Natural Arsenic in Groundwater: Occurrence, Remediation and Management – Bundschuh, Bhattacharya and Chandrasekharam (eds)
© 2005, Taylor & Francis Group, London, ISBN 04 1536 700 X

Prerequisite studies for numerical flow modeling to locate safe drinking water wells in the zone of arsenic polluted groundwater in the Yamuna sub-basin, West Bengal, India

Soumyajit Mukherjee
Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, Uttaranchal, India

ABSTRACT: Arsenic beyond permissible limit from tube-well water has been reported from Yamuna sub-basin, which was initially giving potable water. Locating safe water tube-wells using MODFLOW software can give long-term remedy. Hydrostratigraphy of the study domain is conceptualized up to a depth of 140 m and three principal sediment groups were defined viz., Clay, Sand, and Sand and Gravel. This study indicates that the arsenic concentration in sediment and groundwater does not reveal depth-wise trend. Deviation Factor (DF) indicates irregular trend of concentration levels in sediment as well groundwater depth-wise. Statements on acquisition of arsenic free groundwater are site-specific. These necessitate modeling based decision making for safe well location. Secondly, all the DF values are negative, which means that arsenic in sediments is depleted with respect to their world average values. To locate safe drinking water wells in the Yamuna sub-basin, the modeler should incorporate depth specified hydro-stratigraphy and field constraints. This will be followed by calibration of other hydrological parameters to simulate observed arsenic spreading responsible for its sporadic nature.

1 INTRODUCTION

In the Bengal Basin, in has been reported that even the deeper aquifers have been contaminated with arsenic above the permissible limit (Muralidharan 1998, Mukherjee et al. 1999; Burgess et al. 2000, Bhattacharya et al. 2002a,b, Ahmed et al. 2004). The importance of numerical modeling in locating deep aquifers free from arsenic contamination and optimum pumping rates to extract water from such aquifers have been stressed by several workers (Mallick & Rajagopal 1996; Burgess et al. 2000, Majumdar et al. 2002).

The groundwater flow model using MODFLOW (McDonald & Harbaugh 1988) can be used for this purpose (Majumdar et al. 2002). It is advantageous over other softwares because it has easy to defend codes, easy to update features, and has the facility of adding external modules (Kresic 1997, Herzog et al. 2003). The prerequisites to develop such a groundwater flow model are (i) 3D visualization of hydro-stratigraphy (Mallick & Rajagopal 1996, Vries 1997, Zhang & Brusseau 1998, Weight & Sonderegger 2001, Majumdar et al. 2002, Herzog et al. 2003) in terms of uniform layers of sediment sheets (Majumdar et al., 2002); (ii) depth wise arsenic concentration (Burgess et al. 2000) and its diffusion coefficient/leachability factor; (iii) set of boundary conditions and aquifer parameters and (iv) calibrated hydraulic conductivity of individual layers in three directions, leakance of aquitards, and contaminant dispersivity in three-directions and its molecular diffusion rate (cf. Kresic 1997, Majumdar et al. 2002). Decision variables in this exercise would be well locations, optimum pumping rates, and water withdrawal with arsenic <0.01 ppm, which can be worked out with global optimization technique, or using particle tracking method with MT3D, both of which can be interfaced with MODFLOW.

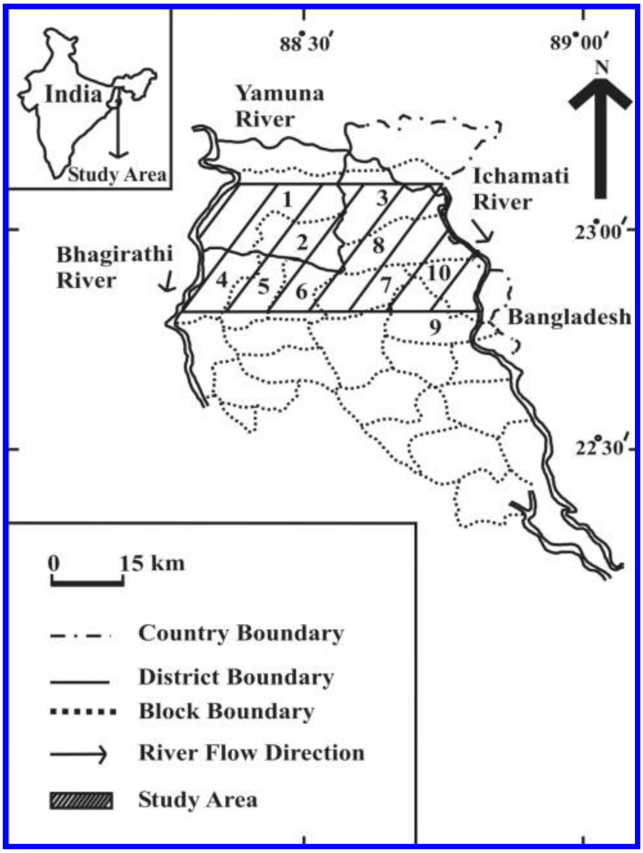

Figure 1. Location Map showing the study area (modified after Majumdar et al. 2002). Blocks under study domain: 1. Chakdah, 2. Haringhata, 3. Bangaon, 4. Barackpore, 5. Amdanga, 6. Habra-I, 7. Habra-II, 8. Gaighata, 9. Baduria, 10. Swarupnagar. Blocks 1 & 2 belong to Nadia district, rest of them belong to North 24 Parganas district.

The present work aims to: (i) establish MODFLOW compliant hydro-stratigraphy, and (ii) to finding out depth wise trends in the variation of arsenic concentration in sediments in the Yamuna Sub-basin (a part of the Bengal basin, India).

2 THE STUDY AREA

The geographic boundaries of the Yamuna sub-basin (latitude: 22°49′–23°03′N; longitude: 88°24′–88–51′E) are demarcated by the south flowing Bhagirathi river on the west and Ichamati river on the east (Fig. 1). This sub-basin covers an area of 1500 km^2 and lies both in Nadia and North 24 Paraganas districts of West Bengal and falls under the domain of Gangetic delta. The Gangetic delta comprises numerous partial fining upward sequences, characteristic of laterally shifting meandering river course (Bhattacharya et al. 1997).

3 HYDRO-STRATIGRAPHIC CHARACTERIZATION

For modeling purpose, it is difficult to simplify the hydro-stratigraphy as “aquifers separated by aquitards” in a deltaic system such as the Yamuna Sub-basin (Freeze & Cherry 1979, Premchitt &

Table 1. A typical borehole lithology from the Yamuna Sub-basin (for referencing, litho-units have been numbered from bottom to top) (Source: CGWB).

Unit	Lithology	Depth (m)	Thickness (m)
24	Light brown silty clay	0–3.96	3.96
23	Grey fine sand	3.96–16.2	12.19
22	Grey medium & fine sand	16.2–19.2	3.05
21	Grey fine & uniform sand	19.2–22.3	3.05
20	Dark grey fine sand & mica	22.3–28.3	6.09
19	Dark grey fine sand	28.3–31.4	3.05
18	Grey fine sand	31.4–37.5	6.10
17	Grey fine sand & sandstone	37.5–40.5	3.04
16	Grey fine sand	40.5–43.6	3.05
15	Grey fine sand & mica	43.6–46.6	3.05
14	Grey medium uniform sand	46.6–49.7	3.05
13	Dark grey silty clay & sand	49.7–52.7	3.05
12	Grey fine sand	52.7–56.4	3.65
11	Grey coarse and medium sand	56.4–68.0	11.59
10	Grey very fine dirty sand	68.0–75.9	7.92
09	Grey coarse sand	75.9–80.2	4.27
08	Grey fine to coarse sand	80.2–83.2	3.05
07	Grey fine sand	83.2–86.3	3.04
06	Grey fine dirty sand & mica	86.3–89.3	3.05
05	Grey sand & sandstone	89.3–93.9	4.57
04	Grey fine sand	93.9–106.4	12.5
03	Dark grey silty clay	106.4–109.1	2.74
02	Dark grey silty sand	109.1–110.6	1.53
01	Grey coarse sand & gravel	110.6–116.7	6.09

Das Gupta 1981). Well-to-well correlation in such a situation is difficult due to frequent vertical repetition and lack of horizontal continuity of litho-units (Fitts 2002). Hydro-stratigraphic conceptualization of the geologic domain, however, remains a prerequisite for developing any groundwater flow model (Zhang & Brusseau 1998).

Extensive lateral migration of meandering rivers during the Quaternary Period within the study area has created vertical repetition and horizontally discontinuity of sediments (clay, sand and gravel). In such a situation, for modeling purpose (using MODFLOW) the hydro-stratigraphy can be simplified by (i) neglecting the narrow lenses of lithounits (Marsily et al. 1978), or (ii) grouping together the litho-units with similar hydraulic conductivity (Martin & Frind 1988, Herzog et al. 2003). Such simplification may lead to zigzag hydro-stratigraphic pattern between the wells. Subsequent to the development of litho-log based model, top and bottom elevations within the MODFLOW grid can be matched and adjusted to simulate stratigraphic conditions (Jones et al. 2002).

In this work, 34 borehole lithological sections obtained from the Central Ground Water Board of India, and those obtained from literature (Bhattacharya et al. 1997; Mukherjee et al. 1999) were utilized. All these boreholes, drilled to depths varying from 25 to 400 m, partially penetrate the upper sedimentary formations. A large part of the subsurface formations are unconsolidated sediments and only at places, due to overburden, diagenesis of sand into sandstone is recorded thus resulting in reduction in permeability.

For the sake of modeling, sedimentary sequences (Table 1) from the study area are grouped into three broad litho-units viz. (i) clay (including soft, hard, compact, sandy and silty clays), (ii) sand of all size ranges, and (iii) sand and gravel (Table 2). The lower limit for these groups is fixed at 140 m due to paucity of large data beyond this depth from the boreholes.

In general, borehole lithological correlation is carried out using certain marker beds, which are characterized by physical, chemical and mineralogical parameters. In the present case, however,it is not possible to select any marker bed due to repetitive occurrence of similar lithological units (Table 1).

Table 2. The reclassified lithological groups.

New unit	Old units	Litho-group	Recalculated depth (m)	Recalculated thickness (m)
6	24	Clay group	0–3.96	3.96
5	14 to 23	Sand group	3.96–49.68	45.72
4	13	Clay group	49.68–52.73	3.05
3	4 to 12	Sand group	52.73–106.37	53.64
2	2 to 3	Clay group	106.37–110.64	4.27
1	1	Sand and gravel group	110.64–116.73	6.09

Table 3. Conceptualized multi-aquifer-aquitard system in the study domain upto 140 m depth.

Hydro-stratigraphic units	Depth (m)	Thickness (m)
Clay group aquitard	0–25	25
Sand group aquifer	25–42	17
Clay group aquitard	42–70	28
Sand group aquifer	70–90	20
Clay group aquitard	90–100	10
Sand & gravel group aquifer	100–140	40

A three-tier multi-aquifer-aquitard system was conceptualized and is shown in Table 3. The depths assigned to the hydro-stratigraphic units are the most frequently encountered depths in the reclassified lithological groups. It must be mentioned here that lithostratigraphic sequence based on a single borehole (see Bhattacharya et al. 1997) is site-specific and thus cannot be used for such modeling purpose.

4 VARIATION IN ARSENIC CONCENTRATION WITH DEPTH

Depth wise variation of arsenic concentration in groundwater (Table 4) and sediments (described later in 'deviation factor') of the study domain (and some also from other parts of the Bengal basin) were compiled and compared by the author (Mukherjee 2002). No agreement in terms of the depth range of maximum arsenic concentration in sediments and groundwater was found in these data. Moreover, generalized statements by various workers (see Table 4) were found true only for their own study domains, hence they must not act as guidelines to locate safe water tube-wells within the Yamuna sub-basin, nor in any other part of the Bengal basin.

Similarly, arsenic content in sediments do not show any systematic relationship with depth. Further, in order to compare enrichment or depletion of arsenic in a repetitive sedimentary sequence 'Deviation Factor' (DF), a unitless number, is defined as:

$$DF = [(Ca - Cw)/ Cw]*100 \text{ (in \%)} \quad (1)$$

where Ca = concentration of arsenic in sediment; Cw = global average concentration of arsenic in that sediment.

A positive DF indicates arsenic enrichment while a negative DF indicates arsenic depletion. A zero value indicates the concentration to be equal to the world average.

Since all the lithounits in the Yamuna sub-basin are fresh water sediments, concentration of arsenic in fresh water sediments from the literature (Ghosh & Chakravorty 1996, Welch et al. 1998, Anawar et al. 2002) are compiled in Table 5, and are used to calculate DF. Average arsenic

Table 4. Arsenic concentration in groundwater in the study area and other parts of the Bengal Basin.

Salient observations	Reference
Nadia district: 73.5–90 m depth: Groundwater As 200 μg/L	Ghosh & Chakravorty (1996)
Nadia district: 24–120 m depth: high arsenic zone (⩽550 μg/L)	Bhattacharya et al. (1997)
Ghetugachi (Nadia): 290 μg/L arsenic at 116 m depth	Jain (1997)
Bengal Basin: Groundwater below 60 m practically arsenic free	Saha et al. (1997)
Nadia: Temporal increase of arsenic conc. in tube-well water	Muralidharan (1998)
Bengal Basin: 'wells more than 10 m below the As enriched aquifers can pump groundwater relatively free of arsenic for some years'	Burgess et al. (2000)
Bengal Basin: Groundwater $<$100–150 m depth are As contaminated	Smedley & Kinniburgh (2002)
N 24 Pargana: groundwater between 70–150 m depth are As contaminated	Basu & Sil (2003)
Nadia: arsenic contaminated water from 14–109 m depth	Bandyopadhyay (2002)
Ghetugachi (Nadia): below 115 m, arsenic conc. in groundwater 1.0 to 0.16 ppm	Bandyopadhyay (2002)
Nadia: "arsenic concentration in sediments and groundwater showing antithetic relationship"	Bandyopadhyay (2002)
Baruipur area: Sand beds with clay caps with more than 30 m thickness contains safe water.	Pal et al. (2002)
Yamuna sub-basin: arsenic conc. in groundwater first increases with pumping, then falls	Majumdar et al. (2002)
Nadia: high arsenic concentration in groundwater restricted within 35–46 m	Smedley (2003)

Note: Published data do not show correlation between the depth and levels of arsenic contaminated groundwater.

Table 5. Average arsenic concentration in fresh water sediments

Lithology	Average conc. of arsenic (ppm)
Sand	4.80
Clay	12.00
Shale	13.00
Sandstone	1.50
Claystone	3.00–10.00

(Source: Ghosh & Chakravorty 1996, Welch et al. 1998, Anawar et al. 2002).

Table 6. Depth wise variation of DF in samples from Itina, N 24-Pargana district.

Lithology	Depth range (m)	Calculated DF
Grey silty clay	1.60–1.64	NC
Dark grey clayey silt	4.48–4.52	NC
Dark grey micaceous	6.28–6.32	<-98.96
fine to coarse sand	13.15–13.30	-33.33
Grey clay	34.70–34.90	-89.58
Reddish brown sand	36.15–36.30	-76.67
Light brown grey fine	40.15–40.30	-79.13
to coarse sand	48.15–48.30	<-98.96

NC: Not calculated.

concentration for mixed sediments (e.g. silty clay) is not available in the literature, hence DF values for these sediments have not been calculated. The DF values (Tables 6 and 7) calculated are negative thus indicating arsenic depletion. Also there is no apparent relationship between the depth and arsenic concentration in the sediments.

Table 7. Arsenic concentration in sediments and DF from the study area.

Area	Lithology	Depth (m)	Calculated DF	Raw data source
N 24 Pargana	Clay	0–25	−93.17 to −99.17	Saha et al. (1997)
N 24 Pargana	Clay	75–115	−54.17 to −95.42	Saha et al. (1997)
Nadia	Sand	64–90	−95.77	Bhattacharya et al (1997)
Ghetugachi (Nadia)	Clay	0–3	−94.81	Jain (1997)
Habra (N 24 Pargana)	Sand	48.00–48.15	−88.33	CGWB
N 24 Pargana	Sand	40.15–40.30	−82.5	CGWB
Birohi (Nadia)	Sand	119	−75.00	CGWB

5 OTHER CONSTRAINTS

For developing a sound MODFLOW model, besides the conceptualized hydro-stratigraphy, the following information are essential: (i) physical boundaries of the study area, its hydraulic head boundaries; (ii) conductance values on the MODFLOW grids; (iii) quantitative water budget of the area in terms of rainfall, irrigation return flow, drawdown etc.; (iv) aquifer parameters (transmissivity and storativity values) obtained from pump test data. All these parameters have been compiled by Majumdar et al. (2002).

6 CONCLUSIONS

In the present study, the entire sedimentary sequence has been grouped into three broad lithological units as discuss above. The arsenic concentration in these sediments does not show any significant variation with depth and hence can be generalized for modeling purpose. The negative DF values indicate depletion of arsenic in the present sequence compared to the world average. There is no significant relationship between the arsenic concentration and depth wise distribution of various sedimentary sequence. Thus any attempt to model using MODFLOW to locate sites for arsenic free groundwater will be a futile exercise.

ACKNOWLEDGEMENTS

The author thanks S.S. Srivastava (IITR), P.K. Majumdar and N.C. Ghosh (NIH, Roorkee), P.J. Martin (University of Waterloo), P.A. Macfarlane (Kansas Geological Survey) and B.L. Herzog (Illinois State Geological Survey) for their help in developing this model. CGWB, Kolkata, NIH, Roorkee, and D. Muralidharan (NGRI, Hyderabad) are thanked for providing data sets for this work. Critical comments from an anonymous reviewer considerably improved the manuscript. The author acknowledges the help received from Prof. D Chandrasekharam (IITB) and Dr. Prosun Bhattacharya (KTH) during the preparation of the manuscript.

REFERENCES

Ahmed, K.M., Bhattacharya, P., Hasan, M.A., Akhter, S.H., Alam, S.M.M., Bhuyian, M.A.H., Imam, M.B., Khan, A.A. & Sracek, O. 2004. Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. *Applied Geochemistry* 19: 181–200.

Anawar, H.M., Komaki, K., Akai, J., Shizuka, T.I., Takahashi, T.Ta., Yoshioka, T. & Kato, K. 2002. Diagenetic control on arsenic partitioning in sediments of the Meghna River delta, Bangladesh. *Environmental Geology* 41: 816–825.

Basu, B. & Sil, S. 2003. Arsenic mapping for North 24- Pargana district of West Bengal -using GIS and remote sensing technology. Map India Conference 2003, Environmental Planing, URL: http://www.gisdevelopment.net/application/environment/water/mi03204.htm (Accessed on August 17, 2004)

Bhattacharya, P., Chatterjee, D., Jacks, G. 1997. Occurrence of Arsenic-contaminated Groundwater in Alluvial Aquifers from Delta Plains, Eastern India: Options for Safe Drinking Water Supply. *Int. J. Water Resources Development* 13: 79–92.

Bhattacharya, P., Frisbie, S.H., Smith, E., Naidu, R., Jacks, G. & Sarkar B. 2002a. Arsenic in the Environment: A Global Perspective. In: B.Sarkar (ed.) *Handbook of Heavy Metals in the Environment*, 147–215: Marcell Dekker Inc., New York.

Bhattacharya, P., Jacks, G., Ahmed, K.M., Khan, A.A. & Routh, J. 2002b. Arsenic in groundwater of the Bengal Delta Plain aquifers in Bangladesh. *Bull. Env. Cont. Toxicology* 69: 538–545.

Bandyopadhyay, R.K. 2002. Hydrochemistry of arsenic in Nadia District, West Bengal. *Journal Geological Society of India* 59: 33–46.

Burgess, W.G., Burren, M., Cuthbert, M.O., Mather, S.E., Perrin, J., Hasan, M.K., Ahmed, K.M., Ravenscroft, P. & Rahman, M. 2000. Field relationships and models of arsenic in aquifers of southern Bangladesh. In: Oliver Sililo et al. (eds.) *Proceedings of the XXX IAH Congress on Groundwater: Past achievements and Future Challenges*, 707–712. Cape Town South Africa 26 November 2000. Rotterdam, Balkema.

Fitts, C.R. 2002. *Groundwater Science.* San Diego, Academic Press.

Freeze, R.A. & Cherry, J.A. 1979. *Groundwater.* Englewood Cliffs, New Jersey, Prentice Hall.

Ghosh, N.C. & Chakravorty, B. 1996. Arsenic pollution in groundwater-a status report: 7-28. CS (AR) 15/96–97. National Institute of Hydrology.

Herzog, B.L., Larson, D.R., Abert, C.C., Wilson, S.D. & Roadcap, G.S. 2003. Hydrostratigraphic modeling of a complex glacial-drift aquifer system for importation into MODFLOW. *Ground Water* 41: 57–65.

Jain, C.K., 1997. Arsenic pollution in ground water of West Bengal. CS(AR)-6/97-98. National Institute of Hydrology.

Jones, N.L., Budge, T.J., Lemon, A.M. & Zundel, A.K. 2002. Generating MODFLOW grids from boundary representation solid models. *Ground Water* 40: 194–200.

Kresic, N. 1997. *Quantitative Solutions in Hydrogeology and Groundwater Modelling*. New York, Lewis Publisher. pp. 304.

Majumdar, P.K., Ghosh, N.C. & Chakravorty, B. 2002. Analysis of arsenic-contaminated groundwater domain in Nadia district, West Bengal (India): Hydrological Sciences-Journal-des Sciences-Hydrologiques 47(s) S55–66. In: B. Soni (ed) Special Issue: Towards Integrated Water Resource Management for Sustainable Development.

Mallick, S. & Rajagopal, N.R. 1996. Groundwater development in the arsenic-affected alluvial belt of West Bengal -Some questions. *Current Science* 70: 956–958.

Marsily, G.De., Ledoux, E., Levassor, A., Poitrinal, D. & Salem, A. 1978. Modelling of large multilayered aquifer systems: theory and applications. *Journal of Hydrology* 36: 1–34.

Martin, P.J. & Frind, E.O. 1988. Modeling a Complex Multi-Aquifer System: The Waterloo Moraine. *Ground Water* 36: 679–690.

McDonald, M.G. & Harbaugh, A.W. 1988. A modular, three-dimensional finite-difference groundwater flow model. USGS TWRI, Book 6, Ch A1.

Mukherjee, M., Sahu, S.J., Roy, S., Bhattacharya, R., Jana, J., Banerjee, P., Dedalal, S.S. & Chatterjee, D. 1999. Groundwater arsenic in the Bengal delta plain: utilization of geochemical material for the removal of arsenic in drinking water: 106–111. In: Workshop on groundwater pollution and its protection with special reference to arsenic contamination. Organized by Central Ground Water Board Calcutta. January 22.

Mukherjee, S. 2002. Geological investigations prerequisite to locate safe drinking water wells in the zone of arsenic polluted groundwater in the Yamuna Sub-basin West Bengal. Unpublished M.Tech. Dissertation. pp. 1–51. Indian Institute of Technology Roorkee. India.

Muralidharan, D. 1998. Protection of deep aquifers from arsenic contamination in Bengal Basin. *Current Science* 75: 351–353.

Pal, T., Mukherjee, P.K. & Sengupta, S. 2002. Nature of arsenic pollutants in groundwater of Bengal Basin. A case study from Baruipur area, West Bengal, India. *Current Science* 82: 554–561.

Premchitt, J. & Das Gupta, A. 1981. Simulation of a complex groundwater system and an application. *Water Resource Research* 17: 673–685.

Saha, A.K., Chakrabarti, C. & De, S. 1997. Studies on genesis of arsenic in groundwater in parts of West Bengal. *Indian Journal of Earth Sciences* 24: 1–5.

Smedley, P.L., 2003. Arsenic in groundwater-south and east Asia. In: A.H. Welch & K.G. Stollenwerk (eds) *Arsenic in groundwater: Geochemistry and Occurrence*: 179–209. Boston: Kluwer Academic.
Smedley, P.L. & Kinniburgh, D.G. 2002. A review of the source, behaviour and distribution of arsenic in natural waters. *Applied Geochemistry* 17: 517–568.
Vries, J.J., de 1997. Prediction in hydrology: two case histories. *Geol. Rundschau* 86: 354–371.
Weight, W.D. & Sonderegger, J.N. 2001. Manual of Applied Field Hydrogeology. New York: McGraw Hill.
Welch, A.H., Lico, M.S. & Hughes, J.L. 1998. Arsenic in groundwater of the Western United States. *Ground Water* 26: 333–347.