

Modelling for pollutant migration in the tannery belt, Dindigul, Tamil Nadu, India

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Groundwater in and around Dindigul town in Tamil Nadu, India, is polluted due to discharge of untreated effluents from 80 functional tanneries. Total dissolved solids (TDS) in about 100 km² area are observed ranging from 2000 to 30,573 mg/l in open dug wells. A mass transport model was constructed to study pollutant migration. The study area covering 240 km² was chosen to construct the groundwater flow model in the weathered part of unconfined aquifer system. The shallow groundwater potential field computed through the flow model was then used as input to the mass transport model. MT3D computer code was used to simulate mass transport in groundwater system. The mass transport model was calibrated with field observations. The available database was, however, quite sparse. Notwithstanding, efforts were made to arrive at reasonable guesstimates of the characteristic parameters. Sensitivity analysis, an integral part of calibration was carried out whereby model parameters, viz. transmissivity, dispersivity, etc. were altered slightly and the effect on calibration statistics was observed. This study clearly indicates that transmissivity plays a more sensitive role than dispersivity, indicating that the migration phenomenon is mainly through advection rather than dispersion. The study also indicated that even if the pollutant sources were reduced to 50% of the present level, TDS concentration level in the groundwater, even after 20 years, would not be reduced below 50% of present level.

Keywords: Dindigul, groundwater pollution, pollutant migration, tannery industry, weather zone.

THE study area, a granitic rock formation in Dindigul district, Tamil Nadu, India possesses poor groundwater potential. Serious contamination of both surface water and groundwater has been reported in this area as a result of uncontrolled discharge of untreated effluents by 80 tanneries for the last three decades¹⁻⁴. The health of the rural farming community and people working in the tanning industries has been seriously affected. They suffer from occupational diseases such as asthma, chromium ulcers and skin diseases⁵. About 100 km² area of fertile land has lost its fertility. Total dissolved solids (TDS) concentration⁶ in groundwater at some pockets varies from 17,024 to 30,575 mg/l. As the discharge of effluents continues, a prognosis of fur-

ther pollutant migration is carried out using a mathematical model. A numerical model of the area was developed using the finite difference technique coupled with method of characteristics and it was also used to predict TDS migration for the next 20 years. Sensitivity analysis was carried out to identify the parameters which influence contaminant migration. Sensitivity analysis shows that advection and not dispersion is the predominant mode of solute migration. There are a large number of reports and papers available to describe the solute transport models to study contaminant migration in the industrial belts, coastal aquifer, etc. (C. P. Gupta *et al.*, unpublished)⁷⁻¹⁴. The computer software MOC developed by Konikow and Bredehoeft¹⁰ based on finite difference coupled with the modified method of characteristics is used for the present study.

The area is a hard-rock, drought-prone region situated in Dindigul District, Tamil Nadu, India (Figure 1) and it lies between 10°13'44"–10°26'47"N lat. and 77°53'08"–78°01'24"E long. It is spread over an area of about 240 km² and is characterized by undulating topography with hills located in the southern parts, sloping towards north and northwest¹⁵. The highest elevation (altitude) in the hilly area (Sirumalai Hill) is of the order of 1350 m amsl, whereas in the plains it ranges from 360 m amsl in the southern portions to 240 m amsl in the northern part of the area. No perennial streams exit in the area, except for short-distance streams encompassing second- and third-order drainage^{15,16}. Run-off from precipitation within the basin ends in small streams flowing towards the main river, Kodaganar.

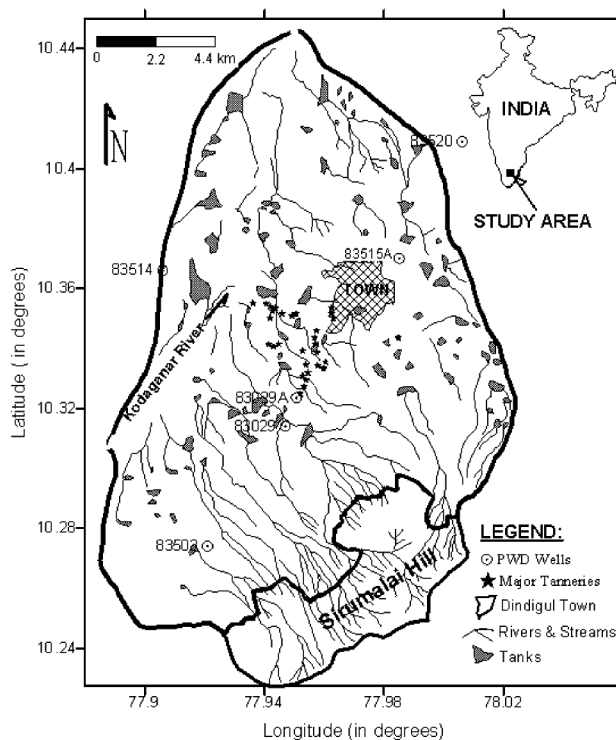


Figure 1. Location map.

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The average annual rainfall¹⁷ is of the order of 915.5 mm for the period 1971–2001. Geologically, the area is occupied with Achaean granites and gneisses, intruded by dykes. Black cotton soil and red sandy soil predominate. The thickness of soil varies from 0.52 to 5.35 m, but thickness of weathering¹⁵ varies from 3.1 to 26.6 m. Distribution of the weathered zone varies from place to place within the basin, and as such this shallow zone may not be a stable source for large demands of groundwater. The weathered zone facilitates the movement and storage of groundwater through a network of joints, faults and lineaments, which form conspicuous structural features. Apart from the structural controls on groundwater movement, the terrain is covered with pediment and buried pediment at the southern and western sides. Another most dominant formation is charnokite, which is found in the extreme southern and southeastern parts of the Sirumalai Hill. Groundwater is extracted through dug well, dug-cum-bore wells and bore wells for different purposes (V. S. Singh *et al.*, unpublished). The general trend of groundwater motion under shallow aquifer is in the north and northwest directions (Figure 2).

The groundwater quality of samples was taken twice a year from five existing dug wells (depth range 14.00–24.85 m) for the period from January 1988 to July 1995 and has been monitored by Public Works Department, Government of Tamil Nadu¹⁷. Locations of the wells are shown in Figure 1. TDS concentration observed in the field at five dug wells during January 1988, January

1990, July 1991 and January 1994 is shown in Table 1. TDS showed increasing trends. The PWD hydrochemical data indicate that major ions such as sodium, magnesium, chloride and sulphate, and total hardness are also (N. C. Mondal, unpublished Ph D thesis) high, corresponding with the high TDS. The groundwater samples were made available for January 2001 from the field. These data also could be incorporated in the present study. The statistical parameters, viz. minimum, maximum, mean and standard deviation of different chemical constituents of groundwater samples are shown in Table 2. These data show that groundwater is highly polluted due to tannery effluents in the eastern side of the Kodaganar river and western side of the town⁶. In order to observe the distribution pattern of TDS and to demarcate the higher concentration zones in the study area, the TDS contour map was prepared as shown in Figure 3.

Geometry and boundary conditions in the aquifer are generally complex, because the aquifer is in hard rock terrain. Analytical methods are rarely applicable to find a

Table 1. TDS values (mg/l) in five-PWD wells

Period	83029	83029A	83503	83514	83515A
January 1988	1046	465	1760	1500	555
January 1990	1309	630	1761	2103	762
July 1991	1901	794	1856	2366	1217
January 1994	1958	1008	2136	3210	629

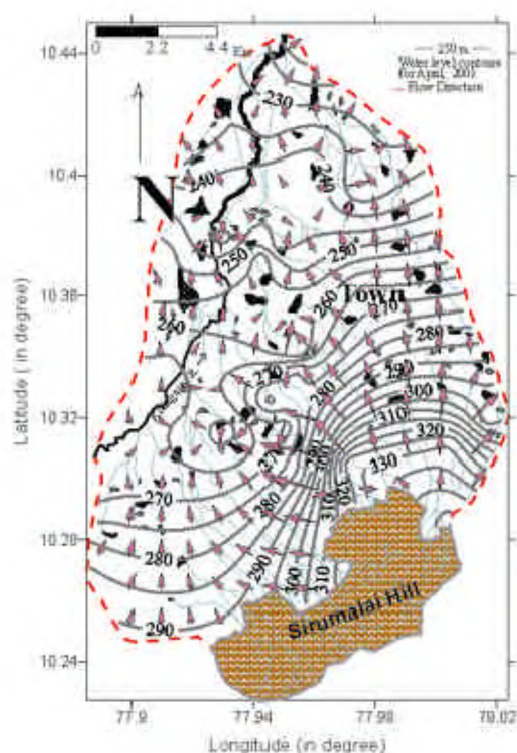


Figure 2. Water level contours (m, amsl) and flow direction (April 2001).

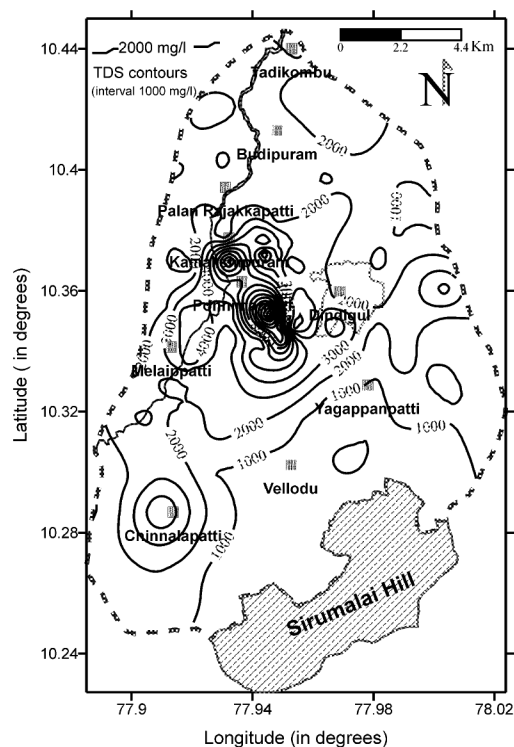


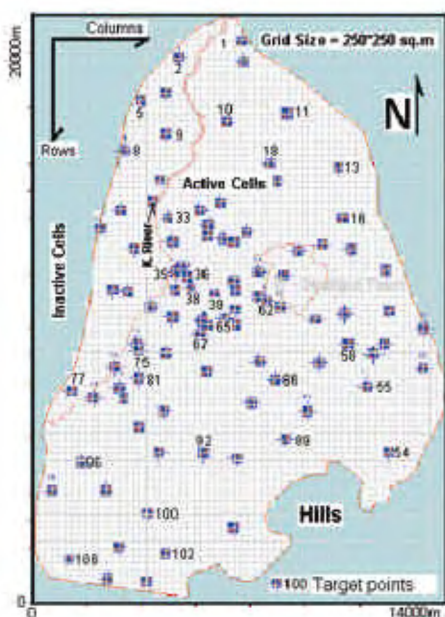
Figure 3. TDS contours map (January 2001).

Table 2. Minimum, maximum, mean and standard deviation of groundwater

	TDS	Ca	Mg	Na	K	HCO ₃	Cl	SO ₄	NO ₃
Minimum	349	38	1	26	1	31	25	13	1
Maximum*	17000	1741	936	4850	215	756	10390	961	252
Mean	2496	288	145	348	21	377	1079	185	35
Standard deviation	2507	307	163	545	34	140	1560	161	44

Ions in mg/l. *Maximum value obtained in the sample collected from the adjutancy for the tannery.

Samples were collected during January 2001.

**Figure 4.** Grid map for flow and mass transport modelling.

closed form solution of the 2D groundwater flow equation¹⁸. An approximate one, which is traceable, replaces this equation only by finite difference approximation technique. It will be easy to handle for numerical compositions. The starting point for the application of this method is discretization of small rectangular sub-regions in a grid form. The partial differential equations were replaced by a finite difference equation at each node. Several techniques, such as iterative alternating direct procedure, successive over-relaxation methods, etc. are available for solving the set of the resultant simultaneous algebraic equations. The main stages of mass transport modelling are as follows:

- Solving the groundwater flow equation using finite difference method.
- Estimation of fluid velocities at each node.
- Solving the mass transport equation using finite difference technique and method of characteristics using the flow velocities.

In order to set up the model in the MODFLOW set of codes, the area of interest needs to be divided into a series of

grid blocks or cells¹⁹. This grid has to be block-centred, i.e. the groundwater heads will be computed at the centre of each grid block. Taking into account that there are no steep slopes in the water table and that the areal extent of the basin is about 209 km², a grid size of 250 × 250 m² (total no. of grids = 3342) was decided (Figure 4). The layer is in unconfined condition and corresponds to a layer type 1 in MODFLOW. This type of layer requires only horizontal hydraulic conductivity values as well as specific yield values to be defined. The actual values of the ground surface elevation and bottom elevation of the bedrock were entered at the model. This is a simplification of the system and can be justified by the fact that the weathering and fracturing processes actually start from the surface of the formations and gradually progress deeper. The aquifer is dipping from southeast to northwest, with variable thicknesses.

In the present case, the boundary conditions had been determined based on the hydraulic condition. Initially, these values were applied in the conceptual model. Figure 1 illustrates the boundary conditions set in the area.

A specified flow boundary (Neumann conditions) is one for which the derivative of head (flux) across the boundary is given. A no-flow boundary condition is set by specifying this flux to be zero¹⁹. No-flow boundary has been set in the southern part of the basin. There are two facts that justify the use of a no-flow boundary: (i) Charnokite has been characterized as practically impermeable in the conceptual model and (ii) the water table is close to the surface. A groundwater flow divide is therefore likely to occur where there is surface flow divide.

The northern boundary of the area was simulated through generalized head boundary, in order to represent groundwater discharge. These values were used in the steady-state simulation. At the calibration time, due to lack of data, it was assumed as constant. Other important boundaries: (i) Weathered part of the aquifer was considered as a porous one; (ii) aerial recharge and pumpages were assigned at random and (iii) wherever dykes and exposures are present, transmissivity values were adjusted and assigned according to their direction and length.

The groundwater flow regime model was prepared only for the shallow aquifer zone tapped by dug wells and dug-cum-bore wells (up to 27.68 m thickness). This implies that the deeper fractured zones do not take part either in

groundwater flow or in mass transport. The aquifer is also treated as a porous one for modelling purposes. TDS concentration in the surface effluents was assumed to be more than 30,000 mg/l during the period September 1988 to February 2002. The quantity of fluid effluents seeping to the groundwater system was assumed to be 30% of the surface effluents. It was also assumed that on a conservative basis the solvent reaching the water table has a solute concentration, which is 30% of that present at the surface. The remaining 70% of the solutes may get absorbed in the unsaturated zones or are carried away by the run-off. An effective porosity of 0.2, longitudinal dispersivity of 30 m and transverse dispersivity of 10 m were uniformly assumed for the entire area. The mass transport model was calibrated in two stages: steady-state and transient state. It was also assumed that TDS did not influence by density and viscosity values, which may affect the groundwater flow and pollutant migration. The computer software developed by Konikow and Bredehoeft¹⁰, based on groundwater flow equation and the modified method of characteristics was used. Various parameters (collected from the field) were assigned to the corresponding nodes.

The purpose of calibration of the groundwater flow model is to demonstrate that the model can respond to field-measured heads and flows, which are the calibration values¹⁹. The purpose of this modelling exercise is to solve an inverse problem, i.e. to find a set of parameters, boundary conditions and stresses that reproduce the calibration values within a certain re-established range of error (calibration targets). In this case, a trial and error calibration technique has been used. Parameters are initially assigned to each node in the grid. Then these parameter values are adjusted in

sequential model runs to match the calibration targets. This method was chosen because information that cannot be quantified is being used (as opposed to an automated calibration procedure). Nevertheless, this method is largely influenced by the modeller's expertise and biases. The calibration parameters set in this modelling exercise are the generalized head boundary, recharge, evapotranspiration, hydraulic conductivity, specific yield, etc.

TDS concentration (C) was then calculated at all node points for September 1988, a date up to which the system was assumed to be in a steady-state condition. There was a mismatch between observed and computed values of C . Therefore, efforts were made to obtain a reasonably better match by modifying the magnitude and distribution of the background concentration and pollutant load. However, the situation could not be improved much. This may be due to a variety of factors, the most important being the lacunae and inaccuracies in the database. To obtain the real representation of the aquifer system, field data (January 2001) were considered for other steady-state condition and were also run to visualize the mass transport model. The computed versus observed C values are illustrated in Figure 5.

As the steady-state model could not reproduce the observed data at all the points, a time-variant simulation was carried out. This was done for the period January 1988 to July 1995 based on available historical data. Pollution load reached the groundwater system at various clusters during this period. Computed C for five PWD wells is higher than the observed values. These values, however, could not be rectified, as there was no basis for modifying either model parameters or pollutant load in the absence of any actual field estimates. It should be mentioned here that the present model only illustrates the feasibility of applying modelling techniques to study this problem and to use it for prediction of system behaviour for some future scenarios.

The impact of varying conductivity, dispersivity, and CW (TDS pollution load at the source) was studied. Variations caused in TDS concentration at selected node points as a result of variations in these parameters are shown in Table 3.

This parameter was changed by 20% (upwards and downwards) of the value assigned in the model at each node. Change in conductivity affects groundwater velocity, causing redistribution of solute concentration. In general, higher the conductivity, faster is the movement of the solute. Therefore, the concentration is reduced near the sources and increased and vice versa (see columns 3 and 4, Table 3).

The longitudinal dispersivity was increased to 50 and 100 m (from 30 m). Transverse dispersivity was taken as one-third of the longitudinal dispersivity. No significant changes in TDS concentration were noticed due to increase in dispersivity (see columns 5 and 6, Table 3). This shows that advection and not dispersion is the predominant mode of solute migration in the tannery belt.

The effect of varying this parameter by 20% (upwards and downwards) at 32 source points (nodes taken at the major

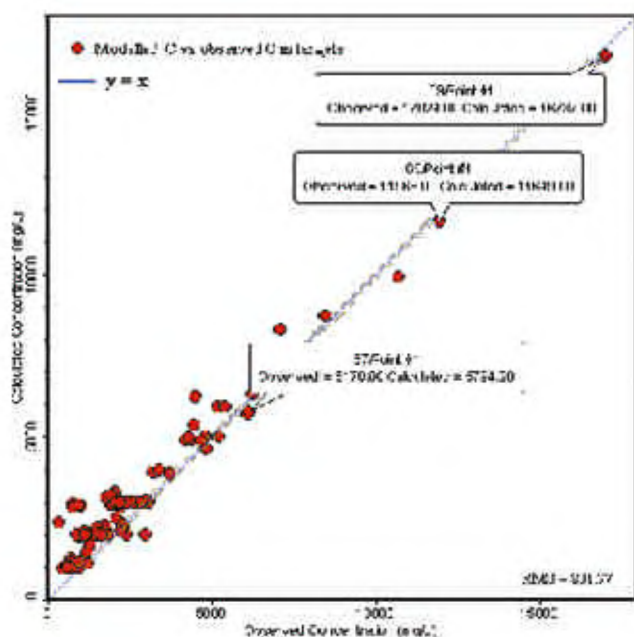


Figure 5. Computed vs observed C in steady-state (January 2001).

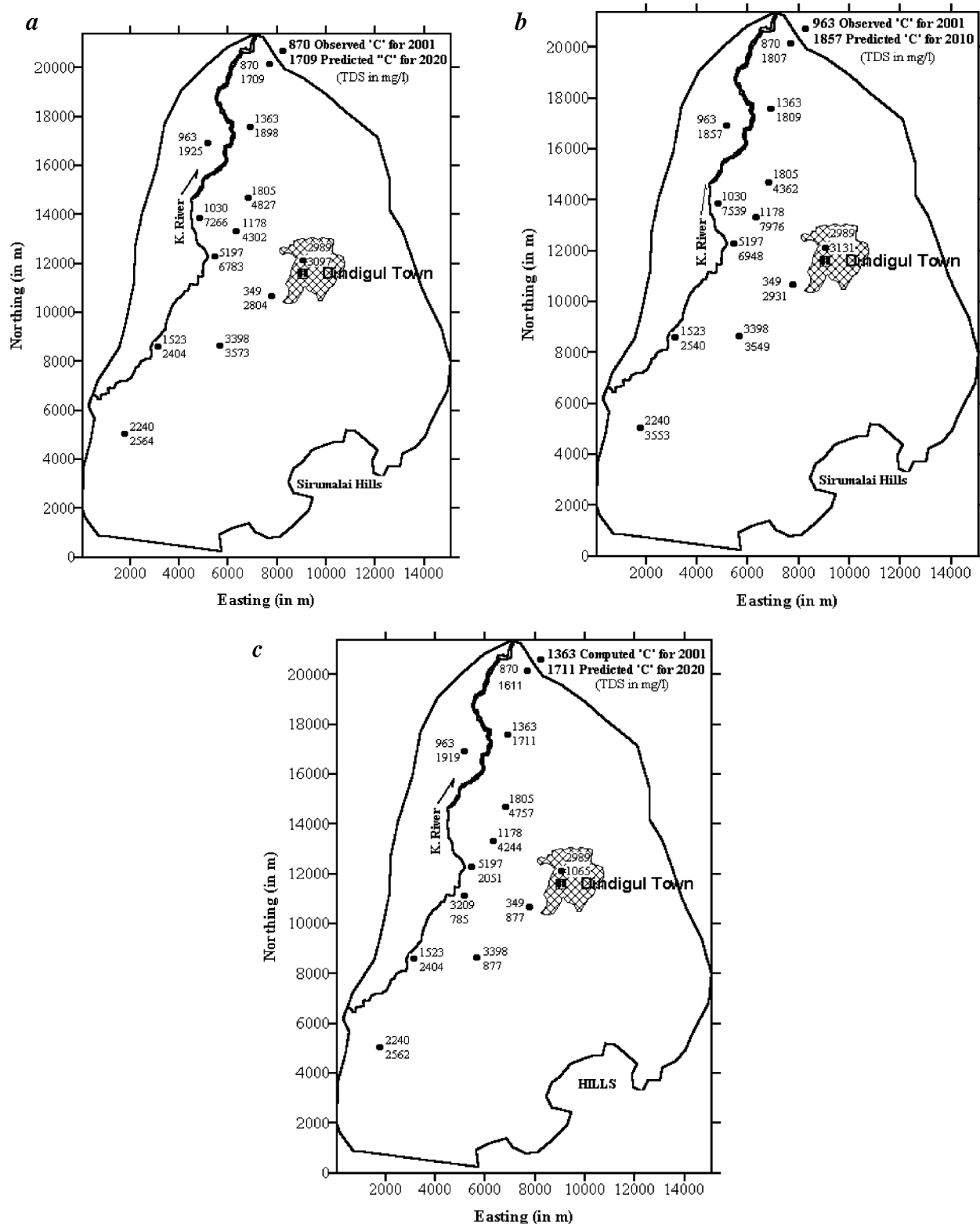


Figure 6. Predicted TDS concentration in (mg/l) for (a) January 2020 (scenario I), (b) January 2010 (scenario II) and (c) January 2020 (scenario III).

tannery clusters) was examined. It was found that C rises with an increase in the pollution load $C'W$ and vice versa (see columns 7 and 8, Table 3).

A reliable prognosis of pollutant migration is possible only if a validated model is available. Notwithstanding the shortcomings of the present model, it could be used to prog-

Table 3. Variation in TDS concentration for a few target points by varying K , A_L and C'

Target	$K0C$ (mg/l)	$K1C$ (mg/l)	$K2C$ (mg/l)	$A1C$ (mg/l)	$A2C$ (mg/l)	$C1'C$ (mg/l)	$C2'C$ (mg/l)
1	1999.9	1999.9	1999.9	2000.0	2000.0	1998.9	2000.9
16	1928.0	1931.7	1938.5	1925.4	1925.3	1928.3	1928.5
33	9915.5	9909.2	9929.6	9911.3	9910.9	9915.4	9915.5
35	5933.2	5778.8	5864.1	5972.2	5970.8	5933.0	5933.4
36	8316.5	8264.1	8292.5	8330.0	8329.6	8316.0	8316.6
38	8748.4	8629.7	8688.5	8781.8	8782.2	8748.0	8748.9
39	16737.0	16773.0	16758.0	16726.0	16726.0	16736.9	16737.1
58	3004.3	3003.2	3004.6	3004.6	3004.7	3004.0	3004.5
62	3877.8	3889.9	3890.5	3872.7	3875.9	3877.6	3877.8
64	6334.3	6191.1	6198.9	6392.7	6392.5	6336.3	6334.3
75	2308.0	2266.9	2275.5	2321.1	2322.2	2308.6	2308.0
77	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
81	2895.0	2913.8	2903.9	2890.1	2889.9	2895.0	2895.0

$K0$ is conductivity for calibrated model in m/d; $A_L = 30$ m (longitudinal dispersivity); $C' = 9000$ mg/l (concentration); $K0C$ is TDS concentration for $K0$, A_L and C' ; $K1C$ is TDS concentration for $K1 = (80\%$ of $K0$), A_L and C' ; $K2C$ is TDS concentration for $K1 = (120\%$ of $K0$), A_L and C' ; $A1C$ is TDS concentration for $A_L = 50$ m, $K0$, C' ; $A2C$ is TDS concentration for $A_L = 100$ m, $K0$, C' ; $C1'C$ is TDS concentration for $C1' = 7200$ mg/l, $K0$, A_L ; and $C2'C$ is TDS concentration for $C1' = 10800$ mg/l, $K0$, A_L . Targets shown in Figure 4.

nosticate some general inferences. The following three scenarios were considered for predicting the extent of pollution in the area at the end of a 20-year period.

- TDS load remains invariant during the entire period of prediction.
- TDS load is increased to double the present level (January 2001) during the entire period of prediction.
- TDS load is reduced to half the present level. The TDS load is a result of both the effluents discharged from the tanneries and the leaching of the previous adsorbed solutes in the unsaturated zone. Thus, effectively overall discharge from the tanneries is assumed to reduce about 50% of the present level.

The predicted TDS concentration level (scenario 1) for the year 2020 is shown in Figure 6a. It can be seen that C progressively increases in the area due to continuous addition of solids to the groundwater system. The area in which TDS content in groundwater may be more than 4000 mg/l is likely to be doubled within the next two decades from the present size between the river and town, towards north and west of Dindigul town. Figure 6b shows a comparison of observed and computed C for scenario 2. It can be seen that at the end of a 10-year period (2010), C will be the same as that for scenario 1, but may still be high at some locations. Figure 6c shows a comparison of predicted and observed C for scenario 3. It can be seen that at the end of a 20-year period (2020), C will be reduced but may still be high at some places. At the centre of the tannery cluster, C is reduced but in the northern side it increase due to movement of pollutant due to advection. Prognosis using the model confirms that the polluted area as well as the concentration of pollutants in the groundwater will continue to increase in future. The study also indicates that even if the pollutant sources were reduced to 50% of the present

level, TDS concentration in the groundwater, even after 20 years, would not be reduced below 50% of the original level (in 2001).

To conclude:

- The concentration of TDS has been computed through MT3D mass transport model, starting with a background concentration of 1000 mg/l. Even though TDS has been selected for simulation of contaminant migration, the migration of any species will follow a similar pattern as mass transport is primarily driven by advection.
- From transient condition, it is inferred that TDS concentration has steeply increased in and around the tannery cluster. The impact of varying TDS in the tannery belt is based on advection than dispersive mechanism.
- Despite lacunae in the database for the modelling of pollutant migration in the aquifer, it has shown that if tannery effluents continue to be discharged at the present level, both as regards the volume and TDS concentration, groundwater pollution will continue to increase.
- It has been noted that even if tannery effluents are reduced to 50% of the present level, even after 20 years, TDS concentration in groundwater will not be reduced to 50% of the original level (in 2001).

However, exact quantification of the affected area and concentration of pollutants in groundwater is possible only if one could make a valid model based on a more representative and accurate database.

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Lower vertebrates from the Late Palaeocene–Earliest Eocene Akli Formation, Giral Lignite Mine, Barmer District, western India

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The first assemblage of lower vertebrates comprising fish, crocodilians and snakes is recorded from subsurface beds of the Akli Formation sampled from the Giral Lignite Mine about 40 km NNW of Barmer in Rajasthan. The fish comprise sharks, rays, lepisosteids, osteoglossids, pycnodontids and enchodontids and include among others *Squatina*, *Ginglymostoma*, *Jaekelotodus*, and *Gymnura*, which previously were not known from the subcontinent, an unnamed new species of *Dasyatis*, and two unidentified ?pycnodontid-like teleosts. Reptiles are represented by crocodilians and ?boid snakes. The fauna supports a Late Palaeocene–Lower Eocene age and a coastal marine deposition under tropical-temperate conditions.

Keywords: Akli lignite, Palaeocene–Eocene, Rajasthan, vertebrates.

IN western Rajasthan, the Lower Tertiary successions of shallow marine sediments occur in vast peneplained, sand covered tracts in three major basins, namely Jaisalmer, Barmer and Palana-Ganganagar^{1–3}. These shelf sediments have attained great importance during the last four decades in view of encouraging prospects of occurrence of hydrocarbon, bentonite, and fuller's earth deposits. Despite this, their biotic content in general and vertebrates in particular remain inadequately studied apparently because of paucity of surface exposures. Open cast mines of lignite, bentonite and fuller's earth in several areas of Rajasthan and neighbouring Gujarat offer an easy alternative to this handicap though collecting sites often vanish by the next field season. Recently we sampled subsurface beds of the Akli Formation in a lignite mine at Giral and recovered rich vertebrate fauna that formed the basis for this contribution and is significant on four counts: (i) it is the first systematic record of vertebrate fossils from the Akli Formation, (ii) it includes four selachian taxa previously unknown from the subcontinent, (iii) it provides corroborative evidence on age and palaeoenvironment of Akli lignites, and (iv) it expands

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