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Hydrogeochemical Investigations and Solute Transport Modeling of Polluted Coastal Aquifer

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ABSTRACT
The study area is an inter stream region of the Pennar and Upputeru Rivers located in the Nellore district of Andhra Pradesh, India. The groundwater levels and samples are collected from 196 observation wells penetrating the near surface aquifer to prepare groundwater contour maps and to analyse the groundwater samples for various chemical parameters. Occurrence of saline water in certain localized pockets due to intensified aquaculture and occurrence of saline water along the coast due to sea water intrusion are verified by various ionic ratios like Ca^{+2}/Mg^{+2}, TA/TH, $Na^{+}/Na^{+}+Cl^{-}$ and $Cl^{-}/CO_3^{-2}+HCO_3^{-}$. The above investigations have revealed that all along the coast, with a strip width of 2 to 5 km, groundwater levels are below the sea level at a depth of 1 to 3 m, consequently, there is seawater intrusion with TDS concentrations ranging from 1500 to 3000 mg/l along this strip. Similarly, the TDS values were found to be as high as 5000 mg/l at a localized pocket at T.P.Gudur due to storing of sea water meant for aquaculture. In general, the seawater spreading is more during the pre-monsoon season and it is considerably diluted in the post-monsoon season due to recharging from Pennar river, Survepalli canal, tanks and precipitaion. The solute transport model indicates that the lateral spread of saline water towards inland is not occurring farther beyond a 2 to 5 km strip due to higher topographic elevations and the groundwater is following the topography. In the contaminated strip, the model predictions are made up to the year 2052 ,with respect to its vertical and lateral spread.

Key words: Solute transport modeling, Hydrogeochemical investigations, Polluted coastal aquifer, Inter stream region, Pennar and Upputeru Rivers.

INTRODUCTION

A report of working group of the ministry of water resources government of India has estimated the extent of waterlogged land in the country and put it at 2.46 million hectares, and that of salt-affected land at 3.30 million hectares (MoWR, 1991). Among different problems related to ground water, it's salinity due to sea water intrusion is the most predominant and resulting in environmental degradation. Such problems are mostly seen in many parts of the coastal districts of India. This calls for proper management of water resources. However, the process of contamination of ground water due to aquaculture is a recent trend in the coastal districts of India.

Since an acre of aquaculture yields more profits than an acre of agriculture, majority of the farmers were attracted towards aquaculture. This has resulted in conversion of fertile agricultural lands into aqua ponds. To maintain the salinity in aqua ponds, water with certain percent of salinity is stored for months together. The agricultural lands, which already contain huge amount of salts got further damaged due to storing of salt water for aquaculture. One more problem in coastal area is the ground water levels are well below mean sea level (m.s.l) up to a certain extent towards continent. Such problem is observed in the study area at all along the coast, in a strip width of 2 to 5 km, where ground water levels were observed below mean sea level to an extent of 1 to 3 m.

Location And Description Of The Study Area

Study area (Fig.1) is part of Nellore District falling within the toposheets of Survey of India bearing Numbers 57 N/15, 65 B/4, 66 B/2 and 66 B/3 in 1:50,000 scale. This area is spread between North Latitudes from 14^0 13′ to 14^0 35′ and East Longitudes from 79^0 59′to 80^0 15′. The study area is bounded by sea coast in the east, Penna River in the north, Upputeru River in the south and Survepalli Canal in the west, covering an area of 624.5 km^2. Survepalli canal originates from Pennar River, to feed Survepalli reservoir and drain the return flows to Upputeru River. Pennar river is a perennial river and carries fresh water, where as Upputeru River, as the name indicates, is a salt water river carrying back waters from sea and agricultural return flows from Survepalli canal. Administratively this area is falling under Nellore District of Andhra Pradesh. Out of a total of 219 villages located in the study area, 196 villages were selected for the observation wells..

The main aim of the study is to investigate the extent of sea water intrusion and ground water contamination due to aqua ponds through hydrogeochemical investigations and solute transport modeling of the near surface aquifer.

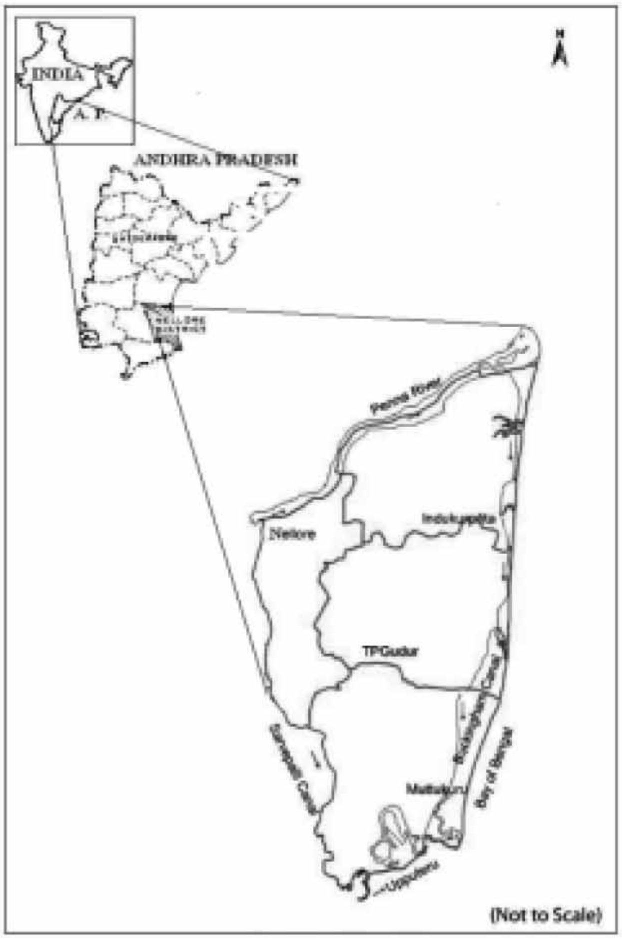


Figure 1. Location map of the study area

Figure 2. Distribution of unconsolidated deltaic formations in the study area.

Earlier Work In And Around Study Area

Rao (1961) has done hydrgeological studies in the soft rocks and the alluvial areas of East Coast of Nellore District, Andhra Pradesh, for delineation of ground water potential areas in the alluvial formations. Nageswar Rao (1963) made a report on the investigation of the reported contamination of native ground waters by salt water in coastal areas near Kavali, Nellore District, Andhra Pradesh. Venkatesan (1969) has carried out hydrogeological studies in parts of coastal plains of Nellore District to delineate ground water potential areas. Venkaiah (1999) has made hydrogeochemical studies by collecting ground water samples near six aqua culture ponds in Nellore District. Rama Krishna et al., (2000) have studied the hydro geochemistry impact on changing environment of Pennar Delta system on East Coast of India and concluded that high chloride concentrations in coastal zone is due to sea water intrusion into fresh water aquifers. Radhakrishna (1997) has described the impact of palaeo channels in the Pennar delta region on aquifer assessment. Radhakrishna and Chowdary (1998) have simulated chloride migration rates in palaeo Pennar delta region. In the present study, groundwater and solute transport modeling in the study area has been attempted to decipher the extent of saline water intrusion into the aquifers both in vertical and lateral directions from its sources such as sea water and aqua culture ponds.

Hydrogeological And Hydrogeophysical Investigations

In the study area, groundwater occurs under water table and semi confined to confined conditions. Out of the 196 monitoring wells, 114 are open wells and 82 are filter points (shallow tube wells). The depth of filter point wells vary from 6 to 30 m (bgl), while that of the dug wells vary from 5 to 12 m (bgl). Most of the wells generally yield from 6 to 12 litres per second (lps). The area is mostly covered with Pennar alluvium followed by coastal alluvium and blown sand deposits (Fig.2), the area is intersected by the palaeo-channels.

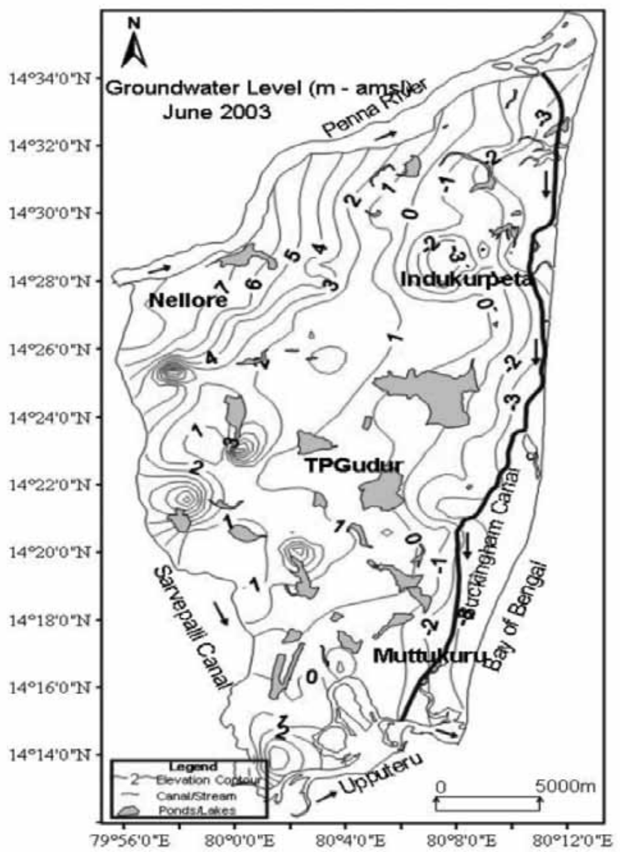


Figure 3. Groundwater level in m above mean sea level during June 2003

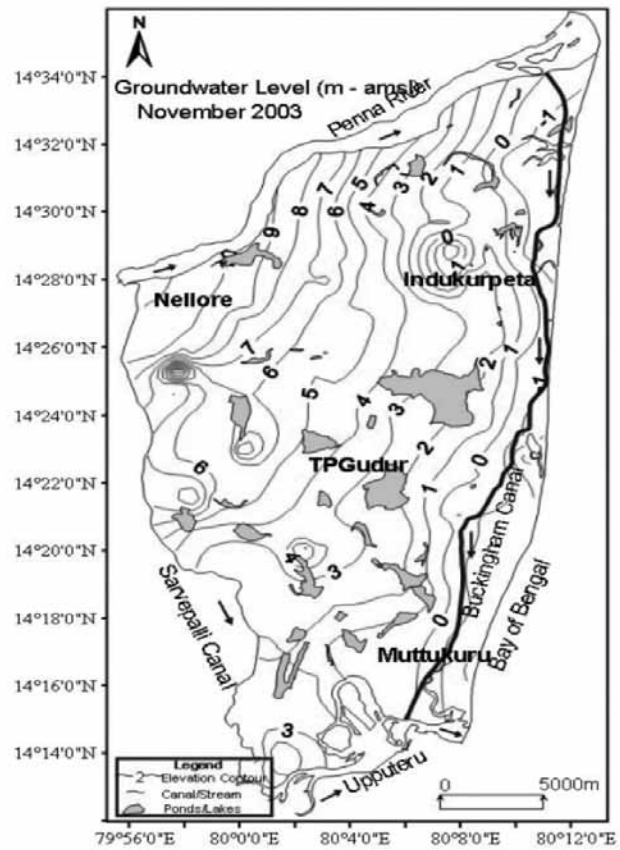


Figure 4. Groundwater level in m above mean sea level during November 2003**.**

Ground water levels in the study area were collected from 196 monitoring wells in the pre monsoon and post monsoon seasons of every year during the study period from 2002 to 2005. Water levels are reduced to mean sea level and ground water contour maps are prepared for every year.

Fig.3 and Fig.4 represent the ground water level contour maps for pre monsoon and post monsoon seasons respectively for the year 2003. In general, the groundwater flow direction is from west to east towards the sea making approximately an angle of 45^0 and 90^0 to the flow direction of the Pennar river and Survepalli canal, respectively. It is interesting here to compare the flow direction indicated by Radhakrishna and Chowdary (1998) in the same area in the year 1985. They have indicated three directions, one almost along the Pennar river and the other two are originating from a ground water mound in the central delta but travelling in opposite directions – one towards the sea and the other towards the Pennar river. By the year 2003, the ground water mound has disappeared due to pumpage and all the ground water flow direction is towards the sea. It can be observed from the maps(figs 3 & 4) that all along the coast with a strip width of 2 to 5 km, groundwater levels are below sea level at a depth of 1 to 3 m during pre monsoon season while during post monsoon season, the depth is reduced to less than 1 m indicating that the fresh water is being recharged from both the Pennar river and Survepalli canal. Because of the groundwater levels operating below sea levels, sea water intrusion along the coast is imminent.

Geophysical Data

Vertical electrical soundings were conducted in the study area at 58 locations covering the entire basin to decipher the geometry of the various aquifer layers. Schlumberger configuration is used to conduct the soundings with a maximum spread of AB/2 equal to 100 meters in view of the field restrictions. As an example a vertical electrical sounding curve with interpreted model is shown in the Fig.5. Four predominant lithologic units namely (1) sand, (2) clayey sand, (3) clay and (4) fine grained sand are observed as alternating bands (Fig. 6). Since geoelectric models indicate the predominant stratification of four layers, for the modeling purpose we have taken these four layers up to a depth of 57 metres.

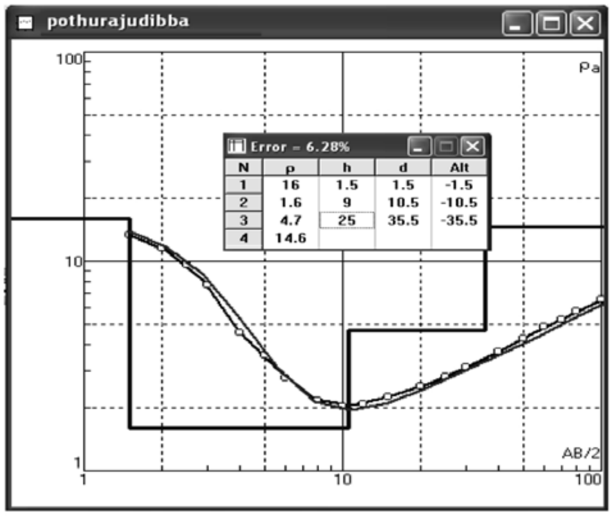


Figure 5. Interpreted vertical electrical sounding.

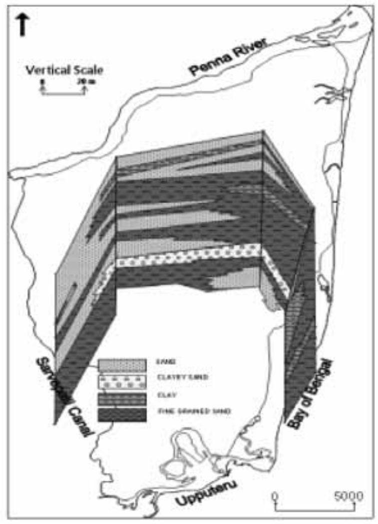


Figure 6. Fence diagram of the study area

Hydrogeochemical Investigations

Ground water samples from the near surface aquifer were collected in sterile plastic bottles from 196 wells in the basin in pre- monsoon season (i.e. From May 15th to June 1st) and in post monsoon season (i.e. From Oct 15th to Nov 1st) in the years 2002, 2003, 2004 and 2005. Anionic and Cationic parameters were analysed apart from p^H, Turbidity, Total Dissolved Solids (TDS) and Electrical Conductivity. Contour maps of TDS values in mg/l for the study area are prepared and are shown in the Fig. 7 and Fig. 8 for the pre monsoon and post monsoon seasons, respectively for the year 2002. It can be observed from these figures that the TDS values are more all along the coast and at a place called T.P Gudur where the aquaculture is predominant. Moreover, the TDS values along the cost have got reduced in the post monsoon season when compared to pre monsoon season indicating more recharging of the aquifer during the monsoon season by Pennar river, Survepalli canal, tanks and precipitation.

Methods To Check The Salt Water Intrusion

Salt water contamination may be identified by the relative concentration of some of the characteristic ions of sea water such as chloride, sodium and magnesium. Revelle (1941) recommended the $Cl^-/(CO_3^{-2}+HCO_3^-)$ or Cl/Alkalinity (Alk) ratio as a criterion to evaluate the salt water intrusion, where all concentrations are expressed in epm, If the ratio is < 0.5, it indicates fresh groundwater. If it is > 0.5 it indicates contaminated groundwater. Ratio of total alkalinity to total hardness, i.e., TA / TH (Hem, 1985) is also indicating the sea water intrusion. If the TA / TH is < 1, it indicates the presence of salt water. Hem (1985) suggested another ratio namely Ca^{+2}/Mg^{+2}. When that ratio is < 0.18, it indicates presence of the salt water. The ratio of sodium and chloride is suggested by Arther and Honslow (1995). If this ratio is < 0.5, there is a salt water intrusion. Using the above ratios, contour maps were prepared for the pre monsoon and post monsoon season of each year during the study period. One such set namely the contour maps of Cl/Alk for the pre monsoon and post monsoon season are shown in the Fig. 9 and Fig. 10, respectively for the year 2002.

From these figures it can be observed that the areas having ratios < 0.5 indicate the fresh water and all the remaining is contaminated with sea water. It can also be observed that all along the coast with strip width of 2 to 5 km, there is more concentration of seawater apart from T.P Gudur (an isolated pocket). During the post monsoon season freshwater extended in to more areas mainly along the Pennar river and Sarvepalli canal due to river and canal recharge ,respectively. All the remaining ratios are showing the similar trend. In order to know the vertical and horizontal extent of sea water intrusion, flow model and mass transparent model is attempted under steady state condition.

Groundwater Flow Modeling

Ground water modeling is increasingly recognized as powerful quantitative tool available to hydrogeologists for evaluating ground water systems (Varalakshmi et al., 2014). A ground water model is a simplified version of the real system that approximately simulates the input/output stress and response relations of the system (Wang and Anderson 1982; Anderson and Woessner 1992; Middlemis 2000). Among the most used approaches in ground water modeling, three techniques can be distinguished:

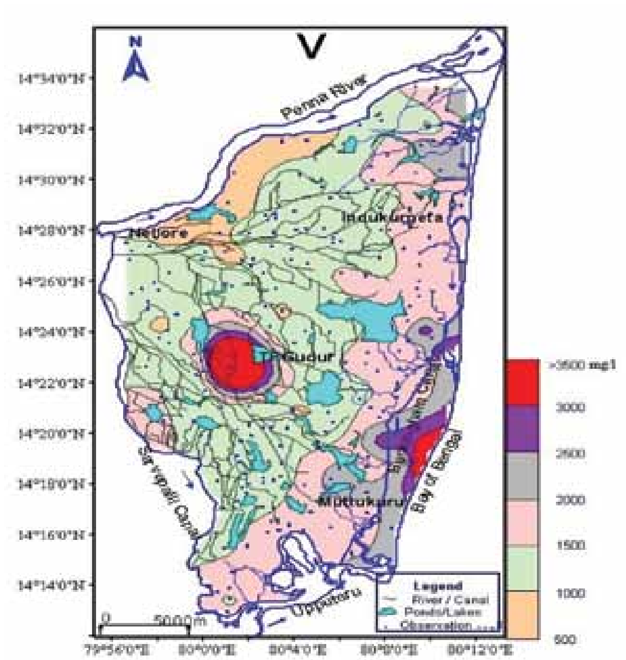


Figure 7. TDS (mg/l)in ground water samples of June 2002

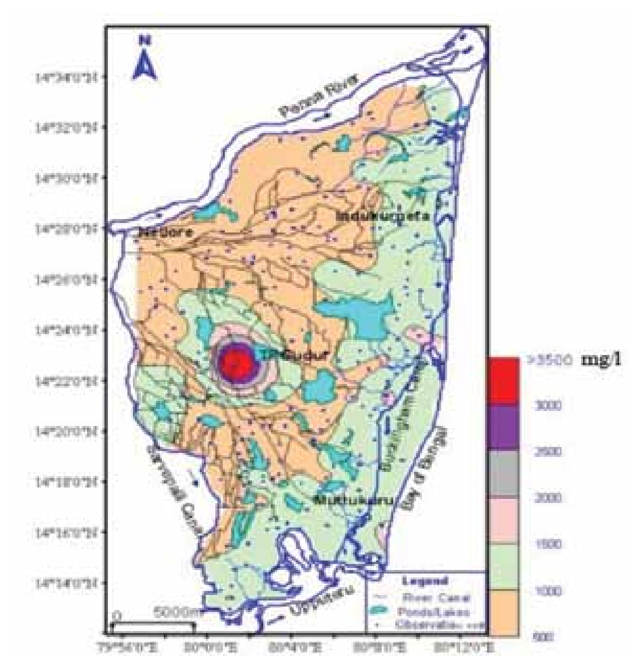


Figure 8. TDS in ground water samples of November 2002

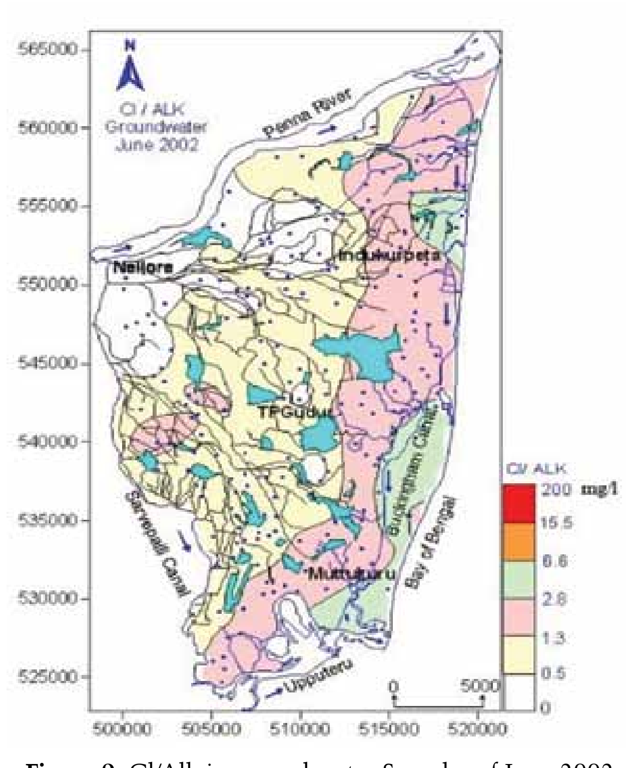


Figure 9. Cl/Alk in ground water Samples of June 2002

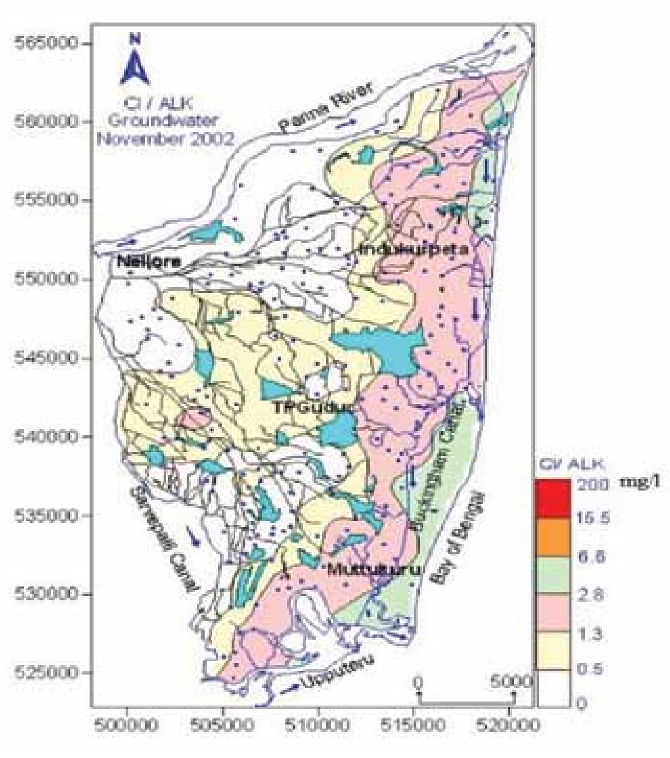


Figure 10. Cl/Alk in ground water Samples of November 2002

Finite Element Method (Zienkiewicz 1971; Pinder and Gray 1977; Yeh and Huff 1983; Voss 1984; Istok 1989 and Kazda 1990), Analytical Element Method (Freeze and Witherspoon 1966) and Finite Difference Method (Pinder and Bredehoeft 1968; Trescott et al. 1976 and McDonald and Harbaugh 1988). All techniques have their own advantages and disadvantages with respect to availability, costs, user friendliness, applicability, and required knowledge of the user. In the present study, ground water flow modeling is achieved under steady state condition using Visual MODFLOW software with Finite Difference method.

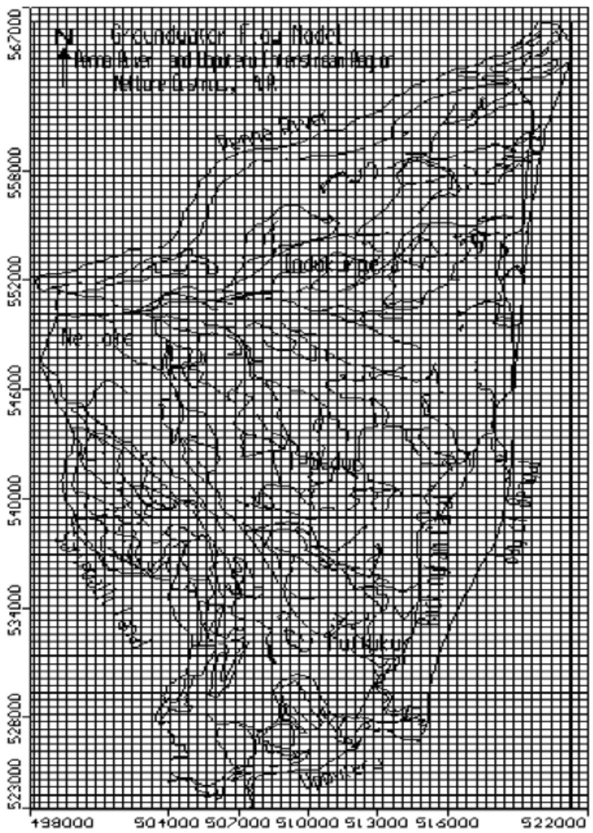


Figure 11. Grid map of simulated model domain (Each Grid: 400m X 400m)

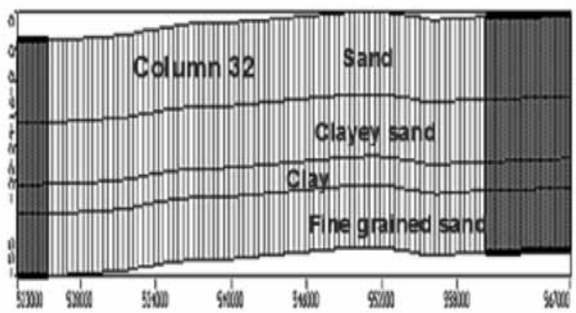


Figure 12. Simulated vertical cross section along column 32

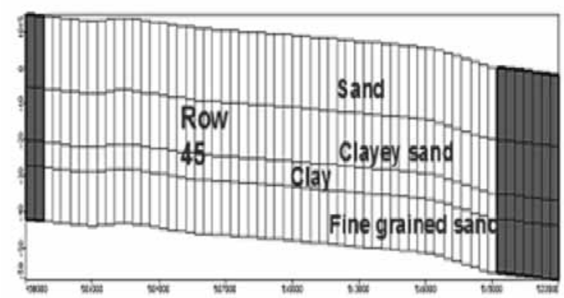


Figure 13. Simulated vertical cross section along row 45

Conceptualization Of Ground Water Flow Model

No flow occurs across the watershed boundaries and these boundaries are coinciding approximately with ground water divides. Recharge of ground water takes place from top layer of the watershed as well as seepage from the river, canal, tanks and sea, which is an additional input to the watershed recharging system. The continuous ground water pumping is prevalent in the watershed due to intensive agriculture and land cover with vegetation. The ground water withdrawal is estimated based on the pumping pattern from the wells in the study area. As the watershed is closed with streamlets, some out flow may take place. There will be some downward leakage also to the alluvium zone from the soil zone.

Aquifer Gridding

The simulated model domain of the study area consists of 4 zones covering an area of 24,000 m x 44,000 m. The entire area was divided into a square grid pattern of 60 X 110 grids. The grid is a finite difference block centered grid i.e., node is located at the center of each block. Each node covers an area of 400 m X 400 m. (Fig. 11)

Aquifer Geometry

Four layers are considered for the ground water flow model and constructed up to a depth of 57 m such that 0 to 20 m as sand, 20 to 35 m as clayey sand, 35 to 42 m as clay and 42 to 57 m as fine grained sand (Fig. 12 and Fig. 13).

The ground water levels measured during June 2002 were used as initial water level configuration for steady state ground water flow model.

Attribution Of Hydraulic Properties

From the pumping tests analysis of the Central Ground Water Board (CGWB), the aquifer parameters of the study area were estimated. The CGWB has conducted pumping tests on the wells penetrating different depths giving scope to evaluate hydraulic parameters of the aquifers at different depths. That means at a given place, for example, two shallow wells were used for conducting the pumping tests for estimating the hydraulic parameters of the shallower aquifer. Similarly at other place, two deeper wells were used for conducting the pumping tests to estimate the aquifer parameters of the deeper aquifer. In both the cases pumping tests were conducted by measuring the water levels at the observation well while pumping the other well. Even though there could be some ambiguity, while conducting the pumping tests in the deeper wells, as the measurement of water levels are affected both by shallow as well as the deeper aquifers, it is confirmed that the effect of shallower aquifers on T and S values of deeper aquifers is limited as different trials were conducted in ascribing the T and S values both during the field work as well as during modelling till the model reproduces faithfully the observed values. The tests have yielded following results: The transmissivity is varying between 152.45 m^2/day to 1685 m^2/day, specific capacity is varying from 42.0 to 371.0 lpm/day/metre draw down and storage coefficient is varying from 7×10^{-4} to 7.25×10^{-4}. After conducting different trials, transmissivity is worked out as 855 m^2/day for the first two layers and for the bottom 4th layer. The same is 57 m^2/day, for the third layer. The uniform permeability value of 15 m/d was assigned for the entire study area for layers 1, 2 and 4. For the third layer it is 1 m/d.

Boundary conditions

For model preparation, Boundary Conditions are assigned to the study area as shown in Fig. 14. Constant head boundary conditions are assigned all along the sea coast and river head boundary conditions are assigned along both the river Pennar, Uppeteru and tanks. No boundary condition is assigned at Surveypally canal as the canal is only feeder canal and is not flowing throughout the year. Therefore river boundary condition has not been assigned to Survepalli canal throughout the year. The water level data measured at 196 observation wells during June 2002 were used to prepare initial water level contours. Out of 196 observation wells, 26 wells were used in the steady state model calibration and are shown in Fig. 15 along with division of study area into four zones.

Estimation Of Ground Water Extraction

Quantity of water extracted is obtained based on village wise data i.e., total number of wells with average pumping hours per day multiplied with pumping rate of well. The net draft available in the study area is as follows.

Quantity of water extracted = village wise number of wells x pumping hours/day x pumping rate. --- (1)

Grid size is adapted as 400 m x 400 m (0.16 km^2). Table. 1 shows the mandal wise pumping rate in each grid of study area. Mandal is an administrative unit.

An average value of 200 m^3/day/grid is adapted for the above first three mandals and 100 m^3/day/grid for Nellore mandal for the preparation of flow model. Out of 196 observation wells, 26 wells were used in the steady state model calibration.

Input and Output Stresses

The rainfall recharge is taken as 10% of the mean annual rainfall based on the previous investigations made by Rangarajan and Athavale (2000). The quantity of recharge for the year 2002 works out to be 294×10^{6} m^3, which is from an average rainfall of 850 mm. Simulated recharge distribution is shown in Fig. 16. Irrigation return flows are assumed as 30% of used water (Venkateswara Rao et al., 2013) and it is calculated as nearly 245×10^6 m^3 per year. The inflow and outflow across boundaries were calculated based on interpolated values of "T" and hydraulic conductivity (K). Seepage from surface water bodies namely, Pennar river, Upputeru river, Survepalli canal, part of sea and tanks have contributed additional input stresses to the flow regime due to pumping stress from the watershed. Total input is simulated as 317.5 MCM per year (Table.2). The output is mainly through ground water withdrawal from dug wells and bore wells which are simulated as 311.0 MCM.

Zone budgeting was also accomplished for all the four zones. The aquifer simulation was carried out by using Visual MODFLOW (Guiger and Franz, 1996) software package. Minor adjustments in permeability distributions have not brought out appreciable changes. Thus, the simulated permeability seems to represent the actual value. The ground water head in the aquifer model was computed by using WHS solver package of visual MODFLOW.

Model Calibration

The actual values and spatial distribution of "T" values were calibrated assuming steady state condition in the year 2002. Input and output stresses along with "T" values were progressively modified till a better match is made between observed and computed values for steady state conditions (Fig. 17).

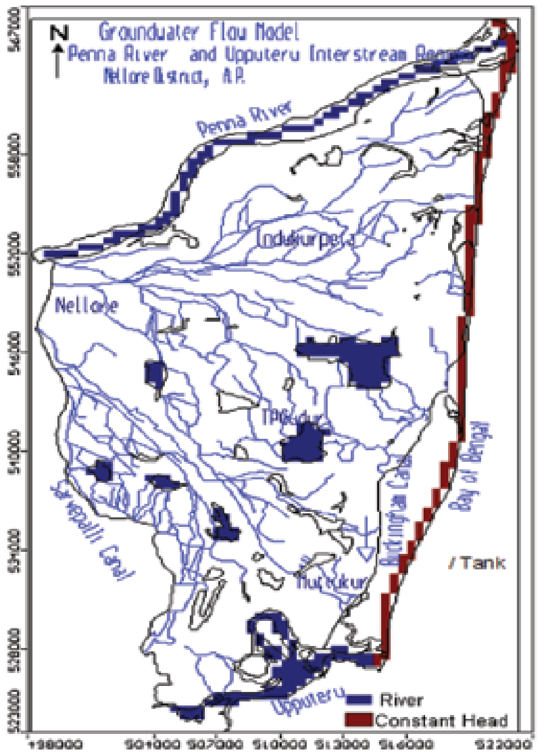


Figure 14. Simulated constant head boundary and river boundary conditions in the model.

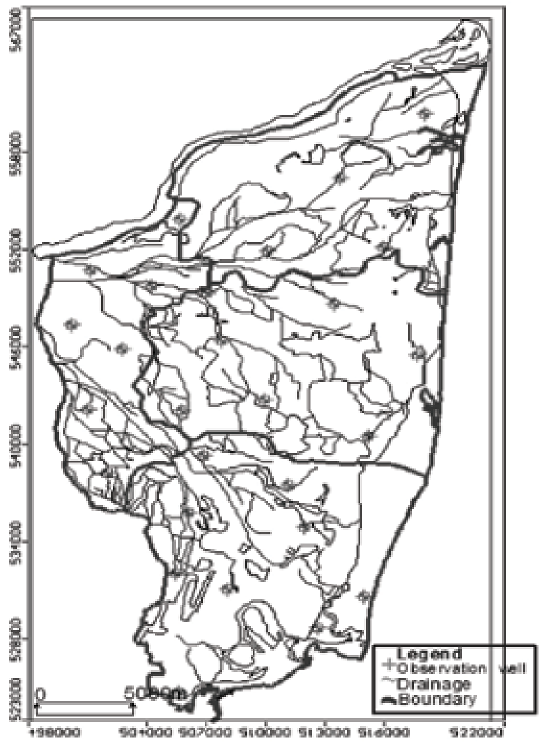


Figure 15. Simulated observation wells in the model for calibration

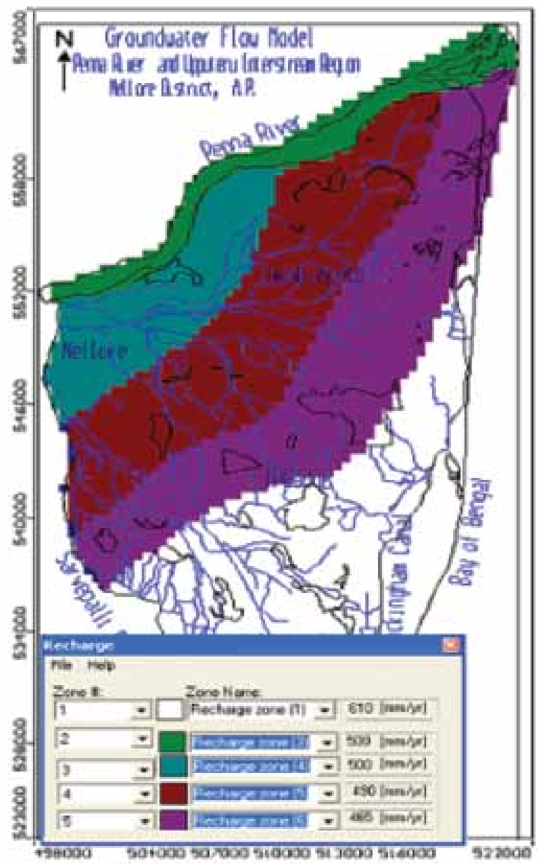


Figure 16. Simulated block wise recharge distribution.

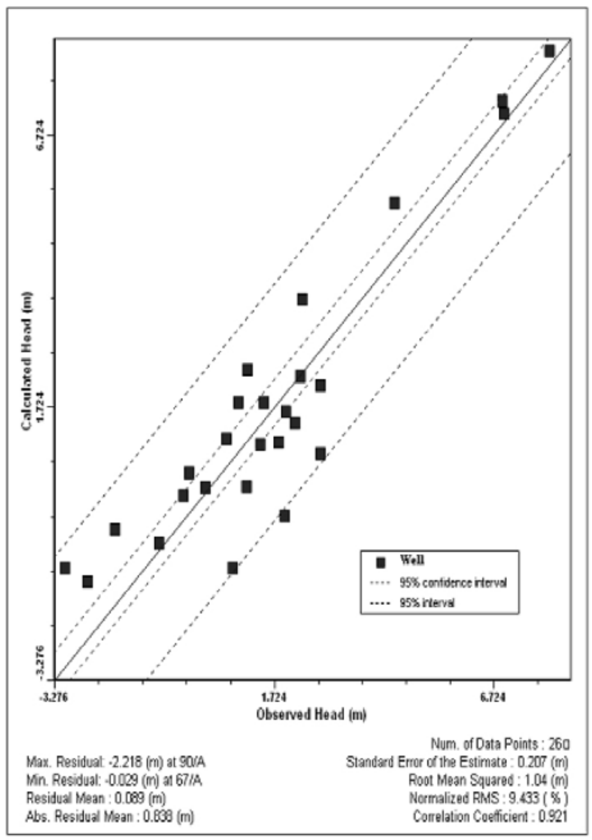
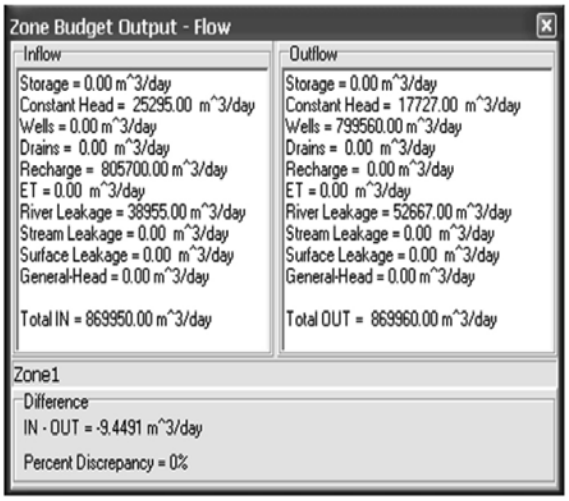


Figure 17. Computed Vs. observed water levels June 2002 for steady state condition.

Table 1. Mandal wise pumping rate for each grid

Name of the Mandal	Pumping rate in m^3/day/grid
Indukur pet	207
T.P Gudur	201
Muthukur	215
Nellore	81

Table 2. Computed Ground Water Balance Under Steady State Condition



Input	Output	Outflow
317.5 MCM / yr	311.0 MCM/ yr	6.5 MCM/ yr

Sensitivity Analysis

The model is sensitive to hydraulic conductivity because of relative mobility in the value of mean error between the mean observed error and RMS error as tabulated in the Fig. 17

The average ground water velocity has been estimated as 0.49 m/day for the first layer, 0.47 m/day for second layer, 0.03 m/day for the third layer and 0.42 m/day for fourth layer.

Solute Transport Model

The MT3D transport model was developed by Zheng (1995) for use with any block-centered finite difference flow model such as MODEFLOW and is based on the assumption that changes in concentration field will not affect the flow field significantly. Some of the case studies nearer to study area include those from Radhakrishna and Chowdary (1998), who have made a two dimensional model to assess Chloride migration rates in the Pennar delta. Thangarajan (1999) has used mass transport model to quantify the pollutant

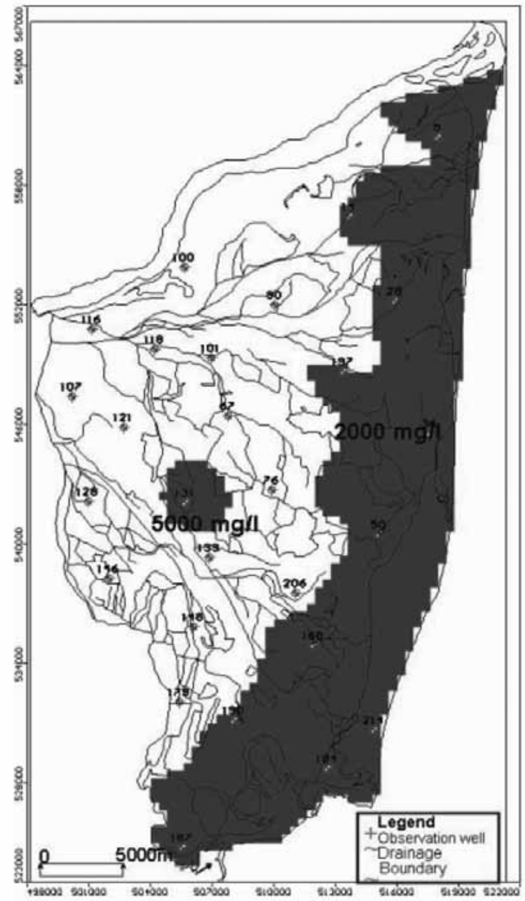


Figure 18. Simulated TDS concentration in the model domain for 2000mg/l and 5000mg/l (June 2002)

migration in upper Palar river basin. Similar attempt was made by Gurunadha Rao and Gupta (2000) for Sabarmati river bed aquifer. Bobba (2002) made numerical model for salt water intrusion in Godavari delta. In the present paper also transport model is attempted to assess the spread of TDS vertically and laterally in the substratum.

Assigning Model Parameters

The values of dispersivity in longitudinal and two transverse directions (Y and Z) were assumed to be 10 m, 0.1m and 0.01 m, respectively based on the experience of the modelers in similar situation. There is a variation of TDS all along the coast. It is varying between 1500 to 3000 mg/l. An average TDS value of 2000 mg/l has been assigned all along the coast with a strip width varying from 2.0 to 5.0 km. However, the highest concentration of 5000 mg/l has been assigned at a place in T.P.Gudur mandal, near aqua ponds. For the rest of the area, the initial TDS background concentration is assigned as 800 mg/l. The above concentrations are assigned based on the Hydrogeochemical analysis data discussed earlier. The

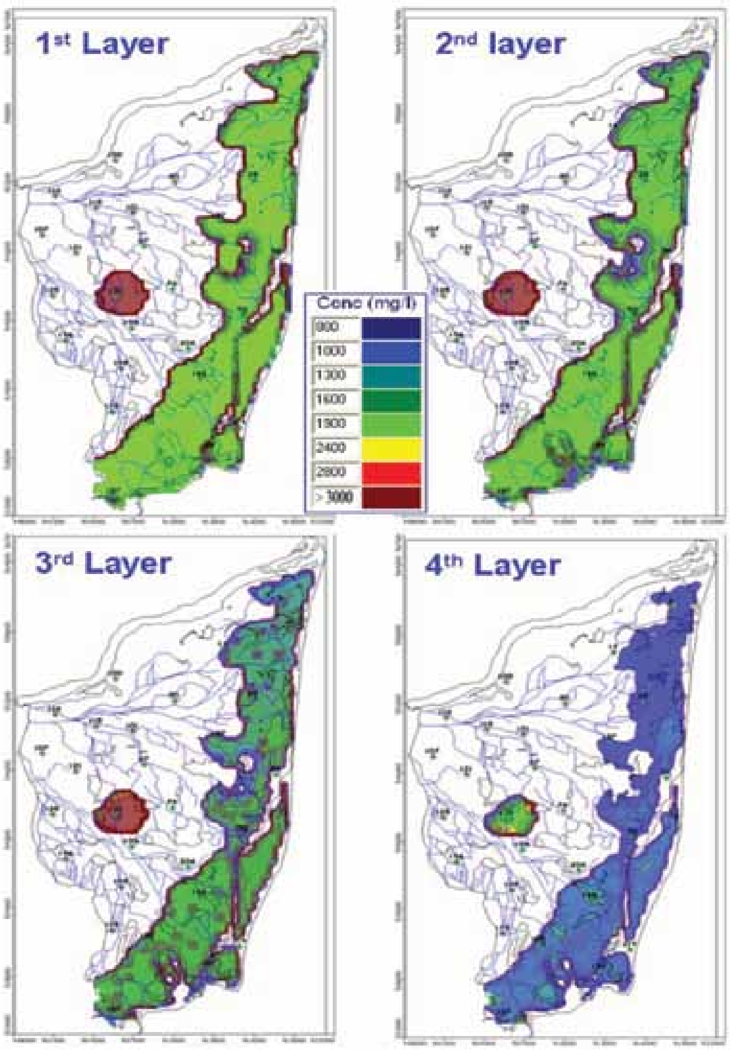


Figure 19. Computed TDS concentration (mg/l) in the study area for June 2052.

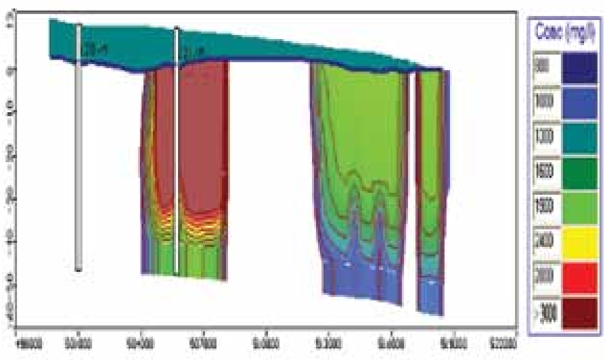


Figure 20. Vertical cross section of the computed TDS concentration (mg/l) along the row 63 for June 2042.

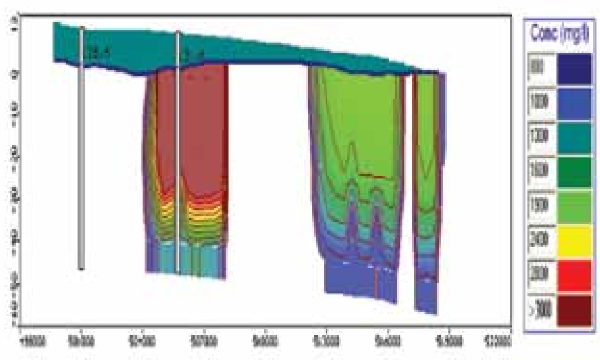


Figure 21. Vertical cross section of the computed TDS concentration (mg/l) along the row 63 for June 2052

calibration of the mass transport model has been carried out for the June 2002. The mass transport model was used to compute concentrations for same amount of loading of effluent in the study area for next 50 years for the 1st, 2nd, 3rd and 4th layers using the velocities obtained from the steady state flow model.

Prognastics

Pollution spread scenarios for the years 2012, 2022, 2032, 2042 and 2052 were prepared in respect of their vertical and horizontal spread. It is observed from the generated maps that the pollutant can penetrate to even fourth layer by the year 2052 (Figs. 19, 20 and 21), while it is confined to same areal extent all along the coast due to higher topographic elevations and the groundwater is following the topography. That is, the sea water intrusion is confined only to an average of 2 to 5 km strip along the coast apart from an isolated place called T.P Gudur ,where aquaculture is practiced. It is again interesting to compare the results obtained by Radhakrisha and Chowdary (1998) in the same area. It is found that the Chloride migration due to sea water intrusion from the coast is limited to 4 Km when they have simulated upto 30 years in the year 1985.

CONCLUSIONS

All along the coast, with a strip width of 2 to 5 km, groundwater levels are below the sea level at an average depth of 3 m below ground level. Consequently, there is seawater intrusion with TDS concentrations ranging from 1500 to 3000 mg/l along this strip. Similarly, the TDS values were found to be as high as 5000 mg/l at a localized pocket at T.P.Gudur due to storing of sea water meant for aquaculture. The ionic ratios are confirming the presence of seawater in these localities and along the coast. In general, the seawater spreading is more during the pre-monsoon season and it is considerably diluted in the post-monsoon season. The solute transport model indicates that the lateral spread of saline water towards inland is not occurring farther beyond a 2 to 5 km strip due to higher topographic elevations and the groundwater is following the topography. In the contaminated strip, the model predictions are made up to the year 2052 with respect to its vertical and lateral spread. The vertical spread of pollutant is upto 4^{th} layer by the year 2052, while there is no change laterally.

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