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Seawater Intrusion into Coastal Aquifer: A Case Study from Puri District, Orissa

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ABSTRACT: About sixty percent of the world population live within a distance of less than 60 km. from the coastline, wherein groundwater is the most important source of freshwater. The quality of groundwater in coastal aquifers is threatened by various human activities like irrigation, industrialisation, urbanisation, tourism etc. Besides, this valuable resource is susceptible to seawater intrusion with the ever increasing development of groundwater. Recently, the '*variable-density 3D transient groundwater flow modeling*' has been successfully employed worldwide in order to simulate, assess, predict and manage the process of seawater intrusion. A case study in a coastal tract (1834 km^2) having a shoreline length of 60.5 km. adjoining Bay of Bengal in Puri district of Orissa has been carried out using SEAWAT-2000 for an optimal management of seawater intrusion. SEAWAT solves the coupled groundwater flow and solute-transport equations through finite difference method. The model simulation shows that the seawater ingress occurs at the semi-confined aquifer of Layer 6 (120–180 mbgl) and Layer 8 (200–240 mbgl). This model can be used for a reasonable representation of a multilayered coastal aquifer system to simulate the three dimensional distribution of groundwater salinity in the regional context of Puri. Moreover, the model can be used as a suitable tool for giving complex groundwater management options in coastal belt of Puri with an input of adequate field data through further calibration and refinement.

Keywords: Seawater Intrusion, Modeling, Bay of Bengal, Puri, Orissa, SEAWAT, Solute-Transport Equations, Semiconfined Aquifer, TDS.

INTRODUCTION

About 30% of total freshwater available on earth is groundwater. This valuable natural resource of fresh water in coastal area is threatened, in coastal areas due to Seawater intrusion into aquifers. Therefore, there is a need to develop the ground water resources of the coastal regions by carefully considering the problems of seawater ingress. The Orissa state of India occupying a geographical area of 155,700 km^{2}is having 428 km of coast line along which a number of cities and urban agglomerates have been developing. Puri town is one such expanding city which has acquired special significance due to factors of growing pilgrims and tourists flocking the city. Such factors have contributed considerably to the phenomenal increase in the floating population of the city which causes significant stress on the water supplies for drinking and other purposes. The only source of drinking water supply to Puri city is from groundwater resources which has been put to considerable pressure because of its strategic location in the coastal area.

PREVIOUS WORK

In the context of coastal aquifer system under Indian situation lately several studies have been undertaken which suggest that the damage is being done to the fresh water bearing zone due to saline water intrusion as a result of increasing stress on ground water resources of the region to meet the demand for agricultural, domestic industrial use warranting remedial measures. Sriram Narayan and Natarajan (1993) have studied the freshwater salt water interface in coastal areas of Tamil Nadu and were successful in delineating the interface. S.B. Raghav Rao *et al.* (1993), used a model for simulating salt water intrusion in coastal aquifers of Gujarat for a period of 5 years by finite difference approximation. Bhat (1994) conducted extensive studies of salt water intrusion in Kutch area of Gujarat and was able to delineate the salt water fresh water interface. He also concluded on the origin of the salinity in ground water in various aquifers of Kutch area. A brief review on the aspect of numerical modeling of salt water intrusion into coastal aquifers considering the physical process of advection and dispersion with density dependant flow approach has been presented by Kashyap and Sharma (2005).The process of sea water intrusion into south Chennai aquifer was analyzed by Mohan and Pramada (2005) using MT3DMS model considering constant density flow condition. Simulation of salt water intrusion in coastal deltas with palaeo-channels along with optimal location and pumpage for ground water development for a group of production wells limiting the salinity below desirable level was conducted by Rao *et al.* (2005) using SEWAT model. Some hydrogeological studies have been conducted during 1990 to 2000 for salt water intrusion into coastal aquifer by analyzing bore hole lithologs and geophysical investigation in the east coast of India by Bhatacharya *et al.* (2000). Some geophysical studies have been undertaken during 1995 to 2000 for assessing the extent of salt water intrusion into coastal aquifers by Radhakrishna (2001) and S.Das *et al.* (2001) in the river delta system in coastal area of Orissa. Depending upon the hydrogeological study by C.G.W.B. and other available data an approximate hydrogeochemical characteristics of East Coast of Orissa with an average space distribution of aquifer characteristics relating to the salinity of the zone was given by S. Das. Reports were available with South—Eastern Region, CGWB, Bhubaneswar regarding ground-water exploration in Puri District. It emphasizes the utilizable groundwater potential of the district as a whole it has to be recognized that in most of the earlier studies, there was an assumption of constant density flow in coastal aquifers near the seawater wedge. However, as explained by several other authors (Todd, 1980, Rastogi, 2005 Kashyap and Sharma, 2005) a realistic study of the dynamics of Seawater wedge in a coastal aquifer should involve the consideration of appropriate density variation.

The present study has been taken up with the objectiveof evaluating the temporal and spatial variation of overall salinity possibly due to seawater encroachment in the coastal aquiferin in Puridistrict, Orissa. SEAWAT code was originally given by Guo and Langevin (2002), has been developed to simulate 3 dimensional variable density transient ground water flow in porous media through finite difference approximation.

SEAWAT is based on the concept of fresh water head or equivalent fresh water head in a saline ground water environment.

$$h_f = \frac{\rho}{\rho_f} h - \frac{\rho - \rho_f}{\rho_f} z \qquad \ldots (1)$$

$$h = \frac{\rho_f}{\rho} h_f + \frac{\rho - \rho_f}{\rho} z \qquad \ldots (2)$$

h_f = fresh water head
h = saline water head
ρ = density of saline water
ρ_f = density of fresh water
z = Elevation

Darcy's Law is expressed by the equation,

$$q_x = \frac{k_x}{\mu} \frac{\partial p}{\partial x} \qquad \ldots (3)$$

$$q_y = \frac{k_y}{\mu} \frac{\partial p}{\partial y} \qquad \ldots (4)$$

$$q_z = -\frac{k_z}{\mu} \left[\frac{\partial p}{\partial z} + \rho_g \right] \qquad \ldots (5)$$

qx, qy, qz are individual components of sp discharge.
μ = dynamic viscosity
kx, ky, kz are intrinsic permeability

The governing equation for variable density flow in terms of fresh water head as used in SEAWAT is,

$$\frac{\partial}{\partial \alpha}\left(\rho K_{f\alpha} \left[\frac{\partial h_f}{\partial \alpha} + \frac{\rho - \rho_f}{\rho_f} \frac{\partial Z}{\partial \alpha} \right] + \frac{\partial}{\partial \beta}\left(\rho K_{f\beta} \left[\frac{\partial h_f}{\partial \beta} + \frac{\rho - \rho_f}{\rho_f} \frac{\partial Z}{\partial \beta} \right]\right)\right) \qquad \ldots (6)$$

$$+\frac{\partial}{\partial y}\left(\rho K_{fy} \left[\frac{\partial h_f}{\partial y} + \frac{\rho - \rho_f}{\rho_f} \frac{\partial Z}{\partial y} \right]\right) = \rho S_f \frac{\partial h_f}{\partial t} + \theta \frac{\partial \rho \partial C}{\partial C \partial t} - \overline{\rho} q_s \qquad \ldots (7)$$

where α, β, γ are orthogonal coordinate axes, aligned with the principal directions of permeability; K_f is equivalent freshwater hydraulic conductivity [LT-1]; S_f is equivalent freshwater specific storage [L-1]; t is time [T]; θ is effective porosity [dimensionless]; C is solute concentration [ML-3]; ρ*s* is fluid density source or sink water [ML-3]; and *qs* is the volumetric flow rate of sources and sinks per unit volume of aquifer [T-1].

The Governing Equation for Solute Transport is,

$$\frac{\partial C}{\partial t} = \nabla.(D.\nabla C) - \nabla.(\overline{v}C) - \frac{q_s}{\theta} C_s + \sum_{k=1}^{N} R_k \qquad \ldots (8)$$

D is Hydrodynamic dispersion coefficient
CS is the solute concentration from source or sink

where:
D is the hydrodynamic dispersion coefficient [L2T-1],
$\overline{v}$ is the fluid velocity [LT-1],
C_s is the solute concentration of water entering from sources or sinks [ML-3], and
R_k (k = 1, …, N) is the rate of solute production or decay in reaction k of N different reactions [ML-3T-1].

STUDY AREA

The Study area is located between 85°32′5″E to 8605′36″E Longitude and 19° 42′4″ N to 20°19′34″ N Latitude (Figure 1). It has a geographical area of 1834 Square Km. The Length of the shore line (adjoining Bay of Bengal) is approximately 60 km. River Kushabhadra borders the eastern and North eastern side of the study area and river kuakhai and river Daya border the North western and Western side respectively. The Bay of Bengal is situated on the southern side of the study area. Chilka lake having brackish to saline water is situated on the southwestern side of the study area.

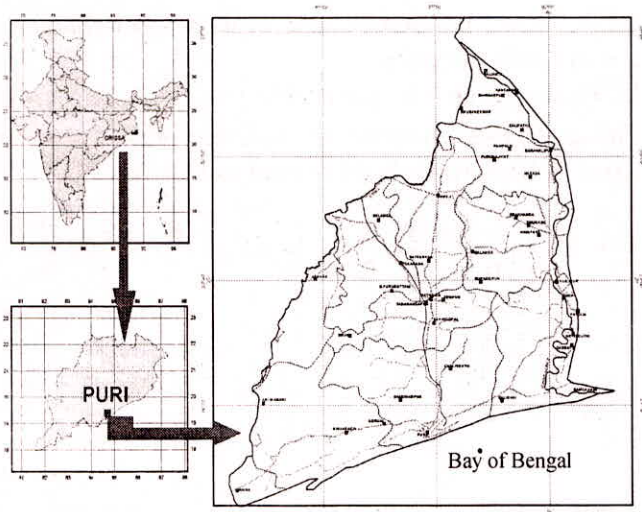

Fig. 1: Location map of the study area

HYDROGEOLOGICAL SETUP

Drainage

The study area falls in the Mahanadi delta (Figure 2) and the main drainage is formed by river Kuakhai Daya and Kushabhadra.River Dya drains into Chilka lake where as river kushabhadra drains into the bay of Bengal. River Kuakhai is a tributary of River Mahanadi and is perenial. The flow in Kuakhai during lean season varies from 85 m^3/sec to 105 m^3/sec. River Daya is also a large seasonal River and there is considerable base flow in the river. The flow in Daya river varies from 55 m^3/sec to 90 m^3/sec.

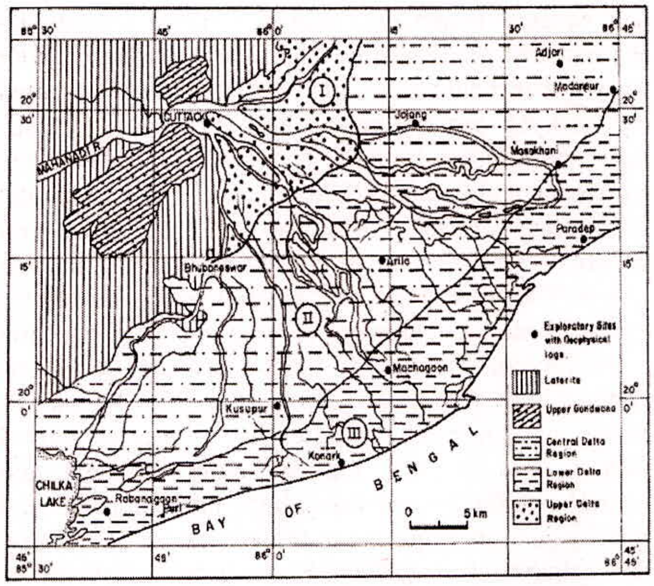

Fig. 2: Mahanadi delta system.

Geology and Geomorphology

The geological formations in the area spans in age from Archean to Recent (Quaternary). The Tertiary and Quaternary formations occur over major part of the study area. The geological succession in the area is given in Table 1.

Table 1: Geological Succession of Formation in Puri Area

	Age	*Lithology*
Quaternary	Recent to Pleistocene	Dunesand, youngeralluvium Older alluvium and laterites
Tertiary	Mio-Pliocene	Brown, Yellowish brown and Gray clays, sand and gravel with fossils, callcareous concentrations
Unconformity		
Mesozaic	Lr. Jurassic to Lr. Cretaceous	Sandstone, carbonaceous shale. Conglomerateetc of Upper Gondwana Group
Unconformity		
Precambrian	Quartz and Pegmatitic veins	Khondalites

The Tertiary deposits are comprised of Brown to yellowish brown and gray clay, sand and gravel, with fossils of Mio-Pliocene age. The younger alluvium, which covers nearly 90% of the study area occurs as flood plain deposits along the course of the rivers. The sediments are comprised of an admixture of silt, sand, gravel and pebble in varying proportions, with increase in total thickness of around 600 mtrs towards the sea. The depth to the basement varies from very shallow in landward side to very deep towards the sea. Around Puri nearer to sea the basement is not reached even upto a depth of 600 m. Rocks like Khondalite, Laeptynite, Granite gneiss and Charnockite form the bedrock.

Hydrogeology

The unconsolidated sand and gravel layers of Tertiary and Quaternary age form the main repository for ground water. The upper aquifer layers are generally unconfined in nature and ground water occurs under water table conditions. These are underlain by semi-confined and confined aquifers with the intervening confining layer being mainly of clay. The aquifers are extensive, interconnected and have prolific yield potential. The thickness of individual aquifer varies from 6 to 10 meters while the cumulative thickness of aquifer horizons down to a depth of 250 meters vary from 15 to 79 m. The unconfined aquifer system continue down to a substantial depth due to absence of persistent confining beds. In the upstream areas the aquifers occur as horizontal layers showing increased dips towards the coast. Based on the lithology of the exploratory boreholes of CGWB and OLIC a fence diagram has been prepared for the study area (Figure 3).

Analysis of the pumping test data for the phreatic aquifer shows that the transmissivity values of Delang and Puri Sadar block range from 32 to 4400 m^2/day.

In Sakhgopal area the transmissivity value range from 14 to 170 m^2/day. The transmissivity values in the southern part of Delang Puri profile range from 32 to 509 m^2/day. The summerised aquifer characteristics of the study area is as under.

Aquifer Characteristics

The water level fluctuation data collected from CGWB from the monitoring wells for the period from 1992 to 2004 was analysed. The hydrographs indicate that for the last 15 years or so there is little longterm change in the groundwater levels though the seasonal watertable fluctuations are well reflected.

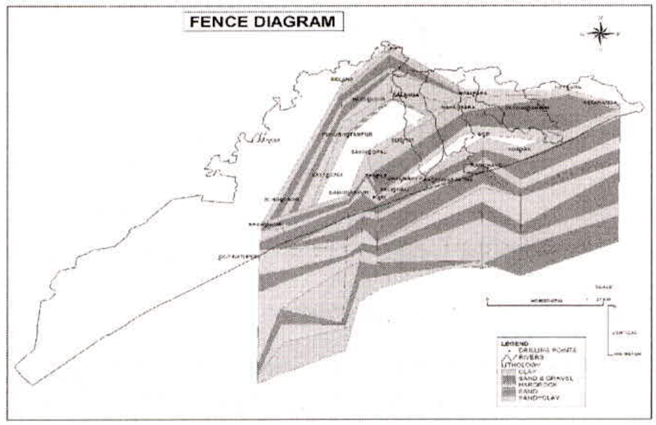

Fig. 3: Fence diagram of the study area.

DISPOSITION OF FRESH WATER AND SALINE AQUIFER

In the eastern part of Puri district in parts of Nimapara, Gop, Balipatna, fresh water aquifers occur upto a depth of 100 m, beneath which the groundwater is brackish to saline in nature. In the Puri-Brahmagiri-Siruli tract aquifers are generally saline, at all depths down to the bedrock except in local pockets. In the area around Sakhigopal, groundwater is slightly brackish to saline down to the bed rock (282 m). In the Tolapada-Delang area fresh water aquifers occur at shallow depths (30 to 100 m). At Puri town fresh water aquifers occur in shallow (within 40 m depth) as well as deeper horizons (135–200 m depth). The deeper fresh water zone pinches out towards northeast.

Basing on the data of CGWB and DANIDA, the fence diagram depicting the disposition of fresh—salinewater has been prepared and is presented in Figure 4.

Table 2: Aquifer Characteristics in Coastal Areas

	No of Wells	*Aquifer Thickness (m)*	*Static Water Level (mbgl)*	*Discharge (lps)*	*Drawdown (m)*	*T (m^2/day)*	*K (m/day)*	*S*
Unconsolidated Quarternary Alluvium (within 100 mtrs depth)	40	10–55	0.8–7.6	12–75	3.1–13.1	256 – 8198	4–330	1.3×10^{-3} to 7.5×10^{-5}
Semi Consolidated Sediments (Tertiary) (below 100 mtrs	27	8–76	7.7–17.7	4.5–28	3–25.3	151–2650	1.5–60	8.9×10^{-4} to 1.9×10^{-6}

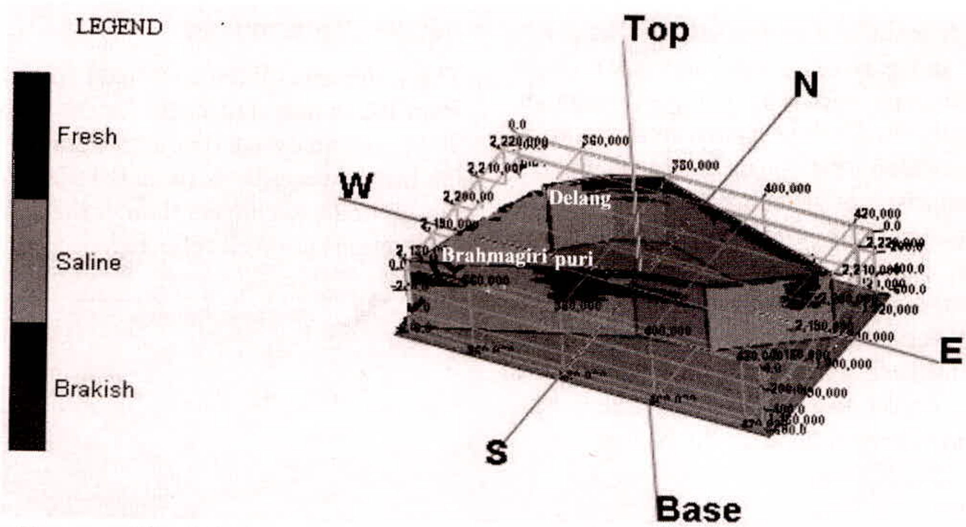

Fig. 4: Fence Diagram of Puri District showing the Disposition of Fresh, Blackish and Saline Water Bearing Zone

THE CONCEPTUAL MODEL

The conceptual model was developed after detailed study of the lithology and interpretation of the available geophysical logging data. Basing on the above data the fencediagram of the study area was prepared and various hydrogeological sections were incorporated in the model. The system boundaries were identified as follows:

On the southern side of the study area Bay of Bengal has been taken as the constant head boundary.

On the southwsten side Chilka lake is there and that side of the system was assigned constant head boundary.

Daya river on the westen side, Kusabhadra in the north and north eastern side and Kuakhai river on the northern side were assigned River boundary condition.

The values of various field parameters like, *K*, *T*, *Sy*, *S* were taken from the observed field values.

Informaton was gathered from various organizations, regarding various hydrometeoro logical data, infiltration factor, number of groundwater abstraction structures, pumping pattern, temporal variation of watertable and waterquality etc.

The groundwater flow direction was ascertained from the field waterlevel monitoring data.

MODEL DESIGN

Depending upon the hydrogeology of the system an eight layered model was developed. The thickness and the geological formation of each layer is presented in Table 3. The thick ness and aquifer materials in each layer was assigned as per the conceptual model developed.

The study area map (grid) was aligned along the principal permeability direction.

A regular finite difference grid with a 500 m × 500 m cell in the horizontal plane was created. The elevation considered 15 m amsl at the top and –225 m amsl at the bottom. The diagrammatic representation in plan view is given in Figure 5.

Table 3: Aquifer Characteristics

Layer No.	Thickness	Type of Soil	K_xm/ day	Kym/ day	Kzm/ day	Effective Porosity	Total Porosity	S_Y	S_S	Long. Dispersivity (m)
1.	20	sandyclay	2	2	0.02	0.1	0.55	0.06	0.0003	36
2.	40	med sand	25	25	2.5	0.25	0.4	0.3	0.00033	15
3.	20	sandyclay	5	5	0.5	0.15	0.5	0.07	0.0003	30
4.	20	sandgravel	125	125	12.5	0.25	0.35	0.25	0.00025	15
5.	20	sandyclay	5	5	0.5	0.15	0.5	0.07	0.0003	30
6.	60	sandgravel	125	125	12.5	0.25	0.35	0.25	0.00025	15
7.	20	clay	0.0003	0.0003	0.00003	0.1	0.55	0.02	0.001	36
8.	40	sandcourse	50	50	0.5	0.25	0.45	0.3	0.00006	15

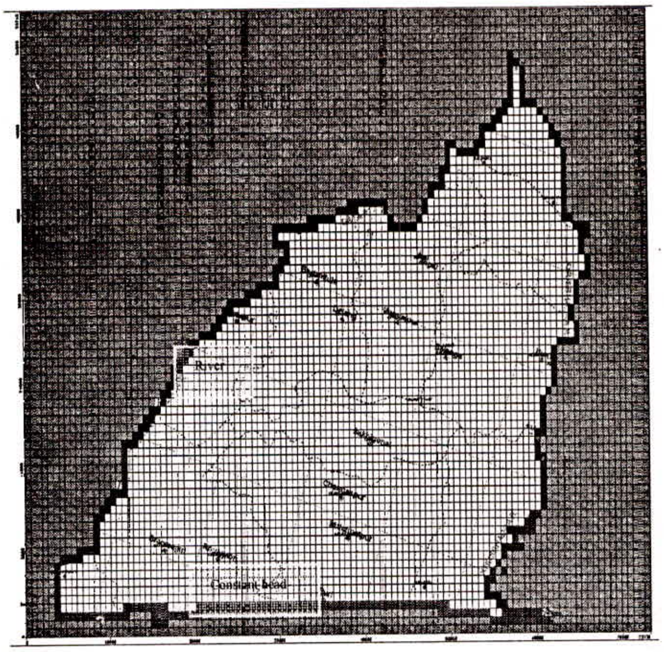

Fig. 5: Grid lay out (plan view)

INITIAL CONDITION

The system condition of 1992 was assumed o be the initial condition. The observed water table of 1992 from the study area was taken as the initial head and the observed concentration as the initial concentration. The values of various stresses acting on the system, like pumping, recharge and, evapotranspiration were assigned starting from the initial condition. The concentration of sea water was taken to be 35000 mg/ltr.

BOUNDARY CONDITION

The Northern, Western and Eastern sides being bounded by river Kuakhai, Daya, and Kushabhdra were assigned river boundary condition. The data collected from central water commission was used to assign the river stage values at different stress period.The river bed slopes were assigned linear gradient. The upper most layer was taken as the recharge boundary. The assigned extinction depth for evapotranspiration was 3 meters. As the Bay of Bengal and Chilka lake are on the Southern side and South western side these sides were taken as constant head boundary and constant concentration boundary. The preliminary values for different aquifer parameters like *K*, *Sy*, *Ss*, total Porosiyu, effective Porosity, Longitudinal Dispersivity for different layers were assigned. The value of *Kz* was taken tobe 1/10 of *Kx* and *Ky*. The horizontal dispersivity and vertical dispersivity were taken to be 1/10 and 1/100 of longitudinal dispersivity.

CALIBRATION

Initially the model was run in MODFLOW 4.2 with constant density flow for 3650 days and the value of Hydraulic conductivity and storage properties were calibrated to match the observed water tables with the computed water table. The correlation coefficient value was brought to more than 0.9 and the RMS error was brought to around or less than 1.Then the model was run through SEAWAT using the calibrated values of *Kx, Ky, Kz.* and storage properties. Calibration of the model was further carried on in transient state till the computed head and concentration values nearly matched the observed head and concentration values at various observed time .This was done by matching the observed contour of head and concentration at different time periods and simultaneously minimizing the RMS error and bringing the correlation coefficient value(computed and observed values of concentration and head) to around 1. The obsehved well hydrographs at different time period was compared with the computed well hydrograph to refine the calibration.

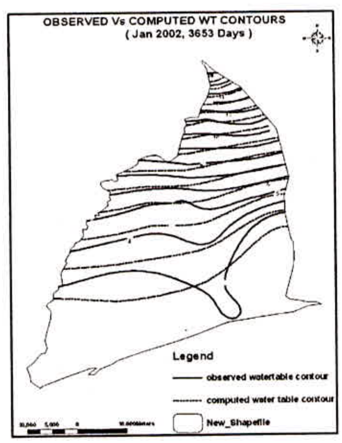

Fig. 6(a): Observed and Computed Water Table Contour

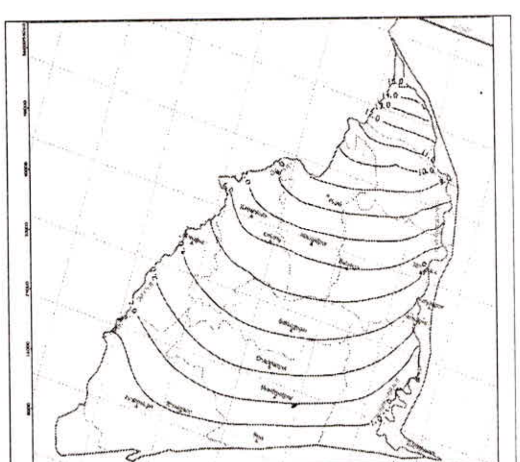

Fig. 6(b): Computed Watertable Contour Jan 2002 (3653) Days

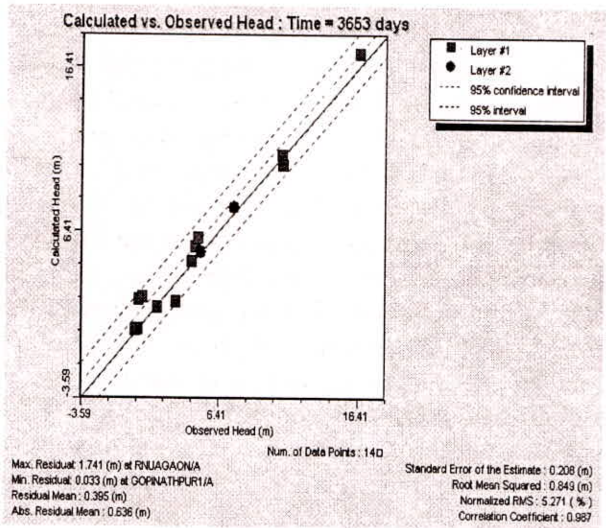

Fig. 6(c): Scattared Plot

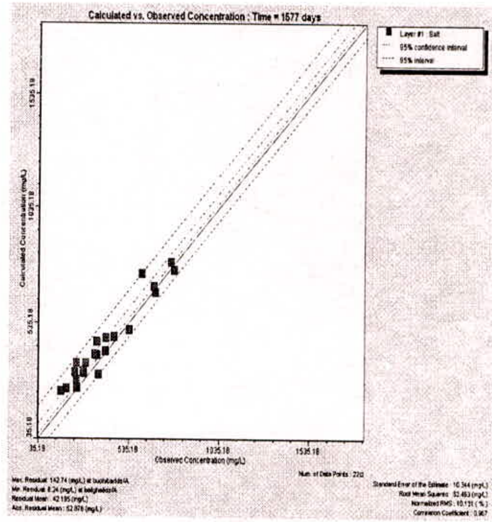

Fig. 7(c): Scattared Plot

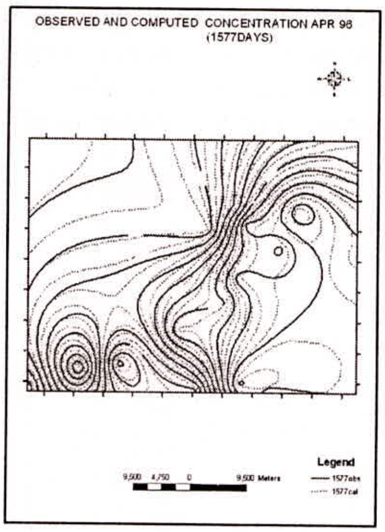

Fig. 7(a): Observed and Computed TDS Consentration Contour

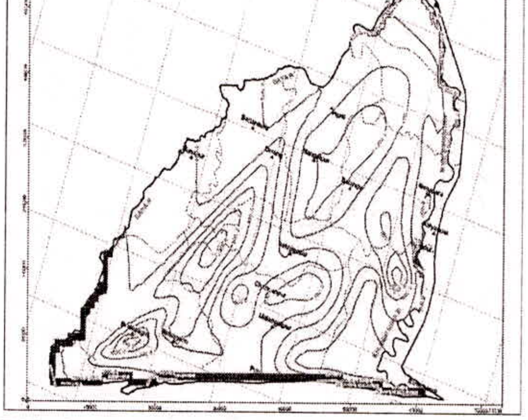

Fig. 7(b): Computed TDS Concentration contour Apr 96 (1577 Days)

Sensitivity Analysis

A sensitivity analysis was done during the model calibration. It was observed that the model is sensitive to River stages, recharge and effective porosity. A minor modification of these values created appreciable changes in the water table elevation and salt (TDS) concentration

Model Verification

The calibrated model was verified by comparing the observed water table elevation of April 2000 and November 2000 with the computed watertable elevation during that period and the oberved concentration of April 1994 and April 1997 with computed TDS concentration.

After calibration and verification the model can be used for predictive analysis corresponding to various stresses like pumping pattern, recharge, recharge concentration etc.

RESULTS AND DISCUSSION

The computed water table elevations and concentration contours, are presented in the following figures .The calibrated model parameters are presented in the in Table 4.

One of the important findings of the above modeling exercise at this stage is that there is seawater intrusion into the coastal aquifer of Puri from layer 6 and layer 8 which are at a depth of around 120 to 180 meter and 200 to 240 meter below ground level. The average linear velocity of intrusion from layer 6 and layer 8 is about 0.2 tr/day. he thick clay layers present as semi confining layers between the aquifers work as barrier to sea water intrusion into the coastal aquifer.

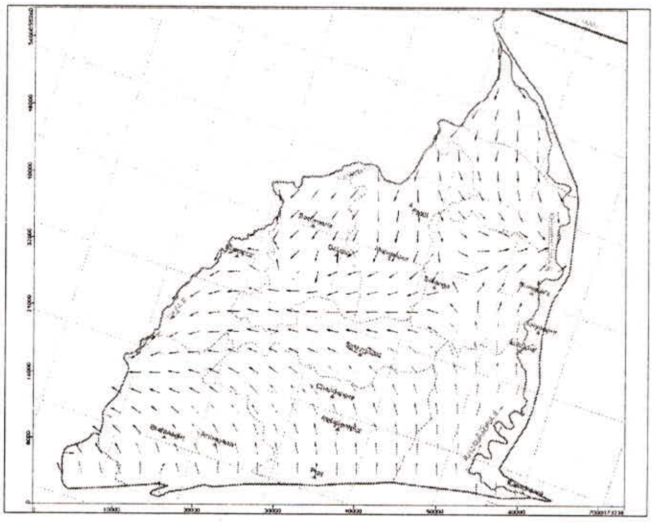

Fig. 8: Saline water intrusion in layer 8 during Jan 2002 (Simulated through SEAWAT)

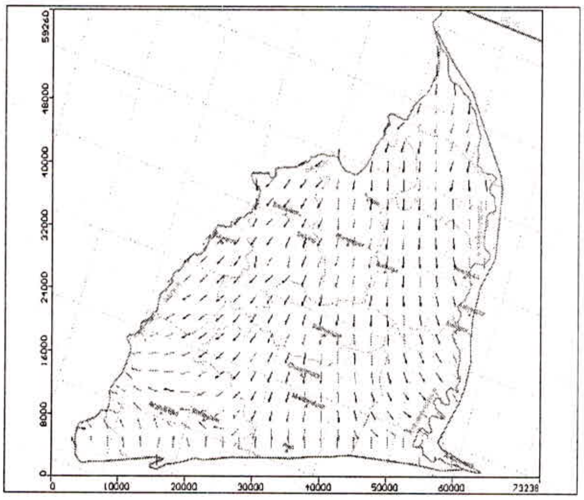

Fig. 10: Saline water intrusion in layer 6 during Jan 2002 (Simulated through SEAWAT)

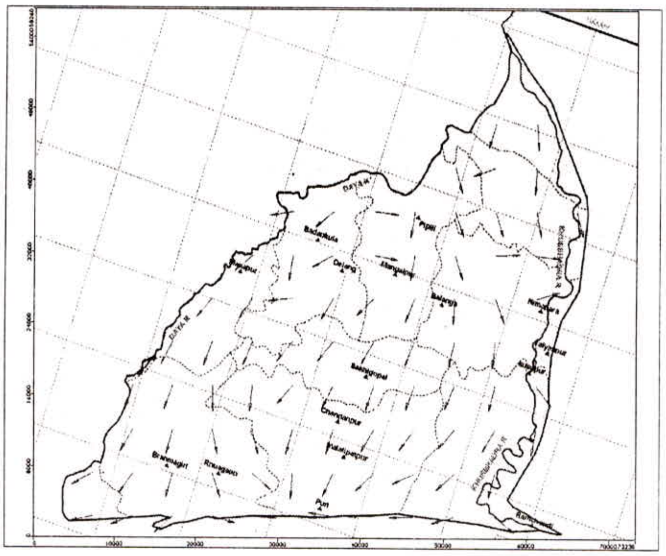

Fig. 9: Fresh water out flow to sea from layer 8 during Jan 2002 (Output of MODFLOW for the same data and parameters)

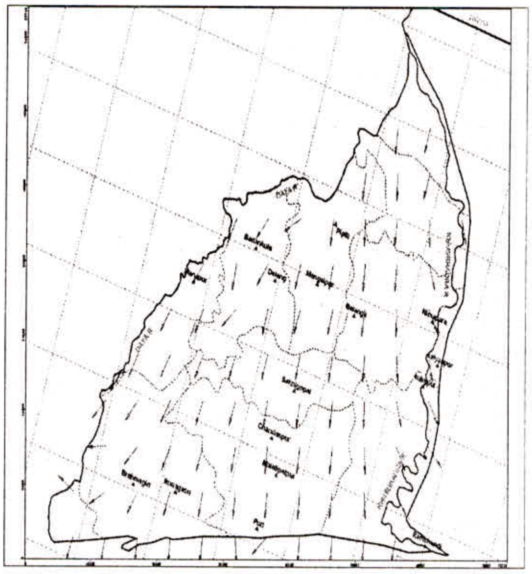

Fig. 11: Fresh water out flow to sea from layer 6 during Jan 2002 (Output of MODFLOW for the same data and parameters)

Table 4: Calibrated Aquifer Parameters

Layer No.	*Thickness*	*Type of Soil*	*K_xm/ day*	*Kym/ day*	*Kzm/ day*	*Effective Porosity*	*Total Porosity*	*S_Y*	*S_S*	*Long Ispersivit (m)*
1.	20	sandyclay	8	8	0.8	0.25	0.55	0.06	0.0003	5
2.	40	med sand	90	90	9	0.4	0.4	0.3	0.00033	5
3.	20	sandyclay	9	9	0.9	0.25	0.5	0.07	0.0003	5
4.	20	sandgravel	125	125	12.5	0.35	0.35	0.25	0.00025	5
5.	20	sandyclay	9	9	0.9	0.25	0.5	0.07	0.0003	5
6.	60	sandgravel	125	125	12.5	0.35	0.35	0.25	0.00025	5
7.	20	clay	0.0003	0.0003	0.00003	0.05	0.55	0.02	0.001	5
8.	40	sandcourse	80	80	8	0.38	0.45	0.3	0.00006	5

Preliminary simulations show that the system is sensitive to river stages and rainfall recharge. For the regional scale model to simulate the hydraulic head accurately, the model must precisely simulate the three dimensional distribution of groundwater salinity. Since most of the water quality monitoring wells are within the shallow aquifer zone the distribution of salinity could not be characterized adequately which has an impact on the proper head distribution. The model is a reasonable representation of a multilayered coastal aquifer system in the regional context. The model can be used to simulate complex management options with the availability of adequate data and further calibration and refinement of input parameter values.

Limitations of SEAWAT Computer Code

The explicit coupling method in the SEAWAT code uses a one time step lag between solution to the flow and transport equation.

Isothermal condition is assumed.

SEAWAT does not account for variation in viscosity.

Model does not account for Evapo-Transpiration from unsaturated zone. If the unsaturated zone is thick the ET process is important.

In general variable density models require accurate simulation of transport process and accurate simulation of flow process. Errors in this type of models are compounded because flow and transport are coupled process.

CONCLUSIONS

1. For modeling multilayered coastal aquifer system variable density flow approach should be followed since constant density flow modeling, though, gives the spatial and temporal distribution of head, may not account for the saline water intrusion, as evident from the study by using MODFLOW and SEAWAT with the same data and aquifer parameters of the study area.
2. Although many geological and geophysical investigations were conducted in the coastal districts of orissa, no conclusion was drawn regarding Seawater intrusion and the cause of salinity of the aquifers were mainly attributed to *remnant seawater*. The present study gives a new direction in this regard wherein it has been established that there is *seawater intrusion* into coastal aquifers of Puri district.
3. For proper simulation of the variable density flow process in the coastal aquifer system data of temporal variability of salinity for different layers is essential. Unfortunately most of the regularly monitored water quality observation wells are located within the shallow aquifer zone.

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