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Subcontinental to Regional Prediction Modeling of Groundwater Arsenic Contamination in Southeast Asia and China

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1. INTRODUCTION

Arsenic (As) contamination of groundwater used as drinking water threatens the health of millions of people worldwide, particularly in densely populated river deltas and inland basins of South and East Asia (Berg et al. 2001, Buschmann et al. 2008). Although many arsenic-affected areas have been investigated in recent years, further regions at risk remain to be identified.

To pinpoint untested areas at risk of groundwater As contamination, we are developing risk maps by combining geological and surface environmental parameters in geostatistical models that with geo-referenced groundwater arsenic concentrations from existing surveys (Winkel et al. 2008a and 2011; Lado et al. 2008; Rodriguez-Lado et al. 2012).

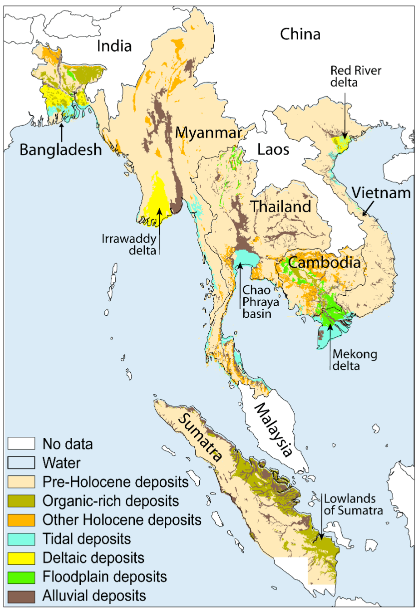

Figure 1. Surface geology of Southeast Asia and Bangladesh, indicating Holocene depositional environments.

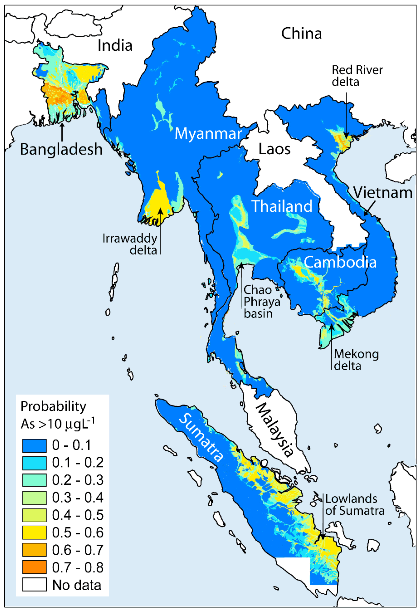

Figure 2. Modeled probability map of As levels exceeding 10 µg/L (WHO guideline) in Southeast Asia and Bangladesh.

The first step made in developing prediction maps was an in-depth assessment of depositional environments in Southeast Asia (Figure 1). We then applied logistic regression analyses to evaluate and quantify relationships between surface proxies (sedimentary depositional environments, soil data and other environmental information from digital maps) and groundwater As concentrations fromBangladesh, Cambodia and Vietnam, and to assess the relative importance of the different surface proxies in these countries.

Such geostatistical prediction modeling required three steps: i) Aggregation of measured As concentrations to reduce spatial variability with the dependent variables, and binary-coding using the WHO threshold value of 10 µg/L; ii) Logistic regression to obtain the weighting coefficients for the environmental proxies; and iii) Calculation of the probability of As exceeding the WHO threshold. The spatial datasets considered as independent variables for the model were sedimentary depositional environments as a proxy for aquifer conditions, and soil variables as a proxy for drainage and chemical maturity of sediments.

These relationships were used to develop prediction maps of groundwater As contamination in Southeast Asia including Indonesia (Sumatra) and other countries where published groundwater quality data is scarce (Myanmar and Thailand). Finally, we tested the accuracy of our predictive model in South Sumatra, where groundwater has not previously been tested for the presence of As (Figure 3).

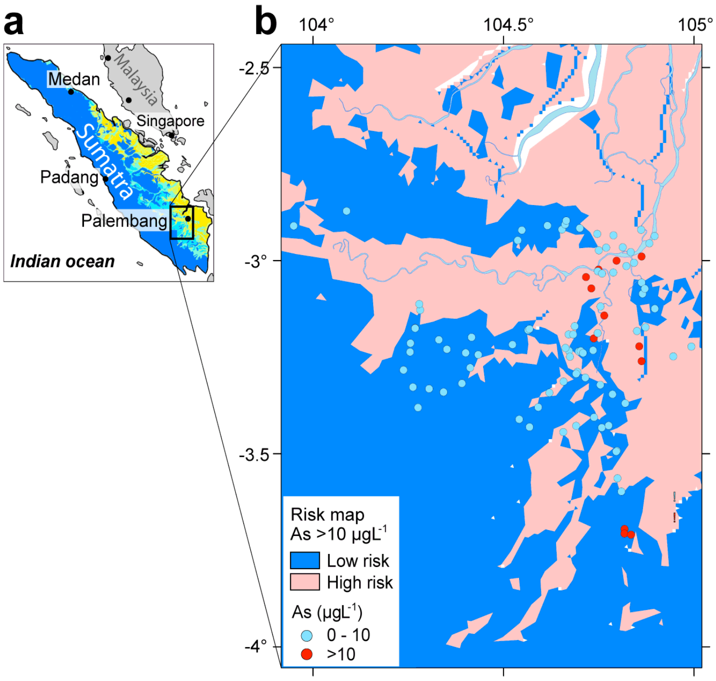

Figure 3. Validation of modeled predictions in the lowlands of Sumatra (61% correctly classified). Winkel et al. 2008a.

2. RESULTS

2.1 Predictions based on surface parameters (2-dimensional models)

The results of this geostatistical model demonstrate that Holocene deltaic and organic-rich surface sediments are key indicators for the prediction of arsenic risk areas. Pre-Holocene deposits, other Holocene deposits and tidal deposits (Figure 1) were found to be statistically insignificant ($p > 0.05$). The combination of surface parameters and statistical modeling is hence a successful approach to predict groundwater As contamination (Amini et al. 2008).

The predicted areas at risk of As contamination agree well with known spatial contamination patterns in e.g. Bangladesh, Cambodia and Vietnam (Figure 2), a finding which is supported by the model classification analysis with 70% correctly classified samples and an absolute average deviation of 7.3% between expected and modeled probabilities of As being ≤10 or >10 µg/L. This is an excellent result considering that neither well depths nor aquifer hydrological data were part of the model.

Apart from the Bengal, Mekong and Red River Deltas where groundwater As contaminations is known, our Southeast Asia probability map (Figure 2) also highlights risk areas that have been largely unknown or unreported, particularly in Myanmar and Sumatra. To evaluate the probability of As contamination in unreported areas, we conducted a ground-truthing survey in the lowlands of Sumatra (Figure 3) which confirmed the presence of elevated As levels in groundwater (Winkel et al. 2008a and 2008b).

2.2 Three-dimensional model based on geology at depth (3D)

All the above is based on two-dimensional data (that is, surface information). We have hence explored avenues of three-dimensional predictions (where depth is the 3rd dimension) in the severely arsenic-troubled Red River Delta (Vietnam), where the probability of groundwater As being >10 µg/L was modeled with 3D geological information (see Figures 4 and 5).

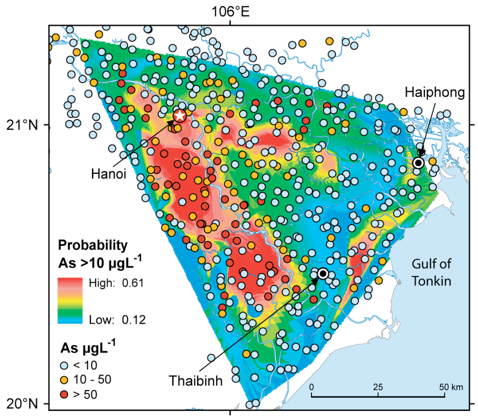

Figure 4. Red River Delta Vietnam: Modeled probability of As concentrations exceeding 10 µg/L, based on three-dimensional geology integrated over the depth range of 0–50 m (74% correctly classified).

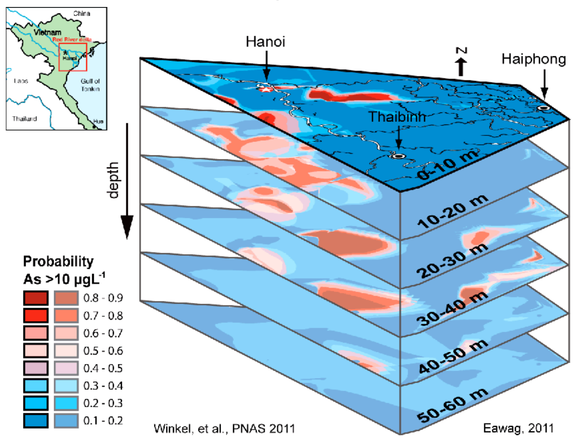

Figure 5. 3-dimensional distribution of As exceeding safe limits in the Red River delta, stacked in 10 m depth intervals (from Winkel et al., 2011).

2.3 Arsenic risk map for China

We are currently modeling the risk of groundwater arsenic contamination over the entire area of China spanning from humid to arid climates and young to old geological surface depositions (Rodriguez-Lado et al. 2012). The risk model identifies large areas where endemic arsenic poisoning has already been detected, but also pinpoints new potentially affected areas such as Tarim basin (Xinjiang), Ejina basin (Inner Mongolia), Heihe basin (Gansu), Qaidam basin (Qinghai), the North-eastern Plain (Inner Mongolia, Jilin and Liaoning) and the North China Plain (Henan and Shandong), which must be confirmed with additional field measurements.. Latest results of this ongoing study will be presented and discussed.

3 OUTLOOK

The presented maps are a valuable and resource-saving tool that can serve both scientists and policy-makers to initiate early mitigation measures in order to protect the people from As-related health problems as well as to efficiently guide water resources management.
Our approach provides a blueprint for further modeling and prediction of As-tainted aquifers around the world. The significance of the method lies in the fact that predictions can be made for regions with no or little groundwater quality data using relatively accessible spatial information. This tool is particularly important for low-income countries with limited water quality surveillance systems.

REFERENCES

Amini M. et al., 2008. Statistical Modeling of Global Geogenic Arsenic Contamination in Groundwaters. *Environ. Sci. Technol.* 42, 3669–3675.

Berg M. et al., 2001. Arsenic Contamination of Groundwater and Drinking Water in Vietnam: A Human Health Threat. *Environ. Sci. Technol.* 35, 2621–2626.

Buschmann J. et al., 2008. Contamination of Drinking Water Resources in the Mekong Delta Floodplains: Arsenic and Other Trace Metals Pose Serious Health Risks to Population. *Environ. Int.* 34, 756–764.

Lado L.R. et al., 2008. Modelling arsenic hazard in groundwater in Cambodia: a geostatistical approach using ancillary data. *Appl. Geochem.* 23, 3010–3018.

Rodriguez-Lado L. et al., 2012. Risk areas of natural groundwater arsenic contamination throughout China. In preparation.

Winkel L. et al., 2008a. Predicting groundwater arsenic contamination in Southeast Asia from surface parameters. *Nature Geosci.* 1, 536–542.

Winkel L. et al., 2008b. Hydro-geological survey assessing arsenic and other groundwater contaminants in the lowlands of Sumatra, Indonesia. *Appl. Geochem.* 23, 3019–3028.

Winkel L.H.E. et al., 2011. Arsenic pollution of groundwater in Vietnam exacerbated by deep aquifer exploitation for more than a century. *PNAS* 108, 1246–1251.

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