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Preliminary evidence of a link between surface soil properties and the arsenic content of shallow groundwater in Bangladesh

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Abstract

The extremely heterogeneous distribution of As in Bangladesh groundwater has hampered efforts to identify with certainty the mechanisms that lead to extensive mobilization of this metalloid in reducing aquifers. We show here on the basis of a high-resolution transect of soil and aquifer properties collected in Araihazar, Bangladesh, that revealing tractable associations between As concentrations in shallow (<20 m) groundwater with other geological, hydrological, and geochemical features requires a lateral sampling resolution of 10–100 m. Variations in the electromagnetic conductivity of surface soils (5–40 mS/m) within a 500 m × 200 m area are documented with 560 EM31 measurements. The results are compared with a detailed section of groundwater As concentrations (5–150 μg/L) and other aquifer properties obtained with a simple sampling device, "the needle-sampler", that builds on the local drilling technology. By invoking complementary observations obtained in the same area and in other regions of Bangladesh, we postulate that local groundwater recharge throughout permeable sandy soils plays a major role in regulating the As content of shallow aquifers by diluting the flux of As released from reducing sediments.

Keywords: Arsenic; Groundwater; Well water; Bangladesh; Health

1. Introduction

The landmark survey of groundwater pumped from thousands of tube wells in Bangladesh conducted by DPHE/MMD/BGS (1999) and BGS/DPHE (2001) has demonstrated that the concentrations of As in aquifers throughout Bangladesh is spatially highly variable on scales of 1–100 km. Even after depth and broad-scale patterns associated with the geology of the country are taken into account, the average arsenic content of wells in a given village, let alone individual wells, is difficult to predict (BGS and DPHE, 2001; van Geen et al., 2003a; McArthur et al., 2004; Horneman et al., 2004). One of our group's goals for the past several years has been to determine if tractable changes in aquifer properties that are related to groundwater As

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concentrations are observed if they are mapped at spatial scales <1 km. We summarize here some of these results by focusing on shallow (<20 m) aquifers and augment recent observations for one particular study area in Araihazar, Bangladesh, with a densely spaced set of measurements of the electromagnetic conductivity of surface soils.

2. Geological setting

Electromagnetic conductivity data and profiles of groundwater and sediment properties were collected within a 25 km^2 region of Araihazar upazila where the distribution of groundwater As has previously been documented by sampling and analyzing groundwater from over 6500 wells (van Geen et al., 2003a, in press). Columbia University scientists and Bangladeshi partners have since 2000 been investigating the health effects of elevated As on a cohort of 12 000 recruited from the 70 000 inhabitants of the area, as well as various approaches to mitigation (van Geen et al., 2002, 2003a,b). Araihazar upazila straddles the present Meghna River floodplain to the southeast and older deposits of the uplifted Madhupur tract to the northwest (BGS and DPHE, 2001; Goodbred et al., 2003; Zheng et al., submitted for publication). The majority of shallow wells in the area tap thick and relatively recent Holocene deposits frequently associated with elevated groundwater As concentrations (van Geen et al., 2003a).

This report focuses on a 500-m transect that extends west of Lashkardi village where the vast majority of wells contain <50 μg/L As (van Geen et al., 2004b). The western portion of the transect starts from a small village (Rishir Char), where a limited number of existing private wells and a nest of monitoring wells indicate elevated groundwater As concentrations in the shallow aquifer (van Geen et al., in press). The westernmost profile of this section was collected on the margin of an abandoned stream channel north of Rishir Char.

3. Methods

3.1. EM induction survey

The geophysical survey of the study area was conducted with a Geonics® EM31 instrument (McNeill, 1980). By generating an eddy current in the ground, the primary field generates a secondary electromagnetic field that is recorded by the receiving coil. The intensity of the secondary field increases with the conductivity of the ground. When the boom is held horizontally at waist height, which corresponds to a vertical dipole orientation, 50% of the signal is generated in the upper 90 cm of the soil whereas only 27% of the signal reflects the conductivity of layers below 180 cm depth (McNeill, 1980; Doolittle et al., 2001).

3.2. Needle-sampler profiles

The needle-sampler consists of an evacuated sample chamber capped with a silicone stopper, a long needle and plunger assembly to transfer groundwater and sediment from a depth slightly greater than that of the drill hole to the sample chamber, and a housing unit that connects the needle and plunger assembly to the sample chamber (van Geen et al., 2004b). The device is deployed by drilling to the targeted depth using the entirely manual method that has been used to install the vast majority of the millions of wells in Bangladesh (Horneman et al., 2004). The chamber fills almost entirely with groundwater and some sediment during deployment. Groundwater samples filtered under nitrogen were acidified and analyzed for As by high resolution inductively coupled plasma mass spectrometry (HR ICP-MS, Cheng et al., 2004). The effective detection limit of the method for As in unfiltered samples is ~1 μg/L; the precision is on the order of ±2% (van Geen et al., 2005).

4. Results

EM conductivities measured in the fields of this portion of Araihazar span a range of 5 to 40 mS/m ($n = 560$). The highest conductivities were measured in the northwestern portion of the study area, near Rishir Char, and gradually declined towards the east (Fig. 1). A diagonal swath of particularly low conductivities (<10 mS/m), ~100 m wide, characterizes the rice paddies near Lashkardi.

Dissolved As concentrations measured in groundwater obtained with the needle-sampler are consistent with As levels measured in shallow wells of Rishar Char and Lashkardi. The spatial features of a transition from elevated groundwater As concentrations in the west to low As concentrations in the east are illustrated with a contour plot based on 5 profiles ~100 m apart from each other (Fig. 1). The contour corresponding to 50 μg/L As, the Bangladesh standard for drinking water, is crossed at a depth of 50 ft (15 m) at NS-F, with Lashkardi. Groundwater As concentrations barely reach this level at the same depth in the next two profiles to the west (NS-1, NS-2), and then actually decrease below this depth. Further west along the tran-

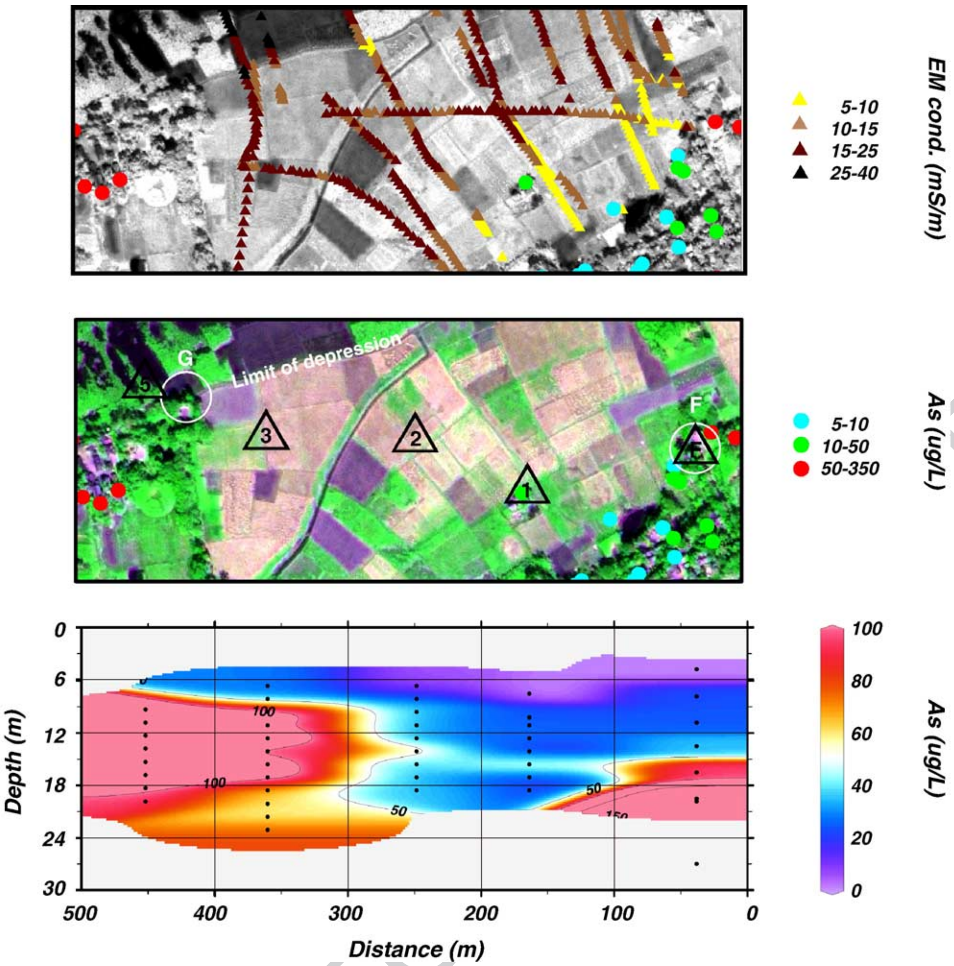

Fig. 1. Comparison of the distributions of surface EM conductivity and groundwater As concentrations across the rice paddies that separate two contrasting villages of Araihazar, Bangladesh. The background for the two upper panels is a portion of a 60 km^2 IKONOS satellite image of the area (van Geen et al., 2003a). Color-coded circles in the same panels show the location and As concentrations in privately owned tube wells. Color-coded triangles in the upper panel indicate the location and range of EM31 measurements. The false color of the satellite image in the middle panel emphasizes in purple areas of high water content. The numbered triangles indicate where 5 needle-sampler profiles of shallow aquifer properties were obtained (van Geen et al., in press). The two white circles show the locations of nests of monitoring wells where profiles of the age of groundwater since recharge have been determined by the $^3H–^3He$ dating method (Stute et al., submitted for publication). The lower panel shows a cross-section of groundwater As concentrations that is based on the 5 needle-sampler profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sect, the minimum in dissolved As content of the shallow aquifer that is located roughly mid-way between the two villages is bound by the sharp transition to NS-3 where concentrations exceed 100 μg/L from 30 to 60 ft depth (9–18 m). At the western end of the transect (NS-4), the depth range of intervals where As concentrations exceed 100 μg/L broadens to include all but the deepest sample.

5. Discussion

A number of studies have shown that hand-held EM instruments can be used to determine the spatial variability of soil salinity (Doolittle et al., 2001). It has, however, typically been difficult to disentangle the direct contribution of fine-grained particles to EM conductivity from an indirect contribution due to the accumulation of salt by evaporation at the surface of impermeable deposits. The likely contribution of both factors to EM conductivity in Araihazar was recently shown by collecting a series of hand-auger cores and analyzing soil samples for grain-size and slurry conductivity (Aziz et al., in preparation). Layers of fine silt dominate the upper 2 m of soil in the western portion of the study area. In contrast, the walls of shallow pits in the eastern part of the study area are composed mostly of fine sand.

Additional data obtained from the same area are important for interpreting subsurface patterns of groundwater As and other aquifer properties. These are measurements of groundwater age relative to recharge obtained by the tritium–helium (^{3}H–^{3}He) dating technique for nests of monitoring wells located at NS-F in Lashkardi and near NS-5 in Rishir Char (Stute et al., submitted for publication). The measurements divide the 2 areas into two distinct hydrologic regimes. Near NS-F, estimated groundwater ages increase from <1 year at ~25 ft (8 m) to ~4 years at 60 ft (18 m). At Site G, instead, groundwater appears to be already several years old in the shallowest monitoring wells and averages 30 years at a depth of 60 ft (18 m).

The simplest, though still tentative, explanation for the observed contrast in groundwater ages is that the sandy deposits surrounding Lashkardi village permit local recharge during the wet season whereas recharge is inhibited by the finer deposits capping the aquifers near Rishir Char. Groundwater dating in several additional villages of Araihazar supports the notion that recharge of shallow aquifers is more rapid in those villages fortunate enough to have low As concentrations in their wells (Stute et al., submitted for publication). The high-resolution transect of profiles connecting Site F and Site G indicates that the effect on groundwater As concentrations of contrasting recharge rates extends at least 100 m laterally beyond the location of the nests of wells where ^{3}H–^{3}He data were obtained (Fig. 1).

6. Conclusions

The concentration of As in groundwater pumped from any particular well in Bangladesh is the result of multiple and still poorly known processes (Nickson et al., 1998; Harvey et al., 2002; McArthur et al., 2004; Zheng et al., 2004). The results presented here illustrate for one particular location an apparently intimate connection between the permeability of surface soils, which can be mapped by EM conductivity, and the As content of shallow groundwater, which can be established with the needle-sampler without installing a well. Establishing causation from spatial correlations of dissolved As concentrations with other properties of Bangladesh aquifers is likely to require more systematic use of these or similar tools, as well as coordination of combined hydrological, geochemical, and microbiological investigations.

7. Uncited reference

van Geen et al., 2004a

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