

# A STUDY OF SALINE FRESHWATER INTERFACE PHENOMINA IN THE MAHANADI DELTA REGION: ORISSA, INDIA

S V N Rao<sup>1</sup> I Radhakrishna<sup>2</sup> Nitin Joshi<sup>1</sup> Ajay Sharma<sup>1</sup> Shashank Shekhar<sup>3</sup>

1. DHI (India) Water and Environment, C R Park New Delhi

2. Integrated Technologies for Groundwater Resource Systems Development, Tarnaka, Hyderabad

3. Department of Geology, Delhi University Delhi

\*Corresponding Author: [rao@dhigroup.com](mailto:rao@dhigroup.com)

## ABSTRACT

The subsurface aquifer systems in Mahanadi delta region in Orissa (India) is largely characterized by two groups of freshwater aquifer systems: 1. The south western Mahanadi delta region is represented by unconfined to semi-confined freshwater aquifers underlain by brackish/ saline aquifer systems with a diffusion boundary 2. The north eastern parts of Mahanadi delta is represented by deep freshwater confined aquifers overlain by brackish/saline water aquifers with aquitard/ aquiclude boundary. Both the systems are prone to saline water mixing/ migration with time and development.

The present paper incorporates results of a simulation study using a finite element based FEFLOW model and examines saline water migration scenarios when subjected to increasing rates of pumping under steady state conditions with the help of a calibrated groundwater model. The results indicate the unconfined and semi-confined aquifer systems in the south western part of Mahanadi delta are prone for faster rates of saline water mixing of the contamination when compared to the deep confined systems in the north eastern parts of Mahanadi delta.

## INTRODUCTION

Coastal groundwater systems constitute a very important resource for drinking, irrigation, agriculture and industrial sectors of the country. These systems are often interfaced with oceanic basins on one hand and upland regions with surface-groundwater development projects on the other hand and become targets for hydrodynamic changes. The fresh ground water resource systems in Indian coastal deltas have been subjected to large scale stresses in the form of ground water withdrawals and reduced recharge potentials over the last two decades or so and as a consequence there is large scale drop of water levels and reduction in fresh water storages besides saline water ingression inland into fresh water systems. Global warming processes and projected rise of sea levels are further threatening these situations. Physico-chemical processes accompanying such ingression, aquifer characteristics and paleo hydro-geological processes in various delta regions and their space-time variations are required to be studied and quantified to develop appropriate optimization schemes/ models with predictive capabilities for sustainable development and management of fresh ground water resources.

The fresh/saline water interface boundary is a complex, sensitive and dynamic in nature and makes the strategies for well field development rather difficult. It demands very accurate information in relation to (a) the thicknesses of fresh/saline aquifers; (b) the nature of the interface or diffusion boundary; (c) estimation of saline/ freshwater wedging and its geometrical variations; (d) designing appropriate monitoring networks; and (e) assessment of possible vertical leakages through the aquitard. Borehole geophysical techniques provide a reasonably powerful tool for estimation of interface/diffusion boundaries and water quality characteristics in multi-aquifer systems of coastal deltas (Jones & Buford, 1957; Radhakrishna & Rao, 1990). The Mahanadi-Brahmani-Baitarni deltaic regions of Orissa (India) coast provide a useful base where the aquifer and interface geometries/boundaries were accurately

defined, mapped and delineated for appropriate model analyses and development of groundwater resources (Radhakrishna 2006).

A number of models have been reported in literature dealing with saltwater-freshwater modeling in coastal environment. Among them SEAWAT (Langevin et al 2004) and FEFLOW (Diersch 2006) are most popular. The SEAWAT is a MODFLOW based density dependent flow and transport model. Masterson and Garabedian (2007) used SEAWAT numerical model to simulate effects of sea-level rise on the depth to the fresh water/salt water interface. Rao et al (2006, 2007) have demonstrated its utility for both conceptual and application based studies. FEFLOW model is not freely available in public domain and hence not many applications (publications) have been reported at least from India.

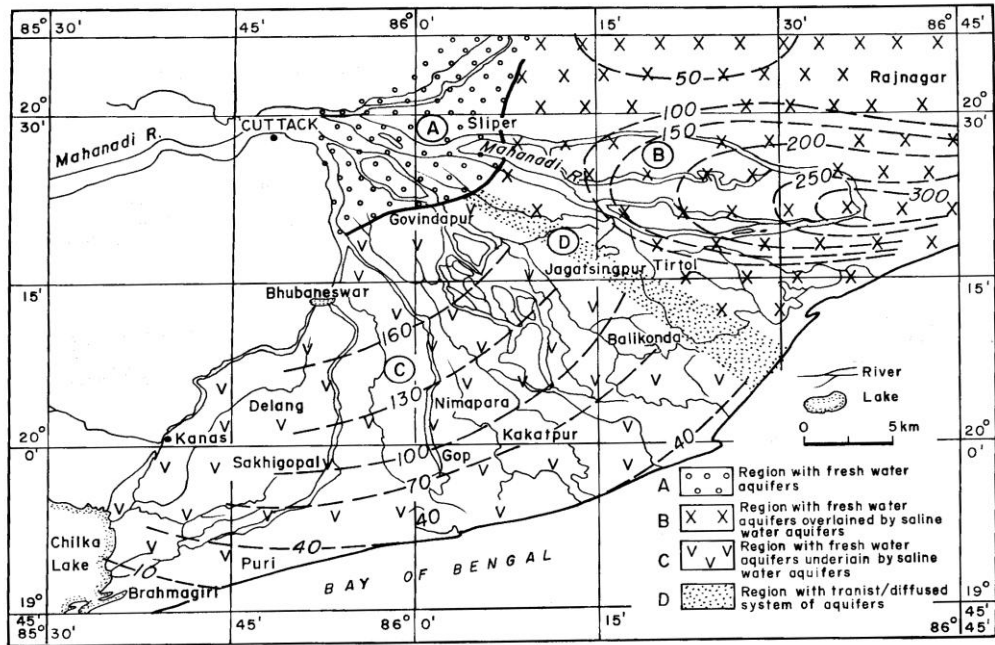
In the present study FEFLOW (Diersch 2006) has been used to simulate fresh-saline mixed interface. It is a 3D-finite element flow and transport model. The model is fully graphics-based and interactive. The GIS framework integrates pre and post processing of data besides a programming interface. The implemented numerical features allow the solution of large problems. This modeling package was chosen because finite elements accurately accommodate steeply varying aquifer systems in three dimensions and for accounting the density dependent flow and transport processes. The goal of this study was to determine model (approximately calibrated) responses to increased rates of pumping in terms for studying the up-coning behavior in a typical deltaic system in India.

## **SALINE FRESH WATER INTERRELATIONSHIPS**

The Mahanadi delta system is the third largest delta plain along the east coast of India and covers an area of about  $0.9 \times 10^4 \text{ km}^2$  which lies between  $85^{\circ} 40' : 86^{\circ} 45' \text{ E}$  long. and  $19^{\circ} 40' : 20^{\circ} 35' \text{ N}$  lat. The delta terrain has a characteristic tropical and humid monsoonal climate with an annual rain fall of 1570 mm. Then cyclonic storms, floods, droughts are rather common. The river after traversing over a distance of about 800 km. spreads itself in the form of delta plain with its apex near Naraj with a network of distributaries and sub distributaries viz: Birupa, Mahanadi/ Chitralla, Katjhor/ Devi and Koyakhai/ Daya/ Kusubhadra/ Bhargavi. A detailed drainage network map with different block centers and major townships is shown in fig.1. A major portion of the delta region is flat with gentle slope towards Bay of Bengal. A typical characteristic geo-morphological feature is the formation of long narrow islands in the central part of the delta system which could be a reflection of the manifestation of the sub surface structure of the delta. The entire delta region could be classified into three morphological units namely upper, central and lower delta regions. The upper delta region is characterized by coarse –medium sandy facies with admixtures of clays and sands. The central delta region is characterized by a number of lenticular islands, developed as a result of bifurcation and rejoining of the sub distributaries river system. The lower delta region adjoining the coastline has a number of low lying swamps, tidal canals and a series of sand ridges and valleys (Radhakrishna, 2001)

Several hydro geological and geophysical exploratory endeavors have been made in this region and brought to light the availability of thick sequences of freshwater aquifer systems belonging to Recent, Quaternary and Tertiary periods (Radhakrishna, 2001). The thicknesses of these aquifer systems increase from 100 m to 400 m and beyond towards the out fall region of the delta from the upstream areas with a gentle slope. At the same time the saline contamination hazards reach peak levels in most parts of northern and central Mahanadi delta region up to the depth levels varying between 60 m to 300 m below which fresh water aquifers occur under deep confined conditions with artesian and sub artesian pressure heads. In contrast the southern parts of the Mahanadi delta region is characterized by fresh water aquifers floating over saline water aquifers with thicknesses varying from 10m to 120m with interface depth levels decreasing towards the coast. A detailed interface depth structure map based on several interpretative analyses of geophysical log profiles is presented in fig. 1 (Radhakrishna, 2001) which forms the basic

material for the present study. The interface depth structure, its nature and boundary conditions are very important to evolve required strategies for sustainable development of fresh water resources. This would also form the basis for an appropriate well field development while estimating the mechanisms involved in understanding saline water intrusion processes.



**Fig. 1 Saline - fresh water Interface depths structure map for Mahanadi delta system**

The above table suggests that the interface could be a hydraulic diffusion boundary with freshwater floating over saline water or a geological aquiclude/ aquitard boundary with freshwater underneath the saline water. The nature of the interface and depths has to be carefully evaluated while designing the well field structures. The south Mahanadi delta region is characterized by a freshwater system sitting over a brackish water system with a diffusion boundary and with depths varying from 20 m to 100 m. The interface depth in general decreases towards the coast. The north Mahanadi delta is represented by a brackish water system sitting over a freshwater system with aquitard/ aquiclude acting as an interface. This interface aquiclude is thicker towards the coast and thinner inland. It is therefore necessary in such systems to adopt cement plugging in the gravel pack area at different depths to avoid vertical migration of saline water while pumping. It is also necessary in such situations to estimate the lateral extension of aquiclude interface boundaries upstream where saline and freshwater systems come into juxtaposition, and to optimize and control the pumping without destabilizing the freshwater regime.

The southern parts of the delta system are basically drained by sub distributaries of Mahanadi River represented by Daya, Bhargavi and Kusubhadra. The fresh ground water systems modeled in the present work are by and large unconfined and some time semi-confined aquifer systems underlain by a number of brackish/saline aquifer systems. It is to be noted that large number of wells structures have already been installed tapping this fresh water resources and some more are expected in the near future. This unregulated developmental activity could lead to saline water mixing into the upper unconfined aquifer systems and may gradually contaminate in course of time with saline water from underneath. Similarly the north eastern parts of Mahanadi delta drained by distributaries like Katzhuri, Mahanadi, Chitrana and

Virupa are characterized by deep confined fresh ground water systems overlain by brackish/saline water aquifers. Both these systems are separated by aquicludes and aquitards. These fresh water systems over last two decades are subjected to large scale fresh ground water withdrawals through a number of deep tube wells and some more are planned in the future. This uncontrolled development could lead to saline water contamination vertically through aquitards and through lateral migration from the upstream side as a result of differential pumping and changing hydro dynamic situations in both fresh and saline water bodies. It is therefore necessary to have very careful optimized schemes for groundwater development to minimize the threats of saline water contamination. In line with the above observation and factual situations a FEFLOW conceptualized model (Dierch, 2006) has been developed to study the contamination impacts on freshwater development.

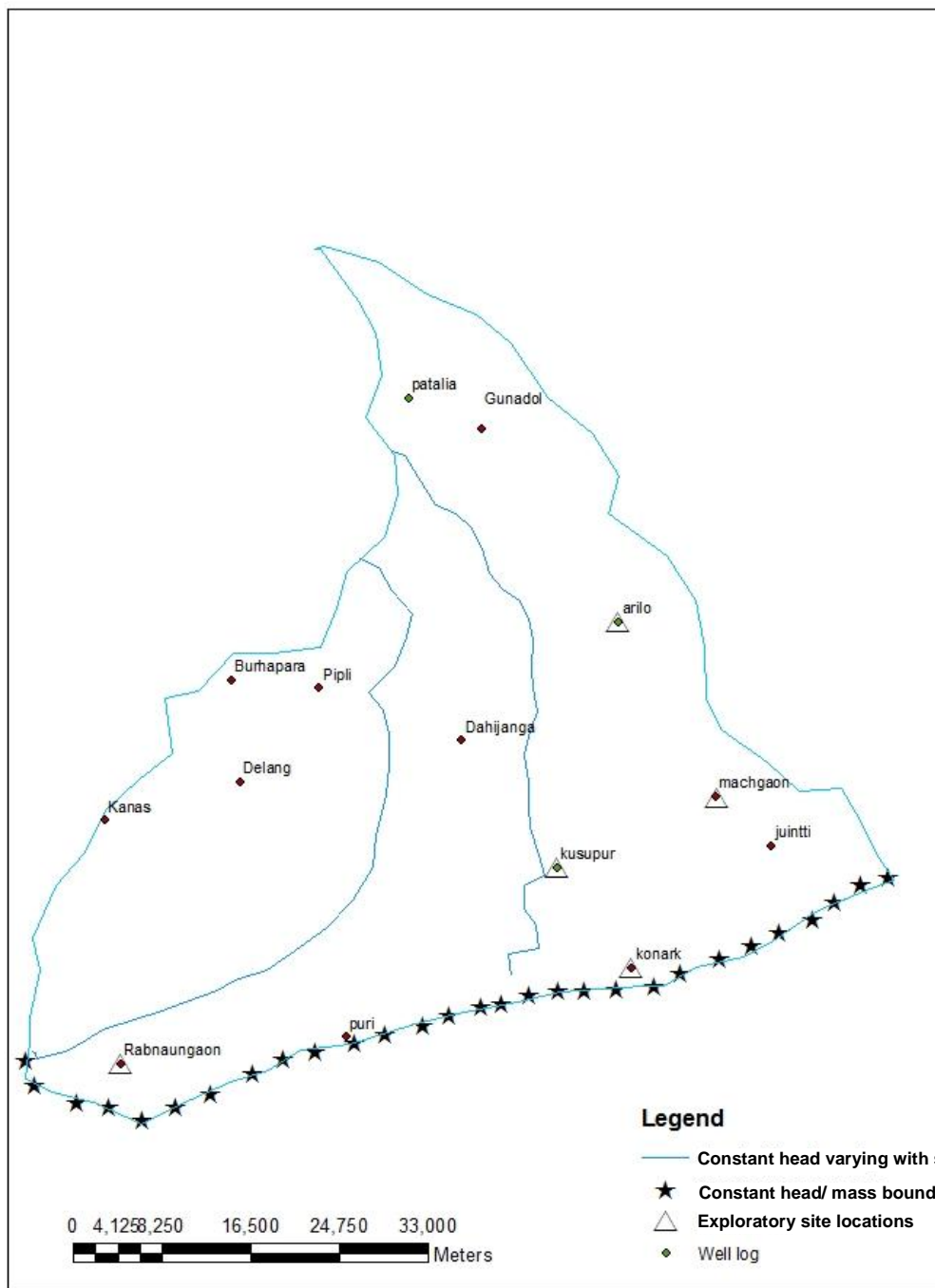
## **MODEL DEVELOPMENT AND CALIBRATION**

The two 5-layer groundwater models for the unconfined in the southern part and the semi-confined in the northern part of the Mahanadi deltaic system were conceptualized and developed using well-log and interface-depth structure map data. The aquifer hydraulic conductivities, specific yield and storage coefficients pertaining to various layers were assigned based on log data in approximated layer thicknesses (clay, sand, etc.) and their values based on information available from experience and literature. The *google-earth* map was used to determine surface features/ topography, boundary conditions for constructing the GIS shape files. The aquifer boundaries and properties are depicted in figures 2 and 3 and in table 1.

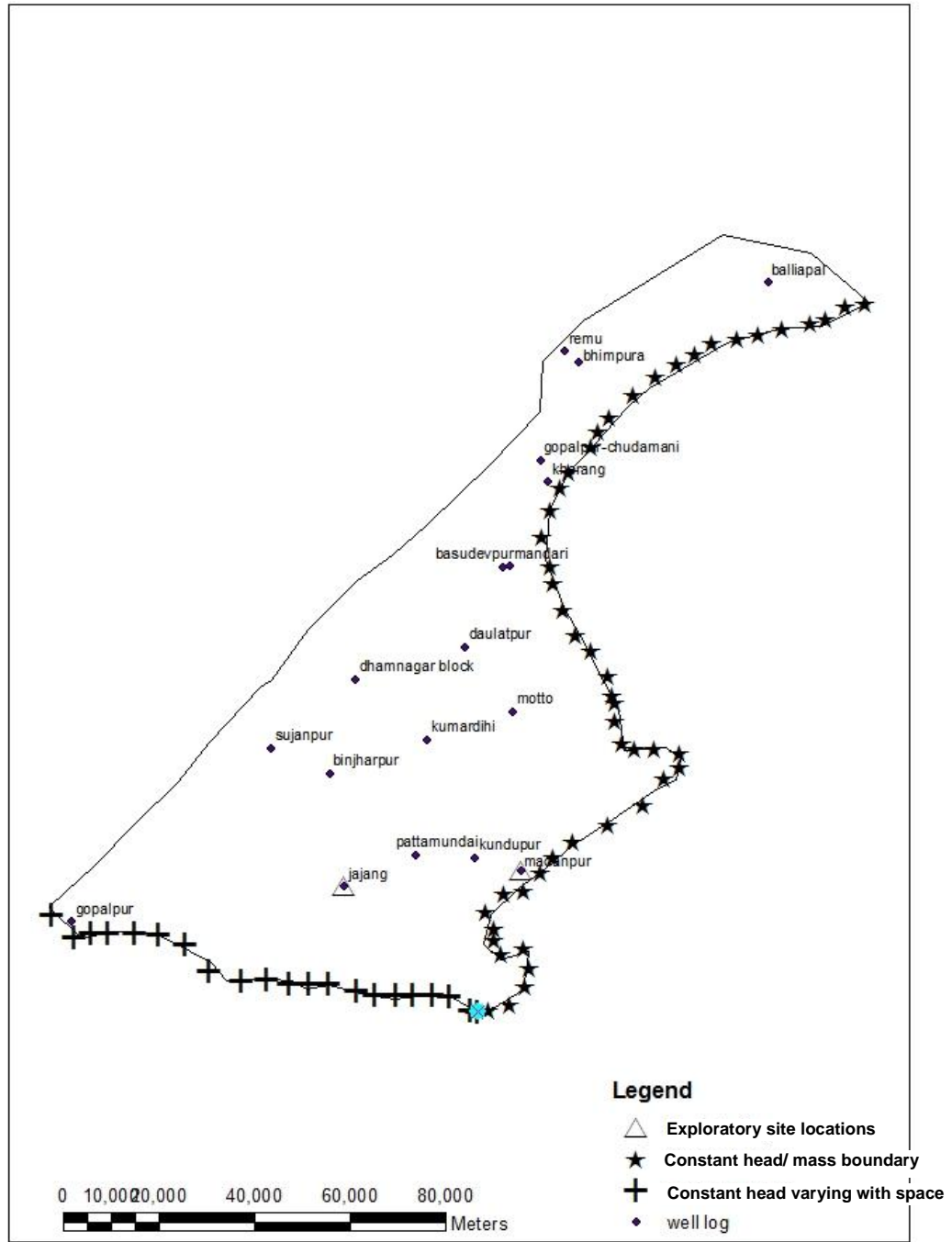
The boundary and initial conditions in respect of unconfined aquifer (southern part) are as follows. Rivers were assumed to act as time-invariant recharging boundaries having constant head (zero concentration) varying spatially with topography. Sea boundary was assumed as constant zero head and constant mass concentration ( $35\text{kg/m}^3$ ). As deeper aquifers indicate high salinity, the nodes in the fifth layer and along the sea boundary were assumed to be of constant concentration of  $35\text{ kg/m}^3$ . The unconfined aquifer was assumed to be recharged from rainfall to an extent of 15% of annual rainfall (1250mm). Pumping for agricultural or consumptive use purposes is extracted from second layer. Concurrent data of rainfall and monthly groundwater levels during 1998 (one year only) at different locations were available for calibration.

The boundary and initial conditions in respect of semi-confined aquifer (northern part) were set as follows. Here deeper layers are productive and fresh (fourth layer), while the shallow aquifer is saline (second layer). The river and sea boundary nodes were similarly assigned as in the case of unconfined aquifer. However since the shallow aquifer here shows high salinity, all the nodes in the second layer were assigned constant salinity ( $35\text{kg/m}^3$ ) until the point where the aquitard (of 3<sup>rd</sup> layer) pinches out approximately midway along X-direction along east to west. Model simulation beginning Jan 1998 groundwater levels were set as initial conditions (hotstart). The shallow aquifer here is not being used for any useful purposes. Rainfall recharge has no effect on deeper aquifers which are recharged by rivers streams in the upper reaches of delta system.

The two models were then simulated for average stresses (pumping/ recharge) based on crop water requirement (uniformly), rainfall recharge (unconfined only) and boundary conditions for one year beginning Jan 1998. The model calibration was accomplished by adjusting the aquifer parameters, mainly the hydraulic conductivity. The model calibration for the two aquifers for pre monsoon (April 1998) and Post monsoon (Oct 1998) are shown in figures 4 through 5. At this stage the model is assumed to be in quasi-steady state conditions i.e. at the end of calibration period.



**Fig. 2 Location of exploratory bore wells and model boundaries for the unconfined aquifer system**



**Fig. 3 Location of exploratory bore wells and model boundaries**

**Table1. Aquifer properties**

S. No	Particulars	Values
1	<p><b>Semi-Confined aquifer in northern part of Delta system</b></p> <p>a) Number of Mesh elements, mesh nodes and layers</p> <p>b) Element type</p> <p>c) Time stepping Scheme</p> <p>d) Aquifer thickness (variable as in figure)</p> <p>e) Global Hydraulic Conductivity values in X, Y &amp; Z directions except for the aquitard in 3<sup>rd</sup> layer pinching out midway along X direction (m/day)</p> <p>f) Hydraulic conductivity of the aquitard in X, Y &amp; Z directions (m/day)</p> <p>g) Specific yield of upper layer</p> <p>h) Specific Storage (/m)</p> <p>i) Longitudinal and lateral dispersivity assumed (m)</p> <p>j) Density of fresh and seawater (kg/m<sup>3</sup>)</p> <p>k) Concentration of fresh and seawater (kg/m<sup>3</sup>)</p> <p>l) Slope of concentration-density</p> <p>m) Steady state boundary conditions</p> <p style="padding-left: 20px;">i. River recharging head on western end (m)</p> <p style="padding-left: 20px;">ii. Sea boundary (m)</p> <p style="padding-left: 20px;">iii. Pumping in 4<sup>th</sup> layer (m<sup>3</sup>/day)</p> <p>n) Period of simulation for calibration (years)</p>	<p>5825, 3936, 5</p> <p>6 Noded Triangular Prism</p> <p>Adams-Bashforth/Trapezoid Predictor-Corrector Scheme</p> <p>Variable as per well log data</p> <p>Variable as per well log data (Clay, sand, etc)</p> <p>- do -</p> <p>0.15</p> <p>0.0001</p> <p>70, 15</p> <p>1000, 1025</p> <p>0, 35</p> <p>0.71</p> <p>Non Uniform</p> <p>0</p> <p>500 - 2000</p> <p>1</p>
2	<p><b>Un-confined aquifer in the southern part of Delta system</b></p> <p>a) Number of Mesh elements, mesh nodes and layers</p> <p>b) Aquifer thickness (variable as in figure)</p> <p>c) Element type</p> <p>d) Time stepping Scheme</p> <p>e) Global Hydraulic Conductivity values in X, Y &amp; Z directions (m/day)</p> <p>f) Specific yield of upper layer</p> <p>g) Specific Storage (/m)</p> <p>h) Longitudinal and lateral dispersivity assumed (m)</p> <p>i) Density of fresh and seawater (kg/m<sup>3</sup>)</p> <p>j) Concentration of fresh and seawater (kg/m<sup>3</sup>)</p> <p>k) Slope of concentration-density</p> <p>l) Steady state boundary conditions/ initial conditions</p> <p style="padding-left: 20px;">i. River recharging head on western end (m)</p> <p style="padding-left: 20px;">ii. Rainfall recharge (15% of monthly rainfall during monsoon)</p> <p style="padding-left: 20px;">iii. Sea boundary (m)</p> <p style="padding-left: 20px;">iv. Pumping in 2<sup>nd</sup> layer (m<sup>3</sup>/day)</p> <p>m) Period of simulation for calibration (years)</p>	<p>11790, 7656, 5</p> <p>Variable as per well log data</p> <p>6 Noded Triangular Prism</p> <p>Adams-Bashforth/Trapezoid Predictor-Corrector Scheme</p> <p>Variable as per well log data (Clay, sand, etc)</p> <p>0.15</p> <p>0.0001</p> <p>70, 15</p> <p>1000, 1025</p> <p>0, 35</p> <p>0.71</p> <p>Non Uniform</p> <p>0.15</p> <p>0</p> <p>500 - 2000</p> <p>1</p>

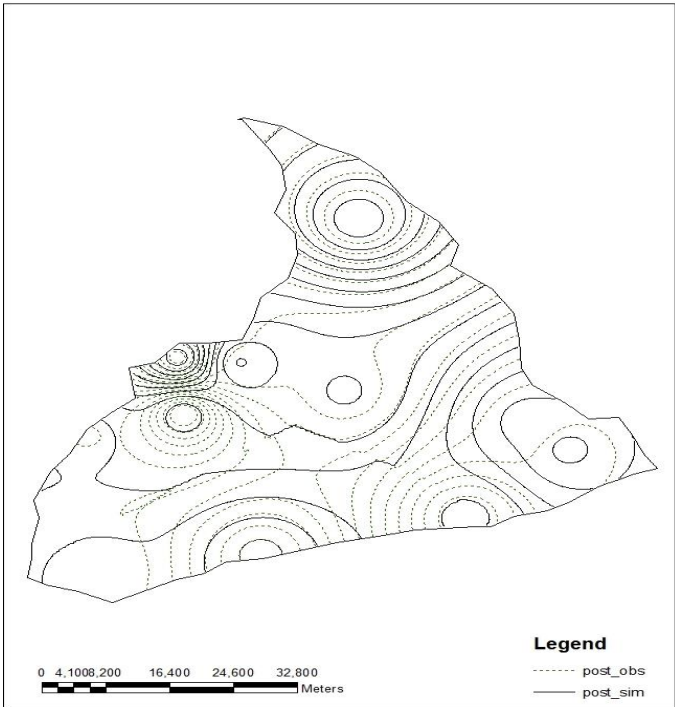
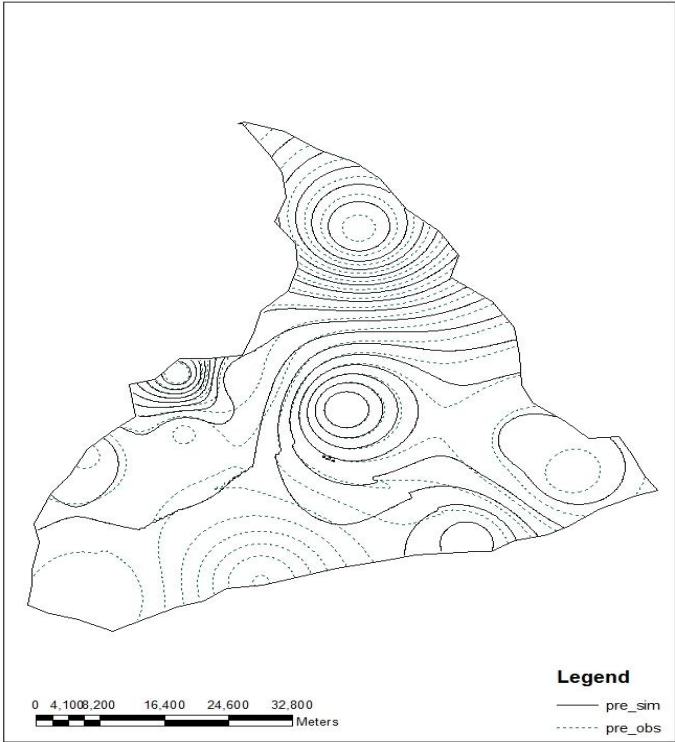


Fig 4 Model calibration for the unconfined system for pre and post monsoon season for the year 1998



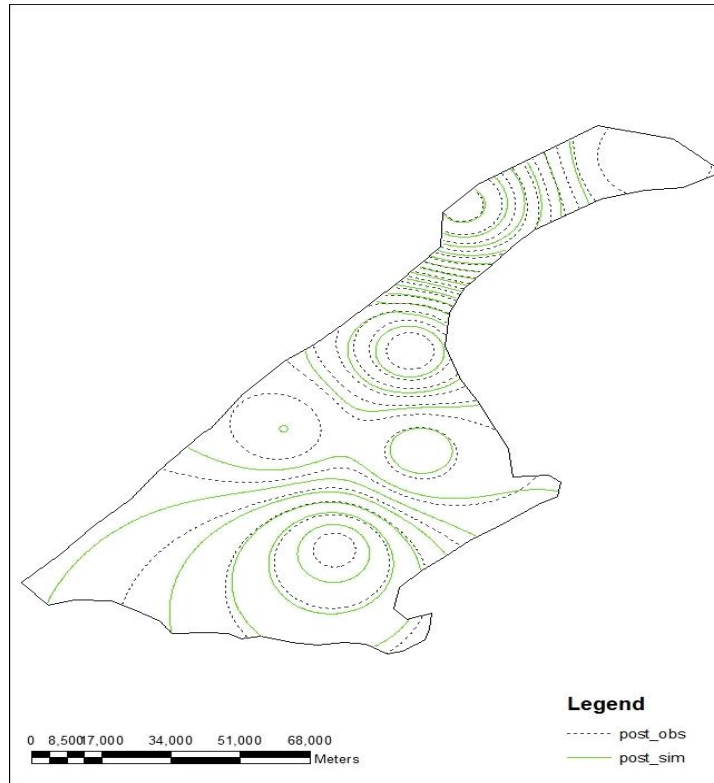
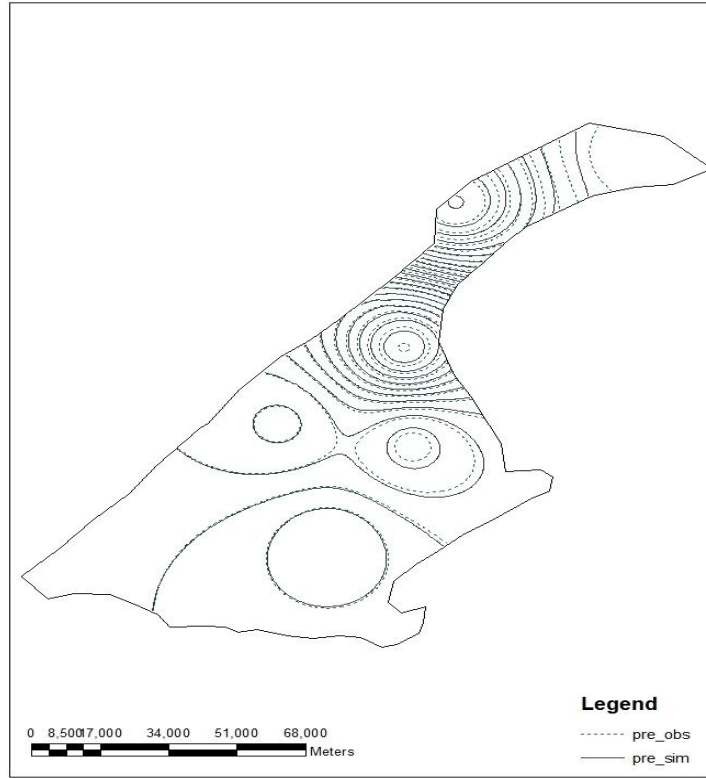


Fig 5 Model calibration for the confined aquifer system for pre and post monsoon season for the year 1998

## **MODELING SCENERIOS FOR GROUNDWATER DEVELOPMENT**

The calibrated models were used to examine the aquifer's spatial responses as a result of incremental high-capacity pumping at typical locations in both the aquifer systems and the results are presented/ described in the following paragraphs. The two models were run for induced pumping from a single point in each aquifer repeatedly beginning quasi-steady-state conditions. The pumping wells are located in the freshwater layers of both the systems. However it is important to note that the figures depict integrated responses of the aquifer geometry, boundary conditions and natural/ induced stresses in a regional perspective. The responses for the two aquifers are shown in figures 6 through 9. The figures graphically depict migration of salinity from their boundaries. The results for the two models may be summarized as under:

1. The unconfined aquifer shows relatively higher effects pumping in terms of salinity concentration. The salinity migration is essentially from bottom layers in the form of up-coning with larger areal coverage. Therefore groundwater development needs to be carefully planned and regulated throughout the southern deltaic region. Further rainfall recharge measures need to be encouraged to augment dilution of saline water as pumping is from shallow aquifer.
2. The deep confined aquifer shows relatively less areal contamination of saline water (in terms of concentration) for corresponding rates of pumping and therefore can permit higher pumpages on a sustainable basis. This is due to the fact that higher rates of pumping induce salinity migration from upper layers from the point where the aquitard pinches out and through aquitard to a small extent. The salinity migration is rather more localized even though the pumping location was chosen nearer to the point where the aquitard (in the 2<sup>nd</sup> layer) pinches out. This indicates the effect will be still less for other locations unless they are closer to sea boundary. The aquitard layer effectively prevents salinity migration from upper layer in the confined aquifer. Therefore regulation of groundwater development must focus in areas where the underlying aquitard pinches out. Here rainfall recharge measures are not of much significance.

## **CONCLUSIONS**

The subsurface groundwater systems in the Mahanadi delta region has two typical diverse aquifer systems, an unconfined fresh water system underlain by brackish water zone in the south west and a deep confined fresh water system overlain by saline water system in the north-east. The aquifer systems were conceptualized to represent groundwater flow model using several interpretive results of geological, geophysical log data. An approximately calibrated model is used to examine scenarios of salinity migration due to mixing when subjected to increasing rates of pumping under steady state conditions. These results also show the impacts of saline water mixing/ migration is relatively less in north eastern parts of the delta when compared with south western parts of the delta. The study concludes that the northern semi-confined aquifer can handle relatively higher pumpages without affecting water quality deteriorations. Also there is a greater need to regulate groundwater development in the southern part of Mahanadi delta system due to shallow freshwater resources, aquifer un-confining conditions and the need to promote rainfall recharge conditions

## **Acknowledgement**

The authors thankfully acknowledge for the support provided by Sri Ajay Pradhan, Managing Director, DHI India, New Delhi.

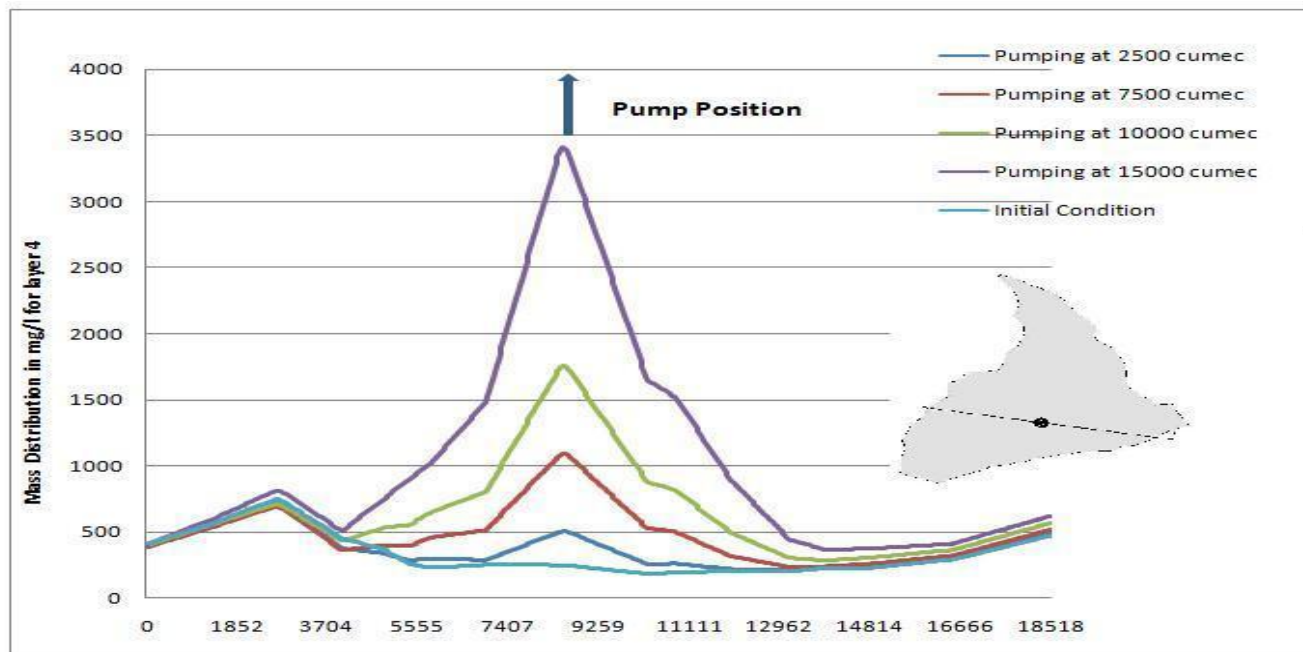


Figure 6 Up-coning scenario for the unconfined system for incremental rates of pumping from second layer

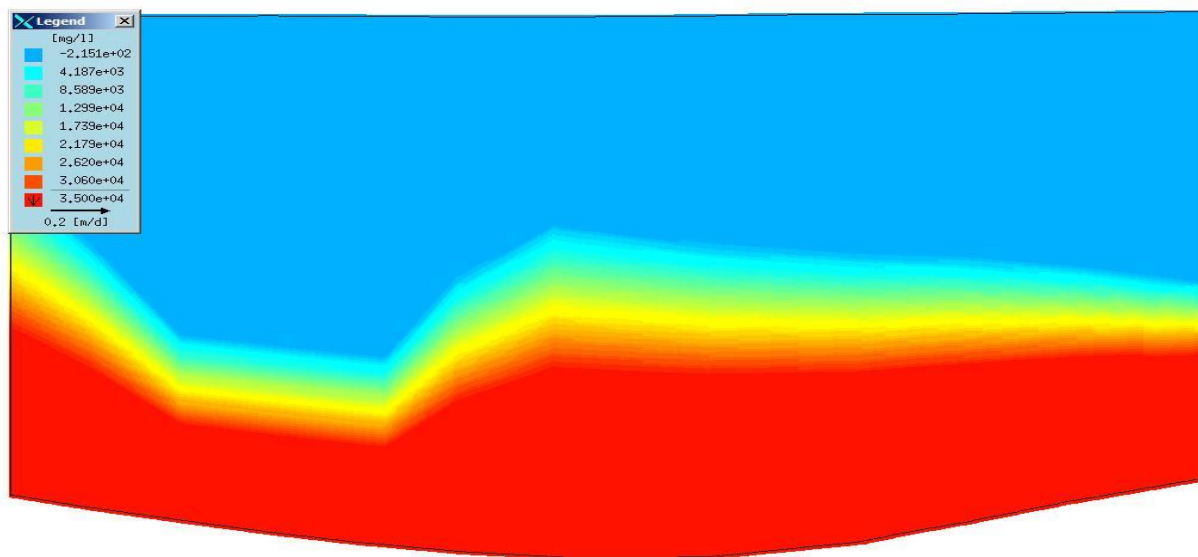


Figure 7 Salinity migrations as result of pumping from second layer – unconfined system

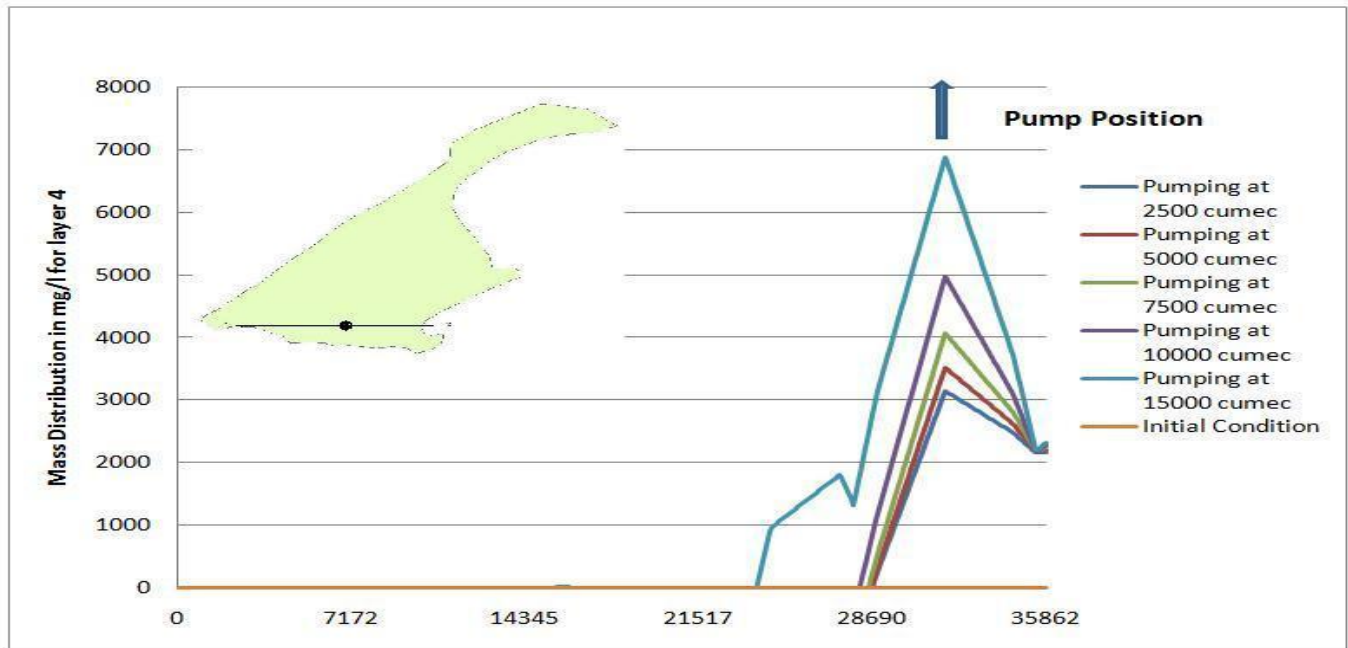


Figure 8 Up-coning phenomena for the confined system for increasing rates of pumping from the fourth layer

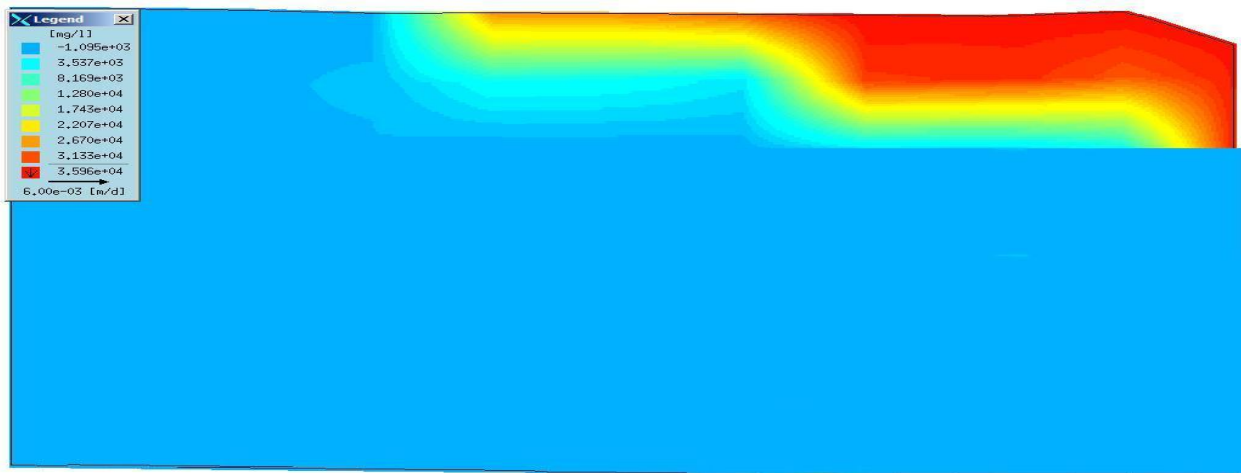


Figure 9 Salinity migrations from second layer through and from the point of aquitard pinching due to pumping from 4<sup>th</sup> layer

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