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Effect of groundwater flow on forming arsenic contaminated groundwater in Sonargaon, Bangladesh

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SUMMARY

Three-dimensional groundwater flow in Sonargaon, Bangladesh is numerically simulated in order to evaluate the flow paths of As-contaminated drinking groundwater in the Holocene aquifer of the Ganges–Blamaptra–Meghna delta plain over a recent 30-year period. The model indicates that vertical infiltration of surface groundwater into the shallow Holocene aquifer occurs frequently in the Ganges–Blamaptra–Meghna delta plain. It predicts that the water recharged from ground surface moves approximately 10–20 m vertically downward beneath the flood plain, with a gradually increasing horizontal flow, toward the underlying Pleistocene middle mud layer (aquitard). The model also predicts that groundwaters containing highest As concentrations (>700 μg/L) are formed on the vertical groundwater flow paths where surface water recharges the Holocene aquifer and not on the horizontal flow paths. Combining with the groundwater chemistry, reducing groundwater condition is not essential for the As-contaminated groundwater of the studied area in the Ganges delta plain.

1. Introduction

Large-scale natural arsenic groundwater contamination has been a serious problem in numerous areas of the world, especially in Asian countries. In many cases it has a major impact on potable water. Such contamination is typically associated with elevated pH in arid or semi-arid areas, or strongly reducing conditions in geologically young sedimentary basins (e.g., Smedley and Kinninburgh, 2002). In the most polluted area, approximately 35 million people in Bangladesh and 6 million in West Bengal, India are exposed to high levels of As (>50 μg/L) in drinking water (British Geological Survey and Department of Public Health Engineering, 2001; Smedley and Kinninburgh, 2002; Nath et al., 2008). Elevated levels of groundwater As (>50 μg/L) in this basin occur on a large scale in strongly reducing alluvium-based aquifers at near-neutral pH, and in flat areas with sluggish shallow groundwater flow. The mechanism and triggers of As dissolution from minerals to groundwater has been addressed by extensive research, and the microbial reduction and dissolution hypothesis, in which As enriched Fe-oxyhydroxides/oxides are decomposed and release the As into the aquifer under reducing groundwater conditions, is widely accepted (e.g., Nickson et al., 2000; McArthur et al., 2001; Bhattacharya et al., 2002; Smedley and Kinninburgh, 2002; van Geen et al., 2003, 2004; Horneman et al., 2004; Zheng et al., 2005). In more recent studies, chemical weathering of detrital basic minerals such as biotite in the aquifer, due to the enforced infiltration of surface water, has been suggested as an essential mechanism for releasing As into the aquifer (e.g., Seddique et al., 2008; Itai et al., 2008).

In previous studies, it has been well documented that As-contaminated and As-free/less contaminated areas are distributed as patches in close proximity to each other (e.g., Smedley and Kinninburgh, 2002; van Geen et al., 2003; Ravenscroft et al., 2005; Mitamura et al., 2008; Itai et al., 2008). Numerous researchers previously considered that the highly contaminated As groundwater appeared in stagnant regions of the aquifer and that dissolved As was flushed out of deep aquifers but not from the shallow aquifers, due to low groundwater mobility. Harvey et al. (2002, 2003), however, documented that the circulation of local groundwater occurred on a scale of a few 100 m in diameter, and that such small-scale circulation activated in this 30-year period promoted

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As release into the groundwater. These results are considered valuable because it revealed that the groundwater flow system was an essential factor causing As groundwater contamination in the Ganges delta plain (e.g., British Geological Survey and Department of Public Health Engineering, 2001; Harvey et al., 2006; Klump et al., 2006; Mukherjee et al., 2007, 2011; Michael and Voss, 2009; Neumann et al., 2010). However, few studies focusing on the relationship between the distribution of varying As contamination levels and groundwater systems have subsequently been published.

By conducting a series of studies in Sonargaon, Bangladesh, we realized that the vertical infiltration of surface water into the shallow aquifer promoted As contamination. In those studies, Mitamura et al. (2008) reported that wells installed into fine sediments were highly contaminated by As (highly As-contaminated wells were occasionally installed into fine micaceous sediments), and that the geological structure of the aquifers was an important factor controlling the formation of As-contaminated groundwater in Bangladesh. Seddique et al. (2008) reported that detrital biotite was a primary source of As and that chemical weathering of this mineral was an essential mechanism affecting the chemical composition of groundwater, including the As concentration thereof (Itai et al., 2008). Heterogeneous distribution of major chemical components and the isotopic ratios of oxygen and hydrogen in the groundwaters indicated vertical infiltration of surface groundwater into the shallow sediments and short groundwater recharge paths (Itai et al., 2008). In this study, three-dimensional transient groundwater flow is simulated with realistic assumptions of hydraulic constants and boundary conditions of the geological structure, focusing on the relationship between the flow paths and the concentrations of As in contaminated drinking groundwater over a recent 30-year period in the shallow groundwater system of the Holocene aquifer.

2. Method

Transient three-dimensional groundwater flow was simulated using a numerical model to document the flow paths and the residence time of As-contaminated groundwater in the Holocene aquifer of the study area over 30 years. The model was constructed based on a data set including topography; geological structure; hydraulic constants; tube well information (numbers, locations and screen depths of wells drilled less than 40 m deep that are used mainly for drinking water); the population living at each levee where there are settlements; transient water head records for three observation wells installed at three different depths at the same site; temporal groundwater level records at eight hand-auger drilling sites; irrigation; precipitation; evapotranspiration; and assumed boundary conditions of aquifers surveyed in 2003–2006. The ground surface of all study area can be recharge area and the river zone can be recharge or discharge area depending on hydraulic gradient between river water head and groundwater head. Of the data used in this study, the temporal groundwater level changes and geochemical characteristics such as major and minor compositions, H, O, N and S isotopes, tritium units, were already published in the previous reports (Mitamura et al., 2008; Itai et al., 2008).

3. Site description and hydrogeological setting

The study area is 3.0 km × 3.0 km in size, located 20 km east of Dhaka, in Sonargaon, Bangladesh. The area is composed of terraces in the west and a flood plain, including natural levees along the old Brahmaputra River, which is an abandoned channel of the present Meghna River. Except for the natural levees, the flood plain is inundated during the rainy season. During the dry season, the floodplain dries and is used for cultivation, and the channel becomes narrower and consists of a series of disconnected ponds (Fig. 1). The flat surface of the ground, which only varies 4–5 m in altitude, and the meandering river channel suggest a very low hydraulic gradient and/or sluggish groundwater flow beneath the flood plain. Drinking water is drawn from groundwater through tube wells installed into shallow and deep aquifers in the populated western terrace and levees. Aquifers less than 90 m deep in the study area consist of upper and lower sand formations separated by a mud layer; the upper Holocene sand formation is commonly 25–35 m thick and overlies the Upper Pleistocene mud formation, which unconformably overlies the lower Plio-Pleistocene sand formation (Mitamura et al., 2008) (Fig. 1). The upper sand formation thus comprises the shallow unconfined aquifer, and the lower formation is the deep confined aquifer. The upper sand formation hosts thin intercalated clay to silt layers in the upper section, and medium sand in the lower section. The upper sand formation can, therefore, be divided into the uppermost sand and the upper sand layers at approximately 0 m altitude. The mud formation, which functions as an aquitard, also includes intercalated lenses of very fine sand to silt. The lower sand formation is exposed as terraces in the western part of the study area. The upper sand formation thus abuts the lower sand formation with an inferred fault along the boundary between the terraces and the alluvial flood plain. The mud and lower sand layers are partly eroded to form valleys in this area.

4. Model description

Three-dimensional groundwater flow in unsaturated–saturated porous media is modeled by the governing equation as follows:

$$\frac{\partial}{\partial x_i}\left[K_r(\theta)K_{ij}\frac{\partial\varphi}{\partial x_j}+K_r(\theta)K_{i3}\right]+q=(C(\theta)+\alpha S_s)\frac{\partial\varphi}{\partial t};\quad i,j=1,2,3 \tag{1}$$

where φ is hydraulic head, x_i is a spatial coordinate, t is time, K_{ij} is the saturated hydraulic conductivity, θ is the volumetric water content (=nS_r), n is porosity, S_r is the saturation index (ranging from 0 to 1), $K_r(\theta)$ is the unsaturated–saturated hydraulic conductivity ratio (also ranging from 0 to 1), $C(\theta)$ is the specific water content (=$d\theta/d\varphi$), S_s is the specific storage, and α is a function with a value of 1 when $S_r = 1$ and 0 when $S_r < 1$.

Eq. (1) is solved for unknown φ under appropriate boundary conditions. In the present study, because unsaturated–saturated seepage flow including rain, evaporation and irrigation recharge in unconfined aquifer is analyzed, the unsaturated–saturated three-dimensional seepage flow analysis code AC-UNSAF3D (developed by Okayama University, Japan in 1980s and opened as a standard code since 2000 in Japan: http://gw.civil.okayama-u.ac.jp/gel_home/download/index.html) was applied with a three-dimensional finite element method (3D-FEM) scheme (Segol, 1977; Frind and Verge, 1978; Huyakorn et al., 1986; Nishigaki et al., 1992) to document the three-dimensional groundwater flow in this study area using a one month time step. This code is specified for advective flow only.

5. Model of stratigraphic structure and hydraulic properties

In the present FEM model, a region 3500 m in the x direction, 3000 m in the y direction and 114 m in the vertical (z) direction is divided into 106,567 rectangular voxels of 100 m × 100 m × Δz [m] (Table 1). Because a rectangular grid system with small $\Delta z/\Delta x$ and $\Delta z/\Delta y$ ranging from 5×10^{-3} to 2×10^{-2} was adopted, FEM was used instead of finite difference method from the point