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REACHING THE UNREACHED: CHALLENGES FOR THE 21ST CENTURY

Safeguarding groundwater from arseniferous aquifers

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OCCURRENCE OF ARSENIC in natural water has received significant attention during the recent years. Source of arsenic in natural water is generally related to the process of leaching from the crystal rocks and sediments derived from the arsenic bearing source rocks (Robertson, 1989; Hering and Elimelesh, 1995). Influx of arsenic from various anthropogenically induced sources may also contaminate both soils and groundwater especially under anoxic conditions (Bhattacharya et al. 1996a). The mobilization of arsenic under anoxic conditions is the reason for the overall greater risk for contamination of groundwater as compared to surface water. Inorganic-As species commonly occur in groundwater either in the form of As(V) as *arsenate* or As(III) as *arsenite*.

The presence of arsenic in groundwater has been reported in recent years from several parts of the world, like USA, China, Chile and India (Robertson, 1989; Das et al. 1994; Chatterjee et al. 1995; Hering and Elimelesh, 1995). Groundwater is used as the primary source of drinking water in several parts of the world particularly in the rural and semi-urban areas within the developing countries.

The natural incidences of high-As in groundwater in the vast tract of alluvial aquifers within the delta plains in West Bengal, eastern India, has attained an alarming magnitude over the last couple of decades (PHED, 1991, 1993; Bhattacharya et al. 1995, 1996b). Large scale exploitation of groundwater resources to meet the rising demand of water for agricultural and drinking purposes has resulted this largest arsenic calamity in the world. The occurrence, origin and mobility of arsenic in groundwater is influenced by local geology, geochemistry and hydrogeology of the alluvial aquifers. The present paper aims to highlight the geochemical approach to understand the problem on mobilization of As from the aquifer materials as a function of water-solid phase interactions. Another aspect of this paper is to suggest some of the low-cost geochemical techniques for the removal of As suitable for application in the developing countries like India.

High arsenic groundwater in west Bengal, Eastern India

High arsenic groundwater is encountered in six districts of West Bengal, namely, Nadia, Murshidabad, Malda, Barddhaman, North and South 24- Paraganas, restricted between the latitudes 22^o and 25^{o}N and longitudes 87^o and 89^{o}E (Fig. 1). The arsenic infested zone covers an area of around 34 000 km^2 represents nearly 39 per cent of the total area of the state which extends for about 450 km from Malda district in the north to 24-Paraganas district in the south. Nearly 35 per cent of the total population (nearly 30-40 million or even more) in the state are affected adversely due to the consumption of high-arsenic groundwater for drinking purposes.

Epidemiological studies (Chakraborty et al. 1987; Guha Mazumdar et al. 1988) have revealed that nearly 92.5 per cent of the population exposed to arsenic in the concentration of 0.2-2.0 mg/l in contrast to about 6.25 per cent of the population with $\leq$ 0.05 mg/l in drinking water are affected by *arsenical dermatosis* and *hepatomagaly*. Clinical symptoms of chronic diseases such as *hyperkeratosis* and *hyperpigmentation* in palms and soles and *non-cirrhotic portal fibrosis* are common among the affected population. Significant accumulation of arsenic has been noted in the urine, nail, hair, skin-scales as well as biopsy samples among the affected people (Chatterjee et al. 1995; Das et al. 1995).

Alluvial aquifers in the delta plains

Sedimentological characteristics

Bengal delta plains comprise a thick pile of fluvial sediments pertaining to Quarternary age. Composite sequence of fining upwards cycles of variable thickness characterize the Proto-Padma Meander Belt (PPMB) in the upper delta plain (UDP). The PPMB has a NNE-SSW trend and merges with the lateritic piedmont plain in the northeast. Four younger meander belts of Padma river (PMB) transect the PPMB in the southeastern part of the UDP. These meander belts are discontinuous in nature and often preserved as festoons or show truncated character (Saha and Chakraborty, 1995; Bhattacharya et al. 1996b). The younger meander belt sequences predominantly comprise fining upward succession of sand, silt and clayey sediments, while the older ones are more sandy and underlain by gravelly sediments deposited by high energy streams during the rapidly rising stage of the Flandrian transgression (PHED, 1991). The extensive clay beds belonging to the Tertiary formations occur at depths of about 150 m and indicate uncomfortable relation to the younger fluvial cycles.

Hydrogeological characteristics

The extensive near surface aquifers in the northern part of Bengal basin are unconfined in nature. Such aquifers are dominated by intercalation of sand, silt and clay sediments of Quarternary age. The hydrological boundaries between the shallower and deeper parts of the basin is

Figure 1. Map of West Bengal showing the areas with incidences of high-arsenic in groundwater

demarcated by subsurface basement ridges. Confined aquifers occur at depths of about 300 m, with possibilities of zonal inter-connection with the upper group of unconfined aquifers especially along the tectonic troughs through which the major rivers flow. Groundwater occurs under unconfined condition particularly in Nadia, Murshidabad, and Malda districts and under semi-confined condition in Barddhaman, North and South 24-Paraganas districts. Thus, the aquifers change gradually from open to semi-confined character towards the south. The closed aquifers are apparently inter-connected with the upper group of open aquifers.

Fining upward sequence comprising fine, medium and coarse sand with gravel of fluvial origin characterize the aquifers in UDP. Dark coloured clayey intercalation possibly reflect dominance of organic matter. Sandy clay mixed with kankar ($CaCO_3$-concretions) and coarse, medium to fine sand characterizes the open hydrological systems. The semi-confined systems are characterized by a sequence of medium to coarse sand with gravel in the bottom and fine white sand with clayey intercalation at the top. Typical lithological succession of a well site in Nadia district is given in Fig. 2.

Deeper aquifers (> 200 m) underlie a blanket of a widespread aquiclude in the near surface zone in the lower delta plains (LDP) and coastal tracts of Midnapur district (Saha and Chakraborty, 1995). Groundwater in the western part of the basin occurs in localized zones both under confined as well as unconfined conditions.

Geochemical constraints

The investigations have revealed that As contaminated groundwater is mainly confined to the intermediate aquifer (20-80 m) within the meander belt of the UDP, while the presence of As is restricted in the shallow and deep aquifers (90-150 m). Mineralogical investigations have revealed that arsenic occurs in the silty clay as well as in the sandy layers as coating on mineral grains. The impersistent clay horizons separating the shallow and intermediate aquifers have also revealed relatively high arsenic content with occasional distinct grains of arsenopyrite (PHED, 1991). The absence of impervious clay partings between the intermediate and deeper aquifers seem to play an important role for the mobilization of As.

The hydrochemical data indicate that the major ions are calcium, magnesium and bicarbonate with elevated contents of iron, phosphate and arsenic. Contents of sulphate, chloride and fluoride are low. Distinct trends of increasing arsenic has been documented during pumping, suggesting a release of As flowing from distant sources (PHED, 1991; Das et al. 1995; Chatterjee et al. 1995). As-chemistry of the groundwater samples from several pumped wells is dominated by As(V) species.

Scrutiny of the preliminary data reveals that As mobilization in the groundwater is related to reduction of As species commonly adsorbed on the secondary Fe- and Al-phases such as goethite and gibbsite. These Fe- and / or Al-phases are characterized by variable surface charge, negative at higher pH and positive at lower pH. At lower pH, these surface reactive phases attain net positive charge leading to significant adsorption of As(V) species. The mobilization of As in groundwater appears to be governed by changing redox conditions where the arsenic phases are selectively desorbed as a response to the reduction of Fe^{3+} phases to soluble Fe^{2+} species. High-As occurrences concomitant with the increased Fe contents in groundwater supports this hypothesis. It can be conjectured that part of the As in the groundwater is quantitatively related to the release of As phases mainly as As(V) form adsorbed on the surface reactive Fe-oxides and hydroxides.

Although the geological sources of As in the alluvial sediments of the Bengal delta plains could be proved unequivocally, more detailed research is needed to characterize the chemistry of the aquifer materials in order to understand the water-solid-phase reactions operating in conjunction groundwater development. Anthropogenic activities such as land use pattern is the other aspect which could create the physico-chemical conditions facilitating mobilization of As by subsequent groundwater exploitation.

Options to safeguard arsenic bearing ground water

Extraction of water from deeper aquifers (150-300 m) has so far remained the most viable alternative to safeguard the drinking water supply, as long as concentrations of arsenic remained below the permissible limit (<50 mg / l). This expensive operation has not been successful as elevated levels of arsenic have been noted in the recent groundwater samples. This could be due to leaching and downward movement of soluble arsenic from the overlying sediments due to forced extraction of groundwater. The mitigation policies to limit the leaching of As in groundwater from unstable minerals are yet to establish their merit.

Experience from a full-scale conventional chemical treatment plant for the removal of As from source water with high As concentrations with variable redox speciation of As in Chile (Sancha, 1995) has indicated that stringent standards for As (<20µg / l) could not be achieved by methods of conventional coagulation (Scott et al. 1994). The redox speciation of As has therefore significant implications on the efficiency of treatment processes (Hering and Elimelech, 1995). Transformation of As species from lower to higher oxidation state can be achieved by a suitable oxidizing agent before coagulation (Mazumdar et al. 1993). Effectivity as well as maintenance of such high-cost, full scale treatment plant is not a viable alternative for municipal water supply schemes in rural and semi-urban areas in developing countries like India with poor infrastructural facilities. Another major aspect of the applicability of such processing plants concerns the safe disposal of sludge containing high As.

Distribution of surface water from distant sources as well as amendment of groundwater by attached filter

Figure 2. Simplified lithological succession showing the disposition of arsenic contaminated aquifers at a borehole site, Nadia District, West Bengal.

units or dug-wells fitted with hand-pumps were among the suggested recommendations by the state planners (PHED, 1993). However, merits of these options are yet to be established for safeguarding the supply of drinking water in this region. Laterite could be a possible filter medium for some of the As contaminated groundwater, notably those in which the arsenate dominates over the arsenite. The laterite could be manipulated in a number of ways to achieve a good physical form and maximum adsorption capacity. Reinfiltration of ironous groundwater high in As may be an option if permeable surface sediments are present. Especially arsenate may be removed by adsorption on the ferric precipitates. Care must be taken for the removal and safe disposal of the filter bed.

The process of bacterial iron oxidation employed at some well sites in UK and France seem to be a very useful method for the removal of iron from groundwater (Bourgine et al. 1994; Tyrell et al. 1996). Naturally occurring bacteria in the well environment carried to such filter beds by groundwater where biological oxidation of Fe^{2+} to Fe^{3+} takes place. These biogenic filters rich in ferric iron precipitates may consequently adsorb the dissolved As species. This type of remedial technique could be considered for the amendment of high-As groundwater for safe drinking water supply in rural and semi-urban areas of West-Bengal.

References

Bhattacharya, P., Chatterjee, D. and Jacks, G. (1995) Arsenic contamination in groundwater within multilevel aquifer system of Indo-gangetic delta plains: A case study from West Bengal, eastern India. *5th Seminar on Hydrogeology and Environmental Geochemistry, B. Bölviken Seminar-95; Geological Survey of Norway*, Report 95.138, pp. 8-9.

Bhattacharya, P., Jacks, G. and Nordqvist, S. (1996a) Soil contamination at a wood preservation site: Experimental studies of Remedial techniques. *Boreal Environmental Research*, (submitted)

Bhattacharya, P., Chatterjee, D. and Jacks, G. (1996b) Occurrence of arsenic contaminated groundwater in alluvial aquifer from Delta Plains, Eastern India: Options for safe drinking water supply. *Int. J. Water Res. Dev.*, (accepted)

Bourgine, F.P., Gennery, M., Chapman, J.I., Keral, H., Green, J.G., Rap, R.J., Ellis, S. and Gaumard, C. (1994) Biological processes at Saints Hill water-treatment plant, Kent. *Journal of the Institution of Water and Environmental Management*, 8(4), pp. 370-393.

Chakraborty, A.K., Banerjee, D., Ghoshal, S. and Barman, P. (1987) Arsenical dermatitis from tubewell water in West Bengal. *Indian Journal of Medical Research*, 85, pp. 326-334.

Chatterjee, A., Das, D., Mandal, B.K., Chowdhury, T.R., Samanta, G. and Chakraborty, D. (1995) Arsenic in groundwater in six districts of West Bengal, India: The biggest arsenic calamity in the world. Part 1. Arsenic species in drinking water and urine of the affected people. *Analyst*, 120, pp. 643-650.

Das, D., Chatterjee, A., Samanta, G., Mandal, B.K., Chowdhury, T.R., Chowdhury, P.P., Chanda C., Basu, G., Lodh, D., Nandi, S., Chakraborty, T., Mandal, S., Bhattacharya, S.M. and Chakraborty, D. (1994) Arsenic in groundwater in six districts of West Bengal, India: the biggest arsenic calamity in the world. *Analyst*, 119, pp. 168N-170N.

Das, D., Chatterjee, A., Mandal, B.K., Samanta, G., Chakraborty, D and Chanda B. (1995) Arsenic in groundwater in six districts of West Bengal, India: The biggest arsenic calamity in the world. Part 2. Arsenic concentration in drinking water, hair, nails, urine, skin-scale and liver tissue (biopsy) of the affected people. *Analyst*, 120, pp. 917-924.

Guha Mazumder, D.N., Chakraborty, A.K., Ghose, A., Gupta, J.D., Chakraborty, D.P., Dey, S.B. and Chattopadhyay, N. (1988) Chronic arsenic toxicity from drinking tubewell water in rural West Bengal. *Bulletin of the World Health Organization*, 66(4), pp. 499-506.

Hering, J.G. and Elimelech, M. (1995) International perspectives on arsenic in groundwater: Problems and Treatment strategies. *Proceedings of the American Water Works Association, Annual Conference*, June 18-22, 1995 *(Preprint)*.

Mazumdar, A., Kahali, B. and Nath, K.J. (1993) Removal of arsenic by chemical precipitation in drinking water. *Journal of Indian Public Health Engineers*, 62, pp. 103-106.

PHED (1991) National Drinking Water Mission: Submission Project on *Arsenic Pollution in Groundwater in West Bengal*, Final Report by Steering Committee, Arsenic Investigation Project, Government of West Bengal. 57p.

PHED (1993) First phase Action Plan Report on *Arsenic Pollution in Groundwater in West Bengal*, Arsenic Investigation Project, Government of West Bengal. 46p.

Robertson, F. N. (1989) Arsenic in ground-water under oxidizing conditions, south-west United States. *Environmental Geochemistry and Health*, 11, pp. 171-185.

Saha, A.K. and Chakraborty, C. (1995) Geological and geochemical background of the arsenic bearing groundwater occurrences of West Bengal. *Proceedings, International Conference on Arsenic in Groundwater*, Calcutta, India.

Sancha, A.M. (1995) Removal of arsenic in drinking water: Chile experience at full-scale water treatment plants and at point of use treatment device. *Proceedings, International Conference on Arsenic in Groundwater*, Calcutta, India.

Scott, K.N., Green, G.F., Dowe, H.D. and MacLean, S.G. (1994) Arsenic removal by coagulation. *Journal of American Water Works Association*, 87(4), pp. 114-126.

Tyrell, S., Gardner, S., Howsam, P. and Carter, R. (1996) Biological removal of iron from well-handpump water supplies.(Manuscript).

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