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Numerical modelling of salt-water intrusion due to human activities and sea-level change in the Godavari Delta, India

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Abstract The effects of human activities and sea-level changes on the spatial and temporal behaviour of the coupled mechanism of salt-water and freshwater flow through the Godavari Delta of India were analysed. The density driven salt-water intrusion process was simulated with the use of a SUTRA (Saturated–Unsaturated TRAnsport) model. Physical parameters, initial heads, and boundary conditions of the delta were defined on the basis of available field data, and an areal, steady-state groundwater model was constructed to calibrate the observed head values corresponding to the initial development phase of the aquifer. Initial and boundary conditions determined from the areal calibration were used to evaluate steady-state, hydraulic heads. Consequently, the initial position of the hydraulic head distribution was calibrated under steady-state conditions. The changes of initial hydraulic distribution, under discharge and recharge conditions, were calculated, and the present-day position of the interface was predicted. The present-day distribution of hydraulic head was estimated via a 20-year simulation. The results indicate that a considerable advance in seawater intrusion can be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the freshwater from the river is channelled from the reservoir for irrigation, industrial and domestic purposes.

Key words salt water intrusion; numerical modelling; SUTRA model; impacts of sea-level change; climate change impacts; Godavari Delta, India

Modélisation numérique de l'intrusion d'eau saline, due aux activités humaines et à la variation du niveau de la mer, dans le delta du fleuve Godavari en Inde

Résumé Cet article présente l'analyse des effets, d'une part des activités humaines et d'autre part des variations du niveau de la mer, sur l'évolution spatiale et temporelle des flux d'eau salée et d'eau douce dans le delta du fleuve Godavari en Inde. Le processus d'intrusion saline, régi par la densité, a été simulé avec le modèle SUTRA (de l'anglais Saturated–Unsaturated TRAnsport). Les paramètres physiques, les conditions initiales et les conditions aux limites du delta ont été identifiées à partir de données de terrain disponibles, et un modèle hydrogéologique régional permanent a été construit pour caler les caractéristiques de l'aquifère lors de l'initialisation. Les conditions initiales et limites déterminées à partir du calage régional ont permis d'évaluer en conditions permanentes les zones de front. Par conséquent la distribution initiale des zones de front hydraulique a été calée en conditions permanentes. Les changements de cette distribution initiale, sous conditions de vidange et de recharge, ont été calculés et l'évolution de la position actuelle de l'interface a été prédite grâce à une simulation sur 20 ans. Les résultats indiquent qu'une progression importante de l'intrusion marine dans l'aquifère côtier peut être attendue si les taux actuels d'exploitation de l'eau souterraine perdurent et si une proportion importante de l'eau douce des cours d'eau est détournée pour satisfaire l'irrigation et les usages industriels et domestiques.

Mots clefs intrusion d'eau saline; modélisation numérique; modèle SUTRA; impacts du changement du niveau de la mer; impacts du changement climatique; delta du Godavari, Inde

Open for discussion until 1 February 2003

INTRODUCTION

The ever-growing demand for freshwater for human consumption has become a world-wide cause for concern. Nowadays, groundwater reserves are exposed to intensive exploitation, which may create serious problems in coastal areas where some hydraulic connection exists between the water reservoirs and seawater. Hydraulic gradients following intensive withdrawal of freshwater in this type of aquifer can favour salt-water intrusion, which in extreme situations can strongly affect the pumping wells (Fig. 1). Drinking water standards established by authorities of developed countries (USA, Canada, European Union) require that salinity values remain low. Hence sea-water intrusion may also rule out important water supplies.

Increases in the sea level along the coast of India as a result of climate change might become a serious problem with dramatic consequences projected for the next century, such as the retreat of shorelines, loss of wetlands, and intrusion of salt water into aquifers and estuaries. However, the effects of higher mean sea level on the hydrology of coastal areas, apart from the effects of increased flooding, have not been explored. This study demonstrates the sensitivity of salt-water intrusion to increases in sea level. In particular, the objective of this study is to apply SUTRA (Saturated–Unsaturated TRAnsport model), a finite element model, to predict the water table elevations and freshwater depth due to anthropogenic effects (e.g. irrigation), and climate change (rainfall and sea-level changes) in the Godavari Delta, India.

HYDROLOGICAL SETTING

In general, a watershed is a topographically defined area which water enters through rainfall and leaves as evapotranspiration, surface runoff, and groundwater discharge. In the case of a coastal watershed, runoff and groundwater discharge enter the sea (Fig. 1). Rainfall and the potential rate of evapotranspiration are determined by

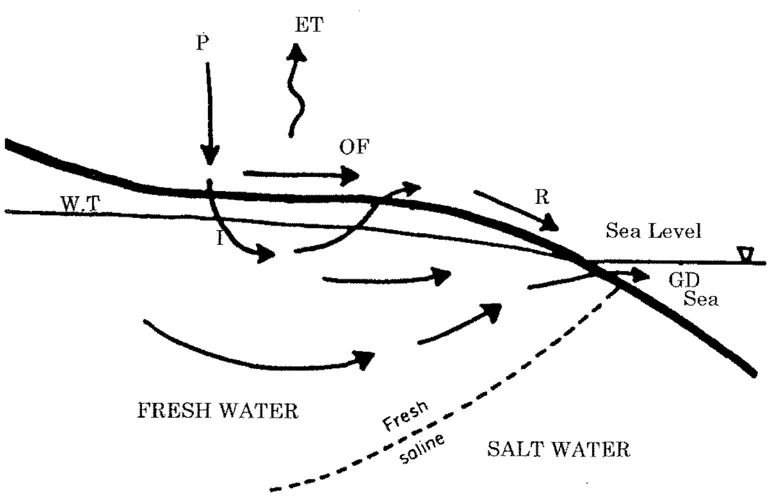

Fig. 1 Conceptual model of the water balance in a coastal watershed.

climate. Actual evapotranspiration is limited by the climatically controlled potential rate, but vegetation and the wetness of the soil also affect it. Soil properties, topography, and the history of rainfall and evapotranspiration determine runoff and groundwater discharge. For the purpose of this discussion, surface runoff includes both direct runoff, which occurs as streamflow immediately following a rainstorm, and drainage of groundwater into creeks, which accounts for streamflow between storms. The amount of direct runoff generated by a storm depends on the amount of rainfall and on the moisture status of the soil. In general, more runoff occurs when the soil is initially wet. Groundwater discharge can be calculated from water balance equations if rainfall, evapotranspiration, runoff, and the change in the amount of water stored on the watershed are known.

A link between rising sea level and changes in the water balance is suggested by a general description of the hydraulics of groundwater discharge at the coast. Fresh groundwater rides up over denser, salt water in the aquifer on its way to the sea (Fig. 1), and groundwater discharge is focused into a narrow zone that overlaps with the intertidal zone. The width of the zone of groundwater discharge measured perpendicular to the coast, is directly proportional to the discharge rate. The shape of the water table and the depth to the freshwater/saline interface are controlled by the difference in density between freshwater and salt water, the rate of freshwater discharge and the hydraulic properties of the aquifer. The elevation of the water table is controlled by mean sea level through hydrostatic equilibrium at the shore. The details of salt-water intrusion due to human activities and sea-level rise along the coastal areas are explained in earlier studies by the author (Bobba, 1993a, 2000; Bobba *et al.*, 2000).

DISCRIPTION OF STUDY AREA

The Godavari Delta is located on the east coast of India (Fig. 2) and lies between sea level and the 12-m contour. The delta, which consists of alluvial plain, has a projection of about 35 km into the sea from the adjoining coast (Fig. 2) and has a very gentle land slope of about 1 m km^{-1}. The coastal line along the study area measures about 40 km and the general elevation varies from about 2 m (a.m.s.l.) near the sea to about 13 m at the upper reach. Texturally, a major part of the study area consists of sandy loams and sandy clay loams. The silty soils, which are very deep, medium textured with fine loamy soils are located all along the River Godavari as recent river deposits. The very deep, coarse textured soils with sandy subsoils representing the coastal sand are also found along the coast.

Climate

The region exhibits a hot tropical climate characterized by a range of oppressively low daily temperatures in summer, high humidity and moderate annual rainfall. The temperature continuously increases from the end of February to the hottest month (May) to between 35°C and over 40°C in the interior. In the coldest month (January), 22°C is recorded in the coastal regions and 19–20°C in the interior. It is obvious, therefore, that there is little variation in the normal annual temperatures, mainly

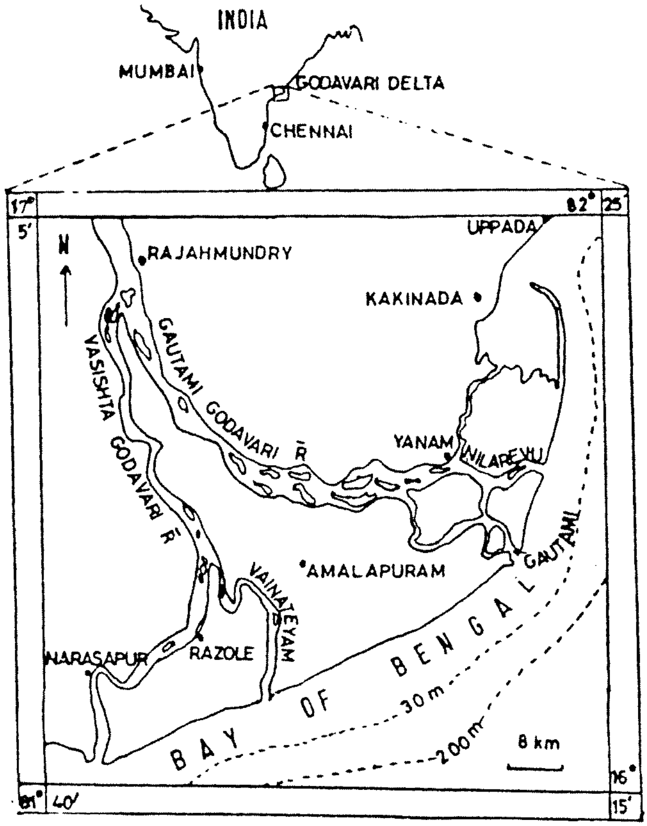

Fig. 2 Location of the Godavari Delta.

because of the low relief and the moderating influence of the sea. The diurnal range of temperature is lower in coastal regions than in the interior, being of the order of 2–3°C during June–December and 4–6°C during January–May.

Agriculture

The Godavari Delta is under the command of Godavari Central Canal System and is served by a main canal, three branch canals, one main distributor channel and a large number of irrigation channels. The canal system remains operational for 11 months with a one-month closure period during April–May. The delta soils are considered to be the most fertile lands, paddy (rice) being the major crop of the region. The study area is predominantly a rice growing area in both "Kharif" and "Rabi" seasons: the Kharif season commences on 1 June, when irrigation water is released through the canal system, and extends up to November; the Rabi season is from December to April of the following year. Crops such as sugar cane and paddy are irrigated by canal water. The vegetable gardens are irrigated partly by tube wells and partly by canal water. A large number of coconut trees also grow in the study area and account for about 15% of the total area. There is no forest in the study area.

Geology

The rock types of the Godavari basin and its tributaries represent nearly a complete cross-section of the geology of peninsular India (Rao, 1993). More than half of the drainage basin of the Godavari consists of the Deccan Trap of late Cretaceous-Eocene age. It is essentially doleritic or basaltic in composition and is constituted of abundant labradorite and enstatite-augite (pigeonite) with interstitial glassy matter altered to plagonite and chlorophaeite. Descriptions of the geology are given in earlier studies (Bobba, 2000; Rao, 1993).

Hydrogeology

The alluvial cover is relatively shallow, underlain by crystalline basement, mostly Khondalites. This delta also lies towards the southeastern end of a Permo-Carboniferous Gondawana trough but the limits of the delta are markedly beyond the limits of this ancient rift valley. The occurrence of marine coastal territories in the region of delta-head near Rajahmundry points to the fact that in the geologically recent past the area occupied by the deltaic alluvium was under the sea. Descriptions of the hydrogeology of the delta are given in Das (1991), Bobba (2000) and NIH (1991).

The alluvium consists of clayey soils with sands. Silts and gravel beds are mixed with clay in varying proportions. The thickness of alluvium varies from a few metres to more than 300 m and it overlies Rajahmundry sandstones. The thickness of granular zones in the alluvium ranges from 18 to 258 m within the explored depths. Groundwater in the deltaic alluvium occurs under both water table and confined conditions. In the alluvium of East Godavari district, dug wells range in depth from 2 to 11 m below ground level (b.g.l.) and tap groundwater mostly for domestic purposes. The depth of the water table ranges from 0.2 to 8.5 m b.g.l. and generally is within 2 m b.g.l. Filter point tube wells and dug-cum-borewells, ranging in depth from 13 to 20 m b.g.l., tap confined aquifers and yield as much as 400 m^3 day^{-1}. In the city of Elleuru, West Godavari district, alluvium the depth to water levels range from 2 to 8 m b.g.l. The wells yield between 700 and 2200 m^3 day^{-1}. The pumping water levels in these wells are generally within 14 m b.g.l. There are two aquifers within the depths of 27 and 61 m b.g.l. near Tamara and Gonchola. In the alluvium of West Godavari district the water table is shallow: within 6 m b.g.l. The freshwater is limited to shallow depths locally. These freshwater pockets are developed by dug wells and filter point wells. At favourable places the filter point wells yield up to 1100 m^3 day^{-1}. In the major portion of the alluvial area the entire alluvium explored down to 300 m depth contains saline water. The quality of groundwater in the alluvium varies widely both horizontally and vertically. The quality is generally good near the positive hydrogeological boundary of the Godavari down to a depth of 300 m, but the freshwater zone tapers gradually towards the coast, the freshwater/saline interface sloping inland. In East Godavari district the waters are alkaline and bicarbonates vary from 220 to 800 ppm, though most of the samples are generally less than 600 ppm. Chlorides vary from 20 to 6000 ppm, though generally less than 200 ppm, and total hardness is 48–2568 ppm, though generally less than 400 ppm. In West Godavari district conductivity values of shallow groundwaters up to 5320 microohms cm^{-1} are recorded in the alluvial areas. In areas adjoining the coast, south of Kakinada, there are extensive salt pans, which are used for salt extraction. The water quality also deteriorates with depth. The total dissolved solids of deeper alluvial deposits are more than 3000 ppm. At Peddada the tube well waters contain 16 400 ppm chloride and 24 329 ppm dissolved solids. The quality of groundwater is deteriorating due to agriculture, aquaculture etc.

NUMERICAL SIMULATION

The SUTRA model

The SUTRA model (Saturated–Unsaturated TRAnsport) (Voss, 1984) is a modular computer program in Fortran-77 that simulates fluid movement and the transport of either dissolved substances or energy in the subsurface. The model can be applied areally or in cross-section. It uses a two-dimensional, combined finite element and integrated finite difference method to approximate the equations that describe the two interdependent processes being simulated. When used to simulate salt-water movement in aquifers in cross-section, the two interdependent processes are the density-dependent saturated groundwater flow and the transport of dissolved solids in the groundwater. Either local- or regional-scale sections having dispersed or relatively sharp transition zones between salt water and freshwater may be simulated. The results of a SUTRA simulation of salt-water movement show distributions of fluid pressures, dissolved solids concentrations, and the magnitude and direction of fluid velocities as they vary with time. Almost all aquifer properties that are entered into the model may vary in value throughout the simulated section. Sources and boundary conditions may vary with time. The finite element method using quadrilateral elements allows the simulation of irregular areas with irregular mesh spacing. The model has been applied to real field data and observed to give favourable results (Bobba, 1993b, 1998a,b; Bobba *et al.*, 2000; Piggott *et al.*, 1994, 1996; Oberdorfer *et al.*, 1990; Emekli *et al.*, 1996).

Model design

The constructed model was two-dimensional (x–y) in nature and employed 261 nodes and 227 elements (Fig. 3), to represent the Godavari Delta (cf. Fig. 2). The data for the groundwater model are the hydrogeological parameters. The boundary conditions, the transmissivity, storage coefficient and hydraulic head must be specified at each node. In addition, boundary nodes and stream nodes must be specified. At the seaward boundary in the coast, specified hydrostatic pressures at each node are based on a column of water having dissolved concentrations specified as a function of depth. Hydrostatic pressures are assumed to be appropriate because the rates of flow at the seaward boundary are extremely slow, and no hydrological basis exists for deriving more accurate pressures. Water that enters the section at a given node as a result of a pressure gradient at the boundary is of the specified concentration; water that exists at such a node is of ambient aquifer concentration. At the coastal boundary, rates of flow are specified. Hydrostatic pressures equivalent to estimated heads in the aquifer are specified at nodes along the coastal boundary. Thus inflow to, or outflow from the aquifer occurs, depending on the direction of the gradient along the coastal boundary.

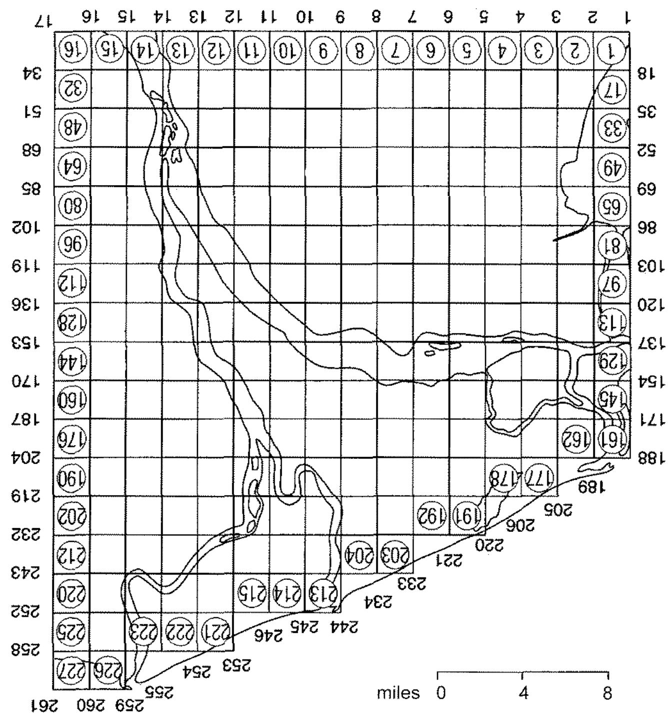

Fig. 3 Finite element nodes of the Godavari Delta (rotated so that north is upwards).

The intrinsic structure of finite element models provides substantial flexibility in designing the mesh and conforming to the boundary conditions as well as making the placement of material property boundaries such as hydraulic conductivity boundaries more realistic. The input also does not allow direct variation of the storage coefficient, but allows variability of this coefficient through changes in porosity, saturated thickness, and compressibility. This model has been successfully applied to real field data (Bobba, 1993b, 1998a,b; Bobba *et al.*, 2000).

Prior to development of the model it was necessary to define the hydrological boundary conditions. Since the prime objective was to simulate the freshwater depth behaviour under natural conditions, and anthropogenic and climatic change effects, the natural water table configuration was used to determine the hydrological boundaries of the freshwater depth in the delta.

Table 1 Input parameters determined from literature values.

Parameter	Value
Compressibility of water	4.4×10^{-10} m^2 N^{-1}
Compressibility of porous media	1.0×10^{-9} kg m^{-1} s^{-1}
Porosity	0.30
Fluid viscosity	1.0×10^{-3} kg m^{-1} s^{-1}
Solute mass fraction, seawater	0.0357 kg salt kg^{-1} seawater
Density, seawater	1025 kg m^{-1}
Density, freshwater	1000 kg m^{-1}

Table 2 Hydrogeological input parameters determined from sensitivity analysis.

Aquifer	Average transmissivity (m^2 day^{-1})	Average hydraulic conductivity (m s^{-1})
Upper	60	3×10^{-3}
Lower	110	5×10^{-3}

The phreatic level has not been imposed as a condition at the model boundaries, even at the coastal boundaries between the land and the sea, which were treated with open boundary conditions. The simulations were carried out in a stationary regime, with a view to establishing how the subsurface reacts with the sea boundary. The aquifer porosity and permeability values used in modelling were obtained from the literature and by trial-and-error method. Some input parameters for the model were taken from standard values given in the literature; others were estimated from field data and then refined with sensitivity analysis (Tables 1 and 2).

Calibration

At first, uniform properties were ascribed to the lenses and a uniform rate of recharge was applied. It became immediately apparent that the theoretical lenses were too thick near to the edges. However, this could be rectified by either reducing the recharge or by increasing the permeability near the edges. The justification for reducing the recharge was that swamps frequently formed the edges of the lenses with the water table near to the ground surface, thus enabling plant transpiration to take place at the potential rate.

The initial justification for increasing the permeability at the lens edge was based upon the fact that there must be more water passing through the edge zone than through the centre, particularly in long lenses. This larger volume of water has to pass through an ever-thinner zone of aquifer, which means that velocities must be higher. Thus, over a period of many years, the edges of the lens would be more permeable than the centre. This situation is compounded by the fact that tidal effects are more profound at the lens edge, further adding to the development of a high permeability in that region. Local structural features may compound this general picture. By adjusting permeabilities, and in some case recharge, a fairly reasonable lens configuration was obtained under essentially steady-state conditions by letting the models run for some 20 years (Fig. 4). 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 results of the computer simulations have been represented according to their three main characteristics: water table levels, the position of the interface between salt water and freshwater and the thicknesses of freshwater available in the aquifer. Using the hydraulic head record during the field season, the steady-state calibration of the model of the aquifer was carried out.

This involved a laborious procedure consisting of several simulations with different input data; in particular the transmissivity distribution and the boundary

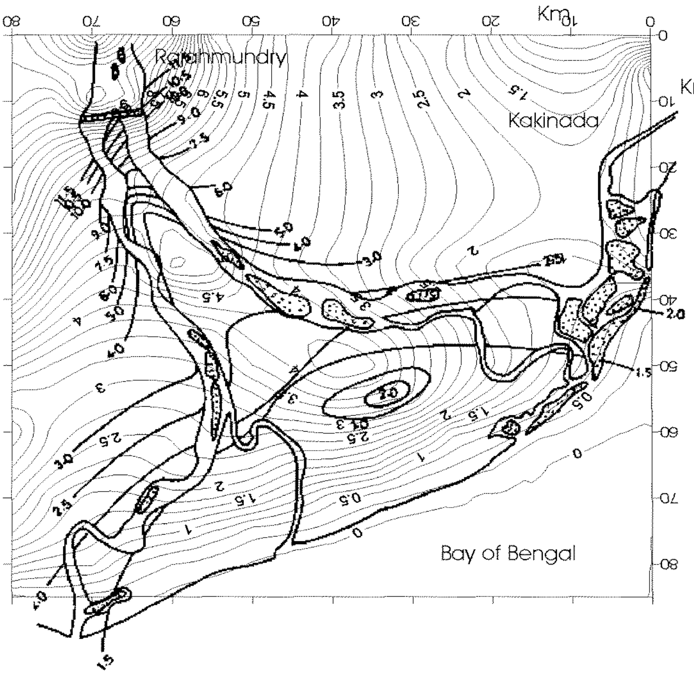

Fig. 4 Comparison between average observed (thick solid line) and computed (thin solid line) water table conditions during summer months (1990).

conditions at the western side were varied. Figure 4 illustrates that the computed hydraulic heads map compared well with the observed map, which is in summer months. Similarly, the observed map compared well with computed hydraulic head map for the irrigation season (Bobba, 2000). These figures have been drawn using the SURFER computer program, and selecting the kriging method.

MODEL PROJECTIONS

Water resources management and groundwater protection comprise a very complex and difficult issue, which will require sustained effort at all levels of government over a long period of time before the resource is adequately managed and protected. The basic components of a management strategy are: (a) to strengthen the groundwater programmes; (b) to cope with currently unaddressed groundwater problems; and (c) to create internal groundwater organisations. This strategy should come about in response to the national recognition of the serious problem posed by the present and possible future contamination of the nation's groundwater.

Figures 5 and 6 illustrate the contour maps of computer simulation results in two horizontal dimensions for the delta aquifer. In the contour maps representing the interface, the area occupied by the interface and the contour of the freshwater thickness are shown. The boundaries of the inland area allocated to the interface on the map represent the zero salt-water thickness (interface toe); beyond these limits, the contour lines represent the thickness of freshwater only. The sector occupied by seawater

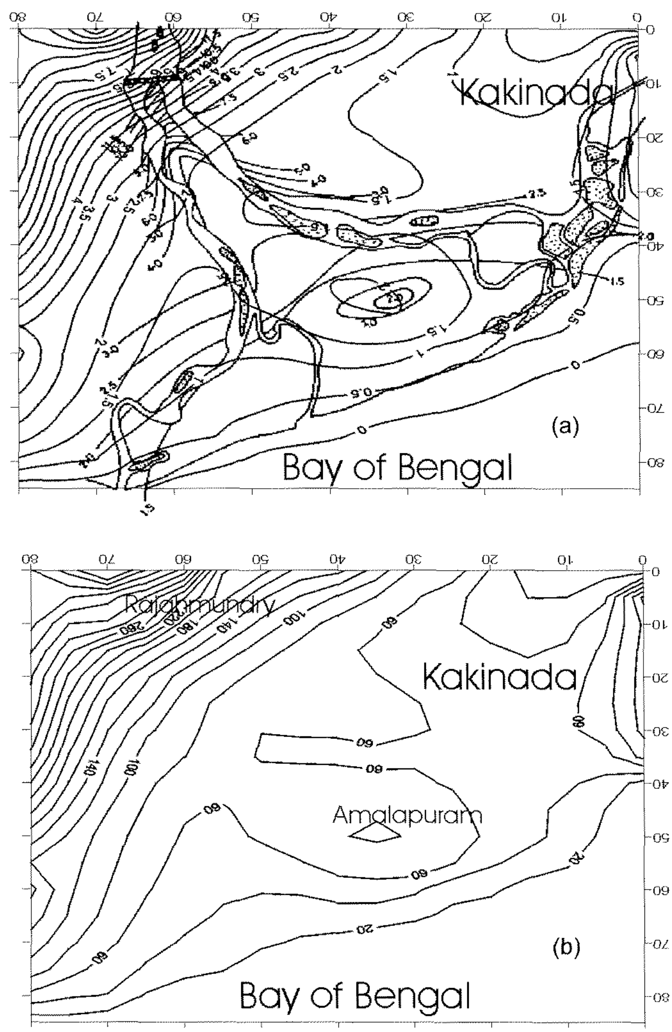

Fig. 5 (a) Simulated hydraulic heads and (b) freshwater depth of the Godavari Delta in non-irrigation months (May 1990).

intrusion 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 (Bobba, 1993a) and a steady-state solution, the sector occupied by seawater intrusion naturally coincides with that occupied by the phreatic levels below sea level. The effect of various management alternatives for the reservoir on water table levels, thickness of freshwater and the position of the interface were considered. These balances are mainly a consequence of natural recharge, pumping exploitation and flow regulations. The contour maps illustrate the possible evolution of the successive states reached by the aquifer in a stationary flow regime. It can be seen, for example, that when the water balance is negative, the aquifer shows clear signs of seawater intrusion.

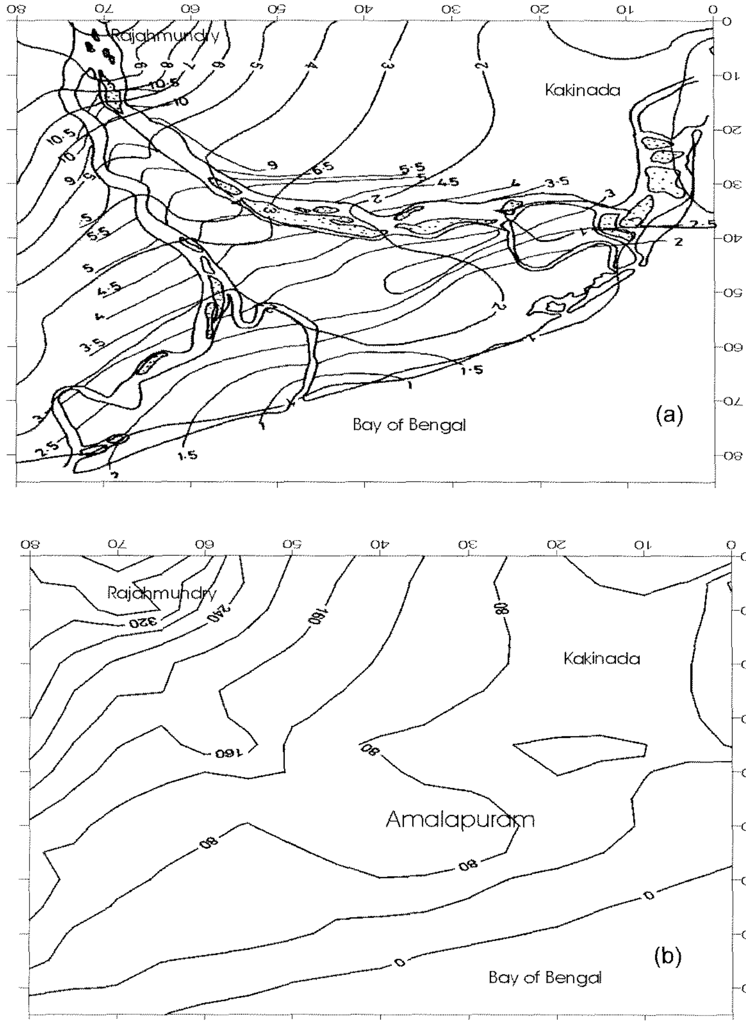

Fig. 6 (a) Simulated hydraulic heads and (b) freshwater depth of the Godavari Delta in irrigation months (October 1990).

Figures 5(a), and 6(a), depict the influence of sea-level rise variations, in irrigation (rainy) and non-irrigation seasons. During high tide level and irrigation (rainy) season periods the water table is raised. The distance between surface soil and water table in the coastal area is very small, and the material is generally composed of sands, which do not retain significant amounts of moisture under unsaturated conditions. Hence, the water that overflows the soil directly recharges the groundwater. The distance between the water table and surface soil is at a minimum in the central portion of the delta. 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 0.5 to 1 m from mean sea level and decreases gradually towards the coast. Patches of freshwater zones are also present along the coastal areas (Figs 5(b) and 6(b)).

The areas of coastal aquifer contaminated by salt water are delineated in Fig. 5(b). Salt water is present at the southeastern end up to a distance of 0.1 km from the southeastern tip. However, during the low-tide period, the saline wedge is limited to a distance of only 0.2 km from the coast. In the tapering southern region, with a width less than 20 m, the stormy beaches, due to reduced lagoonal effects, may facilitate sea-water 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 lagoonal side were affected. A sea-level rise (SLR) may result in an upward movement of saline water in coastal aquifers during the non-irrigation season.

The freshwater potential in the aquifer is depicted in Figs 5(b) and 6(b). The freshwater potential is more towards the central portion of the delta. The minimum freshwater zone is identified at the tip of the coastal area. Figure 6(b) also exhibits the depletion of water availability due to the 50 cm SLR, which may cause an apparent risk of mixing salt water with freshwater thereby causing contamination of freshwater in the wells. It is estimated that the present freshwater will be contaminated by salt water through infiltration into the aquifer. The aquifer likely to be saline is more along the eastern side than the southeastern side. Saline water contamination due to SLR and non-irrigation may be critical to the southern tapering segment of the island. Figure 7

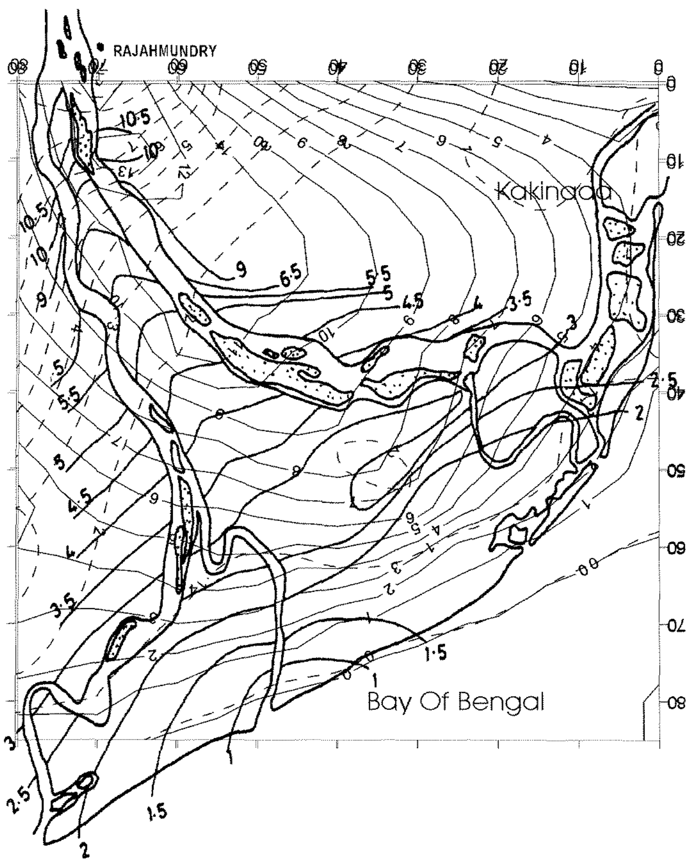

Fig. 7 Simulated hydraulic heads of the Godavari Delta under different environmental conditions (— heavy rainy season, – – – drought).

shows the results obtained under different simulated environmental conditions, such as a heavy and long rainy season and drought due to high temperature and lower rainfall (climate change). Higher water table conditions are observed when more rain and irrigated water are recharged to the aquifer. Then salt water is flushed out or stops sea-water intrusion into the aquifer. However, if severe drought conditions (higher temperature, lower rainfall) occur in the delta, the water table is reduced due to higher evapotranspiration and overpumping of the groundwater for irrigation and domestic purposes. The salt water intrudes into the aquifer and the freshwater thickness in the delta decreases.

CONCLUSIONS

Groundwater investigations are presently very active in Andhra Pradesh because of the urgent need for more water to meet the demands for the agricultural, industrial, and domestic purposes of the growing population in the coastal areas. This research has provided numerical simulation of the influence of surface flows, coming from the water management of the projected reservoir, on the regional groundwater behaviour in the delta aquifer. A two-dimensional finite element model, considering open boundary conditions for coasts and a sharp interface between freshwater and salt water, was applied to the aquifer under steady-state conditions for freshwater surplus and deficits at the coastline. When recharges of salt water occur at the coastline, essentially of fresh-water deficits, a hypothesis of mixing for the freshwater–salt water transition zone allows the model to calculate the resulting seawater intrusion in the aquifer. Hence, an adequate treatment and interpretation of the hydrogeological data, which are available for the coastal aquifer, were of main concern in satisfactorily applying the proposed numerical model. The results of the steady-state simulations showed reasonable calculations of the water table levels and the freshwater and salt-water thicknesses, as well as the extent of the interface and seawater intrusion into the aquifer for the total discharges or recharges in the delta and along the coastline.

As a result of the present hydrogeological conditions, a considerable advance in sea-water intrusion would be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the freshwater from the river is channelled from the reservoir for irrigation, industrial and domestic purposes.

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