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Assessment of groundwater pollution in the Patancheru Industrial Development Area and its environs, Medak District, Andhra Pradesh, India

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Abstract A number of chemical and pharmaceutical industries have opened since 1978 in the Patancheru Industrial Development Area of Medak district, Andhra Pradesh, India. Both treated and untreated effluents from these industries are discharged to the Nakkavagu and Peddavagu streams and the former also receives effluents from an adjacent Industrial Development area. Groundwater level and water quality monitoring have been carried out on 30 observation wells over the last two years in Patancheru and its environs covering a 120 km^2 area, and a number of aquifer parameters were estimated at various pumping wells. Groundwater flow and mass transport models were prepared using visual MODFLOW software, allowing the extent of contaminant migration from Nakkavagu and other streams to be assessed for the last 20 years. The stream-aquifer interaction was found to be responsible for faster migration of contamination in the over exploited area around Nakkavagu in Arutla village.

INTRODUCTION

The Patancheru Industrial Development Area (IDA) forms part of the catchment of Nakkavagu, a tributary of the Manjira River. The area covers about 120 km^2 within the Patancheru, Jinnaram and Sangareddy Mandals of Medak district in Andhra Pradesh, India. More than 400 industries are functioning in this area dealing in the production of pharmaceuticals, paints and pigments, metal treatment and steel rolling, cotton and synthetic yarn and engineering goods. The plant effluents (mostly untreated) are discharged into various unlined channels and streams. The Common Effluent Treatment Plant (CETP) of Patancheru is situated adjacent to Peddavagu and the wastewater discharged into the Peddavagu stream from the CETP was found to have a total dissolved solids (TDS) concentration ranging from 4000 to 5000 mg l^{-1}.

The Pamulavagu, Peddavagu and Nakkavagu streams, while carrying industrial effluent also act as diffuse sources of contamination along their courses to the confluence with the Manjira River (Fig. 1). The alluvium around Nakkavagu marks a paleo-channel course of the Manjira River and forms a potential groundwater-bearing zone. On reaching the groundwater table, contaminants, due to stream-aquifer interaction, migrate into the aquifer system mostly through advective dispersion. The rate of movement and consequent spread of pollutants depends upon the hydraulic gradient and groundwater velocity. To determine the groundwater velocity distribution a groundwater flow model was constructed. The computed velocity distribution was used to analyse advective and dispersive transport to determine contaminant migration in the area.

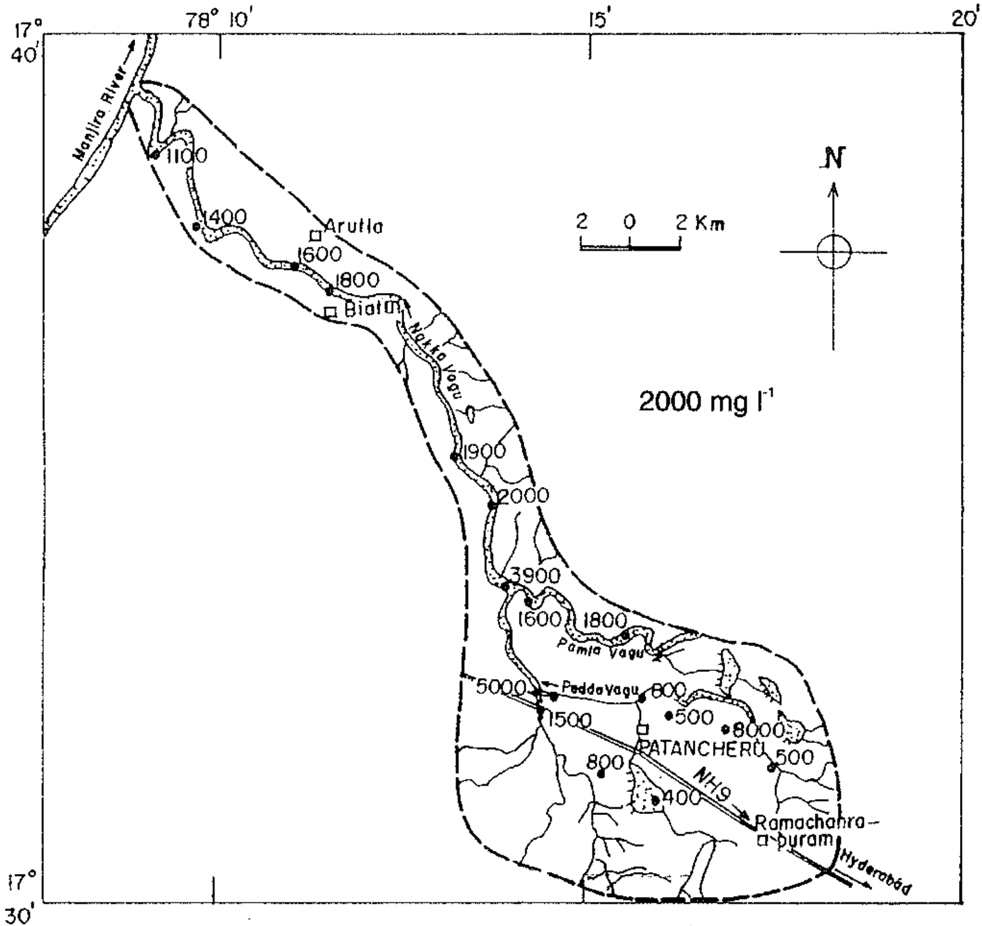

Fig. 1 Total dissolved solids (TDS) concentration (mg l^{-1}) of surface water in streams and tanks during March 1997.

GROUNDWATER MONITORING

Water quality and water level monitoring was carried out on 60 wells of which 30 wells have also been selected for periodic monitoring since July 1996. The water table contours of the pre-monsoon period (June 1997) indicate that the groundwater flow followed the topography. The Nakkavagu gains water from the aquifer around Ganapathigudem and Pocharam villages and in the region between Peddavagu and Pamulavagu, whereas the stream contributes seepage around the Inole and Arutla villages. This is a very significant process that enhances transport of the contaminants in the region.

WATER CHEMISTRY

Chemical analyses of water samples include determination of ionic concentration, pH, and total dissolved solids (TDS). Water samples were collected for analysis from bore wells, dug wells and surface water bodies at 50 locations. Based on total dissolved solids (TDS) concentrations, Davis & Dewiest (1966) proposed a three-fold classification to indicate the suitability of groundwater for:

I domestic use (<500 mg l^{-1}),
II irrigation (500–1000 mg l^{-1}), and
III industry (>1000 mg l^{-1}).

According to the above classification, only one sample falls under category (I), ten samples under category (II) and 26 samples under category (III). The important characteristics that determine the suitability of water for irrigation are total dissolved solids (TDS) and sodium adsorption ratio, etc. Alkali hazard in soils is promoted by water of high sodium adsorption ratio (SAR) and is reverted by water containing a high proportion of calcium and magnesium (Hem, 1959). The sodium adsorption ratio is given by:

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{(\mathrm{Ca}+\mathrm{Mg})/2}}$$

where all the ions are expressed in milli-equivalents per litre. SAR values (which vary between 0.48 to 18.91), can be used to predict the degree to which irrigation waters tend to enter into cation exchange in soil. Higher values of SAR imply that the sodium hazard will damage the soil structure and fertility. The analysed data were plotted on the US salinity diagram and all the existing water quality data collected by various State Government Agencies from 1989 to 1995 was classified including data collected during the present study (Fig. 2). Water samples falling under C_2S_1 were taken as good quality, C_3S_1 as moderate quality and C_3S_2 type water can be used for salt tolerant crops. There has been a gradual change in the groundwater quality during the last two decades. Water samples collected during 1989–1995 were classified into C_2S_1 (7 samples), C_3S_1 (22 samples), C_3S_2 (2 samples) and C_4S_1 (3 samples), and C_4S_2 (3 samples). The water quality of 37 samples during 1997 was classified into C_3S_1 (13 samples), C_3S_2 (3 samples), C_4S_1 (8 samples) and C_4S_2 (11 samples) and C_4S_4 (2 samples). It is significant to note that no sample falls into the C_2S_1 category during 1997, indicating that water is changing from moderate to bad quality. The suitability of water for irrigation was classified according to Wilcox (1948) and an appreciable deterioration in quality during the last ten years can be observed (Table 1).

The impact of industrial and treatment plant effluents on the surface water bodies can be seen in Fig. 1 particularly in the upper Peddavagu and lower Pamulavagu streams. The total dissolved solids concentration at about 100 observation wells (at 30–50 m depth) and 30 locations on surface water bodies was monitored five times

Table 1 Deterioration in water quality for irrigation (based on Wilcox Diagram).

Classification		No. of samples analysed during:	
		1989–1995	1997
1	Excellent to good	7	–
2	Good to permissible	24	13
3	Permissible to doubtful	–	2
4	Doubtful to unsuitable	4	7
5	Unsuitable	2	15

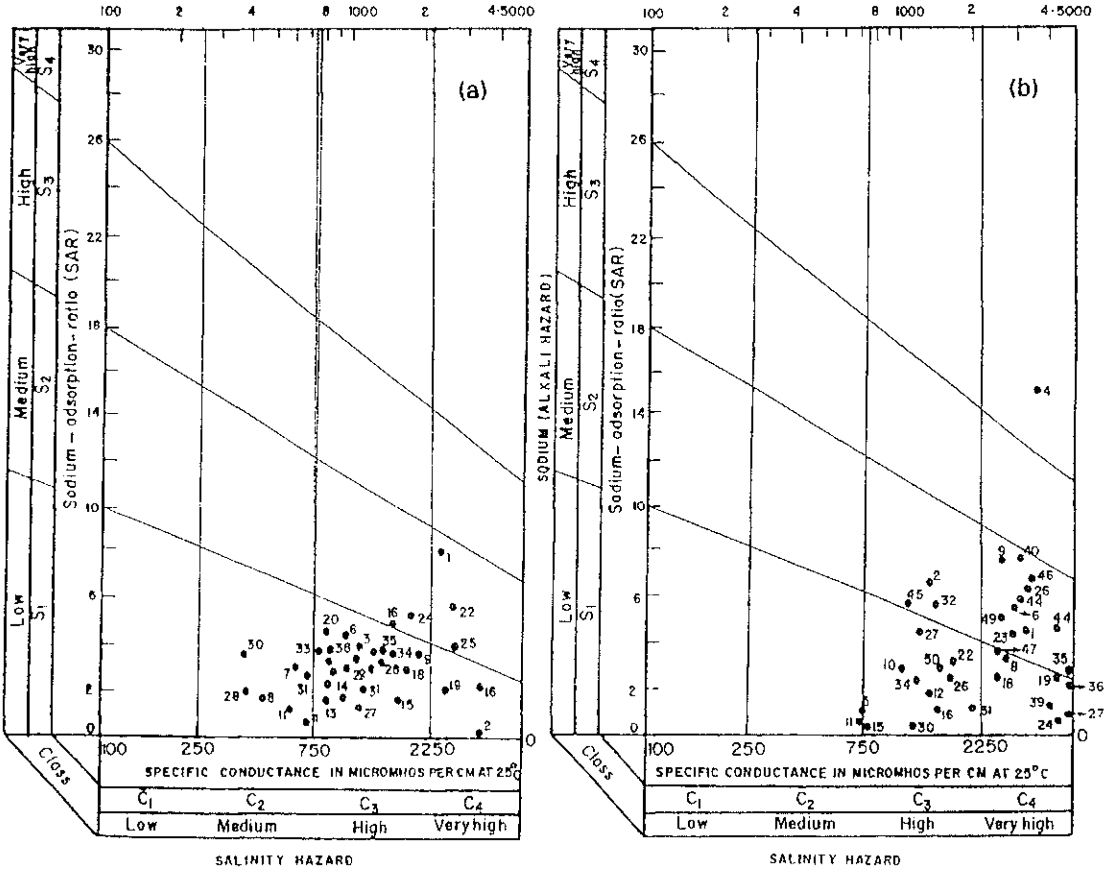

Fig. 2 Classification of groundwater for irrigation use: (a) during 1989–1995; (b) during 1997.

during the study period. The observed TDS concentration of surface and groundwater samples during March 1997 is presented in Figs 1 and 3 respectively, and the impact of pollution due to industrial clustering is evident from both figures.

GROUNDWATER FLOW AND MASS TRANSPORT PROCESSES

The natural starting place for groundwater contamination is with the mass transport process. This determines the maximum extent of plume spread and the geometric character of the concentration distribution. Advection is by far the most dominant mass transport process in shaping the plume with hydrodynamic dispersion acting as a second order process. The magnitude and direction of advective transport is controlled by the configuration of the water table or piezometric surface, presence of sources or sinks, permeability distribution within the flow field and shape of the flow domain.

All these parameters are important in controlling the groundwater velocity, which drives advective transport. Adding dispersion to advective transport can cause important changes in the shape of a plume. The partial differential equation describing

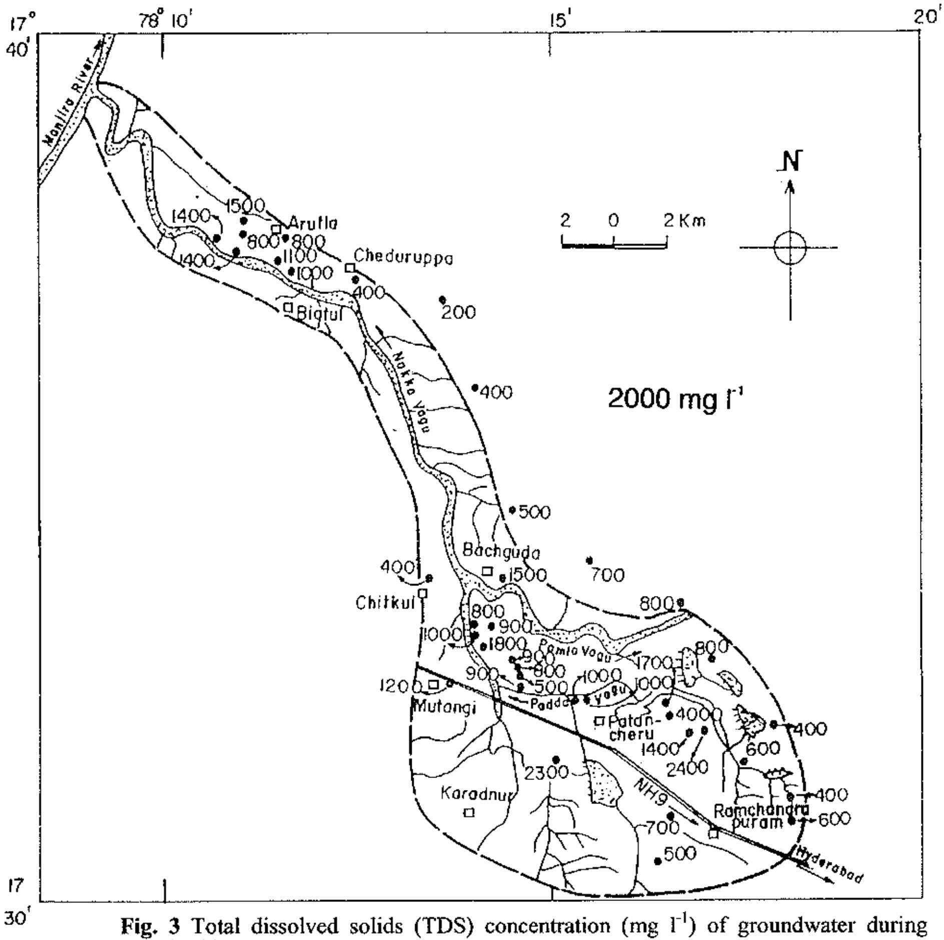

Fig. 3 Total dissolved solids (TDS) concentration (mg l^{-1}) of groundwater during March 1997.

three-dimensional transport of contaminants in groundwater (Javandel *et al.*, 1984) can be written as:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_i}\right] - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s + \sum_{K=1}^{N} R_k \tag{1}$$

where:

C the concentration of contaminants dissolved in groundwater,
t time,
x_i the distance along the respective Cartesian coordinate axis,
D_{ij} the hydrodynamic dispersion coefficient,
v_{ij} the seepage or linear pore water velocity,
q_s the volumetric flux of water per unit volume of aquifer, representing sources (positive) and sinks (negative),
C_s the concentration of the sources or sinks,
θ the porosity of the porous medium,
R_k chemical reaction term.

Assuming that only equilibrium controlled linear or non-linear sorption and first order irreversible rate reactions were involved in the chemical reactions, the chemical reaction term can be expressed as (Grove & Stollenwerk, 1984)

$$\sum_{k=1}^{N} R_k = -\frac{\rho_b}{\theta}\frac{\partial \overline{C}}{\partial t} - \lambda\left[C + \frac{\rho}{\theta}\overline{C}\right] \tag{2}$$

where:

ρ_b the bulk density of the porous medium,

$\overline{C}$ the concentration of contaminants sorbed on the porous medium, and

λ the rate constant of the first-order rate reactions.

Rewriting gives:

$$\frac{\rho_b}{\theta}\frac{\partial \overline{C}}{\partial t} = \frac{\rho_b}{\theta}\frac{\partial C}{\partial t}\frac{\partial \overline{C}}{\partial C} \tag{3}$$

We can rewrite equation(1) by substituting equations (2) and (3):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_i}\right] - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s - \frac{\rho_b}{\theta}\frac{\partial \overline{C}}{\partial C}\frac{\partial C}{\partial t} - \lambda\left(C + \frac{\rho_b}{\theta}\overline{C}\right) \tag{4}$$

Rearranging terms we get:

$$R\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_i}\right] - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s - \lambda\left(C + \frac{\rho_b}{\theta}\overline{C}\right) \tag{5}$$

where R is called the retardation factor, defined as:

$$R = 1 + \frac{\rho_b}{\theta}\frac{\partial \overline{C}}{\partial C} \tag{6}$$

Equation (5) is the governing equation underlying the solute transport model.

The transport equation was linked to the flow equation:

$$\upsilon_i = -\frac{K_{ii}}{\theta}\frac{\partial h}{\partial x_i} \tag{7}$$

where:

K_{ii} a principal component of the hydraulic conductivity tensor, and

h hydraulic head.

The hydraulic head was obtained from solution of a three dimensional groundwater flow equation through the MODFLOW software (McDonald & Harbaugh, 1988):

$$\frac{\partial}{\partial x_i}\left[K_{ii}\frac{\partial h}{\partial x_j}\right] + q_s = S_s\frac{\partial h}{\partial t} \tag{8}$$

where S_s is the specific storage of the porous material.

The numerical approaches for solving the mass transport equations were based on computer based particle tracking methods. Initial conditions and transport parameters were specified for all boundary nodes. The seepage from Nakkavagu was simulated by were specified for all boundary nodes. The seepage from Nakkavagu was simulated by giving uniform recharge as an additional input to the model. Constant concentration was assigned in different blocks of Nakkavagu based on ambient surface water as well as groundwater concentrations measured during field investigations. Continuity consideration of numerical solutions of solute transport requires a smooth and accurate representation of the velocity field, which was obtained by simulation with a flow model. Velocity values were computed by applying Darcy's equation with calculated hydraulic heads and porosity values. The transport model was coupled to the flow model by velocity terms. The water level configuration of July 1997 was considered and the groundwater flow equation was solved once and thereby a single velocity field determined for the mass transport simulation for all times in steady state condition. With a small time step, this particle motion traces a pathline through the system (Konikow & Bredehoeft, 1978). Dispersion was accounted for in the particle motion by adding a random component to the deterministic motion, which is a function of the dispersivities. The mean concentration for each grid block was calculated as the sum of the mass carried by all the particles located in a given block divided by the total volume of water in the block.

CONCEPTUALIZATION OF FLOW AND TRANSPORT

Estimation of aquifer parameters is essential for quantifying the groundwater resources and also to determine well characteristics. Pumping tests were carried out on 10 wells including bore wells, filter points and dug wells. High transmissivity values were obtained in alluvial formations, in spite of limited aquifer thickness. The pumping test data was interpreted using GWW computer software. The transmissivity was found to vary from 140 m^2 day^{-1} in granites to 1300 m^2 day^{-1} in alluvium. Permeability values as high as 50–75 m day^{-1} are found in the alluvium around Arutla village. The surface water, while seeping through the bed of Nakkavagu, carries effluent to the groundwater regime thereby contaminating groundwater up to a distance of 600–800 m to the east of the Nakkavagu. The most important process contributing to the mass transport in groundwater is advection. Longitudinal dispersion is relatively significant but transverse dispersion could be negligible. The total dissolved solids (TDS) concentration in the contaminant was selected for a detailed model study because (a) the concentration remained relatively constant in effluent ranging between 1000–4000 mg l^{-1} along different reaches of the Nakkavagu and (b) it showed a uniform background level of about 300 mg l^{-1} in native groundwater. The initial stage in developing the flow and TDS concentration solute transport models was to define the region of interest and establish boundary conditions for flow and solute transport.

GROUNDWATER FLOW MODEL

The simulated model domain of the Patancheru IDA and environs consists of 51 rows and 88 columns and two layers covering an area of 22 000 m × 8000 m. The number of nodes are large enough to include all the existing monitored wells which will help draw the plume as well as providing room for further migration of contaminant in future. The top layer mostly consists of 10–15 m thick alluvium along the Nakkavagu and is underlain by a 10–15 m fracture zone. The simulated vertical section has a total thickness of 30 m in the model. The blocks in the grid were chosen as sufficiently small rectangles (250 × 200 m) to ensure that development of the plume is not localized in just a few cells. The water level data measured at 30 observation wells was used to prepare an initial water level configuration as existed during July 1997. The outflow from the groundwater flow model was estimated in terms of one constant head node at the confluence of the Nakkavagu with the Majira River, by assuming outflow towards the latter. The highest water table elevation along the southern boundary was defined by the 530 m (a.m.s.l) equi-potential line and the lowest water table elevation at the 490 m confluence point of the Nakkavagu and Manjira rivers. Groundwater recharge at a rate of 110 mm year^{-1} has been used to simulate areal distributed recharge to the aquifer system from the first layer in the recharge package. Continuous seepage from the Peddavagu, Pamulavagu and Nakkavagu streams was simulated as additional input in the model as there is always some effluent flow in the Nakkagu at Ismailkhanpet bridge, even during summer months. The first stage of model preparation is flow simulation for the computation of hydraulic head distribution. The distribution of hydraulic head and hence the velocity field was unaffected by migration of the plume because density and viscosity of the contaminated groundwater was nearly the same as uncontaminated water. The flow equation was therefore, first solved independently of the mass transport equation. Further, water level observations in the area indicate that hydraulic head gradients do not change significantly with time. Thus groundwater flow was assumed to be in steady state. The groundwater head in the aquifer model was computed by using visual MODFLOW (Guiger & Franz, 1996). The Slice Successive Over Relaxation (SSOR) package of MODFLOW was used by dividing the finite difference grid into vertical slices and grouping the node equations into discrete sets, each set corresponding to a slice. The solver checked for the maximum change in the solution at every cell after completion of every iteration. If the maximum change in the solution was below a set convergence tolerance, then the solution had converged and the solver stops, otherwise a new iteration was started (McDonald & Harbaugh, 1988).

The flow model was calibrated by adjusting several parameters within a narrow range of values until a best fit was obtained between observed data and simulated results. The accuracy of the computed water levels was judged by mean error, mean absolute error and root mean squared error computed values for points on the graph which were –0.17, 3.4 and 3.7 m respectively under steady state condition. Nevertheless, by keeping the hydraulic conductivity close to the estimated value, it was expected that the simulated hydraulic heads and resulting velocity field represented the flow system reasonably well.

PARTICLE PATHLINES

MODPATH is a post-processor computer program to calculate three-dimensional particle tracking from the output of steady state flow simulation obtained using MODFLOW (Pollock, 1988) and uses a semi-analytical particle tracking scheme. The method is based on the assumption that each directional velocity component varies 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 time of travel between them, can be computed. The computed particle path-lines indicated that the predominant direction of contaminant migration was from the Nakkavagu and migrated in the direction of groundwater flow. The advective transport has made the contaminants move up to 500–600 m over 20 years, with an average groundwater velocity of 30 m $year^{-1}$ in the alluvium around the Nakkavagu.

SOLUTE TRANSPORT MODEL

Mass transport in three dimensions (MT3D) is a computer model for simulation of advection, dispersion and chemical reactions of contaminants in three-dimensional groundwater flow systems (Zheng, 1990). The model is used in conjunction with a block-centred finite difference flow model, MODFLOW, and is based on the assumption that changes in the concentration field will not measurably change the flow field, and uses a mixed Eulerian-Lagrangian approach to the solution of the advection-dispersion equation, based on a combination of Method of Characteristics (MOC) and the Modified Method of Characteristics (MMOC) known as HMOC.

Longitudinal dispersivity is specified as a characteristic of the soil type (related to the tortuosity of the interconnected pores) which tends to spread out contaminant mass along the advective path of the plume. The horizontal transverse (plume width) and vertical transverse (plume thickness) dispersivities were assigned as ratios (fractions) of longitudinal dispersivity as required by MT3D. The molecular diffusion coefficient value was also given as input. The hydrodynamic dispersion coefficient was computed as a product of dispersivities and velocity (mechanical dispersion) plus a molecular diffusion coefficient. By selecting an appropriate criterion for controlling the switch between the MOC and MMOC techniques, in the present transport simulation the HMOC scheme can provide accurate solutions for both sharp and non-sharp front problems (Zheng, 1990).

The values of dispersivity in longitudinal and two transverse directions (Y and Z) were assumed to be 50 m, 5 m and 0.05 m respectively. The tendency for α_L to be about 10 times larger than α_{TH} and for α_{TZ} to be much smaller than either of them, is in line with the concentrations determined in the area. The relatively smooth decline of TDS concentration away from the Nakkavagu suggests a relatively constant rate of loading. Thus a constant TDS concentration at different nodes on the Nakkavagu was assigned, varying from 3500 mg l^{-1} at source near Patancheru and 1000 mg l^{-1} away from the source at about 18 km downstream on the Nakkavagu near Ismailkhanpet. The computed iso-concentration contours indicate that the plume is expanding and follows the hydraulic gradient implying that advection is the dominant mechanism of spreading. The qualitative shape of the plume indicates that longitudinal dispersion is more significant than transverse dispersion.

The extent of contaminant migration from the Nakkavagu, Peddavagu and Pamulavagu streams can be seen by computed TDS iso-concentration contours for the transport model during 1997. The contaminant migration was found extending up to

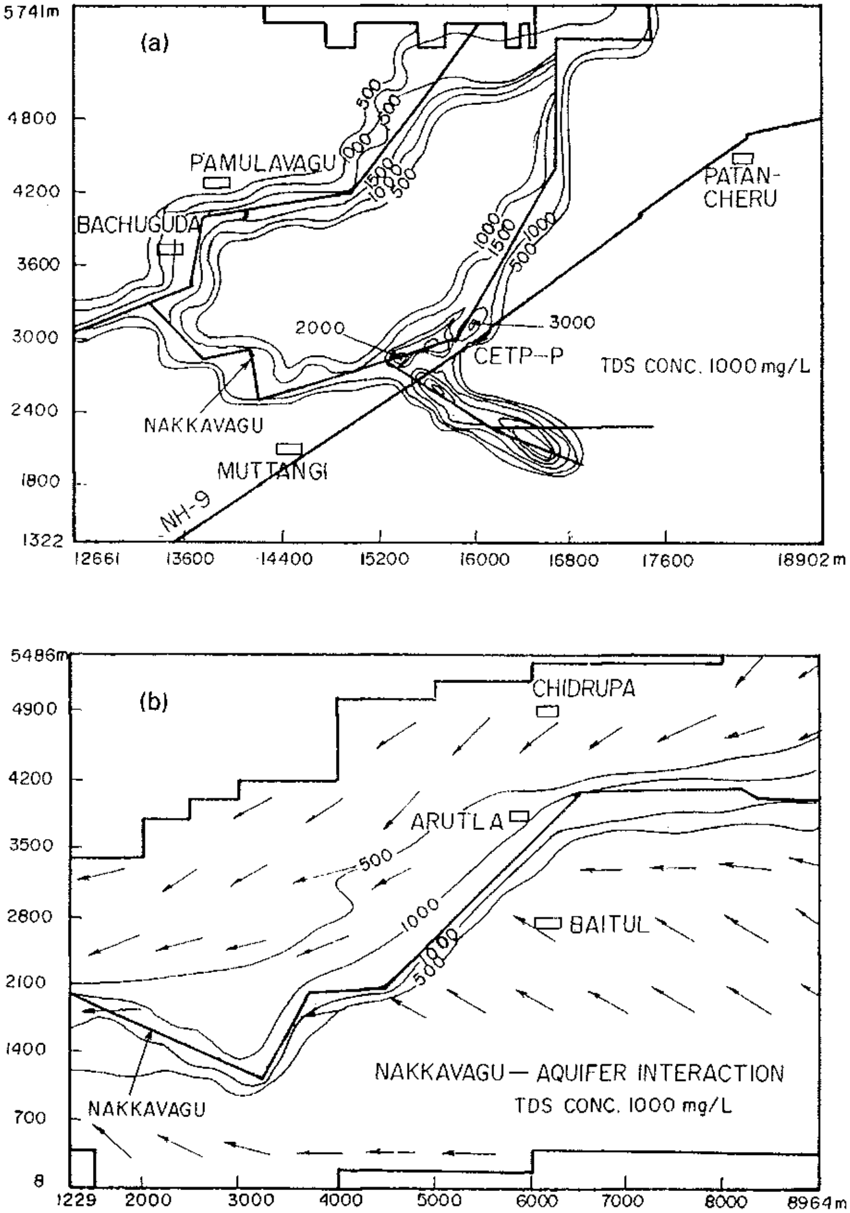

Fig. 4 (a) Computed TDS concentration (mg l^{-1}) of groundwater for 20 years, Patancheru IDA. (b) Computed TDS concentration (mg l^{-1}) of groundwater for 20 years downstream of the Nakkavagu, 15 km from Patancheru.

500–600 m from the Nakkavagu to the eastern part during the last 20 years (Figs 4(a) and (b)). Inaccuracies in the simulated flow field could exist, which would produce a somewhat more divergent flow pattern than actually occurs. This problem could be related to the complex interaction between groundwater and surface waters. Finally, the model could contain undetected numerical dispersion.

CONCLUSIONS

The contaminated groundwater has been exploited for agriculture and industrial purposes in the absence of major surface water sources in the area. Groundwater pollution extends laterally up to 500–600 m in the alluvial areas covering the villages of Chidrupa, Kanjerla and Arutla on the eastern side of the Nakkavagu. The extent of pollution is due to heavy pumping for irrigation resulting in induced seepage from the Nakavagu due to stream aquifer interaction which in turn carries surface water effluent to the groundwater regime. Arsenic was found to be quite high in some bore wells in Bandlaguda and Patelgudem and appreciable amounts of cadmium, boron, barium, manganese and strontium were traced in the Nakkavagu and in other surface water bodies and also in a few bore wells. The vulnerability of the area to contamination is further accentuated due to the removal of aquifer material through sand mining. The high incidence of pumping all along the Nakkavagu alluvial tracts has induced stream-aquifer interaction and spread of pollutants both laterally and vertically. The modelling study has helped gain a better insight of the hydrogeological set-up and assessment of contaminant migration due to mass transport processes. Over-exploitation of groundwater in the alluvial parts of the Nakkavagu has resulted in a decline of the water table resulting in further contamination of groundwater through stream aquifer interaction. Remedial measures, such as reduction of effluent concentrations in waste water let out into streams from the CETP and individual industries, has been suggested to contain elevated concentrations of TDS.

REFERENCES

Davis, S. N. & Dewiest, R. J. M. (1966) In: *History of Hydrogeology*, 5–14. John Wiley Sons Inc., New York.

Grove, D. B. & Stollenwork, K. G. (1984) Computer model of one-dimensional equilibrium controlled sorption processes. *USGS Wat. Resour. Invest. Report 84-4059.*

Guiger, N. & Franz, T. (1996) *Visual MODFLOW: Users Guide.* Waterloo Hydrogeologic, Waterloo, Ontario, Canada.

Hem, J. D. (1959) Study and interpretation of the chemical characteristics of natural water. *USGS Wat. Supply Paper 1973.*

Javandel, I., Doughty, C. & Tsang, C. F. (1984) *Groundwater Transport: Handbook of Mathematical Models.* American Geophysical Union, Wat. Resour. Monograph no. 10.

Konikow, L. F. & Bredehoeft, J. D. (1978) Computer model of two dimensional solute transport and dispersion in groundwater. In: *USGS Wat. Resour. Invest. Book 7*, chapter C2.

McDonald, J. M. & Harbaugh, A. W. (1988) A modular three dimensional finite-difference groundwater flow model. *Techniques of Water Resources Investigations of the USGS, Book 6.*

Pollock, D W. (1988) Documentation of computer programs to compute and display pathlines using results from USGS Modular Three-dimensional Finite Difference Groundwater Flow Model. *USGS Open file Report 89-381.*

Wilcox, L. V. (1948) *The Quality of Water for Irrigation Use.* US Dept Agric. Bull. No. 962, Washington D.C.

Zheng, C. (1990) MT3D, a modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. (Prepared for the US Environmental Protection Agency).