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Review

Mass transport modeling of an industrial belt using visual MODFLOW and MODPATH: A case study

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Groundwater in an industrial belt (namely Upper Kodaganar River basin, Tamilnadu, India) is polluted due to discharge of untreated effluents from 80 operating tanneries. Total Dissolved Solids (TDS) measurements vary in and around the clusters of tanneries from 2,000 mg/l to 30,573 mg/l in open wells. A mass transport model was constructed to study the contaminant migration using Visual MODFLOW and MODPATH. An area of 240 km^2 was chosen to construct the groundwater flow model of the weathered portion of the unconfined aquifers. The shallow groundwater potential field computed through flow model was then used as input to the mass transport model. The mass transport model was calibrated with field observation. Sensitivity analysis was carried out whereby model parameters viz. transmissivity, dispersivity etc. were altered slightly and the effect on calibration statistics is observed. This study indicates that the transmissivity plays a sensitive role than the dispersivity. It shows that the migration phenomenon is mainly through advection rather than dispersion. Particle pathlines also had been computed to trace the movement of contaminants. The contaminant migration is being emanated from the tannery belt and polluted towards eastern side of the Kodaganar river. This modeling study has 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 it. The study suggests immediate measures for arresting the deterioration in groundwater quality as well as augmentation for restoration of aquifer in some parts of the study area.

Key words: Unconfined aquifer, tannery clusters, groundwater pollution, mass transport model, upper Kodaganar river basin, India.

INTRODUCTION

Study area, a granitic rock formation in Dindigul District (Tamilnadu), India, possesses poor groundwater potential. Serious contamination of both surface water, as well as groundwater, has been reported in this area as a result of uncontrolled discharge of untreated effluents by 80 functional tanning industries for the last three decades (Peace Trust, 2000; Mondal et al., 2002; Mondal and Singh, 2003a, 2004a; Mondal, 2007). The health of the rural farming community and people working in the tanning industries have been seriously affected and they are suffering from occupational diseases such as asthma, chromium ulcers and skin diseases (Paul Basker, 2000). About 100 km^2 of agricultural land has lost its fertility.

TDS concentration in groundwater at some places varies from 17024 to 30575 mg/l (Mondal et al., 2005). As the discharge of effluents is ongoing, a numerical simulation of further pollutant migration is carried out using Visual MODFLOW and MODPATH softwares. The numerical model of the area was developed using the finite difference technique coupled with method of characteristics and it also used to predict TDS migration for the next 20 years. These methods are described in detail in many published works, such as Trescott et al. (1976); Rushton and Redshaw (1979); Guiguer and Franz (1996); McDonald and Harbaugh (2003); Bakker et al. (2004); and Huysmans et al. (2006). There are a large number of reports and papers also available to describe the solute transport models to study the contaminant migration; a few of them are mentioned here. Examples of model applications to field problem include Konikow and Bredehoeft (1974); Robson (1974); Konikow (1976);

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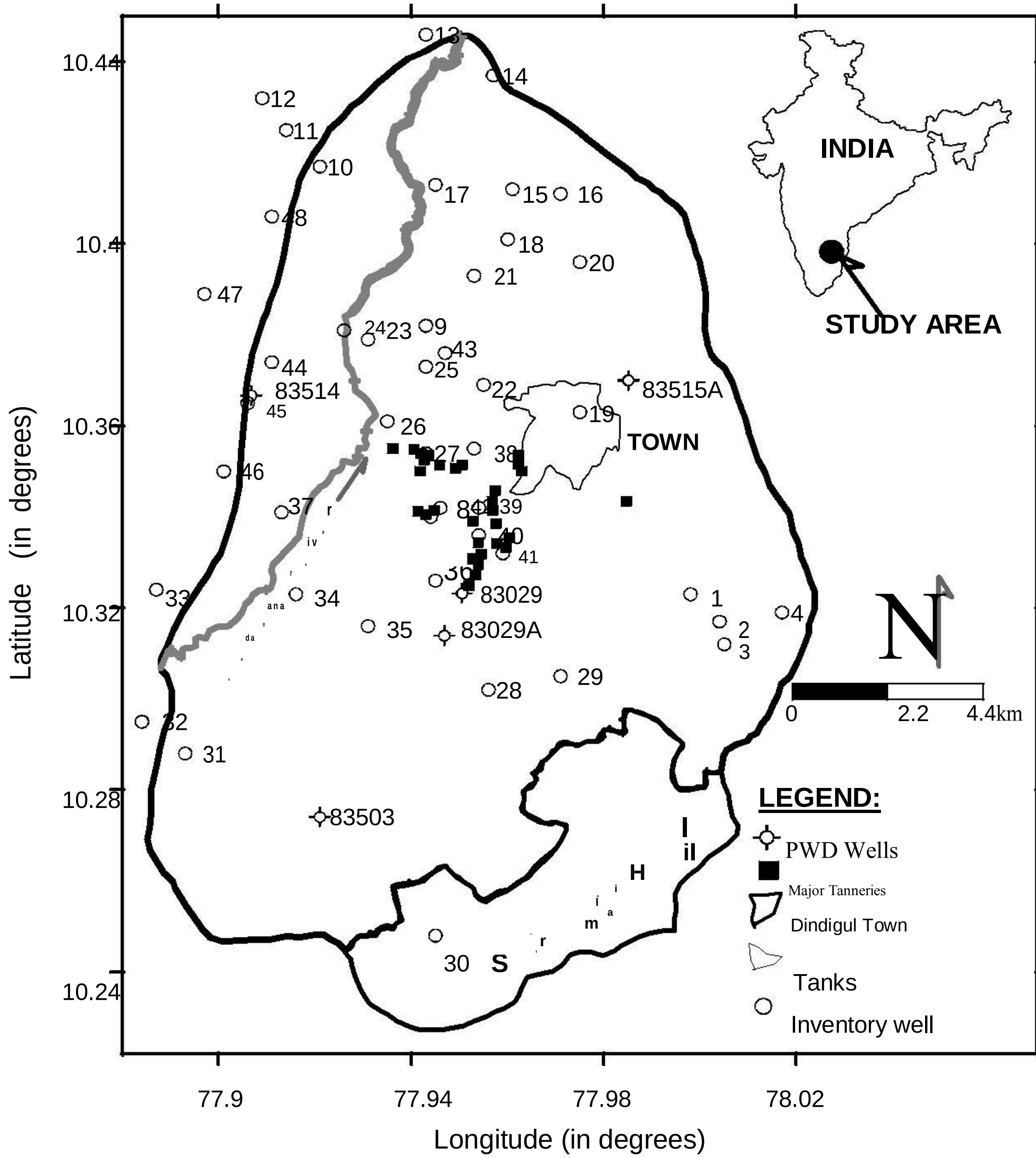

Figure 1. Location map

Konikow and Bredehoeft (1978); Rao and Gupta (2000); Ghosh Bobba (2002); Majumdar et al. (2002); Mckenzie et al. (2002); Mondal and Singh (2003b); Rahman et al. (2004); Tiwary et al. (2005); Martinez et al. (2006); Thangarajan et al. (2008); and Igboekwe et al. (2008). The computer software MOC based on finite difference coupled with the modified method of characteristics is used for the present study.

BACKGROUND OF THE AREA

Study area is a hard rock, drought prone region, which is situated in the Dindigul district of Tamilnadu, India (Figure 1) and lies in between $10^{0}13^{/}44^{//}$ - $10^{o}26^{/}$ 47 $^{//}$N latitude and $77^{0}53^{/}$ $8^{//}$ - $78^{0}01^{/}24^{//}$E longitude. It covers an area of about 240 km^{2}. It is characterized by undulating topography generally sloping towards north and northwest (Mondal and Singh, 2003b, 2004b). The highest elevation (altitude) in the hilly area (Sirumalai hill) is of order of 1350 m (amsl). But it varies from 360 m (amsl) in Southern portions to 240 m in the Northern parts of the area. There is no existing perennial stream in the area. Runoff from precipitation within the basin ends in small streams flowing towards main river Kodaganar. The average annual rainfall is in the order of 915.5 mm from the period of 1971-2001 (PWD, 2000). Geologically, the area includes Achaean granites and gneisses. Black cot-

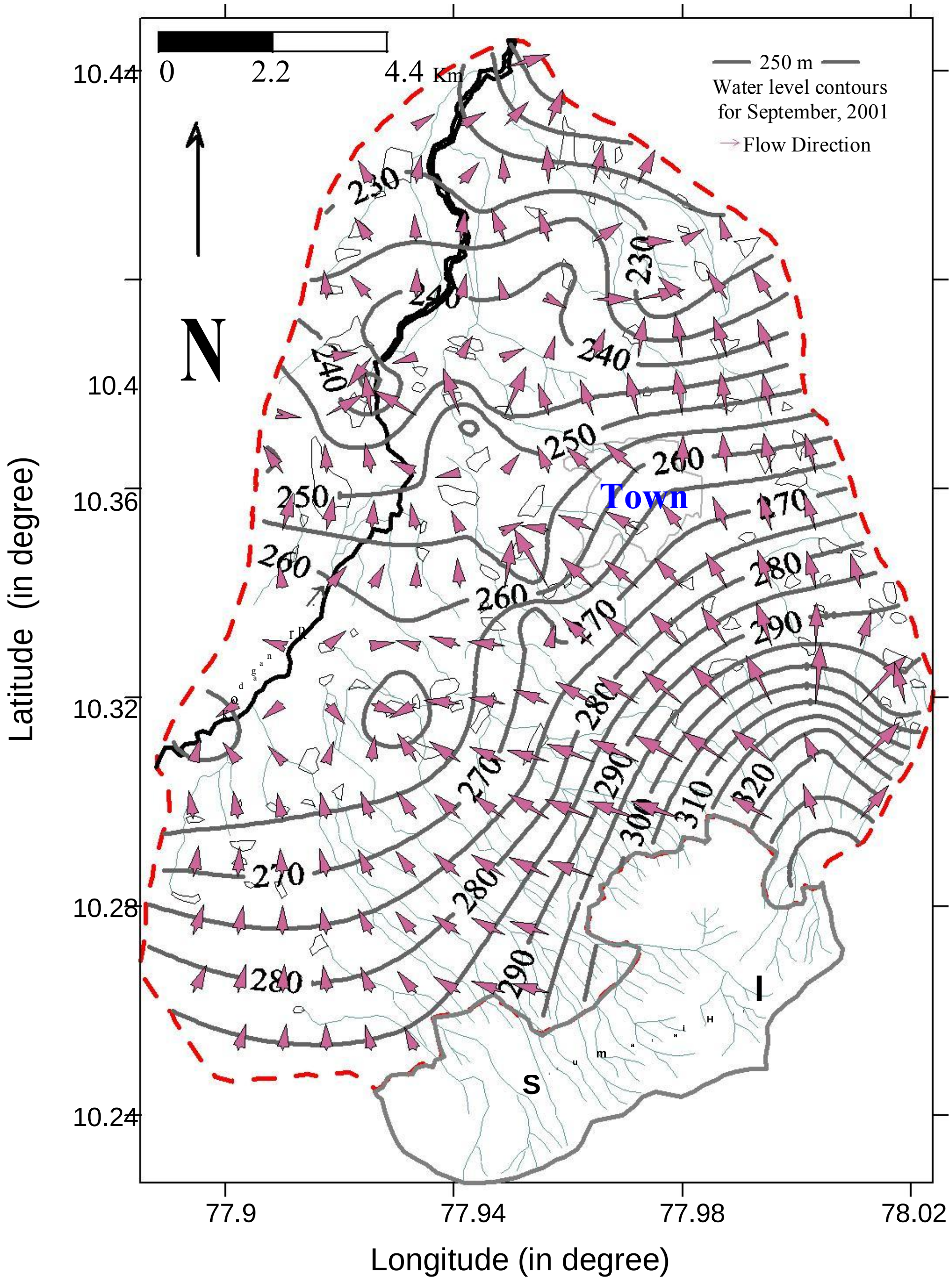

Figure 2. Water level contours (m, amsl) and flow direction (September 2001).

cotton soil and red sandy soil predominate. The thickness of soil varies from 0.52 to 5.35 m, but thickness of the weathered zone varies from 3.1 to 26.6 m (Mondal and Singh, 2003b). The distribution of the weathered zone varies from place to place within the area, and as such this shallow zone may not be a reliable source for large demands of groundwater. Weathered zone facilitates the movement and storage of groundwater and through a network of joints, faults and lineaments, which form conspicuous structural features. Apart from the structural controls on the groundwater movement, the terrain is covered with pediment and buried pediment at southern and western sides of the area. Another most dominant formation is the charnokite, which is found in the extreme southern and southeastern part of the Sirumalai hill. Groundwater is extracted through dug well, dug-cum-bore wells and bore wells for different purposes (Singh et al., 2003). The water level contours and flow direction were prepared with help of 48 water levels collected from the existing wells (shown in Figure 1) during September 2001. The general trend of groundwater motion under the shallow aquifer is in a north and northwest directions Figure 2

Table 1. TDS values in 5-PWD wells in mg/l.

Periods	83029	83029A	83503	83514	83515A
Jan. 1988	1046	465	1760	1500	555
Jan.1990	1309	630	1761	2103	762
July1991	1901	794	1856	2366	1217
Jan. 1994	1958	1008	2136	3210	1629

Table 2. Minimum, maximum, mean and standard deviation of groundwater samples in and around tannery belt (Dindigul, India).

	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
Std. Deviation	2507	307	163	545	34	140	1560	161	44

Ions in mg/l, *Maximum value obtained in the sample which collected from the adjutancy for the tannery, 106 groundwater samples were collected on January 2001.

HYDROCHEMISTRY

The quality of groundwater samples were taken twice a year from 5 existing dug wells (depth: 14.00 - 24.85 m) for the period from January 1988 to July 1995. Monitoring was performed by the Public Works Department of the Government of Tamilnadu (PWD, 2000). The locations of the wells are shown in Figure 1. The TDS concentration 'C' observed in the field at 5 dug wells for the period January 1988, January 1990, July 1991 and January 1994 are shown in Table 1. It shows that TDS is increasing over time. The PWD hydrochemical data indicates that the major ions such as sodium, magnesium and chloride, sulphate, and total hardness are all elevated as well (N.C. Mondal, unpub. Ph.D. Thesis). 106 groundwater samples were also collected during January 2001 from the represented dug wells and dug-cum-bore wells distributed throughout the area and analyzed and therefore, this data also could be incorpo-rated in the present study. The statistical parameters (i.e. minimum, maximum, mean, and standard deviation) of different chemical constituents of groundwater samples are shown in Table 2. This data has shown that ground-water is highly polluted due to the tannery effluents in the eastern side of the river Kodaganar and western side of the Dindigul town (Mondal et al., 2005). In order to know the distribution pattern of total dissolved solids (TDS), Na and Cl, and to demarcate the higher concentration zones in the study area, their contour maps were prepared with help of computer software SURFER 8.0 using kriging method. They are shown in Figures 3, 4, 5.

APPROACH FOR MASS TRANSPORT MODELING

The geometry and boundary conditions in the hard rock aquifer are generally complex. The analytical methods are rarely applicable to find a closed form solution of the partial differential equations of 2-D groundwater flow equation (Equation 1) and 2-D mass transport equation for a non-reactive (conservative) solute (Equation. 2) (Ruston and Redshaw, 1979).

$$\frac{\partial}{\partial x} K_{xx} \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} K_{yy} \frac{\partial h}{\partial y} = S_s \frac{\partial h}{\partial t} \pm W$$
……….. (1)

Where, K_{xx} and K_{yy} are the hydraulic conductivity along x and y directions, respectively, h is the hydraulic head, S_s is the specific storativity, W is the groundwater volume flux per unit area positive for outflow and negative for inflow, and x and y are the Cartesian coordinates.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[D_{xx}\frac{\partial C}{\partial x} + D_{xy}\frac{\partial C}{\partial y}\right] + \frac{\partial}{\partial y}\left[D_{yy}\frac{\partial C}{\partial y} + D_{yx}\frac{\partial C}{\partial x}\right] - \frac{\partial}{\partial x}(CV_X) - \frac{\partial}{\partial y}(CV_Y) - \frac{C'W}{nb}$$
… ………… (2)

where C is the concentration of solute at any point, D_{xx} and D_{yy} are the coefficients of hydrodynamic dispersion along x- and y-directions, respectively, D_{xy}, D_{yx} are the dispersion coefficients in the direction 45^0 from x or y axis; b is the saturated thickness of the aquifer; C' is the concentration of the contaminating solute at source or sink points; n is the effective porosity of the medium; W is the volume of contaminant per unit area reaching ground-water system (positive for outflow and negative for

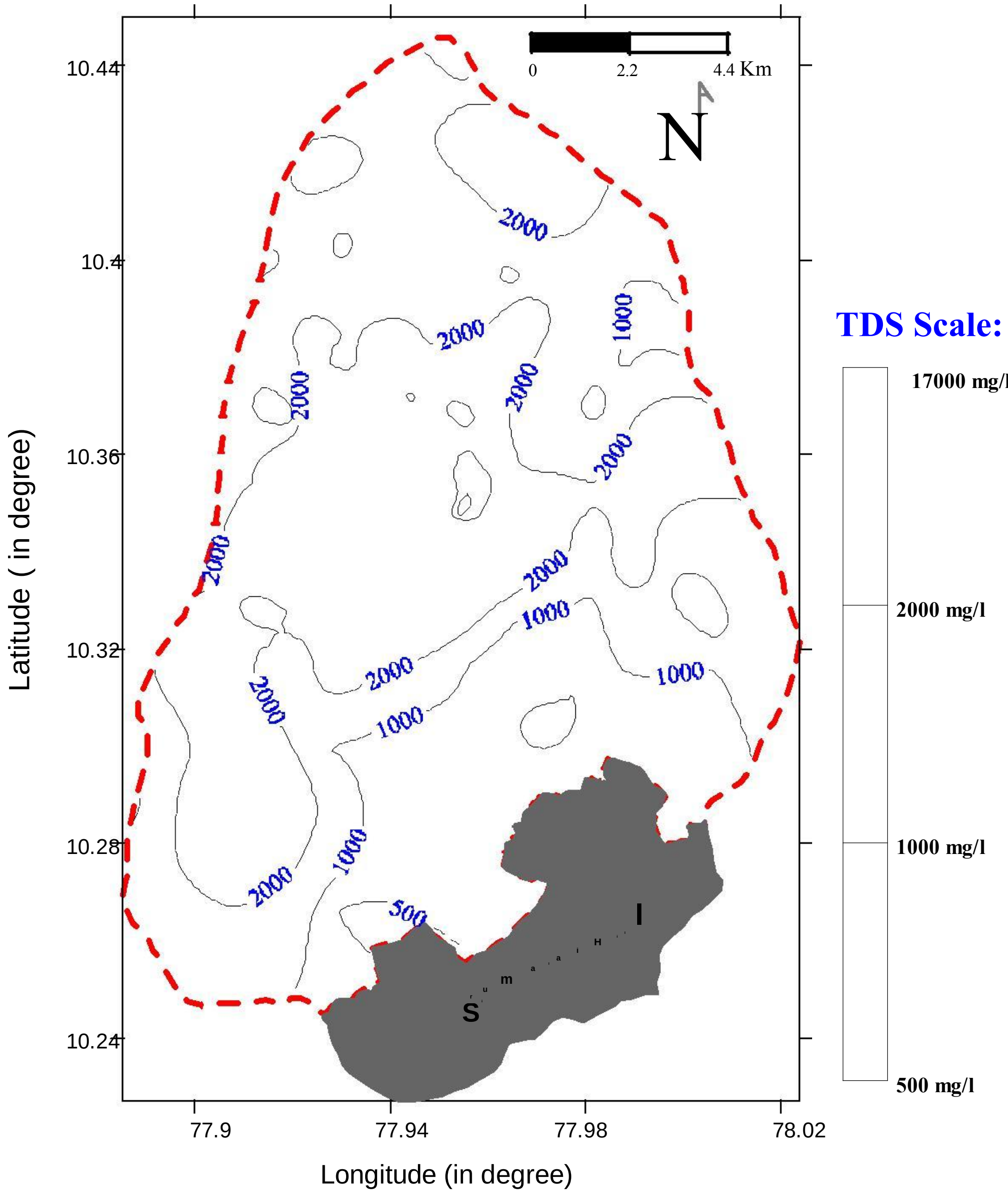

Figure 3. TDS shaded map (January 2001).

inflow); and $C'W$ is the pollutant load at a source or sink.

These equations are, therefore, replaced by approximate ones which are traceable by numerical methods. The most commonly used techniques are the finite element and finite difference methods. In this study only the finite difference approximation technique is used as it is easy to handle for numerical computations. The starting point for the application of this method is discretization of small rectangular sub-regions in a grid form. The partial differential equations hereby replaced by a finite different equation at each node. Several techniques such as interative alternating direct procedure and successive over-relaxation methods etc. are available for solving the set of the resultant simultaneous algebraic equations. The main stages of mass transport modeling 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.

Grid design: In order to setup the model in MODFLOW developed by the USGS, the area of interest needs to be divided into a series of grid blocks or cells (Anderson and

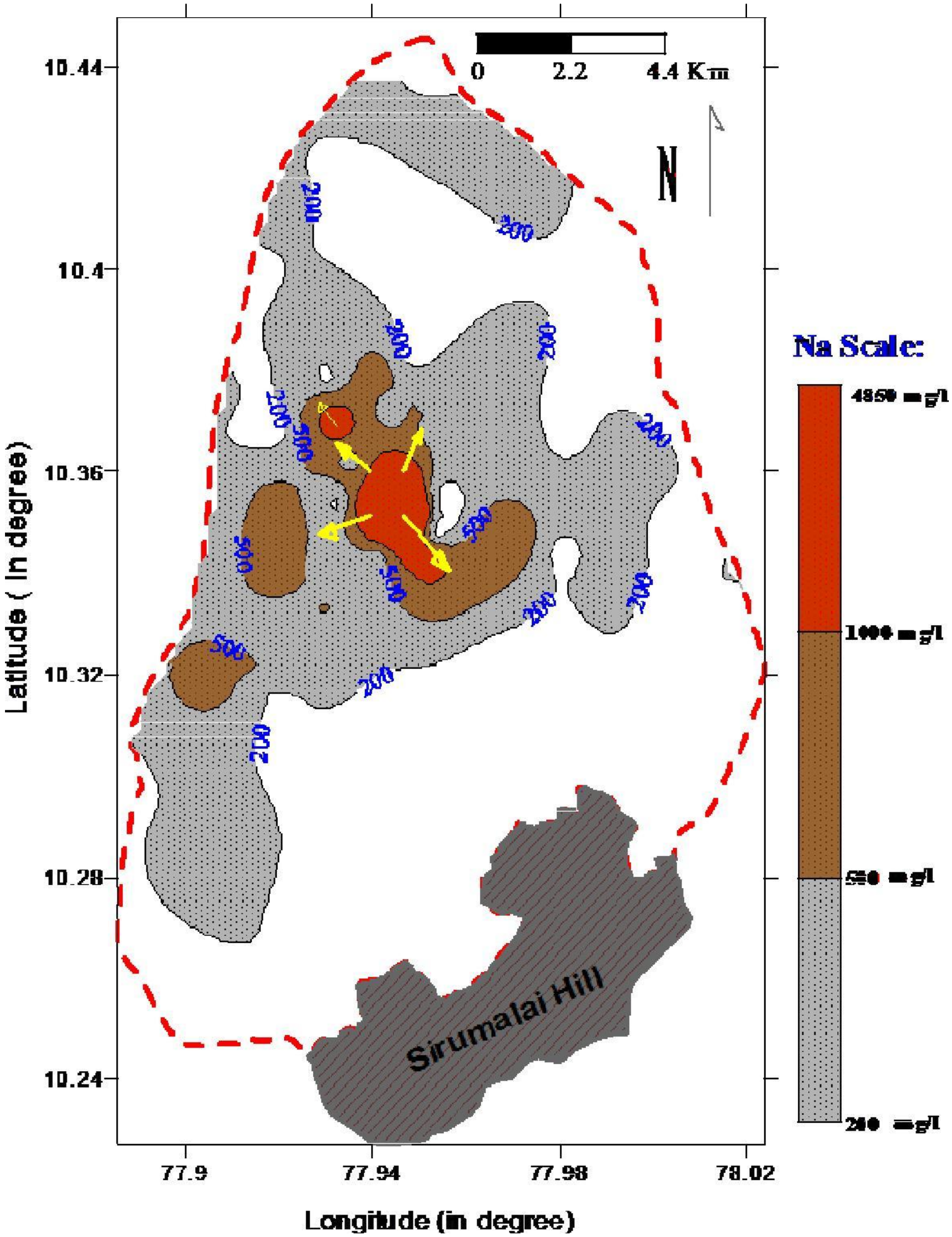

Figure 4. Na shaded map (January 2001).

Woessner, 1992). This grid has to be block-centered (that is, the groundwater heads will be computed at the center of each grid block). Taking into account that there are no steep slopes in the water table and that the real extend of the basin is about 209 km^2, a grid size of 250* 250 m^2 (total of cells = 3342) was selected (Figure 6). The layer is under 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 bottom of soil layer elevation and bottom elevation of the bedrock were entered at the model (Mondal and Singh, 2003b). This is simplification of the system based on the geological setting and the primary and secondary permeability. It is 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 SE to NW and the variation of thickness

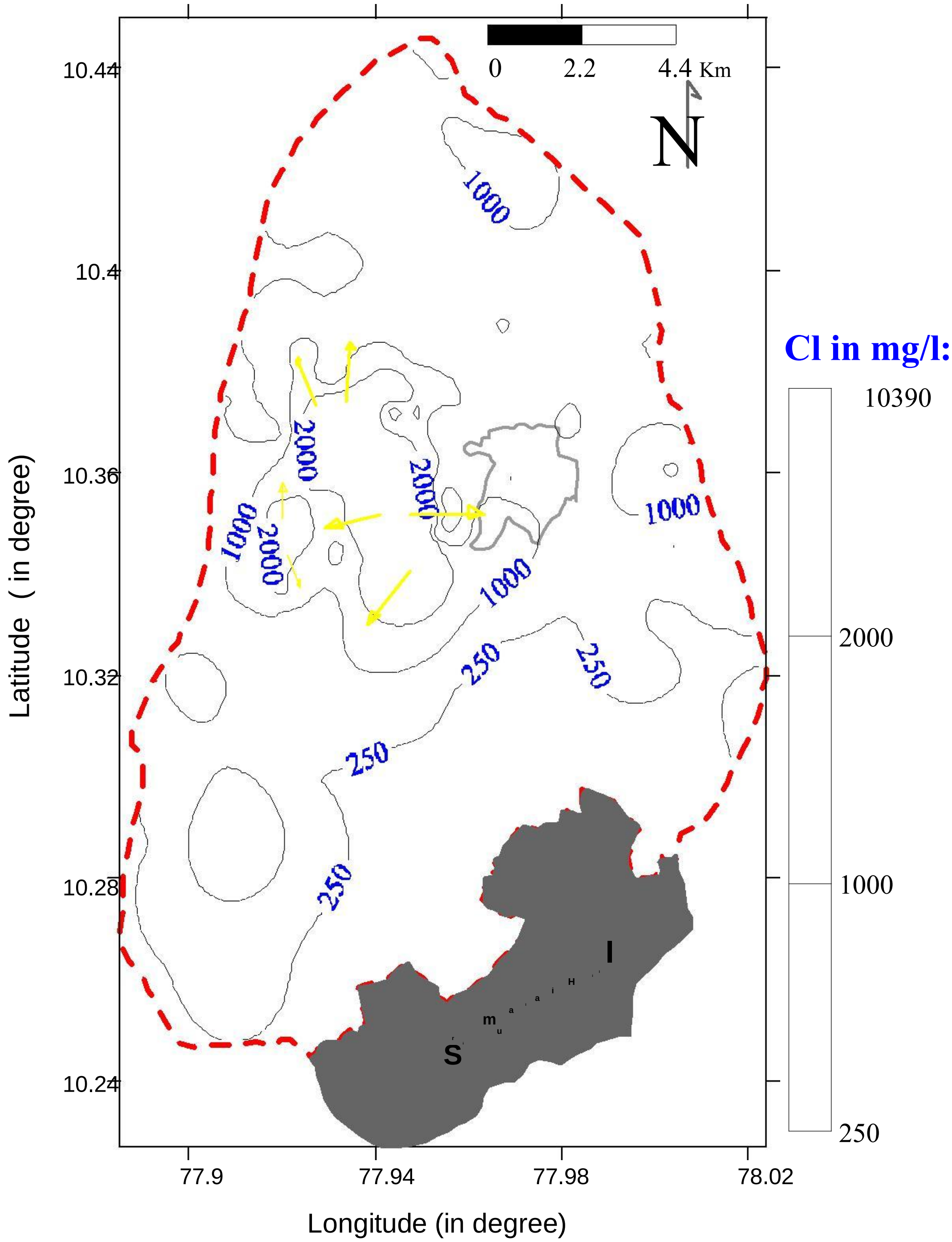

Figure 5. Cl shaded map (January 2001)

thickness (Mondal and Singh, 2003a).

Boundary conditions: In the present case, the boundary conditions had been determined based on the hydraulic condition. Initially these values will be applied in the conceptual model.

No-flow boundary: 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 zero (Anderson and Woessner, 1992). No-flow boundary has been set in the southern part of the area. There are two facts that justify the use of a no flow boundary: (1) Charnokite has been characterized as practically impermeable in the conceptual model and (2) The water table is close to the surface. A groundwater flow divide is therefore likely to occur

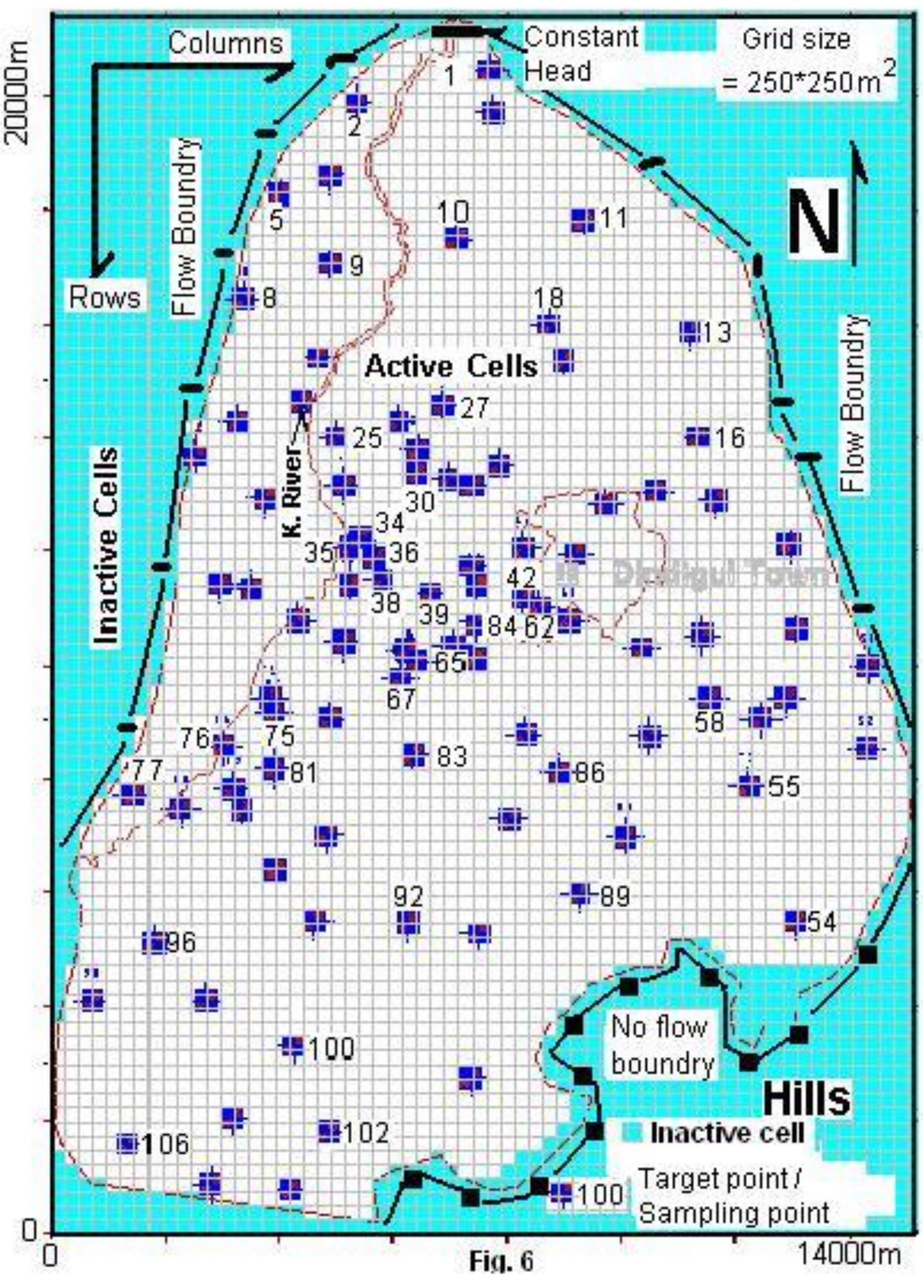

Figure 6. Grid map for mass transport modeling.

where the surface flow divide is.

Head dependent boundaries: The northern boundary of the area (towards hilly area) will be simulated through Generalized Head Boundary (GHB), in order to represent the groundwater discharge. These values will be used in the steady state simulation. At the calibration time, due to lack of data it will be assumed as constant. Other important boundaries: (1) The weathered part of aquifer will be considered as a porous one, (2) Areal recharge and pumpages will be assigned at a systematic manner (PWD, 2000; Mondal and Singh 2004b; N.C. Mondal, unpub. Ph.D. Thesis) and (3) wherever exposures are present, transmissivity values will be approximately zero and assigned as per its dimension.

Assumptions used in the model

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 (extend in the granite) do not take part either in the groundwater flow or in the mass transport. The aquifer under weathered zone

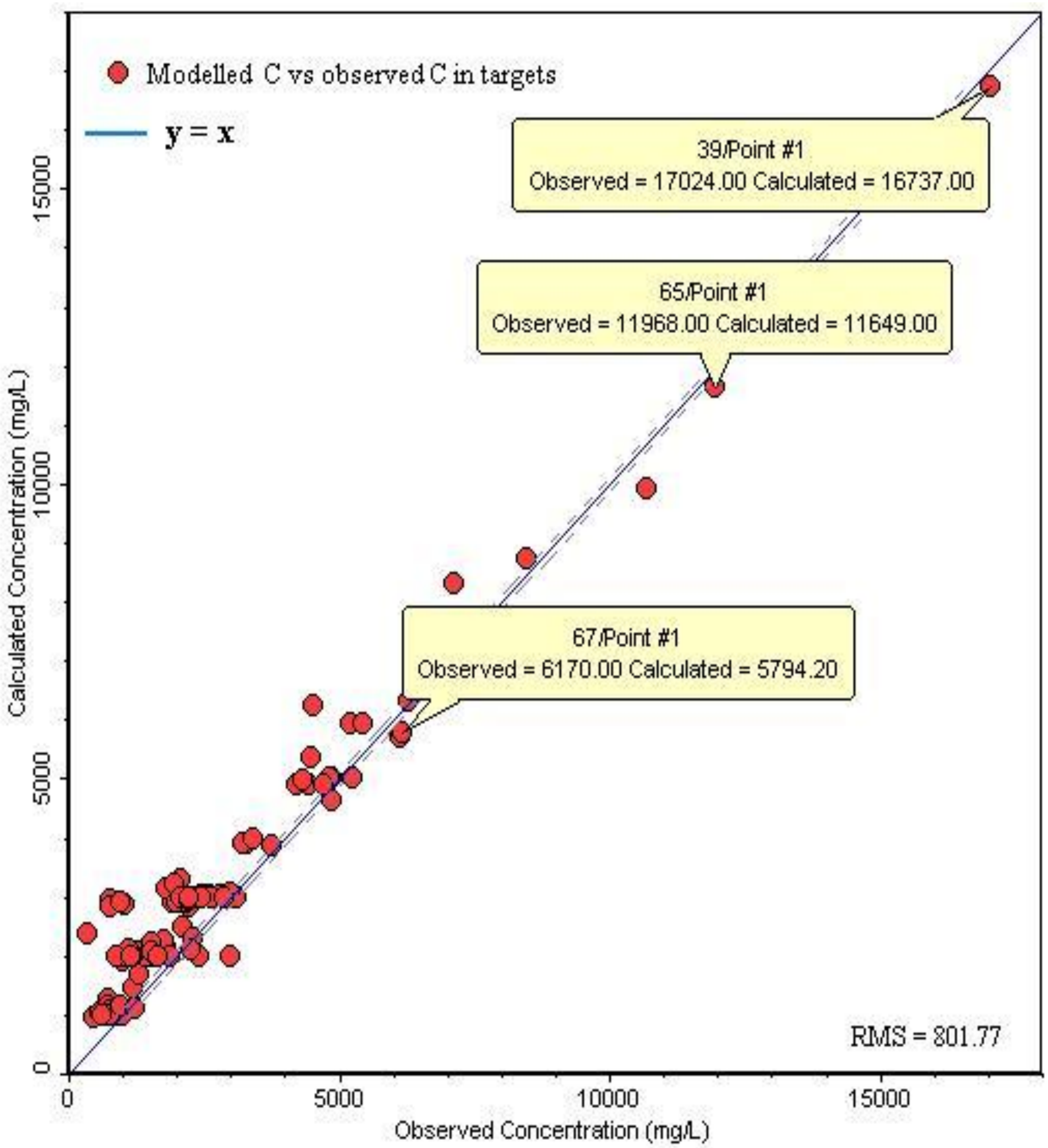

Figure 7. Computed vs. observed C in the steady state (January 2001)

is also treated as a porous one for modeling purposes. The 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 runoff. An effective porosity of 0.2, longitudinal dispersivity of 30 m, transverse dispersivity of 10 m (GEC, 1997) and 1000 mg/l of TDS as constant concentration were uniformly assumed for the entire interested area. There are no perennial rivers in the study area. During NE-monsoon period (October-December) the main river Kodaganar influences to the groundwater system. It was simulated in the model as supported by river boundary of Visual MODFLOW during October- December. The mass transport model was calibrated in two stages: steady state and transient state. It was also assumed that TDS do not influence the density and viscosity values, which may affect the groundwater flow and pollutant migration. The computer software based on the groundwater flow equation and the Modified Method of Characteristics (MMOC) is uses. The various parameters (as collected from the field) were assigned to the corresponding nodes.

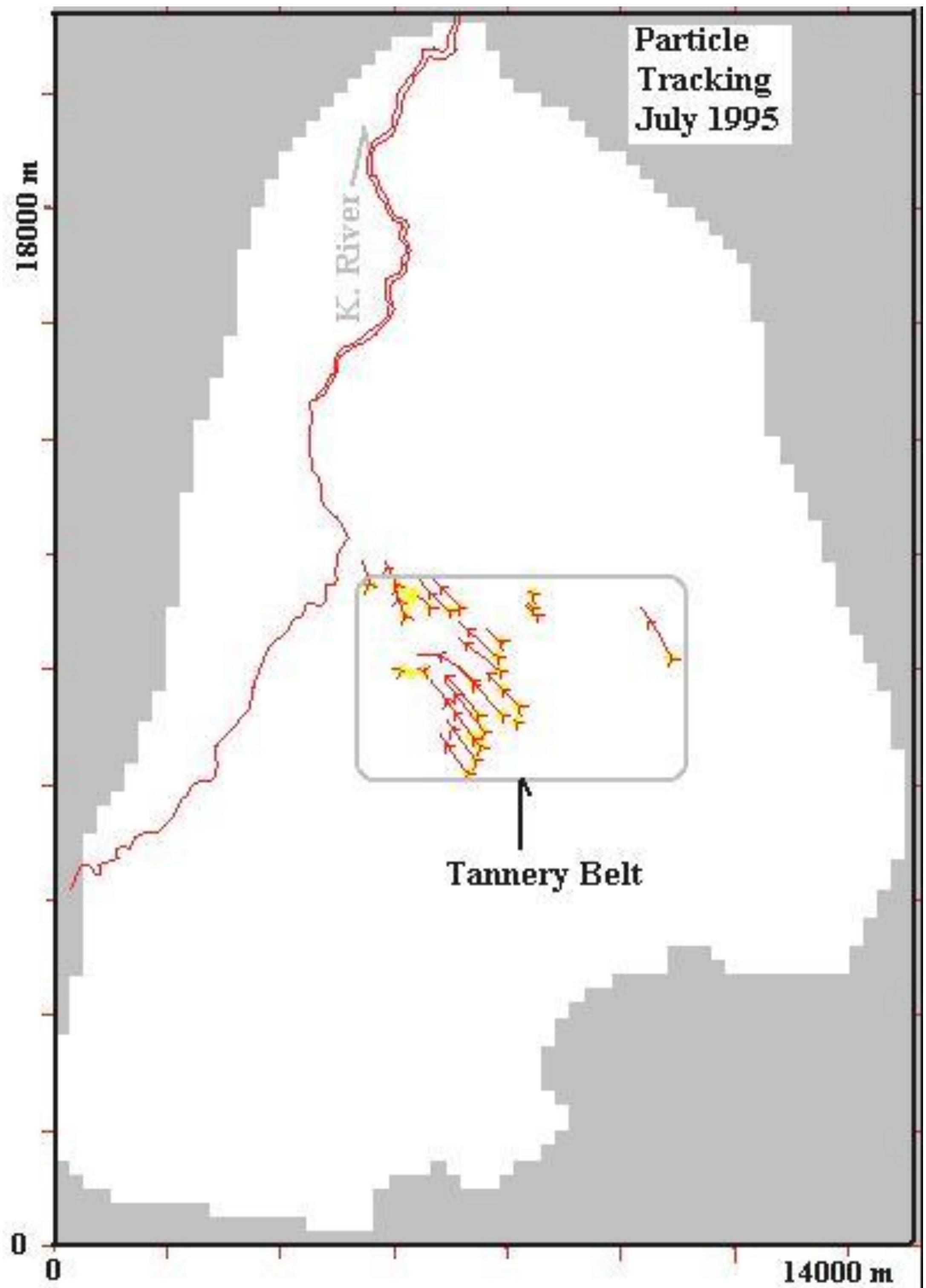

Figure 8. Groundwater streamlines computed for 7 years since 1988

Model calibration

The purpose of the calibration of a groundwater flow model is to demonstrate that the model can response field measured heads and flows, which are the calibration values (Anderson and Woessener, 1992). The purpose of this modeling exercise is to solve an inverse problem, that is, to find a set of parameters, boundary conditions

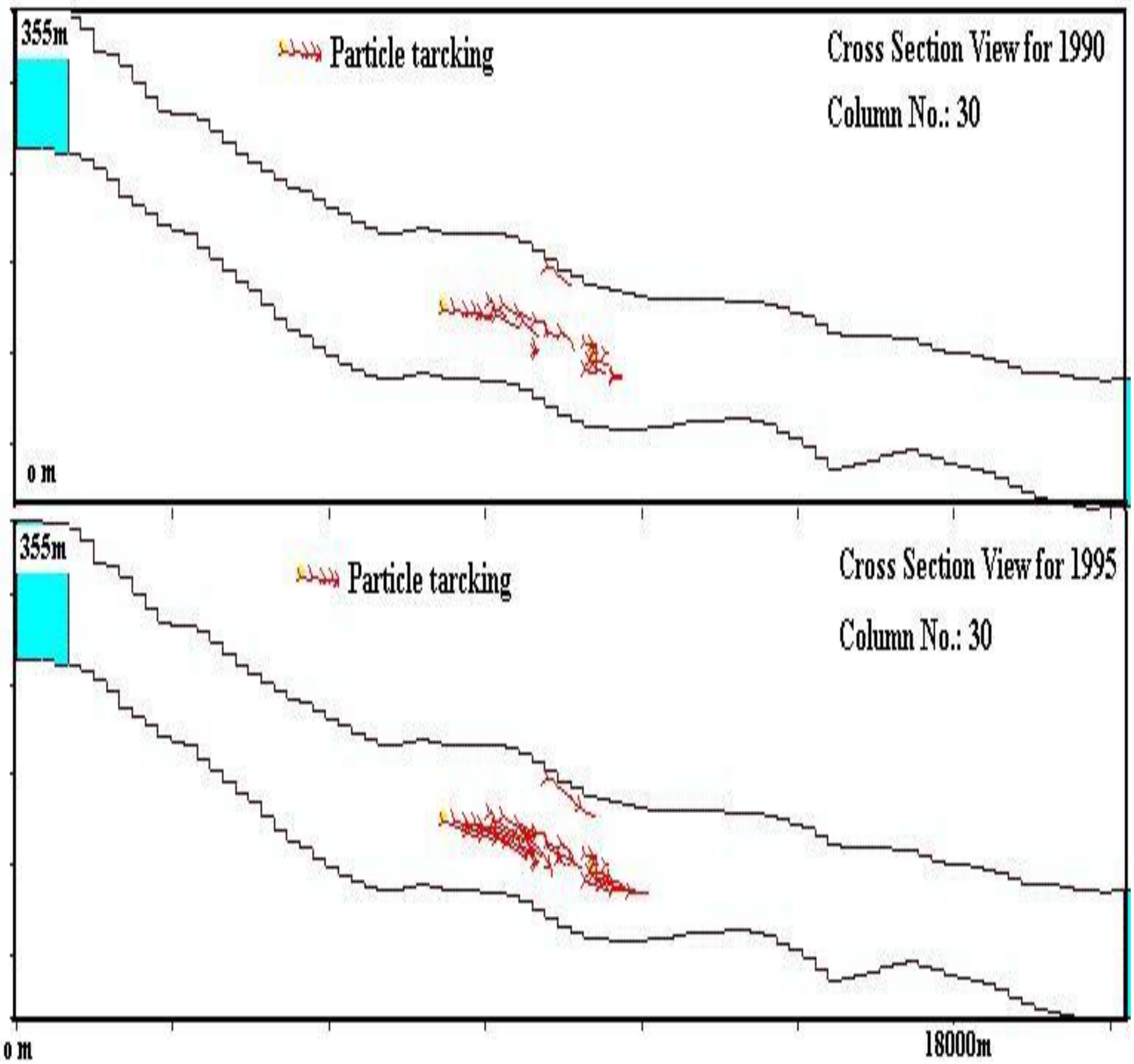

Figure 9. Cross-section view for particle tracking July 1990 and 1995 (Column 30)

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 can not be quantified is being used (as opposed to an automated calibration procedure). Nevertheless, this method is largely influenced by the modeler's expertise and biases. The calibration parameters set in this modeling exercise are the generalized head boundary, recharge, evapotranspiration, hydraulic conductivity and specific yield etc (N.C. Mondal, unpub. Ph.D. Thesis; Singh and Thangarajan, 2004). The calibrated hydraulic conductivity is assigned zone wise. In the southeastern part was assigned the conductivity as 3 m/day, in the central part as 8 m/day and in the northwestern part as 12 m/day whereas specific yield (S_y) are assigned as 0.0005, 0.002 and 0.003, respectively, corresponding the above zones of the area. The calibrated recharge values have been divided into four zones (Mondal and Singh, 2004b). The extreme southern zone is assigned as 200 mm/year, next zone as 130 mm/year, then third zone as 110 mm/year and the extreme northern zone as 80 mm/year. But the evaporation is estimated to a maximum rate of 70 mm/year with an extinction depth of 3.0 m based on the type of crops and plants that grow in the area. The steady state flow model was also calibrated in April 2001 for the real representation of the study area. The summary of this calibration is presented in Table 3. It shows that the water levels monitored from 48 observa-

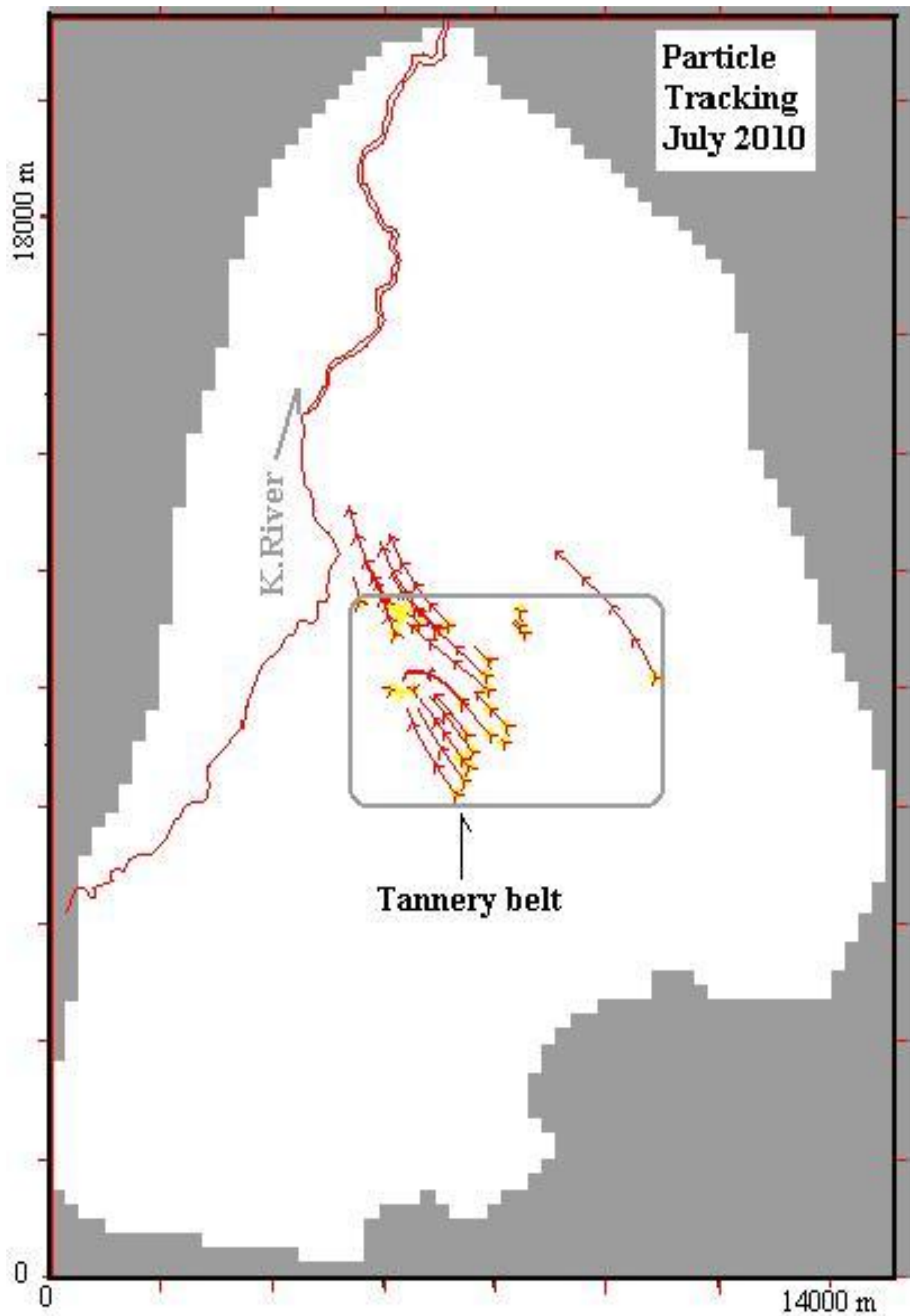

Figure 10. Streamlines migration predicted up to 2010 since 1988.

observation wells and 5-PWD wells (shown in Figure1) during April 2001 vary from 219.40 to 328.76 m (amsl) whereas the computed water levels from 220.13 to 328.62m (amsl). It indicates the minimum and maximum residuals are 0.02 m and 0.95 m in between observed and calibrated hydraulic heads at the targets with mean

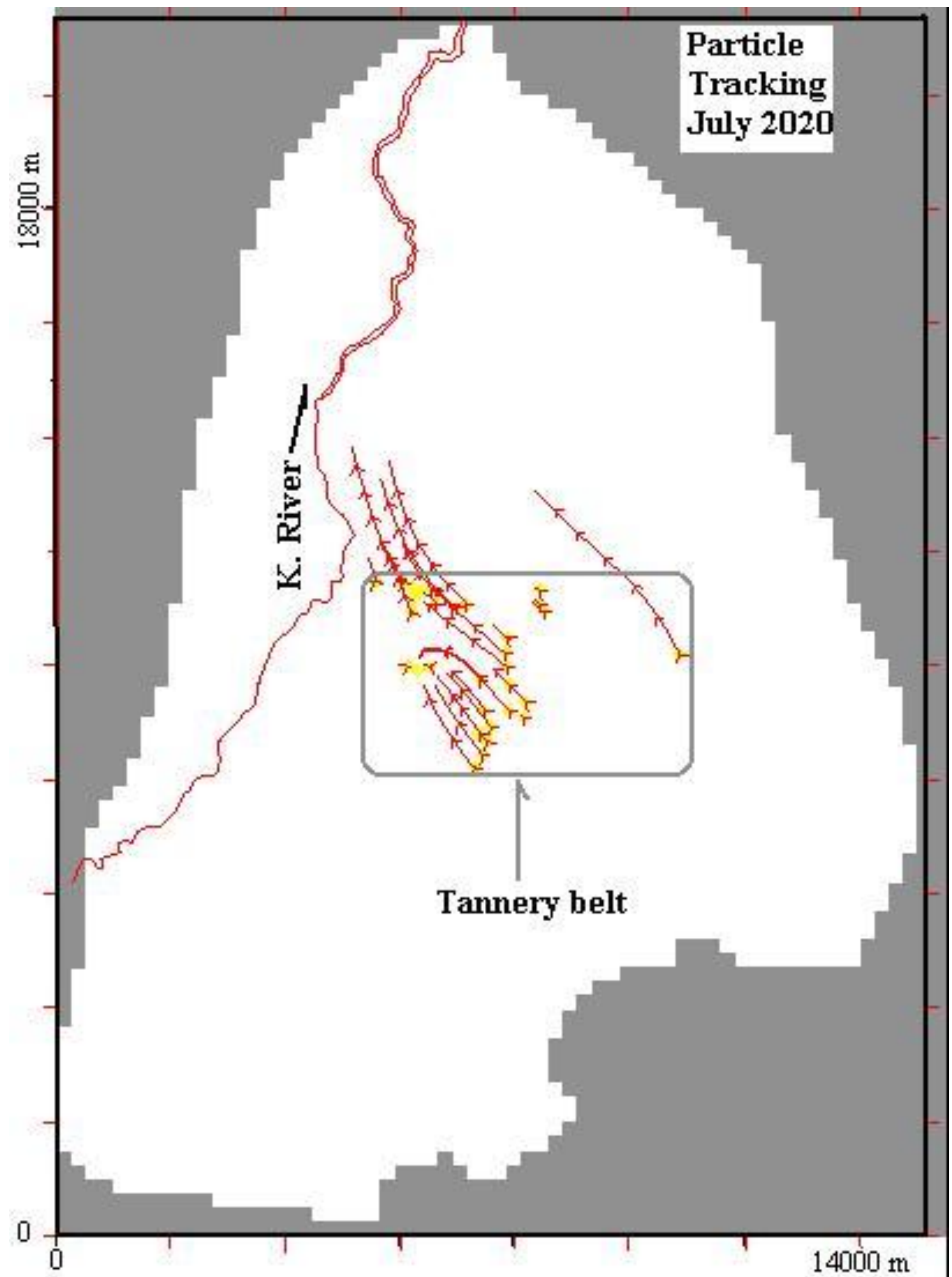

Figure 11. Streamlines migration predicted upto 2020 since 1988

0.45 m but the standard error is 0.04 m.

Steady state condition

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 based on the geological setting and location of the tanneries. However the situation could not be improved much. This may be due to a variety of factors; the most important which are the deficiencies and inaccuracies in the historical database. To get the real representation of

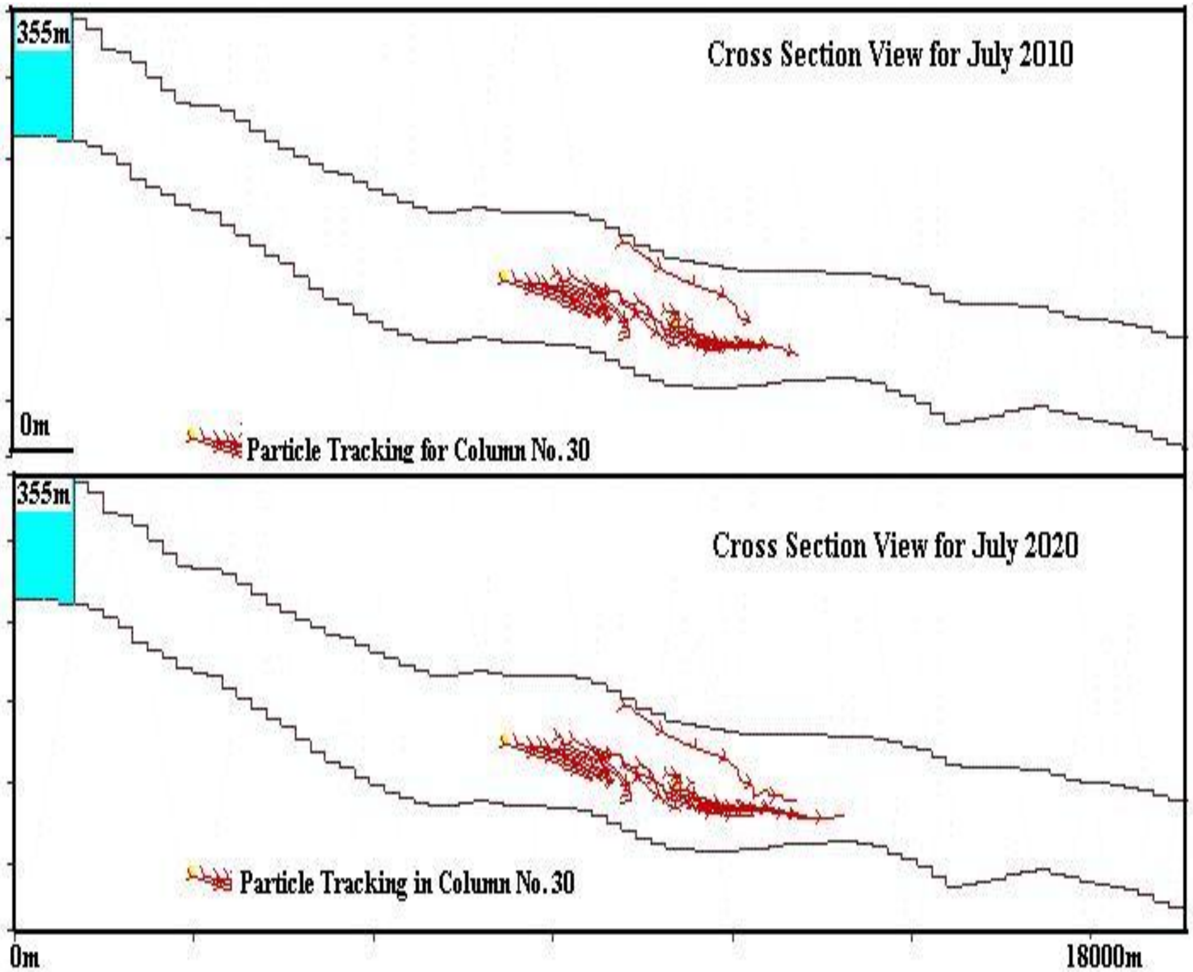

Figure 12. Cross-sectional view for particles tracking (July 2010 and July 2020)

the aquifer system, field data (January 2001) was considered for another steady state condition and it also run to visualize the mass transport model. The computed versus observed C is illustrated in Figure 7. This indicates that most of the calculated TDS-values are little higher than observed values, but others are fallen along the straight line y = x.

Transient condition

A time variant simulation was carried out for the period January 1988 to July 1995 based on available of historical data. The pollution load was reaching the groundwater system at various clusters during this period. The computed 'C'-values for the PWD-wells, which are located nearby the tannery clusters, is being increased steeply than the other wells.

SENSITIVITY ANALYSIS

The impact of varying conductivity, dispersivity, and $C^{/}W$ (pollutant load at the source) was studied. The variation is caused in the TDS concentration 'C' at some selected node points as result of some variations in these parameters is shown in Table 4.

Conductivity: This parameter was changed by 20% (upwards and downwards) of the value assigned in the model, at each node the change in the conductivity affects the groundwater velocity causing redistribution of solute concentration. In general, the higher the conductivity, the 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 of Table 4).

Dispersivity: The longitudinal dispersivity was changed to 50 m and 20 m (from 30 m). The transverse dispersivity was taken as one-third of the longitudinal dispersivity. No significant changes in the TDS concentration were noticed due to increase in the dispersivity (see columns 5 and 6 of Table 4). This shows that advection and not dispersion is the predominant mode of solute

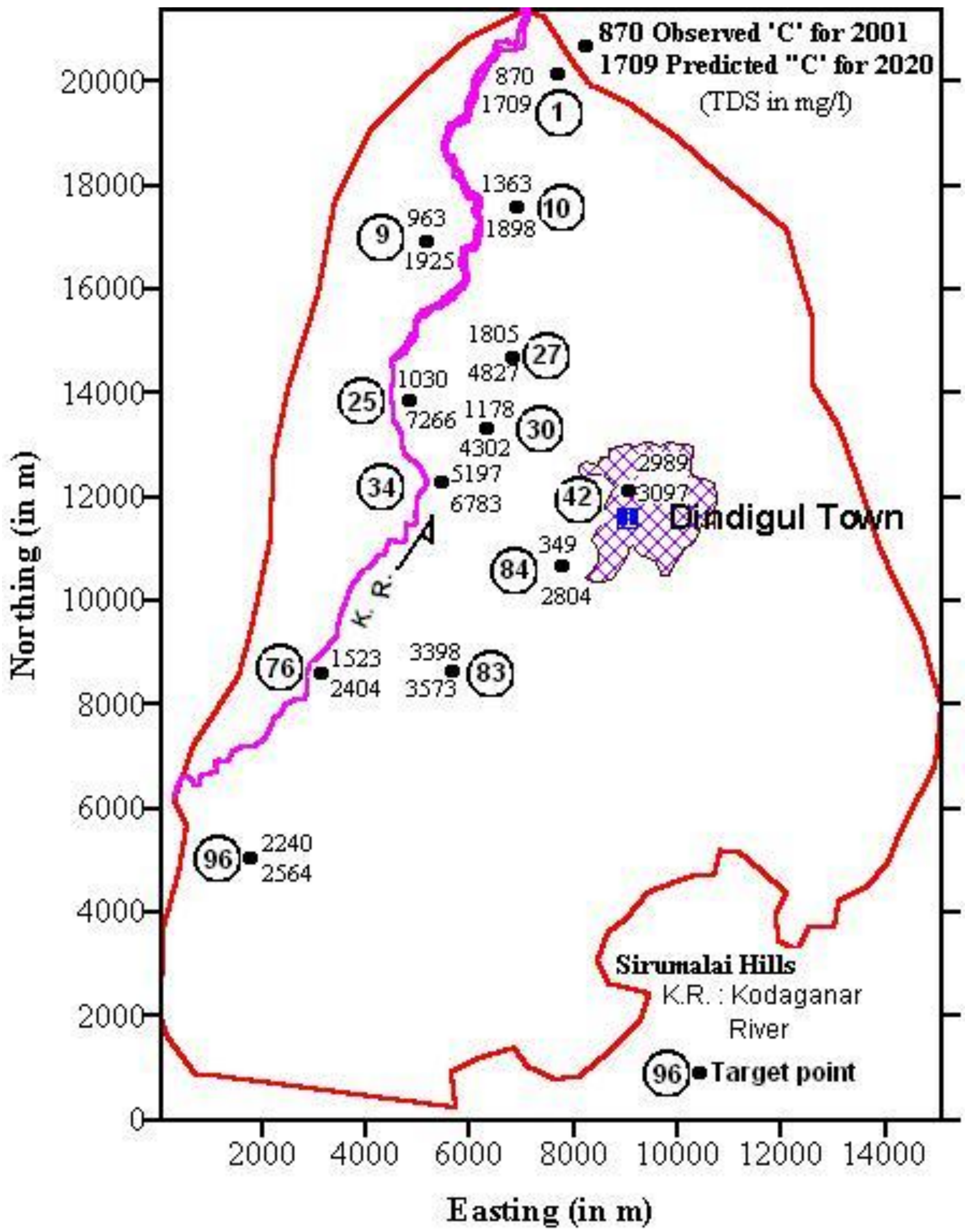

Figure 13. Predicted TDS concentration in mg/l for January 2020 (Scenario-1)

TDS pollution load at sources points ($C^{/}W$): The effect of varying this parameter by 20% (upwards and downwards) at 32 source points (nodes taken at the major tannery clusters) was examined and it was found that TDS concentration 'C' rises with an increase in the pollution load $C^{/}W$ and vice versa (see columns 7 and 8 of Table 4).

PARTICLE STREAMLINES

In addition to the numerical finite difference solution, three dimensional particle tracking is also used to compute two- dimensional streamlines and the position of the particle a specified points in time. The concept of particle tracking is adapted here for tracing the movement of contaminants in the groundwater flow domain from the various contaminant sources. The method is based on the linear (Darcy) flow rule. This allows an analytical expression to be obtained describing the flow path within a grid cell. Given the initial position of a particle anywhere in a cell, the co-ordinates of any other point along its path line within the cell and the time of travel between them can be computed. The computer program MODPATH developed by the USGS (Pollock, 1989) had been used

Table 3. Steady state calibration (April, 2001)

Sl No.	Targets*	Observed Head (m)	Computed Head (m)	Residual Error
1	1	309.00	309.58	-0.58
2	3	328.76	328.62	0.14
3	9	245.70	245.97	-0.27
4	10	231.40	232.13	-0.73
5	14	219.40	220.13	-0.73
6	15	238.20	237.78	0.42
7	16	234.20	235.09	-0.89
8	17	234.30	234.43	-0.13
9	18	243.80	243.69	0.11
10	19	265.30	265.28	0.02
11	21	244.50	243.81	0.49
12	22	249.00	249.13	-0.13
13	23	238.00	238.38	-0.38
14	24	239.00	239.26	-0.26
15	25	258.00	257.50	0.50
16	27	256.10	256.31	-0.21
17	31	273.80	274.04	-0.24
18	34	265.80	266.13	-0.33
19	37	262.10	261.36	0.74
20	38	259.00	258.44	0.56
21	39	254.40	254.86	-0.46
22	41	274.05	273.10	0.95
23	42	258.80	259.47	-0.67
24	43	243.70	244.55	-0.85
25	44	252.30	252.01	0.29
26	83029	266.21	266.79	-0.58
27	83503	289.35	289.79	-0.44
28	83514	248.99	249.10	-0.11
29	83029a	273.05	273.80	-0.75
30	83515a	256.83	257.41	-0.58

***Target points are shown in Figure 1.

to calculate two-dimensional particle tracking from steady state flow simulation using MODFLOW.

The computed steady state head distribution and porosity values had been use to compute the velocity field. A semi-analytical particle-tracking scheme has been used to compute streamlines and the position of particle at specified points in the time by MODPATH. The semi-analytical particle tracking method was used with velocities generated from block- centered finite-difference groundwater flow models. The method is based on the assumption that each directional velocity component varies linearly within a grid cell in its own coordinate directions. This assumption allows an analytical expression to be obtained describing the flow path within an individual grid cell. Given the initial position of a particle anywhere in a cell, the coordinates of any other point along its path line within the cell and the time of travel between them can be computed directly. For steady-state systems, the exit point for a particle entering a cell at any arbitrary location can be computed in a single step. By following the particle as it moves from cell to cell, this method can be used to trace the path of a particle through any multidimensional flow field generated from a block-centered finite-difference flow model (Pollock, 1988). Here the streamlines account for the advective transport only. Groundwater streamlines in the area had been computed to trace the movement of contaminants for 13 years starting from September 1988 and the cross-section view was also prepared. The streamlines indicate predominant direction of the contaminant migration emanating from the tannery belt, drain and Kodaganar river. The advective transport makes the contaminants to migrate

Table 4. Variation TDS concentration for a few target points by varying K, A_L and $C^{/}$

Targets	K0C (unit mg/l)	K1C (unit mg/l)	K2C (unit mg/l)	A1C (unit mg/l)	A2C (unit mg/l)	$C1^{/}C$ (unit mg/l)	$C2^{/}C$ (unit 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	1673.71
58	3004.3	3003.2	3004.6	3004.6	3004.7	3004.0	3004.5
62	3877.8	3889.9	3890.5	3872.7	3872.9	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	3895.0

K0 is conductivity for calibrated model in m/d; A_{L}= 30m (longitudinal dispersivity); $C^{/}$=9000mg/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}= 20 m, K0, $C^{/}$; $C1^{/}C$ is TDS concentration when $C1^{/}$ =7200mg/l, K0, A_L; and $C2^{/}C$ is TDS concentration when $C1^{/}$ =10800mg/l, K0, A_L; Targets were shown in Figure 6).

about 1.0 -1.5 km during last 7 years with a maximum groundwater velocity of 1.6 m/day (Figure 8). The contaminant migration from the tannery is limited to the area extending up to 25 km^2 towards the eastern side of the river. It is noted that the contaminant migration is not taken place toward the western side of the river due to its presence. The cross-section view is clearly showing that the contami-nant is moving slowly downwards (Figure 9).

This same model (streamline) had been used for the extension of contaminant migration to 2020 (Figures 10, 11). Simultaneously, the cross-section views of these particles were also illustrated in Figure 12. These figures show that the particles are slowly moving downwards direction of the aquifer. It means pollutant may be slowly entered into the deeper aquifer. The strength of the contamination is being increased in terms of magnitude wise as well as spatially.

PREDICTION MODEL

A reliable prediction of the tannery pollutant migration is possible only if a validated model is available. The present model could be used to predict some general inferences. The following three scenarios were considered for predicting the extent of pollution in the tannery belt at the end of a 20 years period.

1) Total dissolved solids load remains constant during the entire period of prediction;
2) TDS load is increased to double of the present level (January 2001) during the entire period of prediction; and
3) The load is reduced to half of 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 the 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 13 and the results are presented in Table 5. It can be seen that the TDS concentration 'C' progressively increases in the area due to continuous addition of solids to the groundwater system. The area 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 in between river and Dindigul town towards north and west of this town. The Table 5 indicates a comparison of observed and computed TDS concentration 'C' for Scenario-2. It can be seen that at the end of a 10 years period, TDS concentration will be the same of Scenario-1, but still it may be quite high at some locations. This table also shows a comparison of predicted and observed TDS concentration 'C' for Scenario-3. It can be seen that at the end of a 20 years period (2020) TDS concentration 'C' will be reduced but will be quite high at some places. At the centre of the tannery cluster TDS concentration is reduced, but in the northern side it is increasing order due to the advective movement of the pollutant. Predic-tion 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 indica-ted that even if the pollutant sources were reduced to half fold of the present level, the TDS concentration level in the groundwater, even after 20 years, would not be re-

Table 5. Predicted TDS concentration for a few target points.

Targets*	Observed 'C' for January 2001	Predicted 'C' for January 2020 (Scenario-1)	Predicted 'C' for January 2010 (Scenario-2)	Predicted 'C' for January 2020 (Scenario-3)
1	870	1709	1807	1911
9	963	1925	1857	1919
10	1363	1898	1809	1711
25	1030	7266	7539	785
27	1805	4827	4362	4757
30	1178	4302	7976	4244
34	5197	6783	6948	2051
42	2989	3097	3131	1065
76	1523	2404	2540	2404
83	3398	3573	3349	877
84	349	2804	2931	877
96	2240	2564	3553	2562

***Target points are shown in Figures 6 and 13.

duced below 50% TDS of 2001.

RESULTS AND CONCLUDING REMARKS

- Groundwater is in worse condition due to continuous discharge of untreated effluents from 80 functional tanneries in the study area.
- Streamlines indicate predominant direction of the contaminant migration emanating from the tannery belt drain toward Kodaganar river. This migration from the tannery is limited to the area extending up to 25 km^2 towards eastern side of the Kodaganar river. It is noted that the contaminant migration is not taken place toward the western side of this river. The cross-section view is also clearly showing that the contaminant is migrating slowly towards river and also deeper aquifers.
- TDS concentration has been computed through MT3D mass transport model starting with a background concentration 1000 mg/l. Even through TDS has selected for simulation of contaminant migration, the migration of any species will follow a similar pattern as mass transport is primarily driven by advection.
- It is inferred that TDS concentration is steeply increased in and around the tannery clusters under transient condition. The impact of varying TDS in the tannery belt is based on the advection than dispersive mechanism.
- Mass transport modeling in the damaged aquifers is shown indisputably 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 is noted that even if tannery effluents are reduced to half fold of the present level, even after 20 years, the TDS concentration in groundwater will not be reduced to 50% of the original level (2001). This case study indicates that both Visual MODFLOW and MODPATH are versatile tools for groundwater mass transport modeling. It is also very important to evolve suitable measure for reversal of the damage caused to tannery effluents in this locality. In areas, where water is available abundantly, flushing out of these discharge salts to the nearby streams can be adopted. But for areas like Upper Kodaganar River basin, where water is scarce, some other methods such as biological treatment method, physical method and chemical method are to be adopted. Out of them physical method like creation of percolation ponds and check dams for groundwater recharge is an alternative to check the problem of groundwater pollution. Such method, which will be found to be successful in reducing the pollution load of groundwater and agricultural soil, are to be adopted. There are more than 92 medium and minor irrigation tanks in the study area, which influence the shallow aquifer during surface water spread (monsoon season). These can be used for augmentation of groundwater resources through artificial recharge structures.

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