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Analysis of arsenic contaminated groundwater domain in Nadia district of West Bengal

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Abstract

The paper presents an analysis of groundwater flow and transport process of Arsenic in the flow domain of Yamuna sub-basin located in the Nadia and North 24 Parganas districts of West Bengal. The objectives of the analysis are :1. Conceptualisation of the groundwater flow domain, 2. Determination of groundwater flow paths and groundwater velocities, 3. Study of ARSENIC transport in the flow domain. 4. Study of Well capture zones. First three objectives and issues are addressed by simulation of steady and transient state of groundwater flow and contaminant transport using United States Geological Survey (USGS) developed three - dimensional finite difference code MODFLOW and three - dimensional advective - dispersive transport code MT3D. Calibrated model replicate the observed transient water table conditions perfectly. Contaminant transport analysis indicates in-situ Arsenic source. Using particle tracking algorithm MODPATH, possibility of Arsenic removal from a sample key location, and design of wells for withdrawing Arsenic free groundwater have been studied through analysis of well capture zones.

INTRODUCTION

The study area (Fig. 1) is a part of the upper Ganga-Brahmaputra Delta having a near surface succession of Quaternary Sediments of varying thickness. Abandoned meander scrolls of various wavelengths and amplitudes, chute cutoffs, conspicuous levees along Bhagirathi and other rivers as well as back swamp lakes in between inter-distributory levees are the geomorphic formation which could easily be related to fluvial processes of distributory. Upper delta plain has series of meander belts. In the central part of the delta an older composite belt has been recognized. The study area is on the western side of this composite meander belt from Bhagirathi river. These meander belts are not continuous stretches but are preserved as festoons with the successive belts eroding and in setting into the older ones, finally getting consolidated through expulsion of pore water. Mostly sand, silt and clay are underlain by gravel beds showing several fining upward cycles of various thickness. These sediments rest directly over the extensive clay beds of the tertiary period in the subsurface depth of about 150 m.. Change in lithology in a horizontal plane is quite abrupt. Isoparametric view of the ground surface is depicted in Fig. 2.

Rainfall data of two raingauge stations located in the study area namely; Bongaon and Habra show occurrence of effective precipitation due to SW monsoon during the months of May to October with peak rainfall during July and August. Average annual rainfall at Bongaon and Habra on the basis of the available data (1986 to 1995) reflects 1850 mm. and 1900mm respectively.

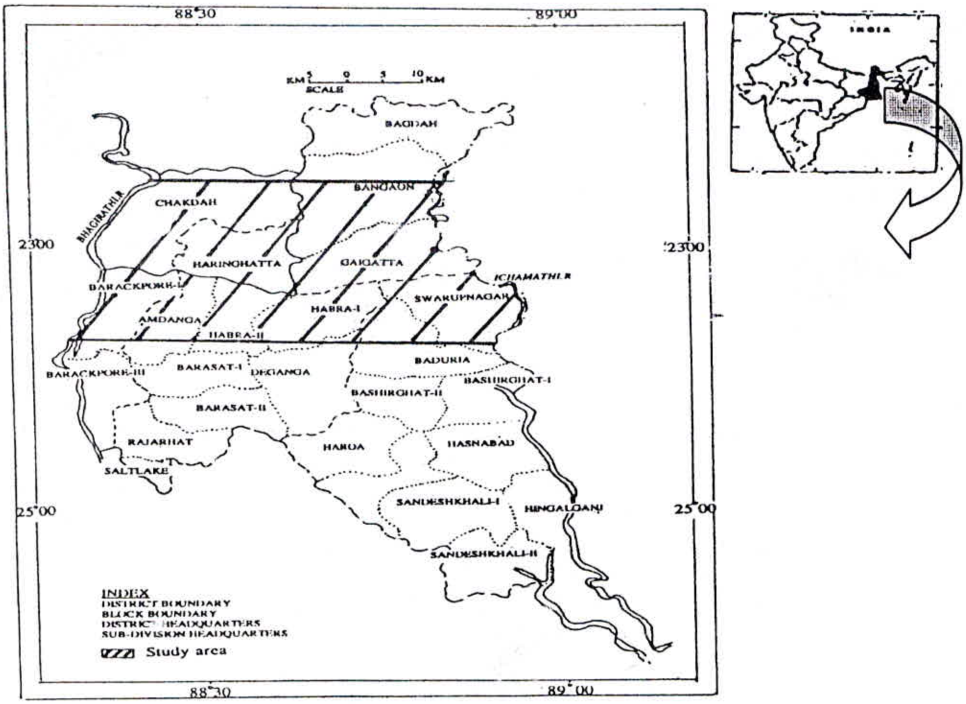


Figure 1. Location Map of Upper Ganga-Bramhaputra Delta.

Yearly average Potential evapotranspiration is estimated to be in the order of 1389 mm. Study area is bounded by Bhagirathi river on western side and Ichhamati river on eastern side. The stretches of Yamuna river not exactly joining the above two main rivers is aligned almost North-West to South-east. Water in Yamuna river remains mostly in ponded condition having rare flow, but tidal effects can not be ruled out in it. Apart from rainfall, irrigation return flows from the agricultural land is a source for groundwater re-charge.

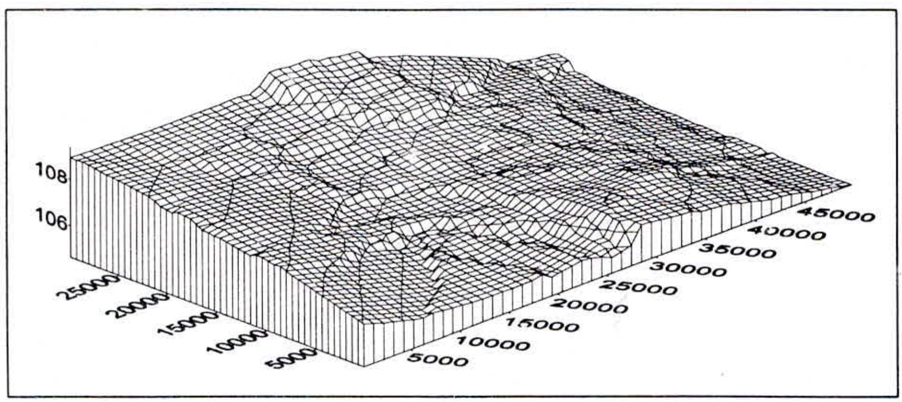


Figure 2. Isoparametric view of the ground surface.

Groundwater occurs under unconfined to semi confined condition with existence of top clay and sandy clay locally, as thick as 20 to 30 m in some parts. Water table fluctuations and lithologs do not indicate any multilayer aquifer system upto a depth of 150 m from the normal ground level. However, based on the water use pattern, it is being distinguished vertically as shallow, intermediate and deep zones. Water table fluctuation is between 1 to 2 m in eastern part and between 2 to 4 m in the western part. Hydraulic gradient is steeper (1:333) in the northern part and gentle in the central and southern part(1:1666). The gradient is in general southerly to south easterly. Transmissivity values as reported from the pumping test range from 671 sq.m/day to 4981 sq.m/day and storativity values from 1.3x10-2 to 6.2x10-4. Yield from shallow tube wells(18m to 54 m bgl) ranges from 23 to 43 cum/hr, while for heavy duty deep tube well(150 m bgl) it ranges from 45 to 200 cum/hr . Isoparametric view of static water levels is depicted in Fig 3. Usual trend of ground water table in a calendar year is; a declining trend from January to April, and then a rising trend from May through July and again declining trend from August onwards. Monthly water level observations for 62 wells with in the study area during year 1997-98 show that the rate of declination of water table in most of these wells are identical from September to April.

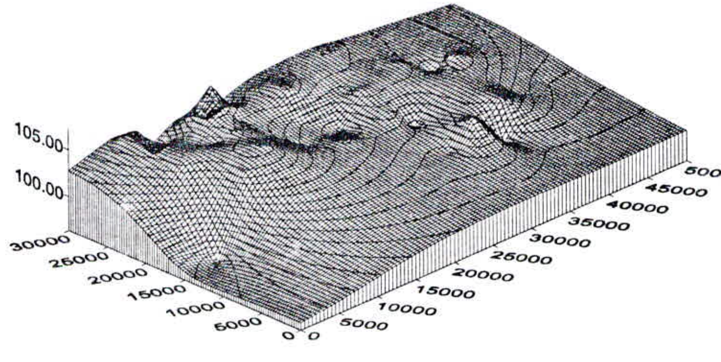


Figure 3. Isoparametric view of static water level (April, 1997).

ARSENIC was first reported in the study area during year 1985. It has been sensed that over the years spreading of Arsenic and its concentration have increased. Abstracted water is found more Arsenic polluted wherever Transmissivity decreases and Storativity increases (Fig 4). The results of Arsenic concentration observed during pumping tests show that, in some of the wells, initially Arsenic concentration of the drafted water increases and subsequently goes down. This is possible when the drafted Arsenic concentrations resemble the drafted water quality, not the water quality of the aquifer. Moreover natural systems like rivers, drains and other water bodies, which are interacting with the aquifer, indicate Arsenic free water quality. Areal discontinuity of the Aresenic plumes in the flow domain has also been noticed. This may be due to the existence of clay patches. However, Arsenic concentration in the region has certain relationship with the local lithology.

Recent scenario of Arsenic concentration in groundwater is shown in Fig. 5, which shows that aquifer has maximum Arsenic concentration near Kundalia, Mandalhat, Khusbasi, Devipur, Ashosnagar and Maslandpur and low concentration around Nagarukra, Napit satbaria, Balidanga and Digra. Clay patches disturb the concentration plumes invariably, whereas it hardly influences the flow domain. Vadose zone sampling shows that, in general, Arsenic is retained by the surface soil and water underneath is found potable. In absence of any history of water quality in the study area it is difficult to conclude about the cause and source of Arsenic in the groundwater. Monthly Arsenic concentrations monitored at different key wells of the region during year1997 also do not reveal any specific trend. In fact, some wells which at one time have indicated presence of Arsenic, have reflected Arsenic concentration below detection level and vice-versa within a comparatively small period of time. Arsenic affected zones indicate presence of various minerals including iron pyrites. Oxidation of Arsenopyrite has been reported as one of the reasons for activation of Arsenic in the groundwater. The most effected zone lies between 13 to 18 m depth below ground level, whereas water table fluctuations had never shown such a big declination over last 10 years.

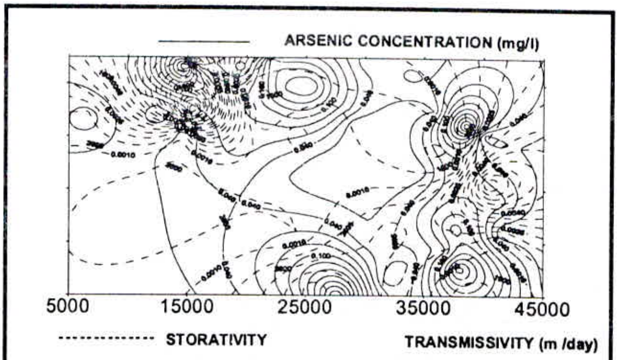


Figure 4. Superimposed plots of Storativity Tramsmissivity, and Arsenic concentration.

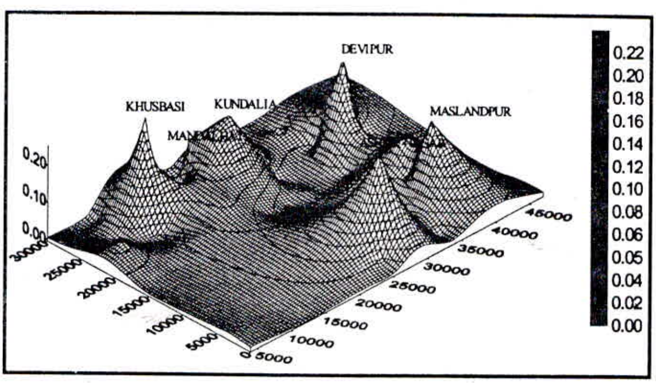


Figure 5. Scenario of Arsenic concentration in the study domain (1997).

Chances of chemical reaction in the aquase phase is remote as the pH is more or less stable areally inside the aquifer domain There is always a scope of solid-liquid phase interaction through adsorption and precipitation of contaminants on clay lenses and subsequent dissolution due to pumping. Area covered under various arsenic concentration ranges is given in Table-1.

Table 1. Range and percentage area covered by the Arsenic in study domain.

Sr.No.	ARSENIC CONCENTRATION RANGE	PERCENT AREA
1	0.0110000 to 0.0511667	50%
2	0.0511667 to 0.0913333	10%
3	0.0913333 to 0.1315000	20%
4	0.1315000 to 0.1716670	10%
5	0.1716670 to 0.2118330	00%
6	0.2118330 to 0.2521000	10%

In order to assess whether the areal spreading of Arsenic contaminated water has any bearing with transport, the study area has numerically been modeled using MODFLOW for flow and coupled with MT3D for contaminant transport and MODPATH for capture zone analysis to conceptualize the following:

i. Three dimensional Finite Difference mesh allowing river / drain.
ii. Vertical and horizontal stratiographic formations.
iii. Steady state groundwater table and Calibration of Model parameters.
iv Transient state validation of the model.
v Contaminant transport with various source of Arsenic.
vi. Study of Well capture zones .

CONCEPTUAL MODEL

Conceptual model is postulated primarily to suit the groundwater quality scenario. Arsenic contamination is detected more in the intermediate zone (15 to 40 m), less in shallow zone (above 15 m) and almost nil in the deeper abstraction zones (40 to 80 m). Since the regional groundwater flow system is unilateral with deposition of clay minerals in abundance upto 150 meter of depth and geological formation being mainly of fluvial deposits, the flow domain has been conceptualised considering set of uniformly thick layers of sediment sheets deposited one above another with identical slope. Three dimensional grid comprising 100 blocks each in X and Y direction having aerial dimension of each block of 500 X 300 m has been conceptualised to suit the study domain. Total depth has been considered as 80 m and has been divided into 10 layers each parallel to the surface layer to accommodate horizontal and vertical anisotropy and variation of local litholog. Ground level data at 62 locations have been krigged to the c.g. of 10,000 blocks with the help of Geo-statistical package, "GEOPACK" ,for generating levels at each block in the flow domain. To avoid negative values, all the reduced levels are transformed to a hypothetical reference level of 100 m below mean sea level.

Overall hydraulic properties are enumerated on the basis of pumping test results in different locations. Grid values of Transmissivity and storativity are generated through SURFER and divided in six zones horizontally, which are used as initial hydraulic parameters for the calibration of the conceptual model. These zones are given in Table-2.

Table 2. Zones of Transmissivity and Storativity including percentage cover.

Zone	Transmissivity Range (m^2/day)	Percent Area Covered	Average Value	Storativity Range	Percent Area Covered	Average Value
A	538 to 1000	14.3%	769	3.30E-6 to 2.20E-4	12.5%	1.12E-4
B	1001 to 1500	4.8%	1250	2.20E-4 to 4.00E-4	12.5%	3.10E-4
C	1501 to 2000	28.6%	1750	4.00E-4 to 1.09E-3	18.8%	7.45E-4
D	2001 to 2500	23.8%	2250	1.09E-3 to 1.30E-3	18.8%	1.19E-3
E	2501 to 3000	14.3%	2750	1.30E-3 to 3.30E-3	18.8%	2.30E-3
F	3001 to 4001	14.3%	3250	3.30E-3 to 1.30E-2	18.8%	8.15E-3

All ten layers are assumed to have same anisotropy in horizontal direction. The Transmissivity zones are shown in Fig 6 and storativity zones in Fig.7. Porosity values for all the zones are considered as 0.38.

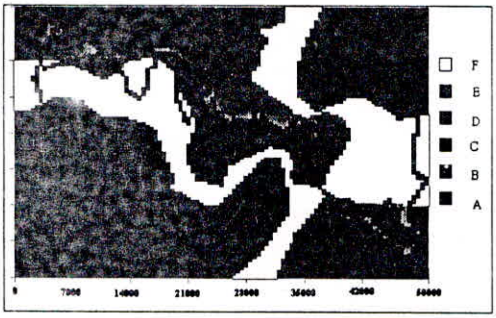


Figure 6. Transmissivity zones.

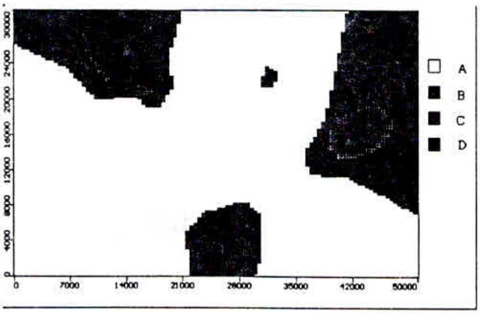


Figure 7. Storativity zones.

Recharge through rainfall and the irrigation return flow have respectively been considered as 20% of the annual rainfall and 20% of the net draft for each block. Withdrawal from the aquifer and the evapotranspiration have been considered as the discharge components. Evapotranspiration value is considered as 1389 mm/year from root zone depth of 2.0 metre, while withdrawals from the aquifer have been assessed from the projection of block-wise groundwater withdrawal data of 1991.

In absence of natural hydrological boundaries, option left out for calibration of the model parameters considering hydrostatic condition of the flow domain. River/drain hydraulic characteristics as available during April'97 are considered as the input. The calibrated model is validated for some other boundary conditions incorporating recharge from the top and using General head boundary condition at the northern and southern boundaries. The static water table of April 1997 (fig 3) has been considered for processing the initial conditions. After the model parameters are validated, it is used for simulation of transient conditions using water table of September 1997 (Fig.8) as initial piezometric condition.

Following boundary conditions are used for transient run:

1. River stages in Bhagirathi, Ichhamati and Jamuna.
2. General Head boundary at northern and southern boundary.
3. Net recharge/discharge component.

Arsenic pollution problem has been conceptualised considering different probable situations of its source. The probable sources are considered as ; i) source from river Bhagirathi, ii) General head boundary at the northern side and iii) in-situ point sources at localized pockets. No sink term has been introduced. Initial Parameters considered in MT3D runs are as follows

1) Longitudinal dispersivity - 150 m
2) Transverse Horizontal dispersivity - 10% of longitudinal dispersivity
3) Transverse Vertical dispersivity - 1% of longitudinal dispersivity.
4) Molecular Diffusion - 1.0E - 6 m^2 / sec

Scenario of Arsenic concentration prevailed during the month of September 1997 (Fig. 9) has been considered as the initial concentration.

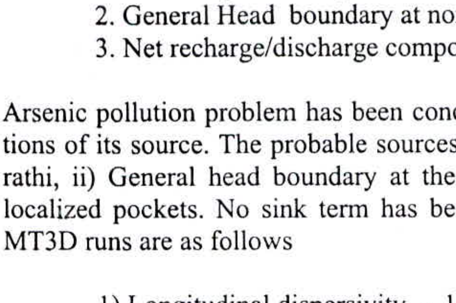


Figure 8. Initial water table considered for transient simulation (September, 1997).

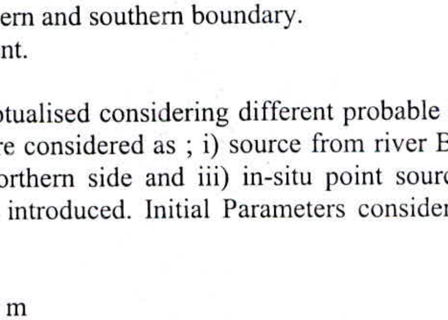


Figure 9. Scenario of Arsenic concentration in the flow domain . (September, 1997)

Calibrated steady state flow model is applied for examining the possibility of following remedial measures.
Cleaning of Arsenic pollutants from the aquifer domain.
Design of wells for pumping of Arsenic free groundwater.

Analysis of capture zones has been carried out using backward tracking of 10 nos. of particles in a circle of radius 1000 m applying MODPATH. Capture zone is the region within which all flow lines converge to the extraction well. Water within the capture zone eventually finds its way to the well and is pumped out of the aquifer. Flow lines outside of the capture zone may be bent toward the well, but the regional flow associated with the natural hydraulic gradient is strong enough to carry that groundwater past the well. The width of the capture zone is directly proportional to the pumping rate Q and inversely proportional to the product of the regional Darcy flow velocity and the aquifer thickness. Pumping rates of clean up wells are considered as 250, 500 and 1000 cum/day while the design wells are analysed for 100, 200 and 500 cum/day.

RESULTS AND DISCUSSION

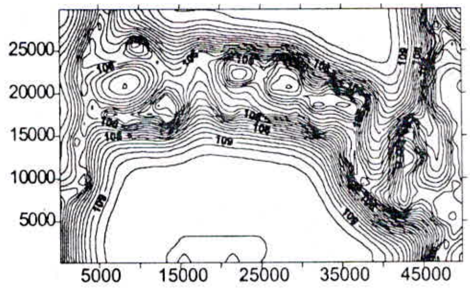
To start with, the framework of the model has been calibrated assuming hydrostatic condition of the flow domain using April 1997 as the base. Initial water table condition has been assigned at the highest altitude of the study domain. River and drainage system have been considered for calibration of the model parameters. The calibrated model parameters are given in Table -3.

Table 3. Calibrated hydraulic conductivity values (zones as indicated in Fig.6)

Zone	Kx(m / day)	Ky(m / day)	Kz(m / day)
F	15.0336	15.0336	1.50336
E	18.3168	18.3168	1.83168
D	21.6864	21.6864	2.16864
C	11.6640	11.6640	1.16640
B	8.29440	8.29440	0.82944
A	4.83840	4.83840	0.48384

The calibrated heads are shown in fig. 10 for layer 1. It is observed that computed water table in northern half is governed by the river/drain and topography and is identical to the observed trend, where as in the southern half, river/drain pattern is solely dominating the scenario which is not alike observed pattern. Some more natural and/or man made inputs and outputs are influencing the water table condition in this half which are taken care of in the subsequent runs. By and large, an agreement in the trend between the computed and observed static water table is observed . This is the case for all other layers due to the unilateral condition.

The calibrated model has been validated for some additional boundary conditions including the areal distribution of recharge from the top and general head boundary values in the northern and southern boundaries. Plot of validated run is shown in fig 11, which shows a perfect matching with the observed static water table condition.



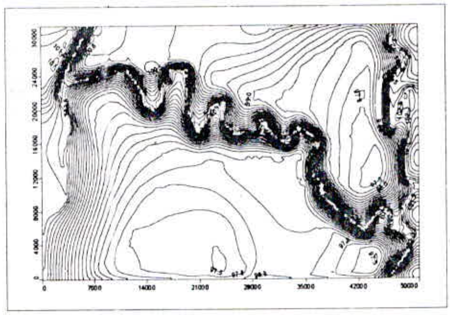
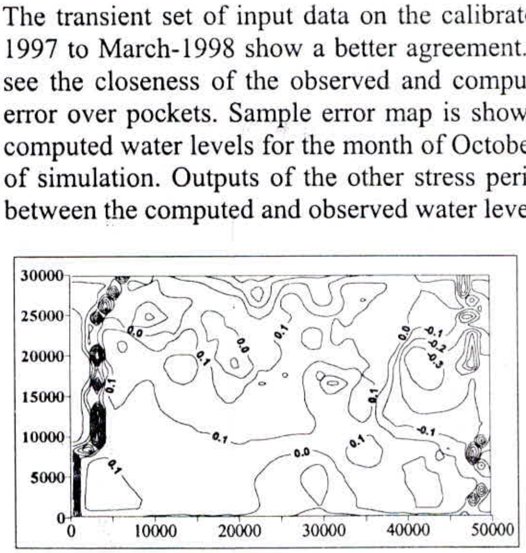


Figure 10. Model outputs corresponding to the response of calibrated model parameters.

Figure 11. Validated outputs of the model.

The transient set of input data on the calibrated model for the period from September-1997 to March-1998 show a better agreement. Error maps developed for each month to see the closeness of the observed and computed values reflect a scattered contours of error over pockets. Sample error map is shown in fig 12. Comparison of observed and computed water levels for the month of October 1997(fig 13) is shown as a sample result of simulation. Outputs of the other stress periods do have the similar degree of fitness between the computed and observed water levels.



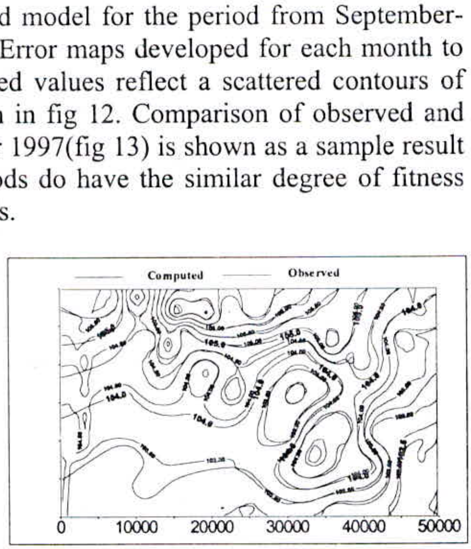


Figure 12. Error map (Observed – Computed) of Piezometric heads for October, 1997.

Figure 13. Comparison of Observed And Computed water levels (October, 1997).

Results of the transient transport runs, considering Bhagirathi river and northern boundary as a source of Arsenic, are found to be of no utility as negligible contaminant transport is noticed even for 5 years of transient transport runs. Transport of contaminants considering in-situ sources at six localized points (Fig. 14) show a similar trend of spreading when compared with the observed spatial distribution except the magnitudal match. It is further observed that occurrence of Arsenic at a place has no bearing with the transport of Arsenic from other pockets but it is due to the in-situ activation. The influence of localized source for the given input condition is found to be of the order of 2 km from the point of release. Temporal variation of Arsenic concentration, for five years of simulation, at the source points have been analyzed considering spreading of the preceding year as the input to the successive year in addition to in-situ activation. One sample output representing variation of concentration 8 meter below the source point at Ashoknagar is stipulated in fig 15. Results of analysis depict that for same quantum of occurrence of Arsenic during recharge period, the magnitude of concentration during de-activation period increases in the corresponding periods of subsequent years, where as away from the source concentration increases over time. This artificial introduction of mass flux is to incorporate the effect of oxidation-reduction process actually occurring in the sub surface.

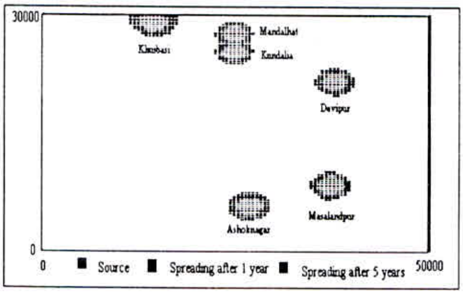


Figure 14. Computed extent of spreading of point Sources at the end of 5 years.

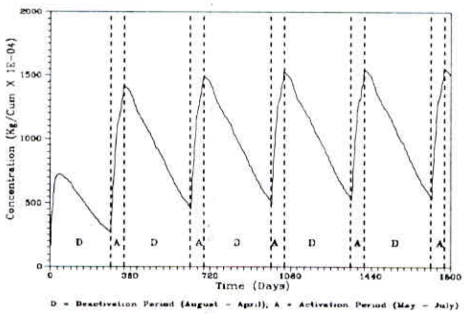


Figure-15 : Variation of concentration Distribution 8 m below source point (Ashoknagar).

Results of Capture zone analysis, for different pumping rates, are exhibited in figs 16, 17 and 18. Redemption of Arsenic through clean-up wells do not show effective outputs even with set of three wells, as no distinct formation of capture zone which could take out the Arsenic plume without disturbing the clean water zones, is evident. Increase of pumping rate results in flow lines to become localized. However, for designing of clean water wells the particle tracking scenarios could be an useful contribution. Well location could be ascertained such that a higher rate of safe water pumping is possible. It is evident from Figs.(16,17,18) that with higher rate of pumping, well nos. CZ1, CZ2, CZ4 and CZ5 drawing water from Arsenic contaminated zones where as well no. CZ3 still draws clean water. All these locations are selected hypothetically but the technique could be used for selecting specific locations.

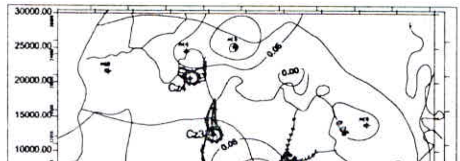


Figure 16. Particle tracking with Pumping rates= 250 & 100 cum/day for Clean-up and Design well respectively.

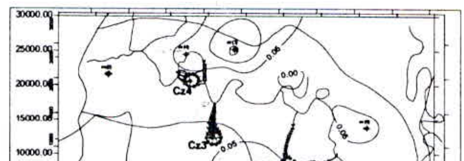


Figure 17. Particle tracking with Pumping rates= 500 & 200 cum/day for Clean-up and Design well respectively.

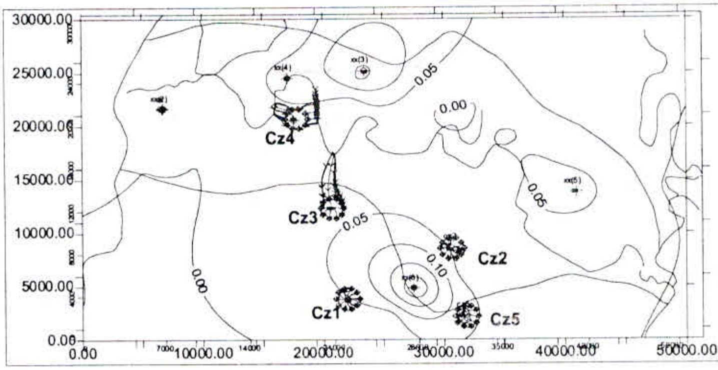


Figure 18. Particle tracking with Pumping rates = 750 & 400 cum/day for Clean-up and Design well respectively.

CONCLUSIONS

Arsenic contaminated groundwater domain, in Nadia and North 24-Paraganas districts of West Bengal, have been analysed. A Three dimensional finite difference mesh comprised of ten layers, each having 10,000 blocks, has been conceptualised. The model has been calibrated, validated and simulated using USGS flow model MODFLOW and coupled with MT3D for contaminant transport and MODPATH for capture zone analysis. Flow model signified the field flow paths and velocities with expected degree of precision. A number of alternatives of source conceptualization has established the trend of Arsenic transport as the localized in-situ sources. Study indicates that the occurrence of Arsenic at a location has no relation with the transport of Arsenic from other sources, rather indicates spreading in a localised scale due to transport of in-situ activation. Analysis of geo-chemical behaviour of the localised pockets to assess the influence of reactive component is recommended which would also help in ascertaining the effects of clay lenses on transport of Arsenic. The model has the scope to accommodate such effects in future. Capture zone analysis does not show encouraging results as far as cleaning of Arsenic through set of clean-up wells are concerned in the study area. However it indicate that the present model can be applied for fixing of the location of wells, and their pumping rate for drafting Arsenic free groundwater.

Acknowledgement

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