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Numerical simulation of saltwater intrusion into east coastal basin of Indian sub - continent due to anthropogenic effects

A. GHOSH BOBBA
Environment Canada, National Water Research Institute, Burlington, Ontario L7R 4A6, Canada

Abstract
Saltwater intrusion is a serious environmental problem in coastal subsurface water systems around the world. In the development of subsurface water protection and rehabilitation strategies, computer simulated models play an important role in the development of subsurface water protection and rehabilitation strategies in coastal areas. This paper discusses the role of subsurface water contamination models in planning, management, and regulation, with a focus on generic and site specific contamination of subsurface water systems. Basic to controlling salt-water intrusion is the determination of its spatial and temporal distribution. Using a case history of Godavari delta in India, this paper apples SUTRA to predict freshwater depth and saltwater intrusion due to anthropogenic and climate change effects.

INTRDUCTION

The ever-growing demand for fresh water for a number of human purposes has become a worldwide cause of concern. Nowadays, ground water 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 fresh water in this type of aquifer can favor 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, EU) require that salinity values remain low. Hence seawater intrusion may also rule out important water supplies.

Sea level rising along the coast of India might become a serious problem due to climate change. Some consequences of higher sea levels projected for the next century, i.e. 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, exclusive of the effects of increased flooding, have not been explored. This work demonstrates the sensitivity of saltwater intrusion due to increases in sea level. In particular, the objective of this study is to apply SUTRA, a finite element model to predict the water table elevations and fresh water depth in Godavari delta, India due to anthropogenic effect (e.g.: irrigation, rainfall etc).

HYDROLOGICAL SETTING OF COAST

A watershed is a topographically defined area that water enters through rainfall and leaves evapotranspiration, surface runoff, and groundwater discharge. In the case of a coastal watershed, runoff and groundwater discharge enter the sea (Figure 1). Rainfall and potential rate of evapotranspiration are determined by 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 runoffs, which occurs as stream flow immediately following a rainstorm and drainage of groundwater into creeks, which accounts for stream flow between streams. 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 by difference 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 general description of the hydraulics of groundwater discharge at the coast. Fresh ground water rides up over denser, salt water in the aquifer on its way to the sea (Figure 1), and ground water discharge is focused into a narrow zone that overlaps with the intertidal zone. The width of the zone of ground water discharge measured perpendicular to the coast, indirectly proportional to the discharge rate. The shape of the water table and the depth to the fresh/saline interface are controlled by the difference in density between freshwater and saltwater, 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.

Naturally, the rising sea level will decrease groundwater discharge to the coast. Darcy's law states that the rate of discharge of water through the aquifer is proportional to the slope of the watertable. If the rate of groundwater discharge remains constant as sea level rises, then the slope of the water table remains constant and the elevation of the watertable in the watershed will rise by the same amount. However, as the watertable rises to soil surface, the moisture content at the soil surface increases, and surface runoff from the watershed increases. As groundwater discharge decreases, the slope of the water table must decrease, and to a first approximation, the height of the watertable above sea level will decrease in the same proportion as discharge. The elevation of the watertable inland from the coast will rise as sea level rises but not by the same amount.

Sea level rise would generally enable saltwater to advance inland in aquifers. Sea level rise could increase groundwater salinity for two reasons. First, some aquifers pumped well below sea level by human activities are recharged by currently fresh water rivers; if sea level rise enables saltwater to advance farther up during droughts, for example, salty water would recharge the aquifers, rendering its water unfit for human consumption. Due to density differences, fresh subsurface water in delta occurs as a lens of fresh water floating atop the saline water that permeates the porous geological substructure of the delta (Bobba, 1993).

In many areas, however, freshwater supplies are not so plentiful. Droughts and wells can deplete the lens to a meter or less. Thus, wells that are currently able to draw freshwater during a drought would be too deep if sea level rose one meter. Fortunately, in areas with several meters of elevation, there would still be as much freshwater; people would merely have to drill new wells. In the lowest - lying areas, however, the actual amount of freshwater under the ground would decline; the Ghyben-Herzberg principle implies that if the top of the freshwater lens does not rise, the bottom of the lens will rise 40 times as much as the sea (Bobba, 1993, Bobba et al. 2000)

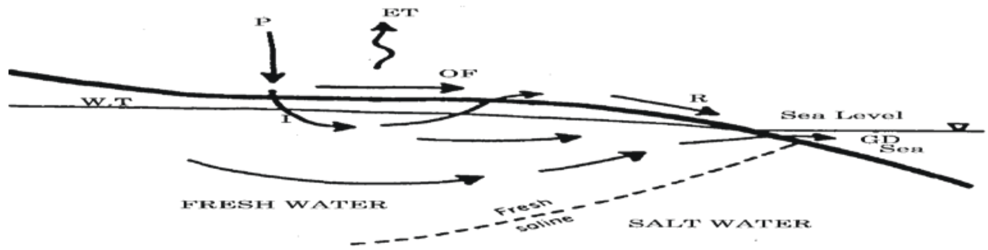

Figure 1. Conceptual model of water balance in a coastal watershed.

GODAVARI BASIN

The Godavari delta is located in East Coast of India (Figure 2). Godavari river originates near Nasik (Maharashtra) in the Western Ghats, flowing towards east and drains an area of about 286,720 sq.km before its confluence with the Bay of Bengal. The river flows 1440 km in a sinuous course due ESE over the Deccan traps, Peninsular Gneissic complex, Pakhals, Gondwanas, and cuts across the Eastern Ghats to enter into the plains near Rajahmundry. The delta of 4163 sq. km containing the towns Rajahmundry, Kakinada, Bhimavaram and Narsapur presents an arcuate shape under low drift current and mesotidal conditions. At Dowlaiswaram, about four miles downstream from the town of Rajahmundry (Figure 2), the Godavari River divides into two main tributaries. The tributary flowing eastward from Dowlaiswaram is known as the Gauthami Godavari, and the branch traversing toward the southeast is the Vasistha. These two tributaries in turn divide into secondary tributaries, which finally empty into the sea. At Dowlaiswaram, the river flow is checked by century old anicut. An extensive network of irrigation canals distributes the water in the resultant reservoir. The height of a maximum flood at Dowlaiswaram is about 16 m above mean sea level. The part of the recent deltaic basin studied is enclosed by latitudes 16^0 $31^{'}$ and 17^0 $0^{'}$ north and longitudes 81^0 $45^{'}$ and 82^0 30^0 east. This area includes the Gautami Godavari tributary and the various transitional sedimentary environments (both the continental and marine facies of the delta) associated with it. To about 26 km downstream from the anicut the Gautami Godavari channel, though at places braided, runs relatively straight, but beyond Yanam meandering of the channel becomes increasingly evident. Large-scale changes in the lower river course have occurred during the past hundred years. A century ago the river emptied into the area presently occupied by Kakinada Bay. The Kakinada spit, which was then nonexistent, developed almost simultaneously with the gradual change in the river course.

Godavari Delta

Godavari delta lies between sea level and 12-m contour. The delta has a projection of about 35-km into the sea from the adjoining coast (Figure 3). The shore of this delta is not lobate. It is probably a projected rectangle. The larger side of this rectangle, lying parallel to the general coastal trend of North Circars is about 90 km long, while the two other sides projecting NW to SE from the coast are approximately of the dimension of deltaic protuberance. This rectangular shape of the Godavari delta is rather unique and appears to be related to the local coastal trends and the direction of winds. The predominant direction of winds is from SW. The resulting long shore drift is likely to streamline the delta face from S.W to N.E. The Godavari delta is the northeastern side of the delta almost orthogonal to the southeastern side but the southwestern side too turns at a rather sharp angle. The topography of the delta has shown in Figure 3.

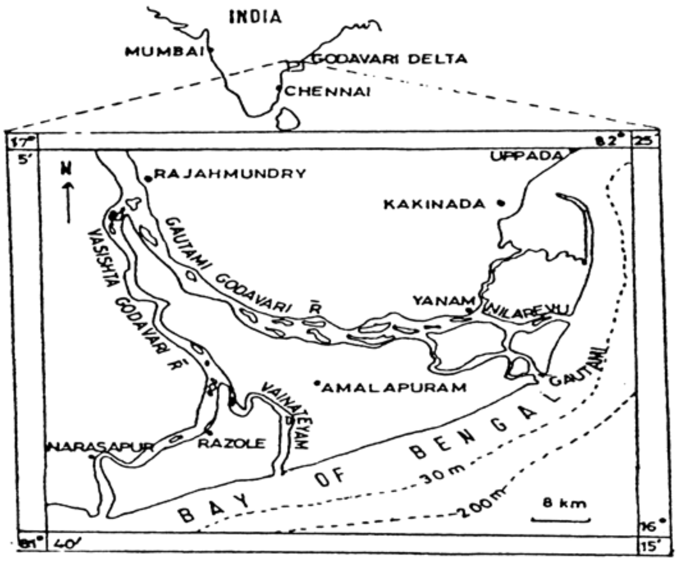

Figure 2. Location of Godavari Delta.

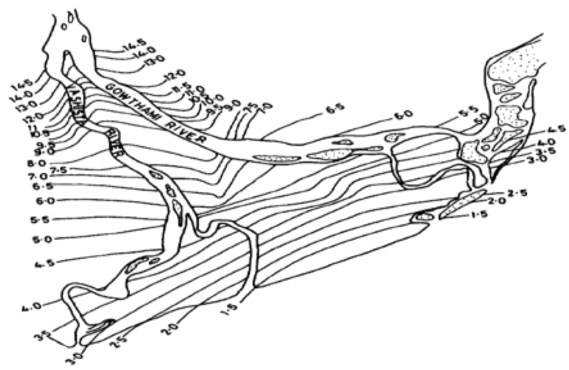

Figure 3. Topography of the Godavari Delta (NIH, 1992)

The Godavari delta consists of alluvial plain. It has a very gentle land slope of about 1-m per km. The coastal line along the study area measures to about 40 km and the general elevations varies from about 2m near the sea to about 13m at 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 is located all along the river Godavari as a recent river deposits. The very deep, coarse textured soils with sandy sub soils representing the coastal sand are also found along the sea.

Climate

The region exhibits a hot tropical climate characterised by oppressive summer low daily range of temperature, high humidity and moderate annual rainfall. Temperature continuously increases from the end of February to the hottest month with 35°C and over 40°C in the interior. The coldest month (January) records a temperature of 22°C in the coastal regions and 19° to 20°C in the interior. It is obvious, therefore, that there is little variation in annual normal temperature mainly because of low relief and moderating influence of the sea. The diurnal range of temperature is lower, than in the interior. It is of the order of 2° to 3°C during June to December and 4° to 6°C from January to May.

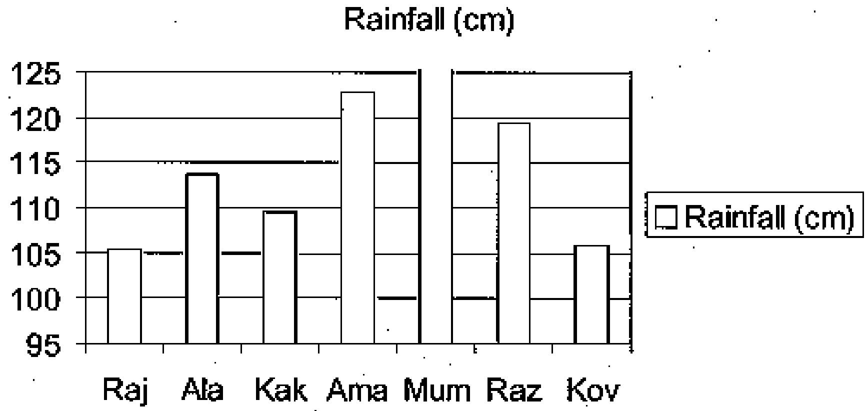

Figure 4. Normal annual rainfall at different locations in Godavari delta
(Raj=Rajahmundry;Ala=Alamuru;Kak=Kakinada;Ama=Amalapuram;Mum=Mummidivaram; Raz = Razole; Kov = Kovvur)

Rainfall decreases from the shore (120 -150 cm) to the interior (70-80 cm) (Figure 4). Kakinada on the coast gets 120 cm, while in the interior Gannavaram gets 100 cm. Showing wide variations in distribution from north to south as well rainfall till it reaches the Godavari delta as shown by Kakinada and Gannavaram. This variation in rainfall distribution is largely due to the fact that Northern Andhra Pradesh get rainfall from the SW monsoon. But further south most of the rainfall is caused by the retreating monsoon which is mainly associated with the storms and depressions originating in the Bay giving copious rainfall while striking the coast.

Moderate rainfall reliability is found in most parts. The regions of low reliability correspond with areas of high inconsistency of rainfall. The moderately high variability is due to the fact that rainfall is associated with depressions from the Bay of Bengal which themselves are erratic. Areas of somewhat moderately low reliability lie in the coastal plains. In general, high humidities prevail throughout the year in coastal areas. Winds are of moderate strength throughout the year becoming stronger in the monsoon season and weaker in October. From October to January winds blow from northeast and from southwest during the summer monsoon. From November to March the prevailing wind is from northeast and east without showing any change during the day.

During the post-monsoon and early part of the N.E. monsoon storms and depressions originating in the Bay affect the weather of the region. Some of these depressions intensify into severe storms with strong winds (80-140 km / hour) and squalls giving heavy rainfall to the coastal regions and causing considerable dislocation to communication and loss to property.

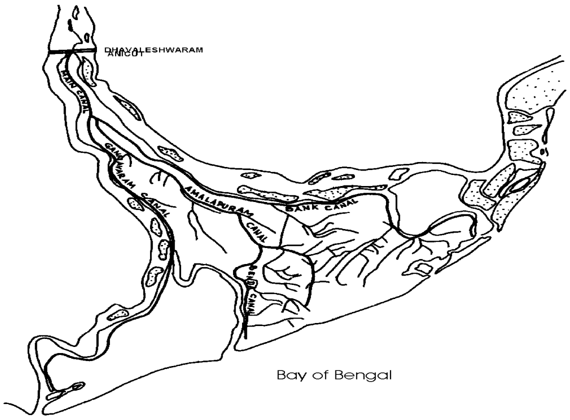

Figure 5. Irrigation canal system in Godavari Delta (NIH, 1992).

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 and a large number of irrigation channels (Figure 5). The canal system remains operational for 11 months with one-month closure period during April - May. The delta soils are considered to be the most fertile lands and paddy being the major crop of the Godavari delta system. The study area is predominantly a rice growing area in both Kharif and Rabi seasons. The kharif season commences from 1st June when irrigation water is released through the canal system and extends upto November. The Rabi season is from December to April of the succeeding year. Canal water and other important crops like sugarcane irrigate the delta under paddy, which is the major crop in both the seasons, and vegetables are partly irrigated by tube wells and partly by canal water. A large number of coconut trees also exist in the study area and account for about 15 % of the total area. There is no forest in the study area.

Geology of the Godavari delta

The geology of the Godavari delta has shown in Table 1. The rock types of the Godavari basin and its tributaries represent nearly a complete cross section of the geology of peninsular India (Table 1). 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. Upon weathering the

Deccan Trap usually give laterite, bauxite, and the black cotton soils. Descending from the Deccan Plateau the Godavari first traverses through a small terrain composed of Archean granites and unclassified crystalline, and then across a complex assemblage of rock types consisting of the Cuddapah, Vindhyan, and Gondwana Group of rocks. The Precambrian Cuddapahs and Vindhyans are metasediments predominantly consisting of quartzites, coarse sandstones, shales, limestones, and conglomerates. The Gondwana Group, extending parallel to the river course, consists of fossiliferous fluviatile and lacustrine sedimentary rocks of Upper Carboniferous to Jurassic age. They are mostly sandstones, conglomerates, shales, and coral beds. Downstream from this point, the river traverses through the eastern Ghats made up of Archean rocks which are chiefly khondalites (quartz-feldspar-siillmanite-biotite-graphite paragneisses), charnockites (hypersthene-perthite granites), and to a lesser extent calc-granulites (quartz - calcite -diopside-grossularite-scapolite granites), corrundum-syenites containing large crystals of zircon, pegmatites, and quartzites. The last two outcrops the Godavari River cuts across, before flowing through the thick alluvium beyond the Dowlaiswaram "anicut", are those of a small band of Deccan Trap and the fluviatile, un-fossiliferous, Rajahmundry ferruginous and feldspathic sand stones of Oligocene - Miocene age. The catchment area north of the Godavari River, giving rise to the most important tributaries, consists essentially of the Deccan Trap and the Dharwars.

Table 1. Generalized Stratigraphy of Godavari-Krishna Basin (modified after Rao, 1993).

Age	Formation	Lithology	Max. Thickness (M)
Holocene		Alluvial sands, clays and kankar, earthy grits, marls, and sandstone	25+
Post-Pliocene		Calcareous, gypseous, and pyritiferous clays, gravelly sands, silts, and poorly sorted sand	200+
Miocene-Pliocene	Rajahmundry Sandstone	Coarse-grained, friable, ferruginous sandstones, grits, conglomerates, and kaolinitic claystone	720+
Pre-Miocene		Claystone and sandstone	110+
Eocene	Inter-Trappean beds and Deccan Trap Volcanica	Inter-Trappean beds, hard massive to earthy limestone with claystone and marlstone. Deccan Trap Volcanica includes basalts and local differentiates	130+
Danain	Infra-Trappean beds	Coarse grits, calcareous sandstone, and a few bands of gritty limestones	70+
Early Cretaceous (Berremian)	Tirupati Sandstone	Medium to coarse-grained clayey and lateritized sandstones	830 (?)
Early Cretaceous (Neocomian)	Raghavapuram Shale and Vemavaram Shale	Variegated brittle shales and soft clays with thin lenses of sandstone	160+
Middle Jurassic	Golapalli Sandstone and Budaveda Sandstone	Micaceous grits, ferruginous sandstone with claystone, and, locally, limestone	200+
Archean	Gneiss	Khondalites, schists, charnockites, and pegmatites	

Hydrogeology of the delta

The hydrogeology of the delta is presented in figures 6 and 7. The alluvial cover is relatively shallowing 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 geologically recent past the area occupied by the deltaic alluvium was under the sea. Subsequent (Pleistocene) emergence of this submarine floor and marine sedimentary made this as well as most other parts of Indian coastal zones, which is known as "coastal plain"- a recently elevated plain from below the sea characterized by gently seaward-dipping marine sediments at an angle slightly greater than the declination of the present plain surface.

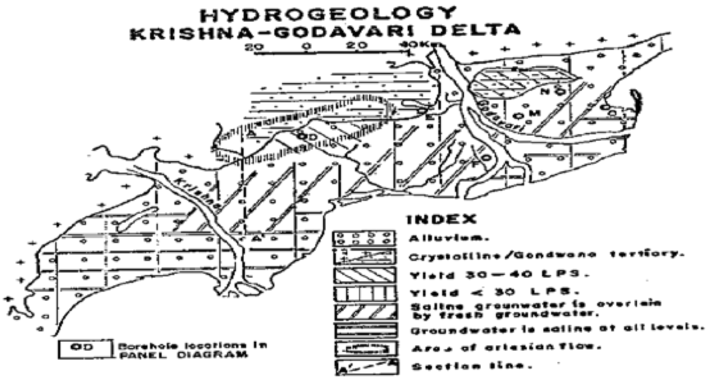

Figure 6. Hydrogeology of Krishna - Godavari Delta (modified after Das , 1991).

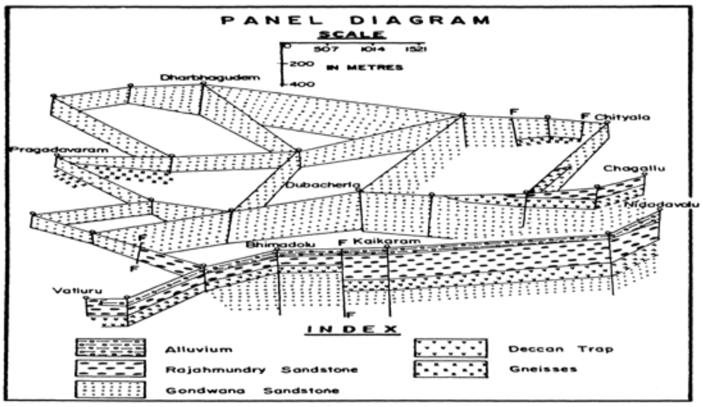

Figure 7. Subsurface Geology of West Godavari Delta (modified after Kumar et al. 1989).

The alluvium consists of clayey soils with sands; silts and gravel beds mixed with clay in varying proportions. The thickness of alluvium varies from few meters to more than 300

m. it overlies Rajahmundry sandstones. The thickness of granular zones in alluvium ranges from 18 to 258 m within the explored depths. Groundwater in the deltaic alluvium occurs under water table conditions and confined conditions. In the alluvium of East Godavari district dug wells range in depth from 2 to 11 m bgl (below ground level) and tap ground water mostly for domestic purposes. The depth of water table ranges from 0.2 to 8.5-m bgl and generally it is within 2 meters below ground level. Filter point tube wells and dug-cum-borewells ranging in depth from 13 to 20 m bgl, tap confined aquifers and yield as much as 400 m^3 / day. In Elleuru alluvium the depth to water levels range from 2 to 8 m bgl. The wells yield between 700 and 2200 m^3 / day. The pumping water levels in these wells are generally within 14-m bgl. There are two aquifers within the depths of 27 and 61 m bgl near Tamara and Gonchola. In the alluvium of West Godavari district the water table is shallow within 6-m bgl. The fresh water is limited to shallow depths locally. These fresh water pockets are developed by dug wells and filter point wells. At favorable places the filter point wells yield upto 1100 m^3 / day. In the major portion of the alluvial area the entire alluvium explored down to 300 meters depth contains saline water. The quality of ground water in alluvium varies widely both laterally and vertically. The quality is generally good near the positive hydrogeological boundary of the Godavari down to a depth of 300 m. But the fresh water zone tapers gradually towards the coast, the fresh-saline interface sloping inland. In East Godavari district the waters are alkaline, bicarbonates vary from 220 to 800 ppm, though most of the samples are generally less than 600 ppm. The chlorides vary from 20 to 6000 ppm, though generally less than 200 ppm, and total hardness 48 to 2568 ppm, though generally less than 400 ppm. In West Godavari district conductivity values of shallow ground waters upto 5320 micromhos/cm 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 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 chloride of 16,400 ppm and dissolved solids 24,329 ppm. The quality of groundwater is deteriorating due to agriculture, aquaculture etc.

NUMERICAL SIMULATION

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 saltwater movement in aquifers in cross section, the two interdependent processes are the densities - dependent saturated ground-water flow and the transport of dissolved solids in the ground water. Either local - or regional - scale sections having dispersed or relatively sharp transition zones between saltwater and freshwater may be simulated. The results of a SUTRA simulation of saltwater movement show distributions of fluid pressures and dissolved - solids concentrations as they vary with time and also show 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 favorable results (Bobba, 1993b, 1998a, 1998b., 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 (Figure 8), to represent the Godavari delta (Figure 3). The data for the groundwater model are the hydrogeologic 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 hydrologic 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 estimate heads in the aquifer are specified 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. 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 applied to real field data and observed favourable results (Bobba, 1993, and Bobba et al. 2000).

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

Table 2a. 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, sea water	0.0357 kg salt kg^{-1} sea water
Density, sea water	1025 kg m^{-1}
Density, fresh water	1000 kg m^{-1}

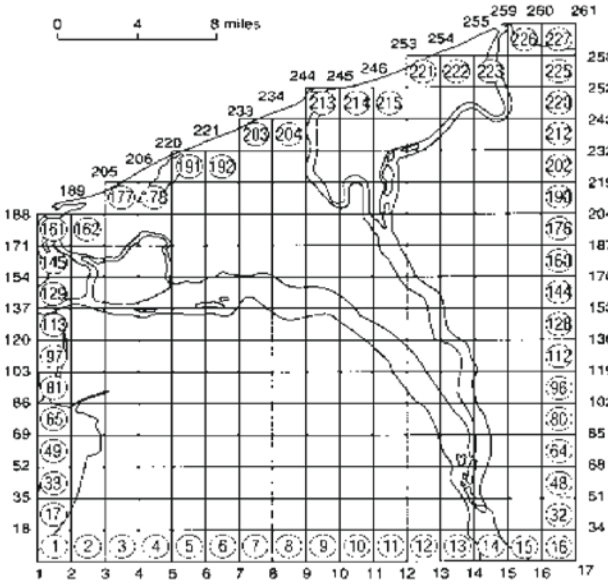

Figure 8. Finite element nodes of Godavari delta.

Table 2b. Hydrogeologic input parameters determined from sensitivity analysis.

Aquifer	Transmissivity (m^2 /day)	Hydraulic Conductivity (m/sec)
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 was treated with open boundary conditions. The simulations were carried out in a stationary regime, with a view towards establishing how the subsurface reacts with sea boundary. The aquifer porosity and permeability values used in modelling were obtained from literature and trial and error method. Some input parameters for model were taken from standard values in the literature; others were estimated from field data and then refined with sensitivity analysis (Tables 2a and 2b).

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 frequently swamps formed the edges of the lenses with the water table near to 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 most be more water passing through the edge zone than 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 cases recharge, a fairly reasonable lens configuration was obtained under essentially steady-state conditions by letting the models run for some 20 years (Figures 9). 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.

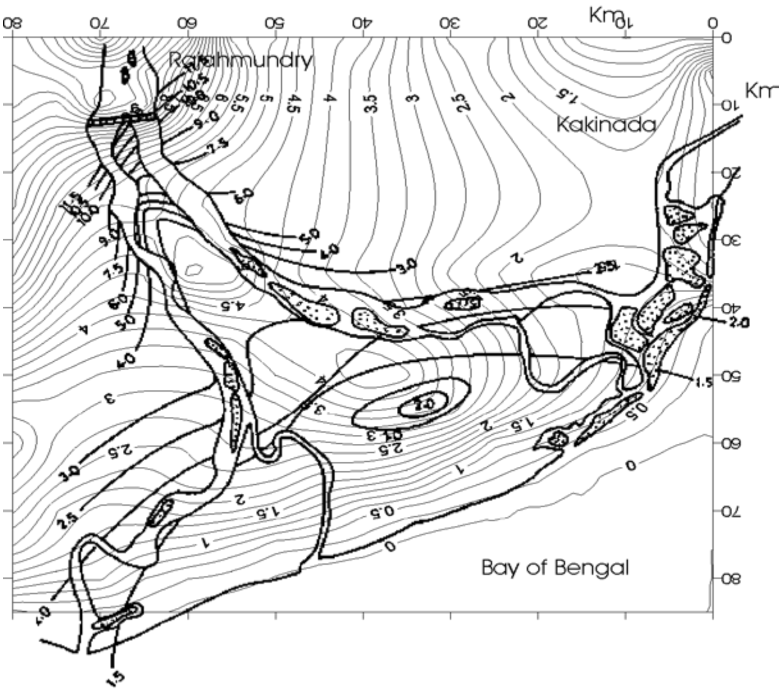

Figure 9. Comparison between observed (thick solid line) and computed (thin solid line) water table conditions during May.

Some input parameters for model were taken from standard values in the literature; others were estimated from field data and then refined with aid of sensitivity analysis. The input values determined by sensitivity analysis (Table 2a and 2b).

RESULTS AND DISCUSSIONS

The water resource management and groundwater protection is 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 protected. The basic components of strategy are: (a) to strengthen the groundwater programs; (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.

The results of the computer simulations have been represented according to their three main characteristics, that is, water table levels, the position of the interface between salt and fresh waters and the thicknesses of fresh water available in the aquifer. Using the hydraulic head record during the field season has made the steady state calibration of the model of the aquifer. This involved a laborious procedure consisting of several simulations with different input data; varying particular, the transmissivity distribution and the boundary conditions at the western side. Figure 9 illustrates the computed hydraulic heads map compared well with observed map, which in summer months. Similarly, the observed map compared well with computed hydraulic head map for the irrigation season (Figure 10). These figures are have been drawn by using SURFER computer programme. This program uses the kriging method.

Figures 11a, 11b, 12a and 12b illustrate the contour maps of computer simulation results on 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 saltwater thickness (interface toe); beyond these limits, the contour lines represent the thickness of fresh water only. The sector occupied by seawater 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, 1993) 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 watertable levels, thickness of fresh water 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 on 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.

It is therefore necessary to bear this circumstance in mind in the rational management of the reservoir, such that a clearly positive water balance must be maintained, in order to prevent severe advance in the interface. These results may serve to approximate the possible impact of the reservoir on the availability of freshwater in the aquifer. Obviously, a multitude of other possible alternatives is open to simulation, in which for example recharge, exploitation, regulation, etc. could be included. In this way, the influence of the conditions imposed on the hydrogeological regime of the aquifer could be estimated. Similarly, it would be possible to simulate other more complex situations, such as the evolution of the aquifer according to varying transient recharges, exploitation and regulation, etc.

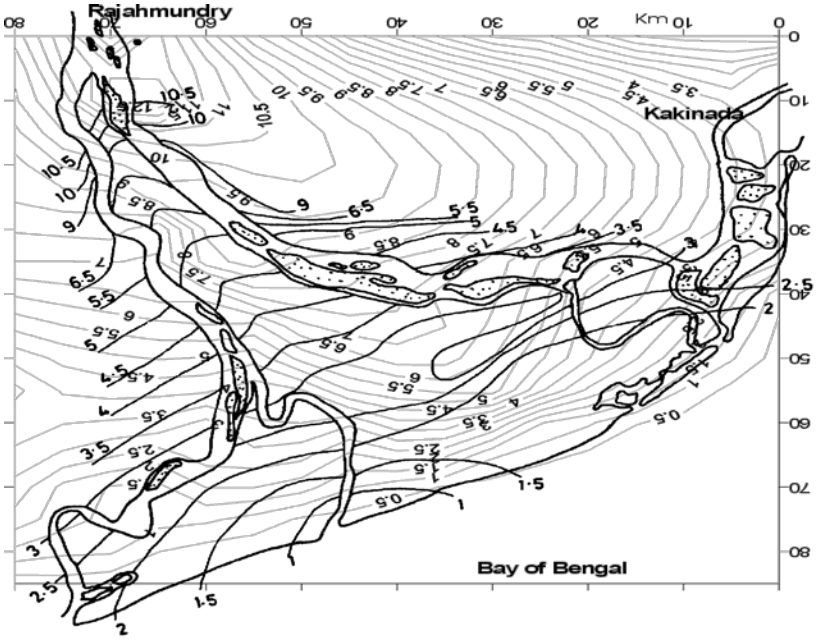

Figure 10. Comparison between observed (thick solid line) and computed (thin solid line) water table conditions during October.

Figures 11b, and 12b, depict the influence of sea level rise variations, in irrigation (rainy) and non- irrigation seasons. During 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 m to 1 m from MSL and decreases gradually towards the coastal side. Patches of freshwater zones are also present along the coastal areas (Figures 11b and 12b).

The areas of coastal aquifer contaminated by salt water are delineated in Figure 11b. 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 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 in a lagoonal side affected by saline intrusion. Sea level raise (SLR) and non-irrigation season may cause an upward movement of saline water in coastal aquifers.

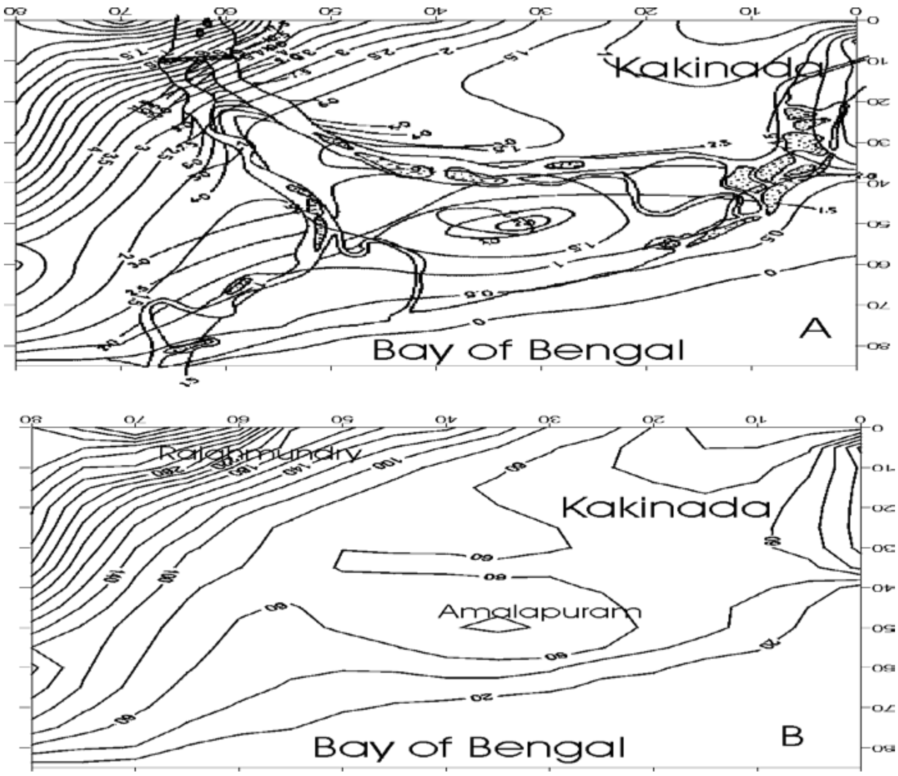

Figure 11. Simulated hydraulic heads (A) and freshwater depth (B) of Godavari delta in non- irrigation months.

The freshwater potential in the aquifer is depicted in Figures 11b and 12b. 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 11b and 12b also exhibit the depletion of water availability due to the 50-cm SLR, which may cause an apparent risk of mixing salt water with freshwater and thereby cause contamination of freshwater in the wells. It is estimated that the present freshwater will be contaminated by saltwater 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 13 shows the results are shown in different environmental conditions due to heavy and long rainy season and drought conditions due to high temperature and less rainfall (climate change). Higher water table conditions are observed due to more rain and irrigated water is recharged to the aquifer. The salt water was flushed out or stopped seawater intrusion to the aquifer. However, if the severe drought conditions (higher temperature, lesser rainfall) occur in the delta, the water table reduced due to higher evapotranspiration and over pumping the ground water for irrigation and domestic puposes. The salt water intruded to the aquifer and freshwater thickness reduced in the delta.

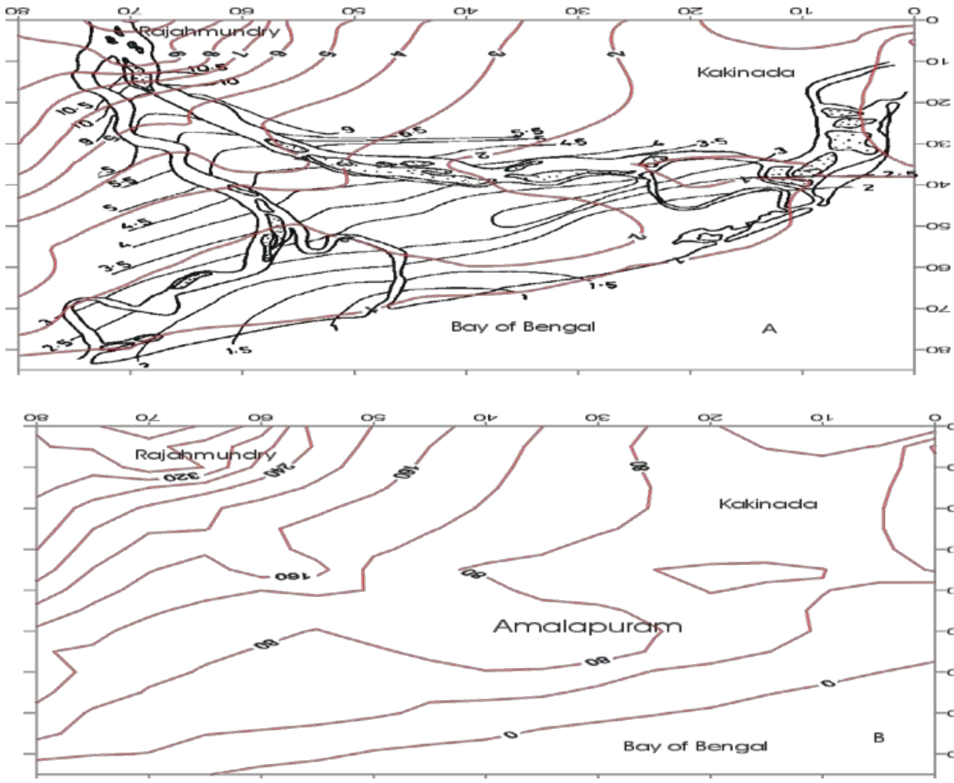

Figure 12. Simulated hydraulic heads (A) and freshwater depth (B) of Godavari delta in irrigation season months.

CONCLUSIONS

Ground water investigations are presently very active in Andhra Pradesh because of the urgent need for more water to meet the demands for agricultural, industrial purposes, population growth in coastal areas. This research was has been provided numerical simulation of the influence of surface flows, coming from the water management of the projected reservoir, on the regional groundwater behaviour on 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 steady-state conditions to the aquifer for fresh water surplus and deficits at the coastline. When recharges of saltwater occur at the coastline, essentially of freshwater deficits, a hypothesis of mixing for the freshwater - saltwater 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. Results of the steady state simulations showed reasonable calculations of the watertable 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 in the delta and along the coastline. As a result of the present hydrogeological conditions on the aquifer, a considerable advance in seawater intrusion would be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the fresh water from the river is annually channelled from the reservoir for irrigation, industrial and domestic purposes.

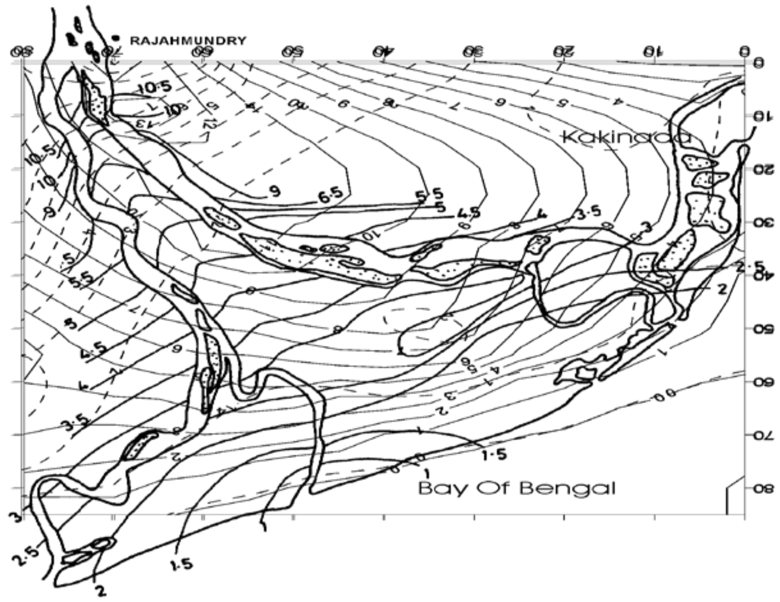

Figure 13. Simulated hydraulic heads of Godavari delta in different seasons (Solid line in heavy rainy season, --- drought conditions).

The change in the water resources management due to climate change effect needs a necessitated a close looks at many traditional activities. Water resource management constitutes a) Proper investigation of water occurrence. b) Best technological, economical, legal and adminstrative procedure for water use and distribution to satisfy present and future needs with few or no negative effects on the environment. These procedures should be subjective to periodic review and updating. c) Construction and maintenance of wells, drains and other control measures to alleviate, stop or retard salt- water intrusion. d) Monitoring the surface and ground water system before, during and after initiating water development.

The control of salt-water intrusion may be accomplished by: a) Physical barriers formed such as curtains of injected soil or backfield trenches with compacted soil. b) Hydraulic barriers formed by well or drain recharge. c) Discharging salt water only below the interface in order to increase the pressures and / or the size of the fresh - water lens. By coupling computer simulation techniques and geographic information system analysis are useful to predict the location of salt-water intrusion areas for future control due to anthropogenic and climate change effects in coastal areas. In future the computer simulation model will be coupled to predict water quality of the groundwater due to saltwater intrusion, anthropogenic effects and land subsidence due to oil and gas exploitation in the delta.

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