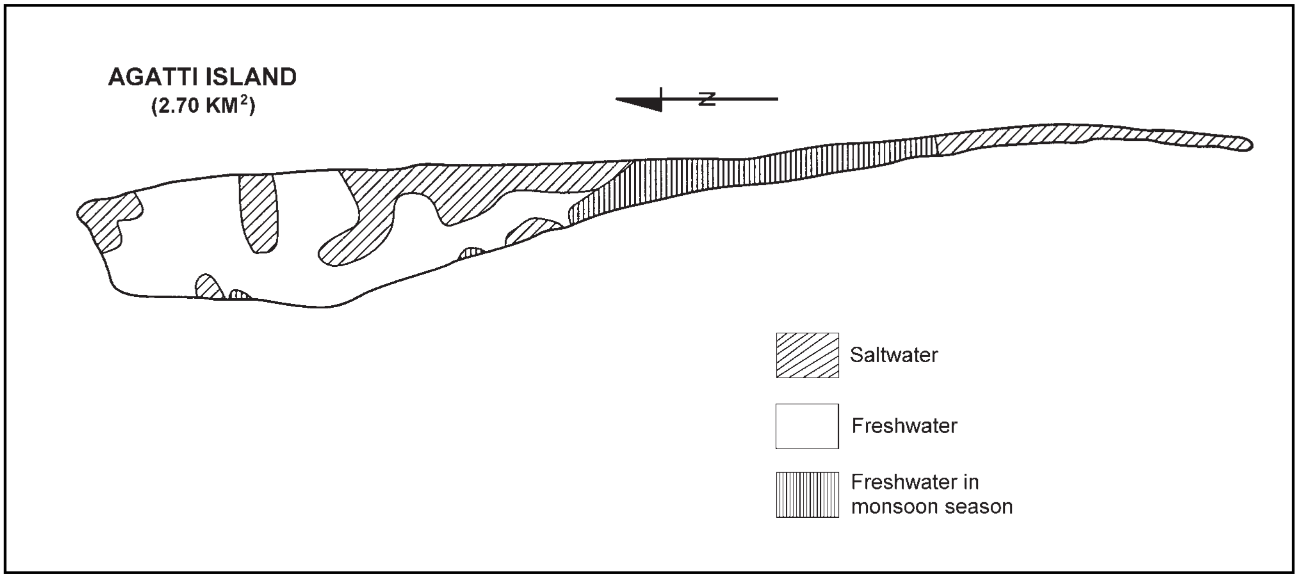

Figure 11. Simulated freshwater availability of Agatti island in different seasons; comparison with Sundaresan (1993).

has similarly been illustrated when its presence is apparent in the simulation results. In this regard, seawater intrusion is considered to exist where the freshwater thickness is nil and where the position of the interface coincides with that of the water table level. For the purpose of obtaining a Ghyben-Herzberg theoretical approximation and a steady-state solution, the sector occupied by seawater intrusion naturally coincides with that occupied by the phreatic levels below sea level.

The influence of sea level rise variations show that during low tide periods the water table is raised. The distance between surface soil and water table in this atoll is very small, and the material is generally composed of coral sands, which do not retain significant amounts of moisture under unsaturated conditions. Hence, recharge to groundwater is direct. The distance between the water table and surface soil is at a minimum in the central portion of the island. It has been observed that areas of minimum depth from ground level to water table have high freshwater potential whereas lowering of the water table from the ground surface reduces the freshwater potential substantially. The water table elevation varies from 60 cm to 395 cm above MSL and decreases gradually towards the coast.

The areas of coastal aquifer contaminated by saltwater are delineated in Figure 11 due to the tidal effect. Saltwater is present at the southern end up to a distance of 0.1 km from the southern tip. However, during the low tide period, the saline wedge is limited to a distance of only 0.2 km from the tip. In the tapering southern region, with a width less than 20 m, the stormy beaches reduce lagoonal effects, which may facilitate seawater intrusion into the aquifer. Most of the areas along the coast have been adversely affected by saline water intrusion whereas only a few areas on the lagoon side have been affected by saline intrusion. A rise in sea level will cause an upward movement of saline water in coastal aquifers.

CONCLUSIONS

This research has provided a numerical simulation of the influence of climate change on groundwater behavior on Agatti island. A single phase, two-dimensional finite element model, considering open boundary conditions for steep coasts and a sharp interface between freshwater and saltwater, was applied with steady-state conditions to determine freshwater surplus and deficits at the coastline. When sea level rises at the coastline, mixing in the freshwater-saltwater transition zone allows the model to calculate the resulting seawater intrusion in the aquifer. Results of the steady state simulations showed reasonable calculations of the water table levels and the freshwater and saltwater thickness, as well as the extent of the interface and seawater intrusion into the aquifer for the total discharges or recharges along the coastline. As a result of these simulations, a considerable advance in seawater intrusion would be expected in the coastal aquifer if climate change causes a rise in sea level.

Providing safe drinking water to the people of the island is a reachable goal. A detailed study of water resources and environmental conditions is necessary for future development. Of course it will take time, money, and dedicated effort, but it can be done. In combination with other efforts to improve overall sanitation, health care, and public education, the provision of safe drinking water will greatly improve public health and the quality of life. Adequate and safe drinking water is something every islander can and should have. It will take a major, long-term effort on the part of the local governments to improve water supplies. The effort must take into account the many factors that influence the condition of these supplies, including potential climate alterations, and must proceed in an orderly, coordinated manner.

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