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SIMULATION OF SEA WATER INTRUSION AND TIDAL INFLUENCE

by

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ABSTRACT

Coastal zones contain some of the most densely populated areas in the world as they generally present the best conditions for productivity. However, these regions face many hydrological problems like flooding due to cyclones and wave surge and drinking fresh water scarcity due to salt water intrusion. This paper presents the simulation of sea water intrusion in Nauru Island through Saturated-Unsaturated TRAnsport (SUTRA) model and examine the effect of tidal forcing on the fresh water resources.

KEY WORDS : Sea water intrusion, SUTRA, Ground water salinity, Tidal influence, Coastal zone.

INTRODUCTION

The development and management of coastal ground water aquifers is a very delicate issue. Under-utilisation of the available resource means that valuable fresh water will discharge naturally to the sea and wasted; overdevelopment, on the other hand, will mine the resource and cause a gradual or sometimes sudden degradation of water quality due to the encroachment of sea water. As an aid to effective management, many models have been developed over the years to represent and study this problem. They range from relatively simple analytical solutions to complex state-of-art numerical models using large computing capability.

Currently, several solute transport models, suitable for the simulation of sea water intrusion and upconing of saline water beneath pumping sites, are commercially available. These include SUTRA (Voss, 1984), HST3D (Kipp, 1987) and SALTFLOW (Molson and Frind, 1994). These models provide solutions of two simultaneous, non-linear, partial differential equations that describe the "conservation of mass of fluid" and "conservation of mass of salt" in porous media. SUTRA (Saturated-Unsaturated TRAnsport) employs a two-dimensional finite-element approximation of the governing equations in space and an implicit finite-difference approximation in time and is suitable for simulation of a vertical section of an aquifer which is subjected to sea water intrusion. HST3D (Heat and Solute Transport in 3 Dimensions) employs three-dimensional finite-difference approximations of the governing equations. This model is capable of simulating an aquifer with irregular geometry. SALTFLOW is also three-dimensional but utilises a finite-element approximation of the governing equations for an aquifer that is subjected to the intrusion of sea water.

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SATURATED-UNSATURATED TRANSPORT MODEL (SUTRA)

SUTRA is a finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground water flow with energy transport or chemically-reactive single-species solute transport. It may be employed for areal and cross-sectional modelling of saturated ground water flow systems and for cross-sectional modelling of unsaturated zone flow. Solute transport simulation module may be used to model natural or man-induced chemical species transport including processes of solute absorption, production and decay. It may also be applied to analyse ground water contaminant transport problems and aquifer restoration designs. In addition, solute transport simulation may also be used for modelling of variable density leachate movement and for cross-sectional modelling of salt water intrusion in aquifers in near-well or regional scales with either dispersed or relatively sharp transition zones between fresh water and salt water. Energy transport simulation module may be employed to model thermal regimes in aquifers, subsurface heat conduction, aquifer thermal energy storage systems, geothermal reservoirs, thermal pollution of aquifers and natural hydrogeologic convection systems.

Governing Equations

The simulation of sea water intrusion requires the solution of partial differential equations that describe "conservation of mass of fluid" and "conservation of mass of solute". These are summarised below (Voss, 1984).

Conservation of mass of fluid

The fluid mass balance in a saturated porous medium can be expressed as :

$$\frac{\partial(\varepsilon\rho)}{\partial t} = -\nabla.(\varepsilon\rho V) + Q_P \qquad (1)$$

where ε (x, y, z, t) is porosity; ρ (x, y, z, t) is fluid density; Q_P (x, y, z, t) is fluid mass source; V (x, y, z, t) is fluid velocity; x, y and z are Cartesian coordinate variables; t is time; and ∇ is $[(\partial/\partial x)i + (\partial/\partial y)j + (\partial/\partial z)k]$. The term on the left hand side of Eq. (1) expresses the change in fluid mass contained in the void space of the local volume with time. The first term on the right hand side of Eq. (1) represents the contribution to local fluid mass change due to excess of fluid inflows over outflows. The second term (Q_P) accounts for external additions of fluid.

The fluid mass balance (Eq. (1)) can also be represented by :

$$(\rho\ S_{op})\frac{\partial p}{\partial t} + \left[\varepsilon\frac{\partial \rho}{\partial C}\right]\frac{\partial C}{\partial t} - \Delta.\left[\left(\frac{\varepsilon\rho k}{\mu}\right).(\Delta p - \rho g)\right] = Q_P \qquad (2)$$

where $S_{op} = [(1 - \varepsilon)\,\alpha + \varepsilon\ \beta]$ is specific pressure storativity; α is porous matrix compressibility; β is fluid compressibility; C is solute mass fraction or mass of solute per mass of fluid (M_s/M); k (x, y, z) is solid matrix permeability tensor; μ (x, y, z, t) is fluid viscosity, p (x, y, z, t) is fluid pressure, and g is the gravity vector.

Conservation of Mass of Solute

The solute mass balance for a single species stored in solution is expressed as :

$$\partial\frac{(\varepsilon\rho C)}{\partial t} = -\Delta.(\varepsilon\rho V\ C)+\Delta.[\varepsilon\rho(D_m I + D).\Delta C]+Q_p C^* \qquad (3)$$

where D_m is apparent molecular diffusivity of solutes in solution in a porous medium; I is the identity tensor (dimensionless); D is the dispersion tensor and C^* is the solute mass fraction of fluid sources (M_s/M). The term on the left hand side of Eq. (3) expresses the change in solute mass with time in a volume due to mechanisms represented by terms on the right hand side. The first term on the right hand side of Eq. (3), involving fluid velocity (V), represents advection of solute mass into or out of the local volume. The second term, involving molecular diffusivity of solute (D_m) and dispersivity (D), expresses the contribution of solute diffusion and dispersion to the local changes in solute mass. The diffusion contribution is based on a physical process driven by concentration gradients, and is often negligible at the field scale. The last term accounts for dissolved-species mass added by a fluid source with concentration C^*.

The simulation is based on a hybridisation of finite-element and integrated finite-difference methods employed in the framework of a method of weighted residuals. The method is robust and accurate when employed with proper spatial and temporal discretization. Standard finite-element approximations are employed only for terms in the balance equations which describe fluxes of fluid mass, solute mass and energy. All other non-flux terms are approximated with a finite-element mesh version of the integrated finite-difference methods.

Data Requirement

The most essential types of data required are salinity records with depth in a number of observation wells, hydro-dispersive parameters (or atleast description of lithology, by which estimates of hydraulic conductivity can be made from similar type of areas) and tidal lags and heights at various points in the region of interest. It is also necessary to have recharge information. This involves not only the knowledge of rainfall but also how much of it enters the ground water system and how much is drawn off by vegetation. Other useful information would include an accurate topographic map, a land use map, water supply data including extraction data, local knowledge and experience, and estimates of expected changes in regional rainfall patterns.

SIMULATION OF SEA WATER INTRUSION IN NAURU ISLAND

The required data for the present study was taken from the paper published by F. Ghassemi. A. J. et al., (1996). Using the available data and information pertaining to Nauru Island in the above paper, the Nauru aquifer was simulated in two-dimensions using vertical section. The results of ground water salinity were reproduced and tidal influence on sea water intrusion was examined.

Hydrogeology of Nauru Island

Nauru Island is a coral island in the central Pacific Ocean, very near to equator, at latitude 0°32' S and longitude 166°56' E. Geologically, the island represents a raised atoll that stands 4,300 m above the ocean floor. The island supports a population of 10,000 and occupies a land area of 22 km². The maximum land surface altitude is 71 m above mean sea level (MSL). Figure 1 shows the surface features of the island.

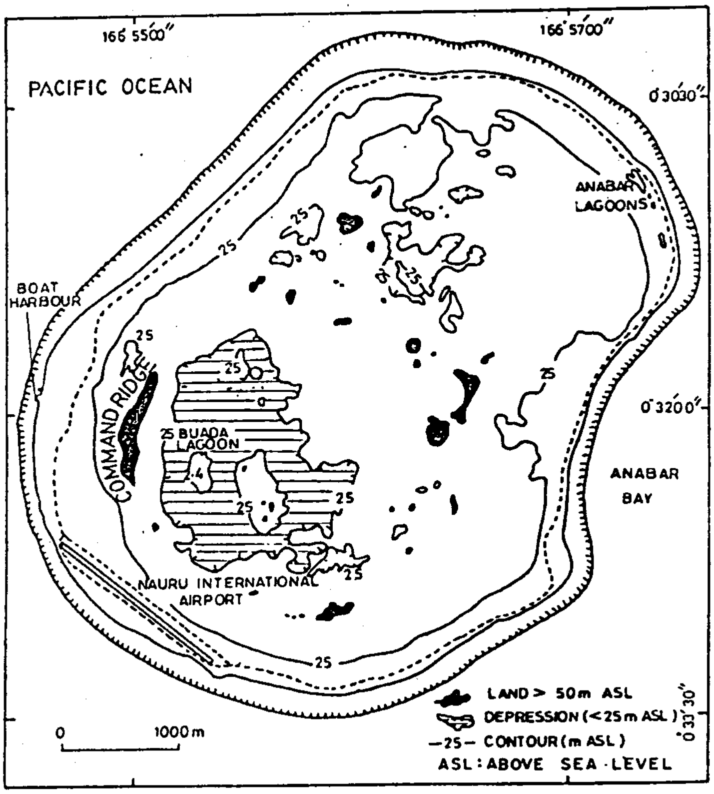

FIG. 1 GEOGRAPHY OF NAURU ISLAND

Nauru Island is a coral island is known for its exceptionally rich phosphate deposits which have been mined since 1906. As a result, vegetation and soil cover have been removed from about 80 percent of the land area, leaving an exposed limestone pinnacle surface. The results of gravity and magnetic surveys show that about 500 m of Late Miocene to Quaternary dolomitized limestone caps the seamount. During the 1987 hydrogeological investigation, 12 holes were drilled to depths ranging from 26 to 83 m. Locations of these holes (P1-P7, Q1 and W1-W4) are shown in Fig. 2. Ground water was sampled for electrical conductivity measurements to determine the thickness of fresh water lens. Ten geoelectrical soundings (DP1-DP10, Fig. 2) were undertaken to estimate the thickness of fresh water lens. Drilling showed intense karstification of the limestone to the drilled depth of 55 m below sea level.

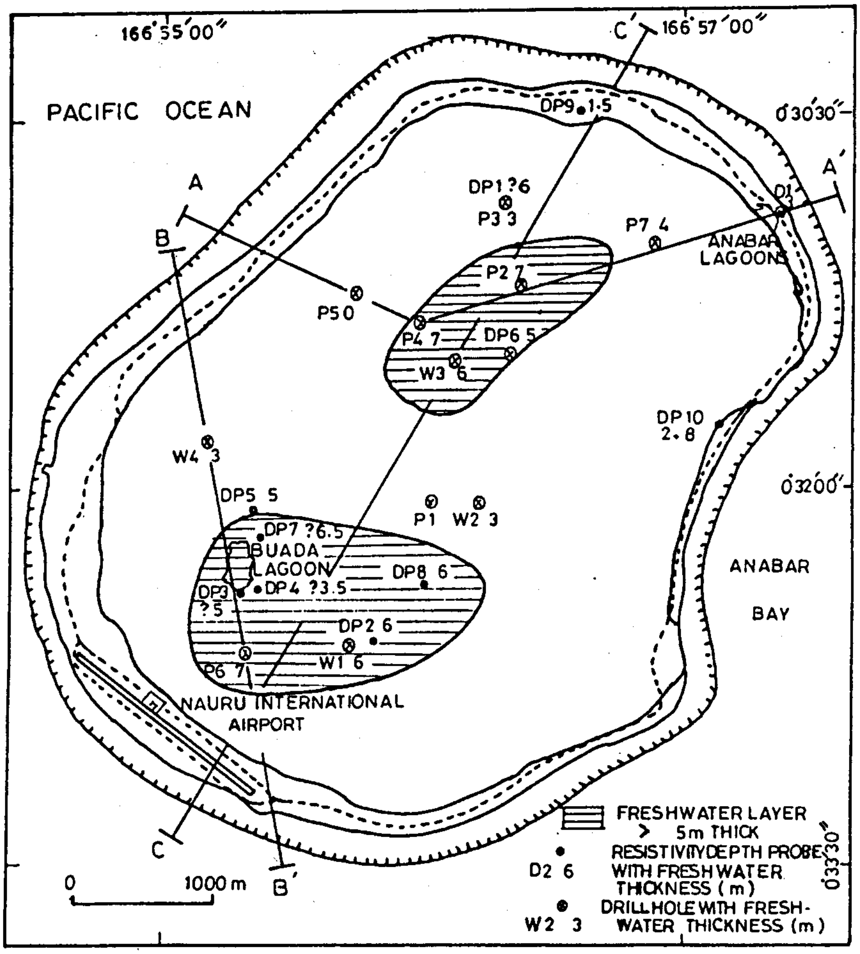

FIG. 2 THICKNESS OF FRESH WATER LENSES AND LOCATION OF SIMULATED SECTION C-C'

The water table is at an average elevation of 0.3 m above sea level and ground water flows radially outward to the sea. Fresh water overlies a thick mixing zone which in turn overlies sea water. The fresh water Buada lagoon (Fig. 1) is perched over the water table. The fresh water lens is thicker under the lagoon than elsewhere because of leakage from the lagoon to the aquifer. The unusual thick mixing zone of brackish water is due to the high hydraulic conductivity of the limestone. Open karst fissures allow intrusion of sea water beneath the island and facilitate diffusion to form zone of brackish water. Quantitative estimates of hydraulic conductivity have not been undertaken in Nauru Island, but by analogy with similar raised limestone islands elsewhere, hydraulic conductivity is estimated to be about 800 - 1,000 m/d. Tidal fluctuations may also have some effect on the distribution of salinity in the mixing zone, particularly in areas near the coastline. Measurements indicate that oceanic tides have an amplitude of 0.8 m and tidal efficiency (ratio of tidal movement in ground water to that in the ocean) declines sharply from the coast towards the centre of the island.

To simulate the Nauru aquifer a vertical section of the aquifer along the line C-C' (Fig. 2) was considered. This section, 6400 m long and 120 m deep with an arbitrary thickness of 1 m, was discretized to 832 rectangular elements and 891 (27 x 33) nodes. The horizontal spacing was kept constant as 200 m. The vertical spacing was made variable, being 2, 3, 5 and 10 m from top of the aquifer to depths of 20, 35, 60 and 120 m, respectively, below mean sea level (MSL). The mesh and boundary conditions are shown in Fig. 3.

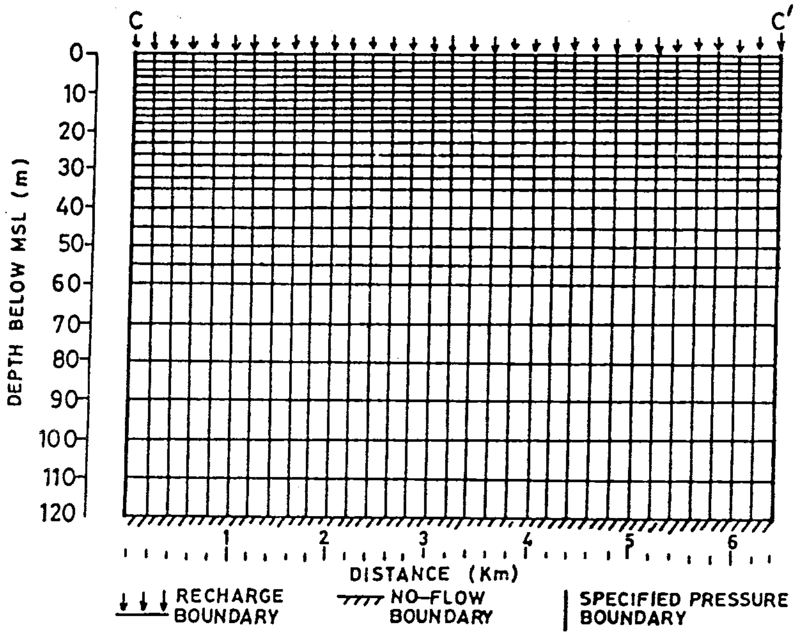

FIG. 3 MESH AND BOUNDARY CONDITIONS FOR THE SIMULATED SECTION C-C' SHOWN IN FIG. 2.

A no-flow boundary condition is specified along the bottom of the mesh at a depth of 120 m where the limestone is considered to be impervious. A recharge boundary due to rainfall is specified at the top of the aquifer. Along the left and right vertical boundaries, a hydrostatic pressure p was imposed,

$$p = \rho_s g d \qquad (4)$$

where ρ_s is the density of sea water, g is the acceleration due to gravity and d is the depth. Therefore, the pressure at the top of these two left and right side boundaries is zero and increases linearly with depth.

The boundary conditions for the transport simulation are dependent on the flow boundary conditions. The total dissolved solids (TDS) of recharge due to rainfall is zero (i.e. $C^* = 0$ kg TDS/kg fluid). Any inflow, occurring through the specified pressure boundaries, has a sea water concentration of 35,700 mg/L TDS (i.e. $C^* = 0.0357$ kg TDS/kg fluid). Any flow out of the mesh, at the specified pressure boundaries, occurs at the ambient concentration of the aquifer fluid. Solute may neither disperse nor advect across the no-flow boundary.

Model Parameters

The Nauru aquifer is presently not under any major stress such as pumping, it was therefore assumed to be in a steady state condition. Only one set of salinity data, measured during the period of investigation in 1987, was available (Jacobson and Hill, 1993). Salinity was initially measured in terms of Electrical Conductivity (EC, in μ S/cm) and converted to TDS, in mg/L, by multiplying the EC values by a factor of 0.69. Due to lack of data, no attempt was made to simulate the leakage from the lagoon. Instead, a uniform recharge rate from rainfall was considered.

No measurement of hydraulic parameters has been undertaken in the island and therefore estimated by trial and error using relevant information from similar cases. A wide range of values for each parameter was tested to estimate the most suitable value (Ghassemi et al., 1996). Table 1 presents the adopted values of parameters.

TABLE - 1

VALUES OF HYDRAULIC PARAMETERS FOR NAURU ISLANDSIMULATION

Horizontal hydraulic conductivity,	K_h 900 m/d
Intrinsic permeability	1.05 x 10^{-9} m^2
Anisotropy, K_h / K_v	50
Recharge rate	540 mm/year
Porosity	0.30
Longitudinal dispersivity, α_L	65 m
Transverse dispersivity, α_T	0.15 m
Molecular diffusivity	1.0 x 10^{-10} m^2/s

Apart from the parameters represented in Table 1, the following fixed values were imposed in the computations : fresh water density ρ (1,000 kg/m^3), sea water density ρ_s (1,025 kg/m^3), fluid viscosity μ (10^{-3} kg/m/s) and the coefficient of fluid density change with concentration $\partial\rho/\partial C$ (700 kg/m^3).

Simulation of Ground Water Salinity

The latest version of SUTRA i.e. V09972D was used for the simulation. To obtain a steady state solution, the simulation run was divided into 1,000 time steps of 15 days each, which corresponds to a total simulation period of about 41 years.

Figure 4 compares the measured and computed (Ghassemi F., et al., 1996) salinity concentrations along section C-C' and Fig. 5 presents the ground water salinity obtained in the present study. It can be observed that the ground water salinity contours for the concentrations 5000, 10000, 20000 and 30000 in Fig. 5 compare well with measured and those obtained by Ghassemi et al. (i996) in Fig. 4. Additionally, in Fig. 5, the ground water salinity contours of

500, 1000 and 35690 (representing the composition of sea water) have been shown indicat the extent of salinity ingress from both left and right vertical boundaries. These results indic that the model represents the behaviour of the aquifer quite well under the existing conditio

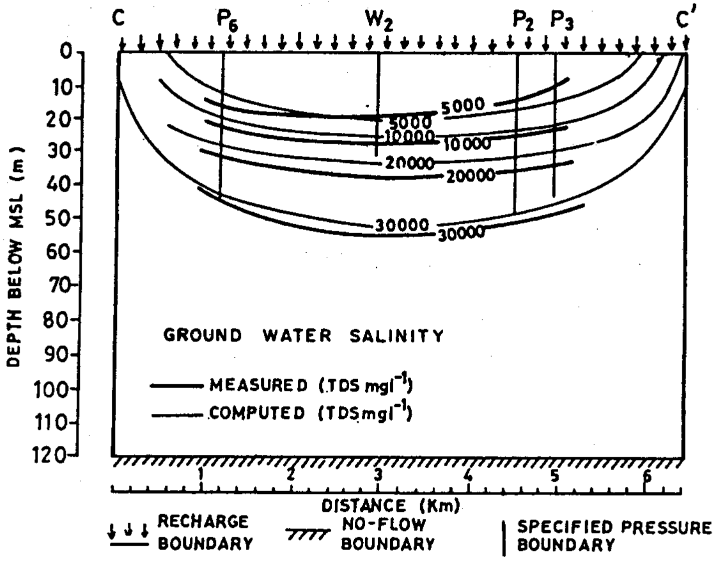

FIG. 4 GROUND WATER SALINITY MEASURED AND COMPUTED (Ghassemi et al., 1996)

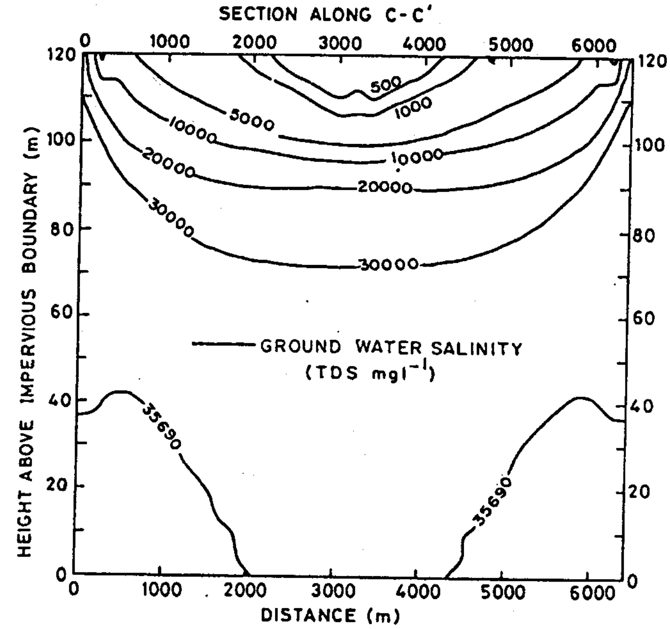

FIG. 5 GROUND WATER SALINITY COMPUTED

The model is very sensitive with respect to changes in hydraulic conductivity and recharge. Higher values of hydraulic conductivity facilitate intrusion of sea water, whereas increased recharge has the opposite effect, diluting saline water within the aquifer. The model is also sensitive to changes in porosity, anisotropy and dispersivity but less sensitive to changes in molecular diffusivity.

TIDAL INFLUENCE

The effect of tidal forcing on the fresh water resources of Nauru Island was also studied using two-dimensional model. The tidal signal is manifested as a pressure wave that propagates inside from the coastal boundaries towards the centre of the model area. Sinusoidally varying pressures were applied at the boundaries to simulate tidal forcing. The amplitude of sine wave function (assumed for sea water tides) was taken as 0.80 m with frequency of two cycles per day. The program SUTRA was modified to set time-dependent specified pressures and a separate simulation was made with same model parameters.

The tidal influence on sea water intrusion has been shown in Fig. 6 which can be compared with Fig. 5 (without tidal forcing). Most of the island is seen to overlie a deep layer of salt water whose concentration is virtually that of the ocean. Figure 5 (without tidal forcing) indicates that a lens of fresh (concentration less than 500 mg/L TDS) drinkable water exists only in the upper ten meters, near the centre of the island. However, comparison of the two Figs. 5 and 6 shows a dramatic reduction of the fresh water lens when tidal influence is also considered. The area of fresh water was reduced by approximately one half in Fig. 6 (with tidal forcing). This result highlights the importance of including tidal forcing in numerical studies of coastal and island aquifers.

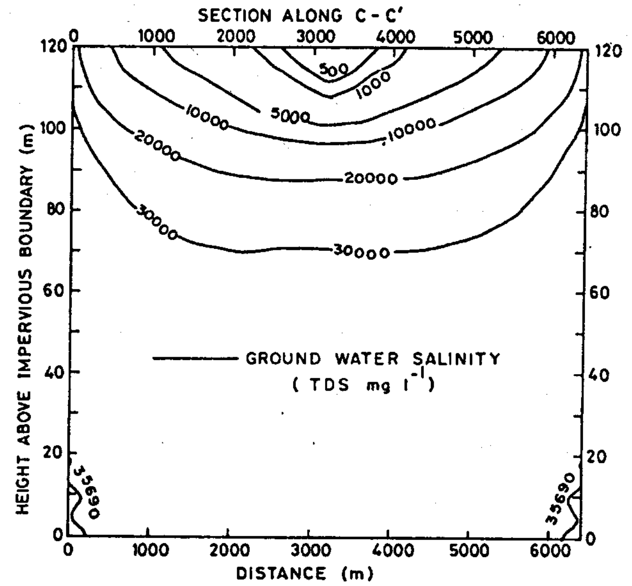

FIG. 6 TIDAL INFLUENCE ON GROUND WATER SALINITY

The two-dimensional simulation of Nauru aquifer indicated the strength of providing stable solutions with relatively long time step of 15 days. However, from a practical standpoint, the results are constrained by the limitation of simulating a three-dimensional problem with a two-dimensional model. In spite of its two-dimensional nature, the model can provide useful insight into the processes involved in sea water intrusion in coastal aquifers, upconing of the fresh water - saline water interface and analysing the effects of various processes on fresh water lenses and their management.

CONCLUSIONS

Sea water intrusion was simulated in Nauru Island under steady state conditions through Saturated-Unsaturated TRAnsport (SUTRA) model. The application of this model is very useful in those cases where a two-dimensional vertical cross-section adequately represents the ground water system. The simulation results highlight the importance of tidal forcing for island and coastal ground water studies. However, sufficient field data are necessary for effective simulation. Observations of tidally-varying water levels and salinities in wells are more readily available than, for example, estimates of dispersivity. Realistic value of dispersivity can be achieved by matching model behaviour to well observations over a range of dispersivity values in a two-dimensional model. Hydrogeological parameters, thus estimated, can then be applied to problems such as response to sea level change or varying rainfall in a three-dimensional model.

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NOTATIONS

C = Solute mass fraction (dimensionless)
C^* = Solute mass fraction of fluid sources (dimensionless)
d = Depth (L)
D = Dispersion tensor (L^2/T)
D_m = Apparent molecular diffusivity of solutes in solution in porous medium (L^2/T)
g = Acceleration due to gravity (L/T^2)
I = Identity tensor (dimensionless)
k = Solid matrix permeability tensor (L^2)
K_h = Horizontal hydraulic conductivity (L/T)
K_v = Vertical hydraulic conductivity (L/T)
p = Fluid pressure [$M/(LT^2)$]
Q_p = Fluid mass source [$M/(L^3T)$]
S_{op} = Specific pressure storativity (LT^2/M)
t = time (T)
V = Fluid velocity (L/T)
x, y and z = Cartesian coordinate variables (L)
α = Porous matrix compressibility (LT^2/M)
α_L = Longitudinal dispersivity
α_T = Transverse dispersivity
β = Fluid compressibility (LT^2/M)
ε = Porosity (dimensionless)
μ = Fluid viscosity [$M/(LT)$]
ρ = Fluid density (M/L^3)
ρ_s = Density of sea water (M/L^3)