Entrapment of arsenic-contaminated groundwater in point bars: case study of Holocene Ganges River deposits, Bihar, India

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1. Introduction

Arsenic-contaminated groundwater causes a wide-spread, serious health risk affecting millions of people world-wide. Arsenic contamination occurs in shallow aquifers in fluvial, lacustrine and deltaic settings. It is only discovered in 2002 that in the Middle Ganges Plain (MGP) of the Ganges Basin in the State of Bihar (NE India) groundwater in Holocene Ganges River deposits is highly arsenic-contaminated (Chakraborti et al., 2003) with concentrations up to 1800 µg L-1, far in excess of the World Health Organization guidelines for safe drinking water of 10 µg L-1 (WHO, 1993). An extensive governmental arsenic inventory campaign in Bihar aims to map the extent and magnitude of the contamination (Saha, 2009). To date, while the inventory is not complete, it is estimated that 25% of the 103.8 million population of Bihar is exposed on a daily basis to arsenic-contaminated drinking and irrigation water.

The arsenic contamination has a geogenic origin. Shah (2010) described pyrite-bearing shale from the Proterozoic Vindhyan Range (West-Central India), arsenic-copper mineralization in the Bundelkhand Granite in Uttar Pradesh, and the gold belt of the Son Valley (Bihar) as potential sources of arsenic. Weathered arsenic is transported in solid phase by rivers to the MGP. Mineralogical studies indicate that arsenic in Holocene sediments of the MGP is associated with hydrated iron-oxide coatings on quartz and clay minerals (Shah, 2008). The arsenic is subsequently released to the groundwater in a redox-controlled environment (Singh et al., 2010). Abundance of organic carbon is a prerequisite for the release of arsenic. Microbial respiration triggers the reductive dissolution of iron and arsenic.

Water wells tapping from Holocene fluvial deposits in the affected areas of Bihar show a large horizontal variability in arsenic concentration on scales between tens of meters to kilometres, and in a vertical sense the largest concentrations are found in the upper 50 m of the aquifer-domain of Holocene Ganges River deposits (Shah, 2008). Sediments have low arsenic concentrations in areas that are well-flushed by groundwater flow due to high-hydraulic head (Shah, 2010). Concentrations increase in a poorly-flushed subsurface environment. Recent studies by, among others, Shah (2008, 2010) and Saha (2010) indicate a relationship between spatial variability of arsenic concentration, and stratigraphy and sediment type.

In this paper the analysis is presented of the role of fluvial facies architecture in the release and entrapment of arsenic in the aquifer-domain of the subsurface. Focus is on the permeability heterogeneity in point bars, and on organic carbon accumulation in the juxtaposed oxbow lakes.

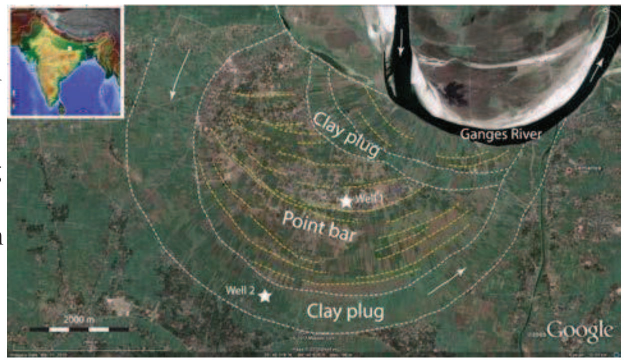

Figure 1 Google Earth image of the study area. Morphology of the point bar and clay plugs is highlighted: White dotted lines mark the outlines of filled-in oxbow lakes. Yellow dotted lines highlight the ridge-and-swale morphology on the point-bar surface.

2. Results

Two 50-m-deep wells were drilled in a fluvial point bar and the juxtaposed clay plug (Figure 1), using percussion drilling with piston samples collected in 60-cm-long PVC core tubes. Core recovery was about 80%, and the cores were accurately depth-constrained. In addition, gamma-ray and deep resistivity logs were run in both boreholes. A transient electromagnetic (TEM) survey with a TEM-FAST 48 HPC device was performed in the area between the two wells to visualize the point bar lithofacies distribution in the shallow subsurface.

Core analysis shows the subdivision in both wells of the stratigraphic succession in two sequences with a sharp break at ~ 28 m depth. The lower sequence consists of thin- to thick-bedded gravel layers and coarse-grained gravelly sand. Permeability is very high, to the point that the drilling mud (bentonite) has completely invaded the core. This sequence is interpreted as formed by shallow braided rivers. The mineralogy suggests that the source area of the rivers was to the south, on the stable Indian Craton. In Well 1, drilled in the point bar (Figure 1) the upper sequence consists of medium- to fine-grained, laminated sand, silt and organic-matter containing clay, organized in three fining-upward units with a thickness of 5 to 12 m. The units formed by vertical stacking of successive generations of Ganges River point bar sediment. In Well 2, drilled in the clay plug, the upper 12 m of the upper sequence consists of silt and black clay, rich in organic carbon. This succession corresponds to the depth of the oxbow-lake that encompasses the point bar sand (Figure 1). The 12 m thickness of the point-bar units and clay plug equals the depth of the present-day Ganges River just north of the well locations. The sharp break between both sequences is interpreted as a sequence boundary which marks the southward shift of the Ganges River belt to this area, with truncation of the upper part of the underlying braided river deposits.

The sequence boundary at ~28 m depth shows up in the TEM survey as a sharp change in resistivity, from high resistivity above to low resistivity below. The inclined point-bar to clay plug interface has a marked resistivity contrast. Lateral lithofacies changes are detected by gradual changes in resistivity. The continuation of the ridge-and-swale topography in the subsurface, which consists of inclined alternating sand and clay layers, is beyond the resolution of the TEM method.

Arsenic concentration measurements in the boreholes and in hand pump wells show high but variable concentrations in the stacked point-bar sequence. From the juxtaposition of: (1) a clay plug rich in organic carbon and (2) permeable point bar sand, we propose that diffusion of organic carbon in the groundwater flux from the clay plug to the point bar is the process to release the arsenic from its solid state. The sequence boundary at ~28 m depth is characterized by a sharp peak in arsenic concentration, whereas in the lower, braided river sequence the concentrations drop. It is interpreted that a free-moving groundwater flux is present in the highly permeable gravel and gravelly-sand below the sequence boundary. The flux effectively flushes the permeable sediment, hence the low arsenic concentration. Arsenic-enriched water that percolates downward from the point-bar sand to the sequence boundary accumulates at the top of the free-moving groundwater flux; hence the peak in arsenic concentration. The assumption has to be corroborated by further, detailed measurements and tracer tests.

4. Conclusions

Arsenic contamination in the shallow aquifer domain of Holocene Ganges River deposits in the State of Bihar (India) is characterized by a large spatial variability of concentration levels. The arsenic is of geogenic origin and its occurrence in groundwater is the result of dissolution of Fe-As oxides in a redox-controlled environment. Diffusion of organic carbon from the clay plug to the adjacent point bar is the process which releases the arsenic into the groundwater. The permeability contrast between low-permeable clay plug and the juxtaposed high-permeable point-bar sand creates a stratigraphic trap in the latter in which groundwater with dissolved arsenic accumulates. Core analysis of two 50-m-deep boreholes in a point bar and juxtaposed clay plug show superposition of two fluvial sequences separated by a sequence boundary at ~28 m depth. The lower sequence consists of stacked, high-permeable braided river gravel and coarse-grained gravelly sand; the upper sequence is made up of 5-12 m thick stacked point-bar units and associated organic matter-rich clay plug sediment. The spatial continuity of the sequence boundary and the overall shape of the permeable fluvial deposits are observed as resistivity contrasts in a time-domain electro-magnetic survey. Measured arsenic concentrations in the boreholes and hand pump wells show high but variable levels in the stacked point-bar sequence and low levels in the underlying braided river sequence. A sharp peak in arsenic concentration at the sequence boundary is interpreted by the permeability contrast between the two fluvial sequences.

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