J. Ind. Geophys. Union (July 2010)
Vol.14, No.3, pp.151-160

Mass transport model studies in the industrial aquifers of Visakhapatnam, Andhra Pradesh

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ABSTRACT
The city of Visakhapatnam has many randomly located industrial sites, sharing common groundwater aquifers. The average TDS levels of groundwaters of industrial aquifers were around 500 mg/l in 1980. In 2005 it has reached an average level of 2500 mg/l. Three major industries, namely, Hindustan Zinc Limited (HZL), Coromandal Fertilizers Limited (CFL) and Hindustan Petroleum Corporation Limited (HPCL), located on a common aquifer and separated by a distance of 2 to 3 Km, have contributed hazardous levels of contaminants to groundwater. Mass Transport Model studies are conducted using Visual MODFLOW (MT3D) to predict the areas that come under the impact of these three industrial effluents with respect to the increasing TDS time and space. The areas, predicted to under the industrial contamination impact by 2025 by model studies are demarcated. The hazardous levels of salinity predicted are also shown.

INTRODUCTION

Many hydro geochemists realized that 'contamination of groundwater by sewage and industrial chemicals has become a major concern in the areas due to their poorly planned solid and liquid waste disposal practices' (Bryan Ellis 1999). Groundwater modeling studies is an effective tool of understanding the plume migration studies in the contaminated sites. Though the study of groundwater quality assumed importance in recent times all over the world, the consciousness for pure and uncontaminated water is more than a century-old phenomenon (Petty John 1971). Needless to say that seventy five percent of the diseases in India are waterborne (Kudesia 1990).

There are 14 industries in the urban area of Visakhapatnam, out of which three are considered as heavy industries. Hindustan Zinc Limited (HZL) Coromandal Fertilizers Limited (CFL) and Hindustan Petroleum Corporation Limited (HPCL). These industrial units, HZL, CFL and HPCL which form the main 'industrial belt' in the city are significantly contaminating the groundwaters of the Visakhapatnam city aquifer.

Heavy Industries, identified for study HZL, CFL and HPCL are situated in the foot hill region of Yarada Hill, 2-3 Km apart from one another, where denser residential localities developed around. The cement lining of the effluent channels of the three industrial units are in a worst shape and the contaminants are freely mixing with the porous surface soil. The contaminants thus derived are transported to deeper levels. The waste dumps in the HZL site are sulphate mixed with fly ash and the remanant during the extraction of zinc from zinc sulphate (spalarite). The waste dumps in the CFL site are ammonium nitrates, generated during the metal precipitation mixed with radioactive wastes and crystallized sulphur. The waste dumps of HPCL contain, mainly, sludge containing black oil (stagnated during transport to other places for further refining) and sulphuric acid. The leachates mixed with various effluents with acquired turbidity are stagnated in the surface soil for years which slowly migrate into weathered layers. Further, heavy pumping in the residential localities for domestic consumption leads to lowering of watertables which promotes active mixing of the fluids.

The present study area is located on the lower Narava gedda basin, situated towards Northwest of Visakhapatnam. Narava gedda is the main stream of lower Narava gedda basin flowing, through the heart of the city, covering the effluent zones of HZL, CFL, and HPCL and draining into Bay of Bengal. The study area with an areal extent of 26 Sq.Km is located between latitudes $17^0 40'14"$N and $17^0 42'38"$N and longitudes, $83^0 12'15"$E and $83^0 15'8"$E. Narava gedda stream, flowing into Bay of Bengal is 3- 4 Km, down stream of the study area. Southern and Southwestern parts are covered by Yarada hills. The location map of the study area is shown in Fig.1.

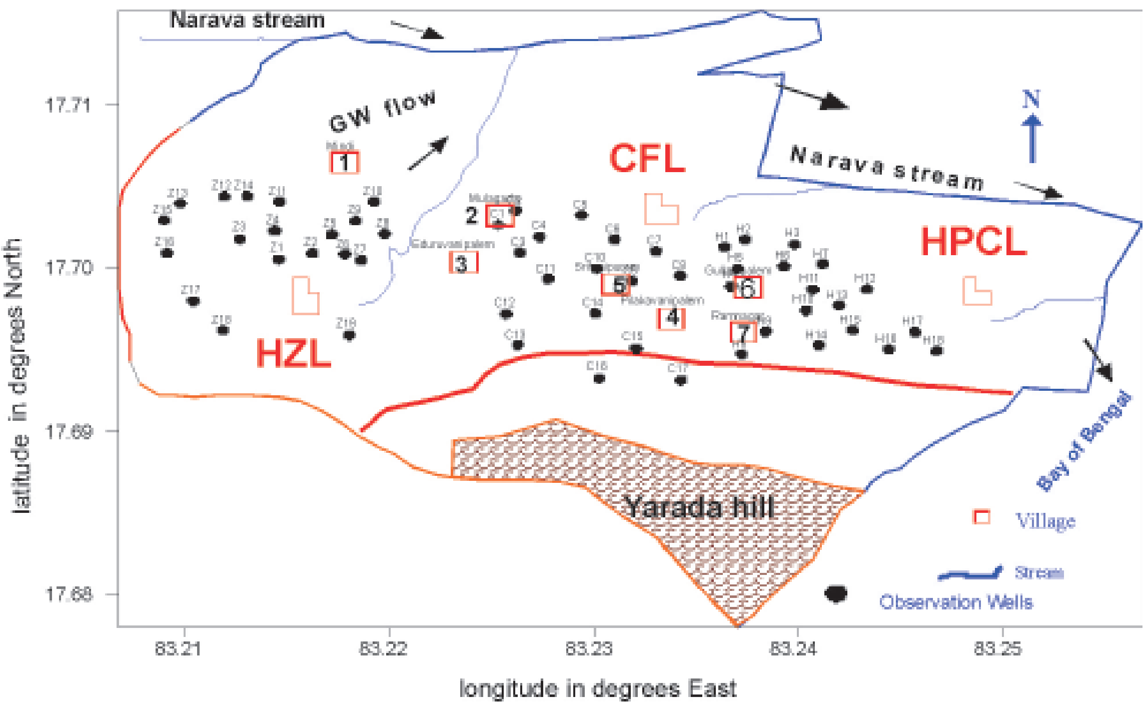

Figure 1. Location map of the study area.

Mindi, Mulagada and Eduruvanipalem are the residential localities in the HZL site. Pilakavanipalem and Sriharipuram are the residential localities in the vicinity of CFL. Gullalapalem and Ramnagar are the residential localities in the vicinity of HPCL (Fig.1). The Hydrochemical analysis of 54 observational wells was made during the period January 2005 to December 2006.

HYDROGEOLOGY

The prominent geological formations in the area belong to Archean and Quaternary periods. The Archean system consists of Khondalites with intruded Charnockite formations (Murthy 1961). The average thickness of the first soil layer of the three aquifers ranges at about 5 m. The average thickness of first and second weathered layers together is 28m. Groundwater exists in both first and second layers.

EARLIER WORK

Before proceeding to study the impact of industries, an overall view is taken to understand whether there could be a long-time variation in salinity leading to the deterioration of groundwater quality in the urban aquifers. Rao & Rao (1981) had estimated the general average ionic levels for the study area. Later, Subbarao (1994) observed the ionic levels in the vicinity of industrial units. From the present study, it is observed that the levels of groundwater salinity in the observation wells are almost doubled. Separate effluent channels are constructed towards north direction for the three industrial units, which drain into Bay of Bengal after traveling a distance of few kilometers through lower gradients of porous media. The maximum and minimum values of ionic concentration during the past work along with those of the present study are shown in Table 1.

The contaminant production is a continually active process, due to the ever expanding and non-stop productions of the industrial units. Over years, the solid dumps are leached and are migrated into the subsurface regions. From the tables, it is clearly observed that there is a steady increase in the ionic status over years. Fluoride, generally, has no significant change with respect to effluent migration due to local geological factors. It is also important to note that the increased production, since the establishment of the industries, increases the quantum of solid and liquid wastes.

Table 1. Status of average Ground water Quality at over years.

Author	Industry	EC (μs/cm)	Cl mg/l	SO_4 mg/l	Total Hardness mg/l	F mg/l	NO_3 mg/l
Rao&Rao (1981)	HZL	2820	260	720	780	1	45
	CFL	2019	230	106	400	0.8	50
	HPCL	4600	200	63	480	0.4	24
Subbarao (1994)	HZL	4000	360	2800	1500	1.4	69
	CFL	2700	300	330	540	1	150
	HPCL	5500	540	112	2000	0.8	89
Present study 2005	HZL	5500	460	3300	2200	2.1	120
	CFL	3000	390	336	1040	1.3	230
	HPCL	7400	1800	280	3400	1.2	180

DEVELOPMENT OF THE MODEL FOR STUDY AREA

The present study area falls in the lower Narava basin where industries are established, and the consequent residential colonies. Lower Narava stream drains into Bay of Bengal, which is 3.5 Km away from the study area. Due to topographical conditions, the run- off from the hill ranges also influences the Groundwater. Groundwater occurs in the unconfined conditions throughout the area. Construction of 'Contaminant Migration Model' is the succeeding step after finalizing the groundwater flow model. The groundwater flow conditions of a hydrologic system mainly depend on the topographical features, stream pattern, inflow, outflow, recharge conditions, hydraulic conductivity, porosity and solute transport properties.

The purpose of the model is to assess the contaminant migration through the industrial sites. Depending on various geohydrological and physiographic features, the study area is divided into zones. In each zone, a group of grid systems is present. Each zone is assigned with specific properties. Depending on the nature of recharge, hydraulic conductivity, pumping rates, and water levels, each grid is assigned with numerical equations which are solved with Finite Difference Method (FDM). Depending on the existing water demand of the particular part of the study area, pumping stations are assessed to calculate the amount of water, discharged from each zone of the study area.

Bredehoeft & Pinder (1973) gave a fundamental equation that describes the groundwater flow in three dimensional, inhomogeneous and anisotropic unconfined aquifer system as follows:

$$\frac{\partial}{\partial x}\left[k_x\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_z\frac{\partial h}{\partial z}\right]=S_s\frac{\partial h}{\partial t}-R^*$$

where k_x,k_y,k_z arecomponentsofhydraulicconductivity tensor.

R^* is the generalsink/source that is intrinsically positive (in flow to the system) or negative (out flow from the system) depending on the properties of the system

S_s is the specific storage

$\frac{\partial h}{\partial t}$ change in hydraulic head with time

$k_x\frac{\partial h}{\partial x}, k_y\frac{\partial h}{\partial y}, k_z\frac{\partial h}{\partial z}$ are specific discharges

The hydraulic head is obtained from the solution of three dimensional groundwater flow equations through visual MODFLOW software (McDonald & Harbaugh 1988). Groundwater flow simulation has been carried out using visual MODFLOW software (Franz & Guiger 1996). Mass Transport Modeling is computed by 3-Dimensions (MT3D) software (Zheng & Bennet 2001). The mass transport of an area depends on the groundwater flow direction. The flow direction can be obtained through groundwater-level contour studies. Gurunadha Rao, Dhar & Subrahmaniam (2002) studied the extent of contaminant migration in the surroundings of industrial areas of Pathancheru, Hyderabad. In the present study, input data of recharge, permeability, elevation features of observation wells, well yield data, pumping rate and run off conditions of the study area are applied as input data base to Visual MODFLOW software. After applying input parameters, the groundwater flow model was run for steady state. After repeated modifications of input parameters and running of visual MODFLOW software, calibrated curve between the computed and observed groundwater heads is obtained. Calibrated Vs Observed curve is shown in Fig 2. Root Mean Square value, Standard error, Correlation coefficient and other relations, calculated on the calibration graph are used for deciding the best fit between computed and observed heads.

It is easy to estimate the direction of migration as the solute passes in the direction of groundwater flow. The initial concentrations of a particular time period have to be given at source points as input data to get mass transport model. As the contamination is derived from point source (industrial effluents) in the study area, there is a continuous supply of loading of effluents. Initial concentrations for the industrial units are fixed after observing the levels of TDS (present and past) of the respective observation wells of the industrial units. Fig. 3 shows the initial concentrations of the various industrial units for which the plume/contaminant migration patterns have been computed. The initial concentrations are taken from the year 1975, when they were measured, as the earliest data.

The contaminant migration in the groundwater has been computed since 1975. The 'sink' is fixed at the marshy land where all the effluents of the industrial units are draining. The sources are the industrial points.

The initial concentrations are fixed from the points where the effluents start their journeys and the distances to wells are measured from these points. As was previously discussed, the excess pumping in the residential localities is creating cones of depression. The groundwaters, mixed with leachates of the solid dumps and the solutes of the effluents are thus contaminated. The migration level was predicted for both first and second layers together for every 10 years since 1975 and presented in the figures. Figures 4, 5, 6, 7 and 8 represent the migrations predicted for 1985, 1995, 2005, 2015 and 2025.

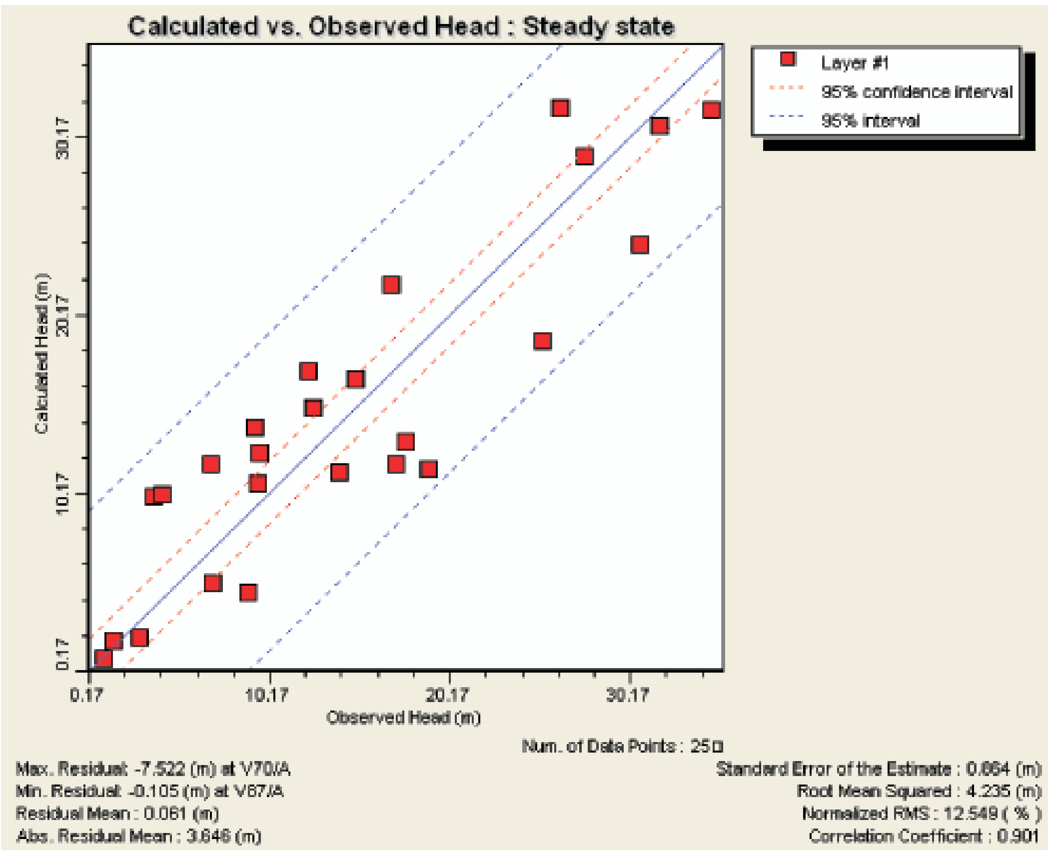

Figure 2. Steady state computed and observed head in meters (amsl).

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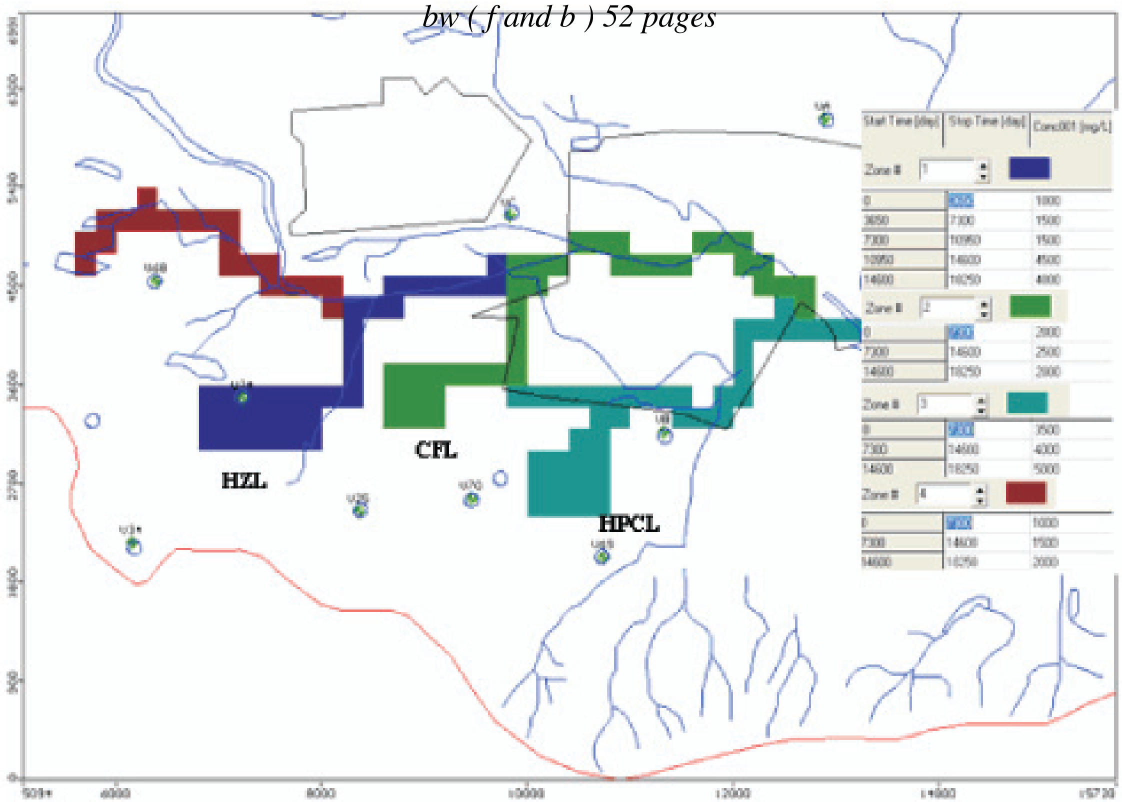

Figure 3. Variable head concentration (TDS in mg/l) since 1975 for the industries situated in the lower Narava watershed area.

RESULTS OF PREDICTED 'CONTAMINANT MIGRATION' IN THE INUSTRIAL AQUIFERS FROM THE MASS TRANSPORT MODEL

The same prediction is simulated for the concentration and distribution of the migrants in the first and second layers of the three industrial sites as the two layers are connected by groundwater table. The first layers are sandy soils. The initial concentrations are raised due to the stagnated effluents on the surface when, naturally, first layers are affected by the 'Contaminant migrations'. The TDS of waters from first layers crossed the WHO limits by 1980. However, 20 years after 1975 (by the time of 1995) the second layers also are predicted to have the same levels of TDS. The areal distribution of migration almost equaled with that of their first layers. The TDS levels observed now are fitting well into the respective predicted values. Contaminant migration is also predicted to be towards the north direction of the three industrial units as the groundwater flow is towards north and northeast direction of the three industrial units.

Predicted 'Contaminant Migration' status after 10 years from 1975 (Fig.4):

The TDS predicted due to contaminant migration through HZL localities was 900 mg/l, migrated for a distance of 200 m from the source. In the localities of CFL, a TDS of 1300 mg/l moved for a distance of 300 m from the source. Due to this impact, groundwaters of 'Pilakavanipalem' village (situated in the Southwest direction of CFL site), might have crossed the natural standards. In the localities of HPCL, the predicted TDS of the contaminant was 3000 mg/l, migrated to a distance of 600 m from the effluent source. Gullalapalem village, situated on the Southwest corner at an approximate distance of 500m from the HPCL site, came under the impact.

Predicted 'Contaminant Migration' status after 20 years from 1975 (Fig.5):

In the year 1995, the concentration levels of HZL rose to 2500 mg/l and traveled to a distance of 600

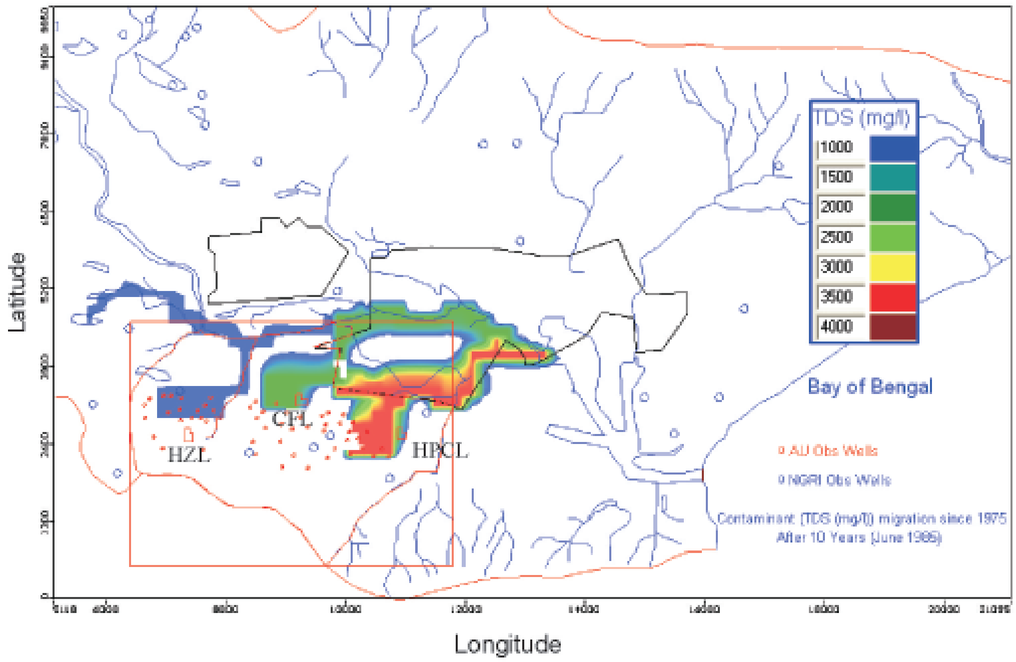

Figure 4. Predicted Contaminant [TDS (mg/l)] migration after 10 years (June-1985).

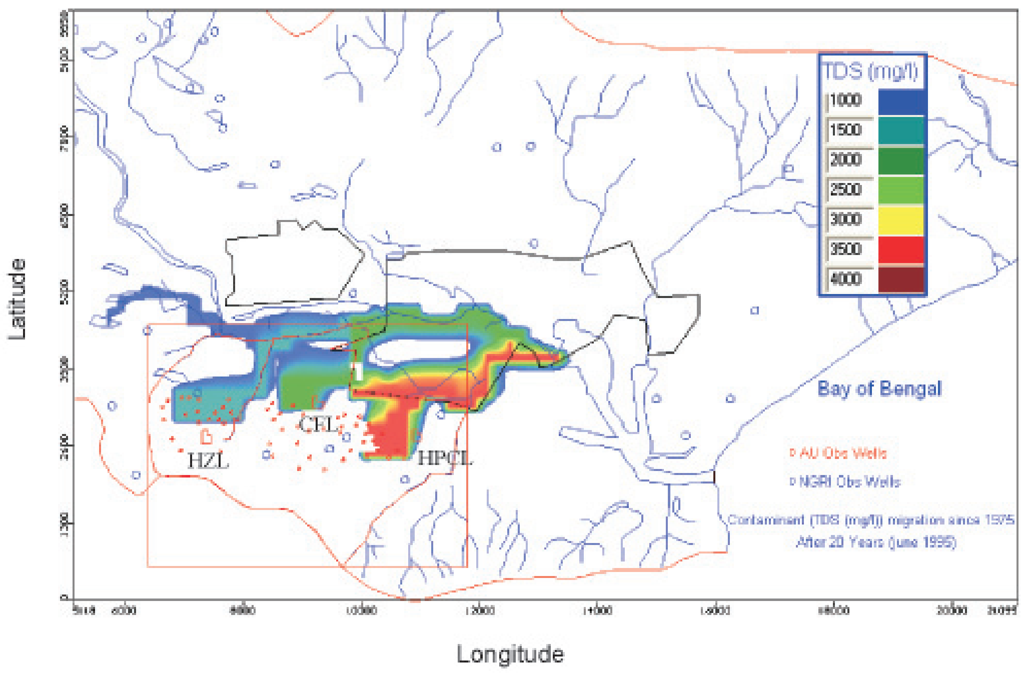

Figure 5. Predicted Contaminant [TDS (mg/l)] migration after 20years (June-1995).

m from the source where the groundwaters of Mindi village, situated north of HZL, were affected. There is a slow rise of predicted TDS (1600 mg/l to a distance of 500 m from the source) in the layers of CFL unit, as compared to HZL and HPCL. Pilakavanipalem village of CFL came completely under the impact and few groundwater samples of 'Sriharipuram' village (situated on either side of CFL) of CFL site, crossed the WHO drinking standards. The distance of the travel path of migrants in the layers of HPCL has increased to 1000 m with a concentration level of about 3500 mg/l. The areal extent and the densities of concentrations of migrants expanded when compared to the 1985-1995 decade. The similar trend of spread is predicted for all the three industrial units.

Predicted 'Contaminant Migration' status after 30 years from 1975 (Fig.6):

By June 2005, the rise in the concentration levels and areal extension of contaminants is clearly observed. The subsurface layer concentration in the HZL industrial unit rose to 2500 mg/l with a spread of 1150 m from the previous decade. Due to this, the groundwaters of Mulagada village in the vicinity of HZL, at an approximate distance of 1250 m in the North-East direction, are affected. The TDS of CFL rose to 1800 mg/l with a spread of 1100 m. The 'Sriharipuram' village of CFL came completely under the effluent impact. In HPCL region, the values of Gullalapalem and Ramnagar villages have recorded a TDS greater than 4000 mg/l within a distance of 1400 m from the source. The migrants in the HPCL region are spreading more rapidly than those of HZL and CFL.

Predicted 'Contaminant Migration' status after 40 years from 1975 (Fig.7):

Ten years after 2005(in the year 2015), it is predicted to be much worse in the locations of HZL and HPCL

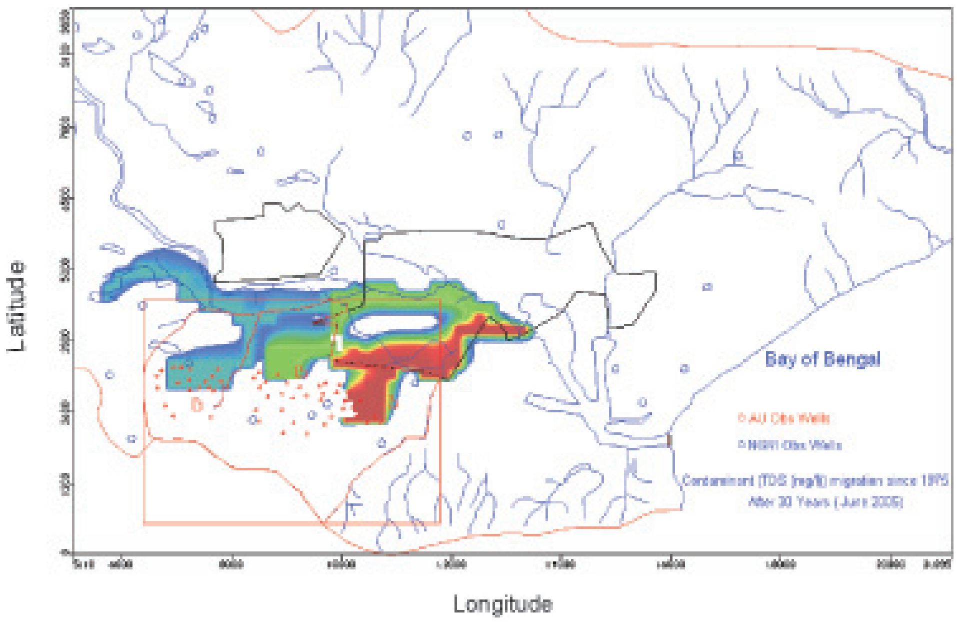

Figure 6. Predicted Contaminant [TDS (mg/l)] migration after 30years (June-2005).

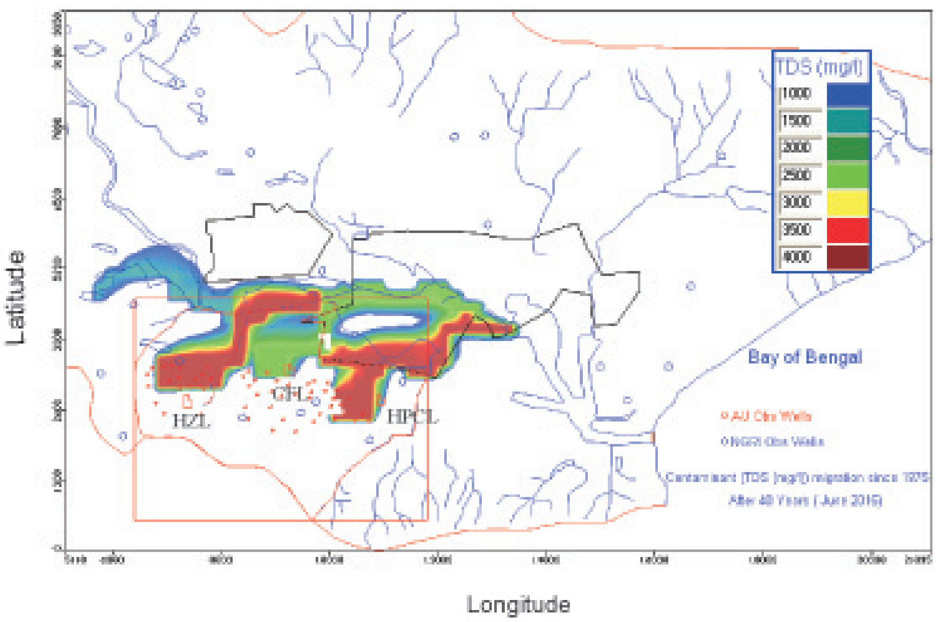

Figure 7. Predicted Contaminant [TDS (mg/l)] migration after 40years (June-2015).

as compared to CFL. Both spatial and concentration levels are expanding. The concentration levels may reach above 4000 mg/l up to 1200 m in the first layer of HZL. A small hamlet of HZL site, Eduruvanipalem which is at an approximate distance of 450m in the South-West direction is predicted to be receiving the impact by 2015 with a TDS of 3500 mg/l. CFL unit is predicted to reach a level of 2300 mg/l within a distance of 1800 m .In the HPCL unit, the concentration level is observed to be greater than 4500 mg/l, distributed up to a distance of 1900 m from the source. The outlier area, 'Malkapuram' came under the impact of HPCL.

Predicted 'Contaminant Migration' after 50 years from 1975 (Fig.8):

The outliers of HZL and HPCL are predicted to be under the impact by 2025. CFL industry is taking measures by treating and discharging the effluents carefully away, compared to HZL and HPCL. HZL and HPCL aquifers are predicted to be highly contaminated by migrants. The TDS of groundwater is estimated to be around 4500 mg/l and 5000 mg/l by 2025.

The 'unforeseen' factors in the urbanization might add 'fuel to the fire' levels of pollution by 2025. Even assuming that the effluents of HZL and HPCL will be totally tamed, the continual battering of solid dump leachates is likely to go unabated.

RESULTS AND DISCUSSION

On the whole, by the year 2025, the industrial aquifers of the three units are predicted to have the worst situation of groundwater salinity. The water should be completely avoided for usage. Almost all the domestic wells of industrial localities should be abandoned, if the situation continues to be at the present scenario. In the present scenario, out of the 54 observation wells selected, about ten samples which are close to the foot-hills of Yarada are in the safe position. Remaining samples crossed the drinking water standards of W.H.O. The localities at higher altitudes (on the foot-hills of 'Yarada Konda') shall be in the safe position. But a considerable level of contamination may be expected due to rise in Nitrate levels with no proper drainage and sanitation system. As the first and second layers are predicted to have the same distribution of 'Contaminant Migration' and TDS levels, the generalized pattern of TDS and migrated distances can be visualized. Details of the areas likely to come under the impact of effluent migrants for every decadal increase are presented in Table 2 for the three industrial sites

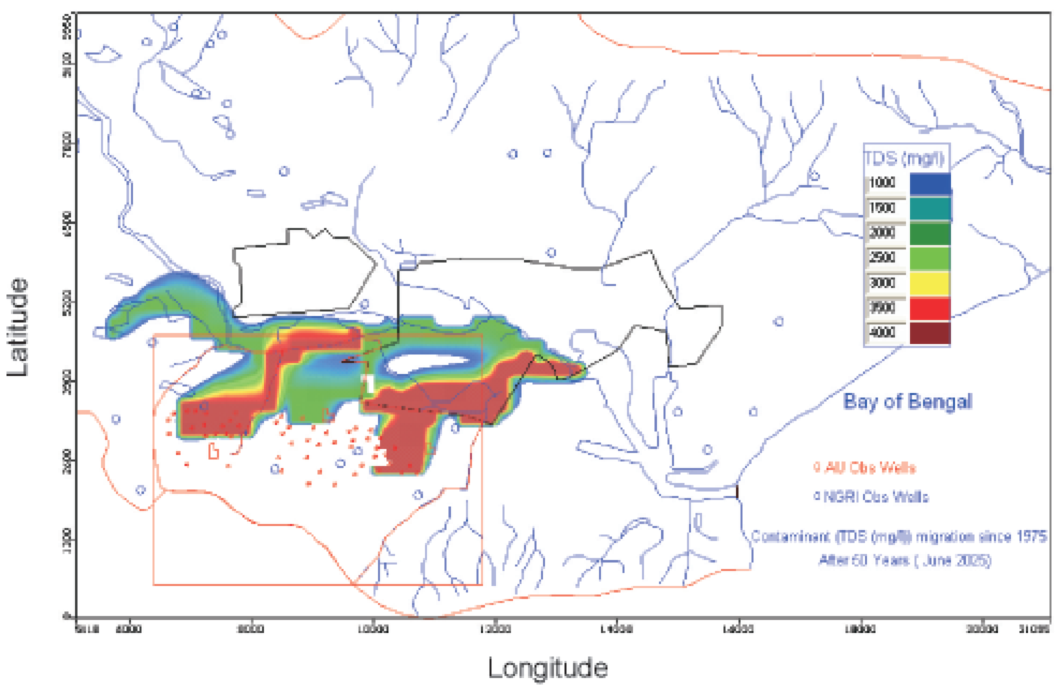

Figure 8. Predicted Contaminant [TDS (mg/l)] migration after 50years (June-2025).

Table 2. Areas likely to come under the impact of Contaminant Migration of the three Industrial sites.

Year	Villages predicted under the impact of HZL	Villages predicted under the impact of CFL	Villages predicted under the impact of HPCL
1985	Few groundwaters of 'MINDI' were observed to have crossed WHO limits of drinking standards.	Few groundwaters of 'PILAKAVANIPALEM' crossed WHO drinking standards, situated at Southwest direction at an approximate distance of 200m from CFL.	'GULLALAPALEM' village situated at Southwest direction at a distance of 400m had received the impact.
1995	'MINDI' received impact situated at North to HZL site	'PILAKAVANIPALEM' village came under the impact and few groundwater samples of 'SRIHARIPURAM' situated on either side of CFL at a distance of 800m received the light traces of pollution	'RAMNAGAR' followed by 'GULLALAPALEM' came under the impact
2005 Present	'MULAGADA', situated in the Northeast direction at an approximate distance of 1150m from the HZL site received contaminant impact.	Groundwater samples of 'SRIHARIPURAM' received the impact.	
2015	'EDURUVANIPALEM' situated at Southwest direction at an approximate distance of 450m from HZL site is predicted to be under impact by 2015.	No outlier areas of CFL are being affected by 2025 as there was less impact predicted.	MALKAPURAM (predicted outlier area might be under impact by 2025)
2025	SHEELANAGAR, NATAYYAPALEM (outlier areas might be under impact by 2025)		

ACKNOWLEDGEMENTS

We thank Dr. V.V.S Gurunadha Rao, Scientist, National Geophysical Research Institute (NGRI) for his valuable suggestions on the model aspects of the study area. We also thank to Mr.K.Lakshminarayana, analyst in the State Groundwater Department, Visakhapatnam for his suggestions on the status of groundwater quality in the vicinity of Industrial sites of Visakhapatnam. I thank Prof. P.Rajenrdra Prasad, Principal, College of Science & Technology and Andhra University for providing us the research facilities.

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(Revised accepted 2010 April 2; Received 2010 Februay 23)

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