Irrigation-induced recharge flushes mobile arsenic from shallow groundwater in the Bengal Basin, Bangladesh

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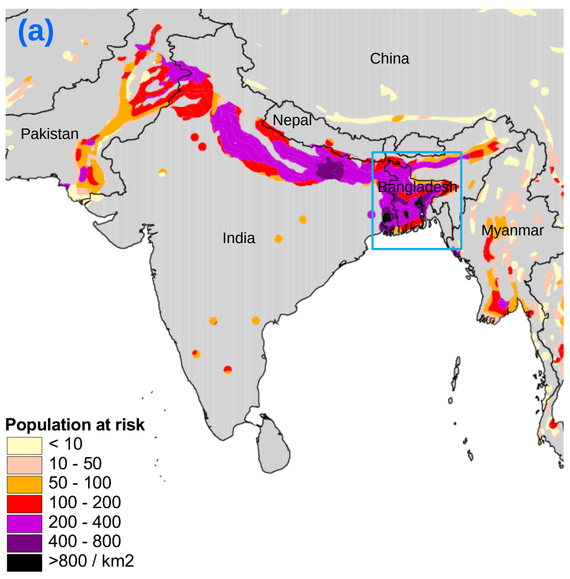
Introduction and Rationale

The health of nearly 100 million people living in South and Southeast Asian Mega-Deltas and low-lying floodplains of the Himalayan rivers is currently affected by chronic consumption of elevated arsenic (As) in drinking water (Figure 1a) (Ravenscroft et al., 2009). Currently, two dominant but contradictory hypotheses describe the hydrogeological conditions under which the mobilisation of As in very shallow (Figure 1b) (<50 m below ground level) groundwater takes place. The "Young Carbon Hypothesis" (Harvey et al., 2002; Neumann et al., 2010) contends that groundwater-fed irrigation mobilises As by inducing greater recharge laden with reactive organic carbon from surface sources (e.g. rice fields, ponds) to drive the reductive dissolution of As-bearing iron-oxyhydroxides. In contrast, the "Aquifer Flushing Hypothesis" (McArthur et al., 2004; Stute et al., 2007; van Geen et al., 2008) argues that intensive groundwater-fed irrigation reduces As concentrations as abstraction induces groundwater recharge that flushes mobile As from shallow aquifers. Both hypotheses derive from localised studies (2−25 km^2) and the explanatory power of neither hypothesis has been rigorously tested regionally. Each hypothesis is predicated upon a specific hydrodynamic condition, that groundwater recharge has been induced by recent abstraction. As a result, a fundamental water management question in the Bengal Basin remains: are recent (1985-1999) increases in groundwater-fed irrigation associated with higher or lower As concentrations in shallow groundwater?



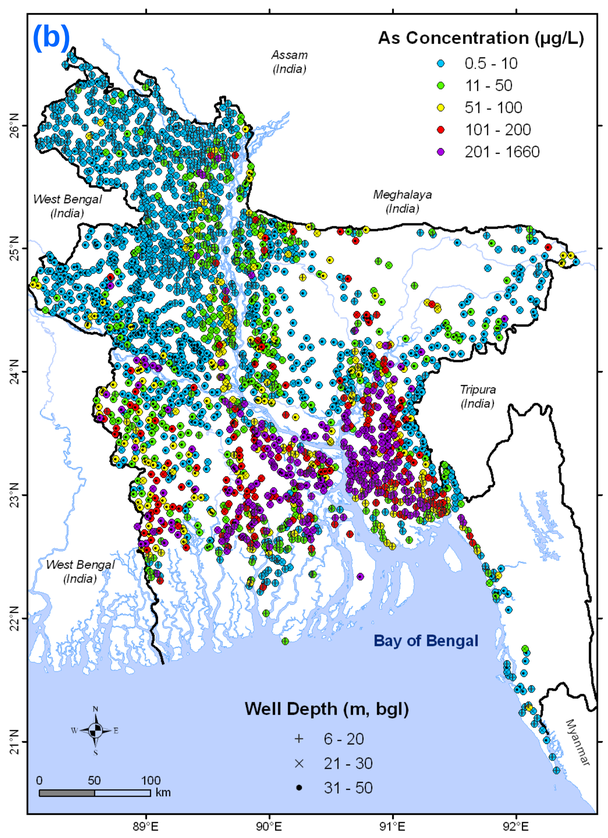


Figure 1: (a) Population in South and Southeast Asian countries who are affected by elevated As concentrations in groundwater (Ravenscroft et al. 2009); (b) spatial distribution in As concentrations in very shallow (<50 m below ground level) groundwater in Bangladesh [As data from the National Hydrochemical Survey in Bangladesh conducted jointly by the Department of Public Health Engineering, British Geological Survey, and Mott MacDonald Ltd, UK (DPHE, 1999; BGS and DPHE, 2001)].

The objectives of the present study are to explain the national-scale spatial variation in observed As concentrations in groundwater in Bangladesh by constructing a robust statistical model, and to examine statistical associations between As concentrations and groundwater recharge rates and groundwater-fed irrigation trends (1985 – 1999).

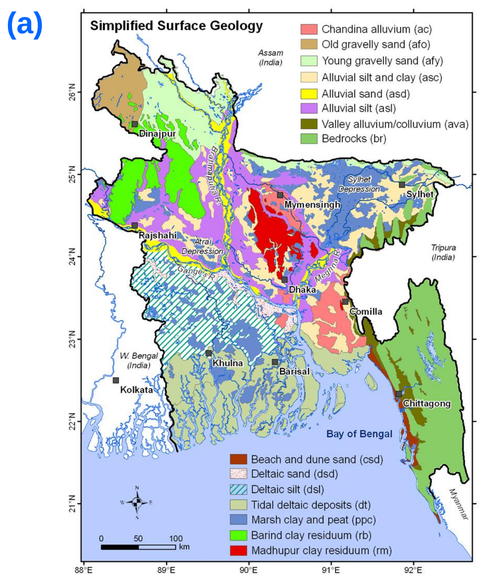
Research Methods

We examine statistical relationships between As concentrations in shallow (<50 m bgl) groundwater (response variable) and a set (*n*=16) of potentially relevant hydrogeological and hydrodynamic factors as independent variables (covariates). To do this, we construct a generalized regression model (GRM) at the national scale. The constructed GRM explains the spatial variation in As concentrations nationally at 1643 locations that were surveyed (DPHE 1999; BGS and DPHE 2001) once during 1998 and 1999. Time series data of As concentrations are not used in the model as they do not exist at the national scale. This advanced statistical modelling approach was applied in place of simple correlation analyses or linear regression techniques because the groundwater As dataset (DPHE 1999; BGS and DPHE 2001) in Bangladesh features (Figure 2):

(1) a highly skewed (non-normal) distribution – positively skewed As concentrations;

(2) a substantial number of records below detection limits (i.e., censored or non-detect observations); and

(3) strong correlation between observations from neighbouring spatial locations (i.e., spatial dependence) at the regional scale (within broad geological units).



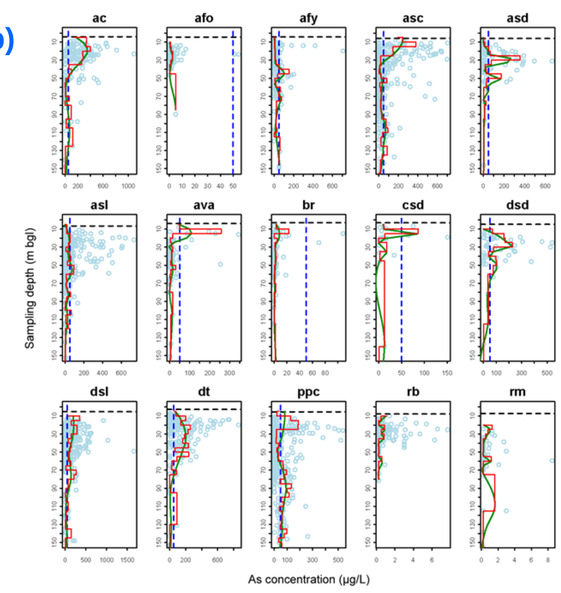


Figure 2: (a) Simplified map of the surface geology of Bangladesh (modified from Alam et al., 1990); (b) groundwater As concentrations by surface geology. In each panel, blue circles are individual As data points; step-wise red lines are the 75th percentile values in each 5-m bin of sampling depth; green lines are the Lowess smooth line; vertical, dashed blue lines represent Bangladesh As standard; and horizontal, dashed black lines are the mean dry-season groundwater table in each geological units.

Modelling Results

Important statistical associations are reported in Table 1. As concentrations are negatively associated with net changes in recharge between pre-development of irrigation and development periods, groundwater-fed irrigation trends, and hydraulic conductivity. The effect of groundwater-fed irrigation trends (Figure 3) on As concentrations is strong and negative. Results indicate than an overall increase in groundwater-fed irrigation trend of 1 mm yr^{-1} is associated with lower (5% lower than the national mean) As concentrations in groundwater.

Table 1: Summary of key results from the national-scale GRM. Estimated coefficients of model parameters and their adjusted (for inter-site spatial dependence) standard errors with corresponding P values.

Covariates	Unit	Coefficient	Std. error (adjusted)	*P* value
Geological and hydrogeological variables:				
surface geology (*n*=15)	(categorical)	-	-	-
TSSC	(m)	-0.025	0.020	0.207
hydraulic conductivity	(m day^{-1})	-0.023	0.008	0.004
specific yield	(-)	-0.068	0.107	0.522
Darcy flux	(cm day^{-1})	-0.014	0.022	0.543
sampling well depth	(m)	-0.013	0.010	0.184
Hydrodynamic and groundwater recharge variables:				
mean groundwater recharge	(mm yr^{-1})	0.0007	0.004	0.867
net changes in recharge	(mm)	-0.004	0.001	0.001
wet-season groundwater table	(m bgl)	-0.004	0.094	0.963
mean groundwater-level trends	(cm yr^{-1})	0.030	0.016	0.066
mean groundwater fluctuation	(m)	-0.171	0.097	0.078
Groundwater-fed irrigation:				
irrigation trends (1985−1999)	(mm yr^{-1})	-0.050	0.024	0.040

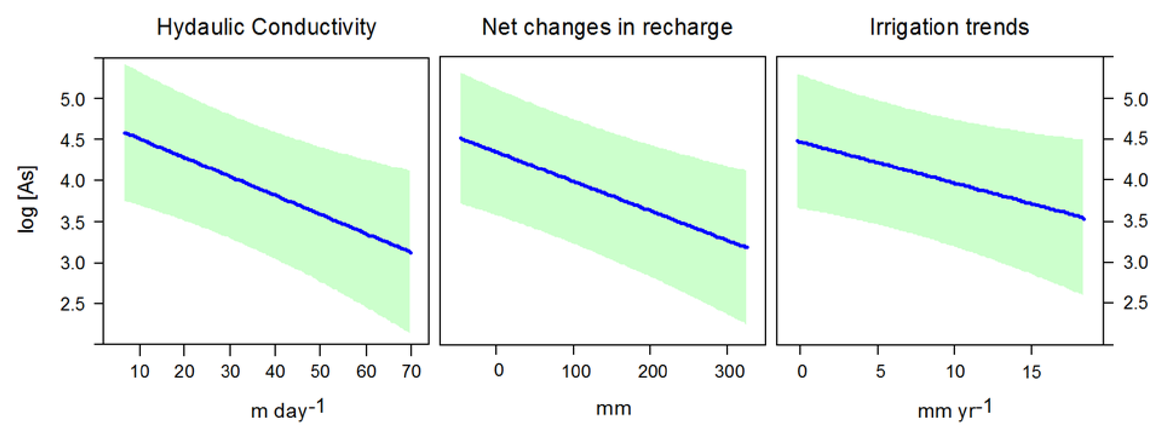


Figure 3: Graphical presentation of key GRM results. On each panel the vertical axis is labelled as logarithm of As concentrations, the horizontal axis denotes measurement unit for each covariate, and a 95% pointwise confidence interval is drawn around the estimated effect. For example, modelled effect of irrigation trends on As concentrations in shallow groundwater is negative when all other covariates in the model are set to their median values.

Conclusions

Statistical model explains the national-scale spatial variation in As concentrations of shallow (<50 m bgl) groundwater in Bangladesh. Statistically significant inverse associations are observed between As concentrations and three key covariates: (1) net changes in mean recharge between periods prior to (1975 to 1980) and following (1995 to 1999) the development of groundwater-fed irrigation; (2) hydraulic conductivity of the shallow aquifer; and (3) irrigation trends (period 1985 to 1999). Modelled associations presented here are consistent with the assertion that increased recharge has flushed mobile As from shallow groundwater. However, since pumped groundwater is often applied as irrigation water, the implication is that induced groundwater recharge may not necessarily remove mobile As from the environment but simply redistribute As to the soil where it can continue to pose a threat to food security and human health.

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Acknowledgements

- Dorothy Hodgkin Postgraduate Award (Ref. GR/AKFX-DHPA, 2007-2011) funded by the UK Engineering and Physical Sciences Research Council.
- Wingate Geography Scholarship (Ref. 4387, 2010-2011) funded by the Harold Hyam Wingate Foundation, UK.

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