

# Pattern of Groundwater Arsenic Concentrations: What Level of Arsenic Exists in Different Aquifers?

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## **Abstract**

Arsenic occurs naturally in the environment at a very low concentration. Groundwater arsenic pollution in Bangladesh is caused by a complex combination of geochemical factors and concentrations vary with different aquifer depths. Some research demonstrates a decreasing trend of arsenic concentrations with increasing aquifer depth, and some reveals deep aquifers to be free from arsenic and are therefore safe as a source of drinking water. Analysing the pattern of spatial variation of groundwater arsenic concentrations with depth in Southwest Bangladesh is the main objective of this paper. We also seek to explore whether arsenic is to be found in the deep aquifer or not.

An arsenic mitigation option of installing tubewells for arsenic-free water from deep aquifers is being implemented by the BAMWSP (Bangladesh Arsenic Mitigation Water Supply Project). This paper will also justify this policy.

The cokriging interpolation technique is employed to create surfaces for producing 'isopleth' maps of regionalised variation of arsenic concentration according to aquifer depth. In addition, Generalised Linear Models (GLM) are used to investigate the relationship between arsenic concentrations and aquifer depth, revealing, first, differential relationships between arsenic concentrations and aquifer depths and, second, an uneven spatial distribution of groundwater arsenic concentrations with aquifer depth.

***Keywords:*** Arsenic, Aquifer, GLM, Cross-Semivariogram, & Cokriging.

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## 1.0 Introduction

Groundwater is the main source of safe drinking water in Bangladesh and presently much of it is contaminated with arsenic. It is ironic that so many tubewells were installed in recent times for pathogen-free drinking water, but that water is now polluted with toxic levels of arsenic (Hassan *et al*, 2003). Arsenic, in very small quantities is necessary as a nutrient to humans, but ingesting excessive amounts can be poisonous (Harding, 1983). The extensive use of groundwater arsenic for drinking and cooking threatens the health of tens of millions of people in the world, remarkably 35 million of whom are in Bangladesh alone. More than 30 per cent of the 4.37 million tubewells analysed so far are contaminated with arsenic, and about 36,500 patients have been registered as suffering from the symptoms of arsenicosis (BAMWSP, 2004). Rahman & Axelson (2001) speculate that long-term drinking of water containing 500µg/l of arsenic may ultimately result in one in ten persons dying from arsenic-induced lung, bladder and skin cancer. This situation has been described as the ‘worst mass poisoning in human history’ in a WHO bulletin (Smith *et al*, 2000).

Groundwater is derived from varying depths, but reports vary of whether there is positive or a negative association between arsenic concentrations and aquifer depths. Fujii & Swain (1995), in their study from California, show increasing groundwater arsenic concentrations with an increase of well depth, but in Bangladesh the BGS & DPHE (2001) report that deep tubewells with tapping depths of more than 150–200 metres, almost invariably have low arsenic concentrations – less than 0.005 mg/l and usually less than 0.0005 mg/l.

Wang (1984) and Wang & Huang (1994) also reported that arsenic concentrations in artesian groundwater from deep boreholes (up to 660 metres) were found to increase with depth in Xinjiang Province of China. Smedley *et al* (2001) show the presence of relatively high arsenic concentrations (up to 0.556 mg/l) in some shallow dug wells in Inner Mongolia. The present paper mainly seeks to analyse the relationships between the pattern of arsenic concentrations and aquifer depths in Southwest Bangladesh, along with the spatial pattern of groundwater arsenic concentrations with aquifer depth.

## 2.0 Data & Methods

**Arsenic Data.** Tubewell screening is important priority work in arsenic data collection. But which tubewells should be sampled and how many? Since arsenic concentrations in groundwater are highly uneven in both space and time, all of the tubewells in the study area were screened rather than attempting to follow the kind of representative sampling strategy widely used in quantitative inquiry.

The methods and analyses of arsenic in groundwater are well known and have been described in literature (Irgolic *et al*, 1987). The use of field test kits (FTK) is one approach and the E-Merck kit, ANN-NIPSOM modified kit, and HACH kit are widely used in

Bangladesh. These FTK are easy to use and are cost-effective, but their results are less reliable and less accurate than laboratory methods (Hassan, 2003). In addition, FTK results are not accurate enough to permit testing at the WHO permissible limit (0.01 mg/l) and sometimes even the Bangladesh Standard limit (0.05 mg/l). To assure reliable and accurate arsenic data, we analysed the collected water samples ( $N = 375$ ) using a laboratory method of Flow Injection Hydride Generation Atomic Absorption Spectrometry (FI-HG-AAS) at the SOES of the Jadavpur University, Kolkata, India.

**Spatial and Attribute Data.** The data for spatial analysis by GIS are categorised as: (a) vector data; and (b) attribute data. The vector data for this paper were mainly the display of points (tubewell locations); lines (boundary information); and polygons (administrative units) which were allocated x/y coordinate values; while the attribute data were stored as records (rows) of a relational database. Groundwater arsenic concentrations were mainly analysed by collecting water samples from all the tubewells having water availability during January 2001. Along with the arsenic content in the water, two main attributes were collected for each tubewell: (a) tubewell locations were plotted on *mauza* maps (scale 1:3960), which were transformed into real world co-ordinates in ArcGIS; and (b) tubewell depth for determining the safe and contaminated aquifers, or, whether there is any relationship at all between arsenic concentrations and different aquifer levels.

**The Study Area.** The water samples ( $N = 375$ ) for this paper were collected from Ghona *union* (the 4<sup>th</sup> order local government administrative unit in Bangladesh) under Satkhira district of southwest Bangladesh during Professor Hassan's field visit in 2001 (Figure 1). The study area consists of 5 *mauzas* (the lowest level administrative territorial unit having separate jurisdiction list (JL) numbers in the revenue records) and 9 administrative wards having an area of 17.26 Km<sup>2</sup> (1,726 hectares), with a population of about 11,000 in 1991 (BBS, 1993). The area is geologically and physiographically a part of the Ganges Plain (Rashid, 1991), and has been dominated by irrigated agriculture for the last three decades.

[Figure 1]

**Cokriging Interpolation.** Cokriging is an extension of kriging in which random variables are simultaneously predicted by utilizing their interrelationships and their spatial co-dependence (Myers, 1982; Lark, 2003; Gloaguen *et al*, 2005). Cokriging is a mathematical interpolation and extrapolation tool that can be utilized when measurements have been made at scattered sampling points. Cokriging gives weights to data that minimize the estimation variance (cokriging variance) (Isaaks & Srivastava, 1989; Pan *et al*, 2004; Wu & Murray, 2005; Yue *et al*, 2005). When more than one property has been measured then cokriging is preferred for spatial prediction through the cross-semivariogram functions, and, when the form of the cross-semivariogram is known, it is possible to estimate the concentrations of the variables at any unsampled location by the cokriging technique.

**Cross-Semivariogram Estimation.** The cokriging treatment quantifies the variation of arsenic concentrations with aquifer depths in the form of a cross-semivariogram, which graphically expresses the relationship between the semivariance and the sampling distance (Serón *et al*, 2001; Teegavarapu & Chandramouli, 2005; Valley *et al*, 2005). Once the cross-semivariogram has been derived, cokriging is a straightforward process (Atkinson *et*

al, 1994). The semivariogram,  $\hat{\gamma}(h)$ , is half the average squared difference between pairs of data  $Z(x_i)$  and  $Z(x_i + h)$  at locations  $x_i$  and  $x_i + h$ . The cross-dependence between two variables, e.g. tubewell depth  $Z_1$  and arsenic concentrations  $Z_2$ , can be described by the cross-semivariogram  $\hat{\gamma}_{12}(h)$  with the estimator (Walter et al, 2002):

$$\hat{\gamma}_{12}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{Z_1(x_i) - Z_1(x_i + h)\} \times \{Z_2(x_i) - Z_2(x_i + h)\} \quad (1)$$

Where,  $Z_1(x_i)$  and  $Z_1(x_i + h)$  are the tubewell depths at locations  $x_i$  and  $x_i + h$ ;  $Z_2(x_i)$  and  $Z_2(x_i + h)$  are the arsenic properties at locations  $x_i$  and  $x_i + h$ .  $N(h)$  is the number of sampling point pairs separated by a distance of  $h$  (lag). The variables  $Z_1$  and  $Z_2$  do not necessarily need to have the same number of samples; however, the cross-semivariogram estimation is based only on locations at which both variables are measured.

After obtaining the variogram and cross-semivariogram, a theoretical model is needed to fit them. Such a model needs to be positive, definite and coregionalised to ensure the cokriging variance is positive or zero (Wu & Murray, 2005). The groundwater arsenic interpolation map produced by cokriging method was constrained by spherical cross-semivariogram fit by weighted least-squares approximation, using geostatistics. A spherical model (2) was used to fit the raw cross-semivariogram (Chang et al, 1998).

$$\hat{\gamma}_{12}(h) = \begin{cases} 0 & h = 0 \\ C_0 + C_1 \left[ \frac{3}{2} \left( \frac{h}{a} \right) - \frac{1}{2} \left( \frac{h}{a} \right)^3 \right] & 0 < h < a \\ C_0 + C_1 & h \geq a \end{cases} \quad (2)$$

Where,  $C_0$  is the nugget variance, and the lag,  $h$  required to reach the sill ( $C_0 + C_1$ ) is called a range,  $a$ . *Nugget* is a measure of spatial discontinuity at small distances, *sill* is an estimate of sample variances under an assumption of spatial independence, and *range* is the distance at which sample data is spatially independent (Kallas et al, 2003).

The cross-semivariogram of arsenic concentrations suggests that the variation is spatial and it was fitted best by a spherical model (Figure 2). A graph of the cross-semivariogram for the arsenic data shows  $\hat{\gamma}(h)$  as a function of lag distance  $h$  and the model illustrates the features common to the arsenic semivariogram (Gerlach et al, 2001): (a)  $\hat{\gamma}(h)$  increases from smaller to larger lags but a limiting ‘sill’ is always found; (b)  $\hat{\gamma}(h)$  approaches for small lags suggesting the large ‘nugget effect’; and (c) the spherical cross-semivariogram model gives good and acceptable fits to  $\hat{\gamma}(h)$ .

[Figure 2]

In producing prediction maps for spatial arsenic concentrations by the Cokriging method, the cross-semivariogram and search neighbourhood were specified in the interpolation. By using a spherical cross-semivariogram with 31 input neighbours (5 neighbours including at least 2 in 8 angular sectors) from a test location (X: 2637966 and Y: 552476), the cokriging prediction map was produced.

**Spatial GIS Analysis and Mapping:** Spatial GIS methodologies were used to figure out arsenic concentrations with aquifer depths in the groundwater. GIS modelling involves a symbolic form of representation (abstract representation) of locational properties (where), as well as thematic (what) and temporal (when) attributes describing characteristics and conditions of the arsenic magnitudes in the space-time dimension. This spatial analysis is an expression of the mathematical relationships among mapped variables concerning arsenic issues. The spatial analyses were mainly composed of spatial data editing and transformation, attribute database creation and manipulation, and data analysis and interpretation in performing geographical data analysis with GIS mapping.

**Statistical Analysis.** The quantitative data were analysed by statistical methods to address the research objectives. The GLM were mainly used to identify the pattern of association between arsenic concentrations and aquifer depths. GLM are mathematical extensions of linear models that do not force data into unnatural scales, and thereby allow for non-linearity and non-constant variance structures in the data (McCullagh & Nelder, 1989; Jin *et al*, 2005; Liquet & Commenges, 2005). They are based on an assumed relationship (called a link function) between the mean of the response variable and the linear combination of the explanatory variables (Guisan *et al*, 2002). Since arsenic data are not normally distributed, the GLM are suitable for this research.

Hypothesis tests applied to the GLM do not require normality of the response variable, nor do they require homogeneity of variances. The maximum likelihood estimation technique is an important advent in the development of GLM (Nelder & Wedderburn, 1972; McCullagh & Nelder, 1989; Harrell, 2001; Hastie *et al*, 2001; Smyth & Verbyla, 1999). Estimation of regression coefficients in GLM is performed using the Newton-Raphson or Fisher-scoring algorithm (Yee & Mackenzie, 2002). The Newton-Raphson (maximum likelihood) optimisation technique was employed for this paper to estimate the GLM using Stata software. In addition, scatter plotting with polynomial regression, inverse quadratic model and lowess smoothing techniques were adopted.

### 3.0 Arsenic Concentrations with Depth

#### 3.1 What level of arsenic exists in aquifers?

This question answers the pattern of geographical distribution of arsenic concentrations with aquifer depths. Aquifer levels in the study area range between 18 metres and 200 metres. Drawing upon the sub-surface aquifer ( $\leq 50$  metre), upper-shallow aquifer (51-75 metre) and lower-shallow aquifer (76-150 metre), about 41% ( $n = 153$ ), 46% ( $n = 172$ )

and 10% ( $n = 38$ ) tubewells have been identified respectively; while at the deep aquifer (>150 metre), only about 3% ( $n = 12$ ) tubewells have been found (Table 1).

[Table 1]

Arsenic concentrations in the study area are highly uneven with aquifer depth. We have calculated from the database that there is an increasing pattern of arsenic concentrations with depth down to at least 75 metres, with some regional variations and a very little contamination was found in tubewells at the deep aquifer. The field data show that at a depth of  $\leq 50$  metres, only 1% of the total tubewells ( $n = 4$ ) are found to be safe and about 41% ( $n = 153$ ) are found to be contaminated with arsenic at different concentration levels; at the depth of 51-75 metre aquifer, only 0.53% ( $n = 2$ ) are found to be safe and about 45% ( $n = 170$ ) are contaminated; while at the 76-150 metre aquifer level, only 0.27% of tubewells ( $n = 1$ ) are safe and about 10% ( $n = 36$ ) are contaminated (Table 1).

The database illustrates that only 3% ( $n = 12$ ) of tubewells are located in the deep aquifer, of which 8 tubewells fail to meet the WHO standard (Table 1). The mean arsenic concentrations for the samples of sub-surface aquifer, upper-shallow aquifer, lower-shallow aquifer, and deep aquifer are 0.227mg/l, 0.257mg/l, 0.255mg/l, and 0.025mg/l respectively (Table 1). The standard deviations of these aquifers (0.11mg/l, 0.112mg/l, 0.111mg/l and 0.026mg/l) indicate an uneven distribution of arsenic concentrations with depth (Table 1).

The cokriged prediction shows isopleth maps of estimated arsenic concentrations with aquifer depth. The cokriged prediction map shows that the safe zones are mainly concentrated in the north, central and south part of the study area in a scattered manner. Contamination zones are found everywhere in the study area but with a decrease in the degree of contamination from west to east. These zones are concentrated on the west, northeast and east sides. The south and southeast sub-regions appear to show safe zones with some local variability. The west and northeast part of the study area are generally contaminated; while the southwest part of the study area is contaminated with a high, irregular pattern (Figure 3).

[Figure 3]

A tendency is reported of a decrease in arsenic concentrations with the increase of aquifer depth, and in the deep aquifer the presence of arsenic concentrations is low (Nickson, 1997; Tsushima, 1997). The NRECA (1997) has reported highly contaminated wells (>0.25 mg/l) occurring within a depth range of 20-40m below ground; while only a few at >0.1 mg/l below 100m depth. The BGS (1999) shows that only 1 percent of deep tubewells are contaminated with arsenic above 0.05 mg/l; while 41 percent of the contaminated tubewells are tapping water from shallow aquifers.

There is a marked relationship between arsenic concentrations and aquifer depths in the study area. From the GLM, we have calculated that, at the 95% confidence level with a standard error of 0.0336995, there is a low negative correlation ( $r = -0.0999765$ ) between arsenic concentrations and aquifer levels in the study area. This value shows that arsenic concentrations decrease slowly with the increase of aquifer depth. The inverse quadratic trend line shows an increasing trend of arsenic concentrations up to a depth of 75 metres

and a decreasing trend beyond that; while the lowess smoothing curve with a bandwidth of 0.6 shows more or less the same with little fluctuation (Figure 4). The inverse relation between arsenic concentrations and aquifer depth is striking visually, yet the correlation coefficient between the values indicates only a weak relationship. The spherical cross-semivariogram model also shows the relationships between the pattern of arsenic concentrations and aquifer depth. The nugget variance (0.00378) represents the locally erratic component of the variation of arsenic with depth (Figure 2).

[Figure 4]

The scatter diagrams of arsenic concentrations with a polynomial regression line against different aquifer depths show different relationships. The correlation coefficient value ( $r = +0.0078$ ) for the sub-surface aquifer indicates a very low positive relationship with arsenic and there is a tendency to increase the concentrations with the increase of depth (Table 1). The value ( $r = +0.096$ ) for the upper-shallow aquifer indicates a low positive relationship between arsenic concentrations and aquifer depth (Table 1). At the lower-shallow aquifer (76-150 metre depth), the value ( $r = -0.035$ ) designates a low negative relationship with arsenic, i.e. arsenic concentrations slowly decrease with the increase of depth; while in the deep aquifer the value ( $r = -0.0789$ ) also specifies a low negative relationship with arsenic concentrations (Table 1).

### 3.2 What regional variation exists in arsenic-depth relation?

The pattern of arsenic concentrations varies with depth, and the relationships between arsenic-depth shows a considerable contrast. In the broad category of shallow aquifer zone, arsenic concentrations range from 0.034mg/l at 42m depth in Ward-2 to 0.535mg/l at 46m depth in Ward-7 at the sub-surface aquifer; at the upper-shallow aquifer the concentrations range between 0.032mg/l at 51m depth in Ward-6 and 0.600mg/l at 71m depth in Ward-7; while at the lower-shallow aquifer the concentrations range between 0.011mg/l at 92m depth in Ward-6 and 0.568mg/l at 80m depth in Ward-7. Moreover, in deep aquifer, arsenic concentrations range between 0.003mg/l at 180m depth in Ward-9 and 0.093mg/l at 180m depth in Ward-6 (Table 2).

[Table 2]

The correlation coefficient values between arsenic concentrations and aquifer depths, and the scatter diagrams with polynomial trend lines suggest different relationships between them for different administrative wards (Figure 5). From the correlation coefficient values, a low positive relationship was found between arsenic concentrations and aquifer depth in Ward-7 ( $r = +0.27$ ) followed by Ward-1 ( $r = +0.22$ ) and Ward-2 ( $r = +0.02$ ); low negative relationships are found in Ward-5 ( $r = -0.28$ ) followed by Ward-3 ( $r = -0.20$ ), Ward-8 ( $r = -0.19$ ) and Ward-6 ( $r = -0.14$ ); while moderate negative relationships are found in Ward-9 ( $r = -0.50$ ) and Ward-4 ( $r = -0.49$ ). The survey as a whole yielded a weak negative relation between aquifer depths and arsenic concentrations in the study area. This study shows regional variations of arsenic concentrations with depth in different parts of the study area following the administrative wards.

[Figure 5]

### 3.3 How uneven is arsenic variation with depth?

Arsenic concentrations are highly uneven with depth; even at the same depth arsenic concentrations are found to be paradoxical. At a depth of 42 metres (sub-surface aquifer), a sharp variation in arsenic concentrations is identified in 51 tubewells having a range of 0.034mg/l in Ward-2 and 0.428mg/l in Ward-7, with a mean ( $\bar{X}$ ) concentration of 0.2035mg/l and a standard deviation ( $\delta_n$ ) of 0.0988mg/l (Table 2). At a depth of 42 metres, 6 tubewells in Ward-2 have been found located within a radius of about 215 metres of each other, having concentrations of arsenic between 0.179mg/l and 0.375mg/l; while 9 tubewells have been found in Ward-9 within a 135 metre radius that have values between 0.142mg/l and 0.241mg/l (Table 2 and Figure 6a).

[Figure 6]

At a depth of 55 metres (upper-shallow aquifer), a substantial variability in arsenic concentrations for 28 tubewells is found between 0.037 mg/l in Ward-4 and 0.515 mg/l in Ward-7, with a mean ( $\bar{X}$ ) of 0.2542 mg/l and a standard deviation ( $\delta_n$ ) of 0.1176 (Table 2). At the boundary line of Ward-5 and 6, there have been identified 4 tubewells located within a radius of about 135 metres having readings between 0.108 mg/l and 0.251 mg/l of arsenic (Figure 6b).

At a depth of 74 metres (upper-shallow aquifer), a sharp variation in arsenic concentrations is identified in 25 tubewells having a range of 0.069 mg/l in Ward-2 and 0.392 mg/l in Ward-4, with a mean ( $\bar{X}$ ) arsenic concentration of 0.2365mg/l and a standard deviation ( $\delta_n$ ) of 0.0955mg/l (Table 2). In Ward-4, there have been found 7 tubewells located within a radius of 80 metres having concentrations of arsenic between 0.142 mg/l and 0.196mg/l, with a mean ( $\bar{X}$ ) concentration of 0.031mg/l of arsenic (Table 2 & Figure 6d). At a depth of 180 metres (deep aquifer), dissimilarity in arsenic concentrations was also found for 7 tubewells having a range of <0.003 mg/l in Ward-9 to 0.093 mg/l in Ward-6, with a mean ( $\bar{X}$ ) of 0.031mg/l and a standard deviation ( $\delta_n$ ) of 0.033mg/l (Table 2 & Figure 6e).

The sharp regional variation of arsenic concentrations in the same aquifer raises different questions. Is geological variability the main cause of the differences or are there other factors in this regard? It has been found from this study that the most affected aquifers lie beneath the Ganges floodplains of the study area. In addition, the variation of arsenic concentrations with depth suggests that, within the zone of water table fluctuation and where residence times are shortest, arsenic is being either flushed away or immobilized (BGS, 1999).

### 4.0 Deep Aquifer & Deep Tubewell: Policy & Implications

The Government of Bangladesh has already decided to install deep tubewells to provide people with arsenic-free water from the deeper aquifer that presently seems in most cases to be arsenic-free. The policy has mainly been formulated on the basis of the British Geological Survey (BGS) report. The [BGS \(1999\)](#), in their studies, made a recommendation for deep tubewells. They reported that, “available data shows that aquifers deeper than 150-200m are essentially arsenic-free over much of Bangladesh. Systematic sampling showed only 2 out of 280 wells deeper than 200 metres to be contaminated”. On the basis of this report, the UNICEF allocated two million dollars to the Department of Public Health Engineering (DPHE) for the installation of some 5,500 deep tubewells (Lockwood, 1999: UN Resident Co-ordinator, in *The Daily Star*, 07/09/2001, Bangladesh). Such drilling has now contaminated most of the deep aquifers of Faridpur, Kushtia and other northern districts ([Anwar, 2001a](#)). In another example, two new tubewells were drilled under the BAMWSP arsenic mitigation programme in Faridpur and both of them were found to be highly contaminated with arsenic - one contained 1.76 mg/l of arsenic and another was measured at 40 times higher than the WHO standard permissible limit ([Anwar, 2001b](#)). Unfortunately, people were drinking this contaminated water as it was certified to be safe by the BAMWSP.

In addition, [Mandal \*et al\* \(1996\)](#) found that, in 1990, the Public Health Engineering Department of India installed deep tubewells to deeper depths (150 metres) in Nadia, where the shallow aquifer was found to be arsenic contaminated. At the beginning, arsenic was not found in deep tubewells but in the course of time all of these deep tubewells have become contaminated. It is also noted here that, areas where concentrations were previously low, now show extremely high concentrations of arsenic. Green marked safe tubewells are being found with arsenic concentrations of above 0.5 mg/l (*The Daily Star*: 07/09/2001, Bangladesh). Our paper shows that almost all of the shallow tubewells and some of the deep tubewells are arsenic contaminated in the study area. The government should therefore seriously consider a policy to stop the fresh installation of tubewells.

## 5.0 Concluding Remarks

In this paper an attempt has been made to promote the associations between arsenic concentrations and aquifer depths using statistical and spatial analytical techniques. This study has also examined the capability and functionality of GIS and spatial interpolation method in identifying the spatial arsenic zoning in the light of the existing micro level arsenic data. The cokriging interpolation method has provided the spatial variation of arsenic concentrations with aquifer depths in the study area.

GIS in this study has been demonstrated to be a valuable tool to handle a wide range of arsenic data in a meaningful form. GIS has been used to produce smoothed cartographic models but the astonishing micro-spatial variability of contamination means a strong component of indeterminacy and these models therefore do considerable violence to the data and are of questionable predictive value on the ground ([Atkins \*et al\*, 2006](#)). In addition, GLM have also been established as a useful technique for analysing the quantitative data for this research. From the overall discussion, it may be noted here that

the methodological approaches adopted in this paper have been justified for analysing the spatial arsenic concentrations.

The pattern of arsenic concentrations varies considerably and unpredictably over distances of a few metres. Most of the literature shows that the maximum concentrations of arsenic are at depth between 20 and 45m, but we have found dissimilar relationships between aquifer levels and arsenic concentrations. Moreover, deep tubewells were found to be contaminated with arsenic, but with a low level of concentration.

The relations between arsenic concentrations and aquifer depths in different administrative wards suggest that geology is the major factor controlling the spatially dependent component of the variation of arsenic concentrations at different aquifer levels. It has also been suggested, from the spatial arsenic variation in the same and certain aquifer depth, that in some parts of the study area, factors other than geology can account for a substantial proportion of the spatial variation in arsenic concentration.

## **Acknowledgement**

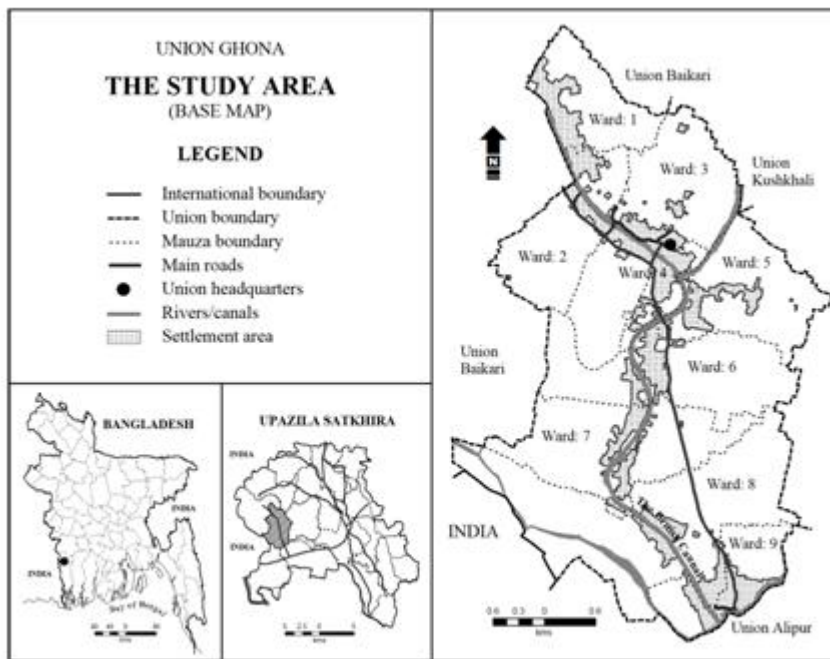
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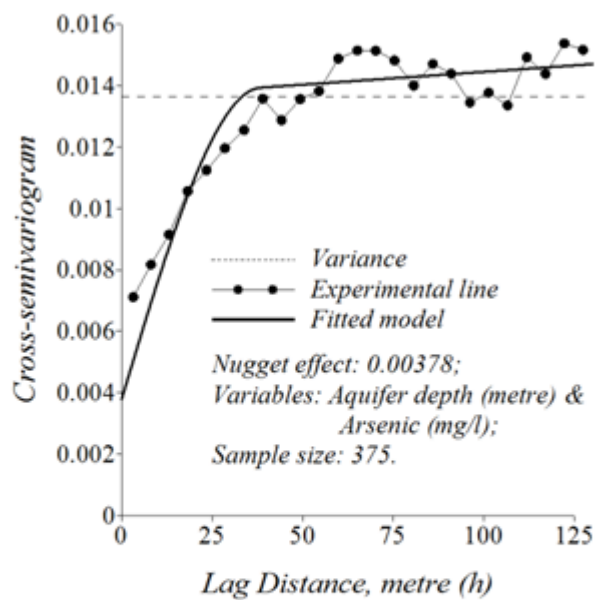
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**Figure 1:** The study area: Ghona *Union*, Southwest Bangladesh.



**Figure 2:** Spherical cross-semivariogram and geostatistics for arsenic concentrations with aquifer depths.

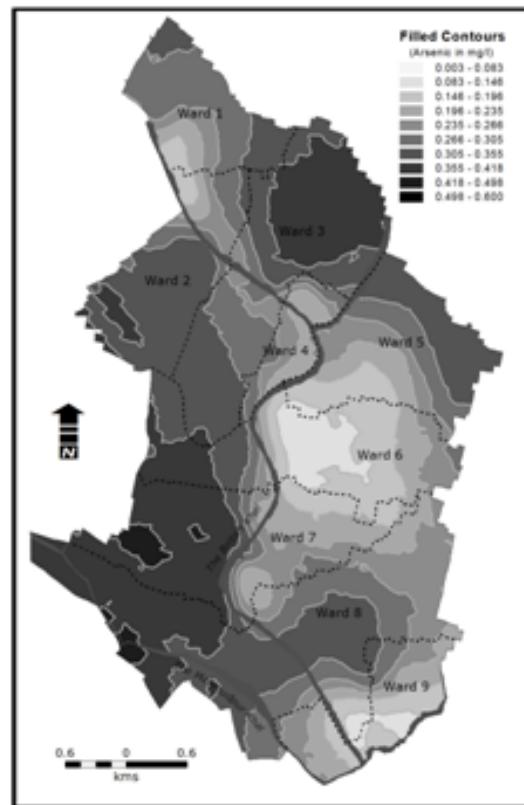


Figure 3: Spatial pattern of arsenic concentrations with aquifer depths.

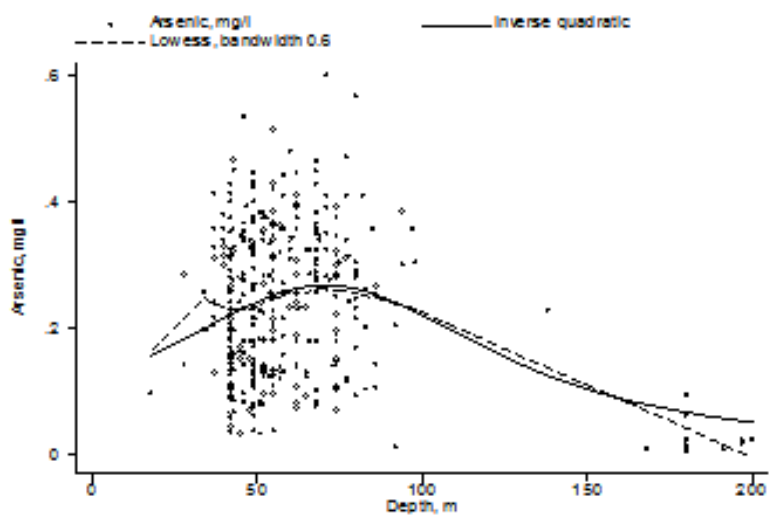


Figure 4: Relationships between arsenic concentrations and aquifer depths.

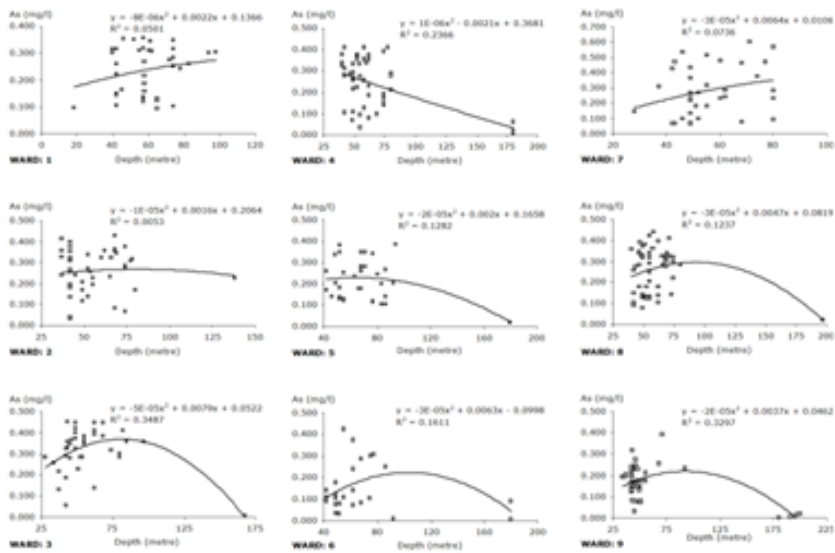


Figure 5: Polynomial trends and associations between arsenic concentrations and aquifer depths.

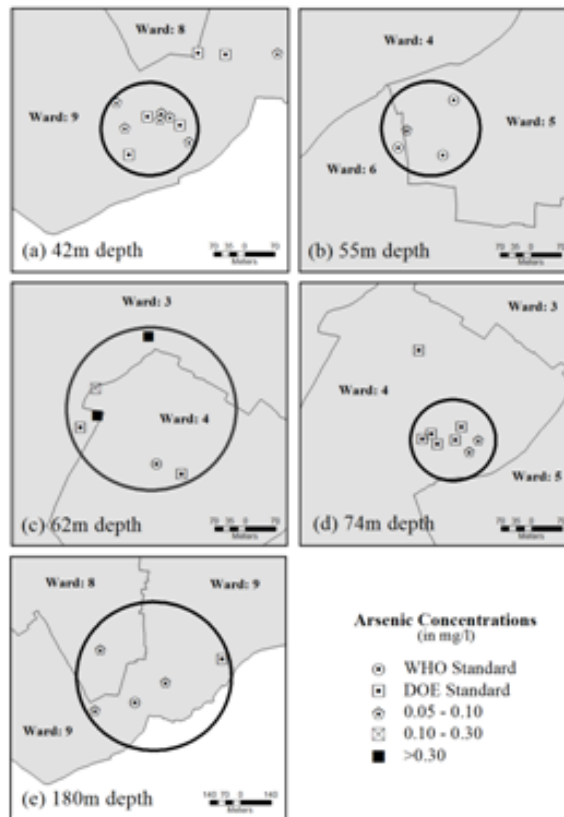


Figure 6: Arsenic concentrations at certain depths.



**Table 1**  
Geographical distribution of arsenic with aquifer levels and descriptive statistics.

Major Aquifer Levels	Depth (metre)	Arsenic magnitudes					Overall picture						
		Safe Level		Contamination Level			Safe Level (<0.05mg/l)		Cont. Level (>0.05mg/l)		Total		
		<0.01	0.01-0.05	0.05-0.1	0.10-0.3	>0.3	F	Statistics	F	Statistics	F	Statistics	
Shallow aquifer (<150 metres)	≤50	-	4 (1.07)	17 (4.53)	86 (22.93)	46 (12.27)	4 (1.07)	}	149 (39.73)	<b>0.2325</b> <i>+0.0142</i>	153 (40.80)	<b>0.227</b> <i>+0.0078</i>	
	51-75	-	2 (0.53)	12 (3.20)	90 (24.00)	68 (18.13)	2 (0.53)		<b>0.0321</b> <i>-0.9149</i>	170 (45.33)	<b>0.259</b> <i>+0.072</i>	172 (45.87)	<b>0.257</b> <i>+0.0962</i>
	76-150	-	1 (0.27)	1 (0.27)	23 (6.13)	13 (3.47)	1 (0.27)		37 (9.87)	<b>0.271</b> <i>-0.051</i>	38 (10.13)	<b>0.264</b> <i>-0.035</i>	
Deep aquifer (>150 metres)	>150	4 (1.07)	6 (1.60)	2 (0.53)	-	-	10 (2.67)	<b>0.0144</b> <i>+0.4892</i>	2 (0.53)	-	12 (3.20)	<b>0.025</b> <i>-0.0789</i>	
<b>GHONA TOTAL</b>		4 (1.07)	13 (3.47)	32 (8.53)	199 (53.07)	127 (33.87)	17 (4.53)	<b>0.0217</b> <i>-0.767</i>	358 (95.47)	<b>0.248</b> <i>+0.0433</i>	375 (100.00)	<b>0.238</b> <i>-0.2157</i>	

**Source:** Hassan, 2003.

Figures in the parentheses indicate the net percent of the sample tubewells. The **bold** figures represent the average arsenic concentration of tubewells at the respective depths; while the *italic* figures are for correlation co-efficient values between arsenic concentrations and depths of tubewells.

At the safe level, in the depth of <50m, the **mean** arsenic is 0.0363 mg/l and the **r**-value is -0.304 for 4 samples; while at the depth of <150m, the **mean** arsenic concentration is 0.0321 and the **r**-value is -0.9149 for 7 samples. At the contamination level, in the depth between 51-150m, the **mean** value of arsenic concentration is 0.261 and the **r**-value is +0.057.

**Table 2**  
Pattern of arsenic concentrations and variation at selected aquifer depths in the study area.

Selective depth (metre)	F	Arsenic range (mg/l)	Mean arsenic (mg/l)	Standard deviation	Pointing circle radius (metre)	Frequency (circle)	Arsenic range in pointing circle (mg/l)	Mean arsenic at circle (mg/l)
42	51	0.034 – 0.428 (WD: 1 & WD: 7)	0.2035	0.0988	WD-2: 215 WD-9: 135	WD-2: 6 WD-9: 9	WD-2: 0.179 – 0.375 WD-9: 0.142 – 0.241	WD-2: 0.290 WD9: 0.194
49	41	0.036 – 0.446 (WD: 6 & WD: 3)	0.170	0.1179	WD-7: 210 WD-8: 160	WD-7: 5 WD-8: 4	WD-7: 0.061 – 0.266 WD-8: 0.040 – 0.321	WD-7: 0.181 WD-8: 0.167
55	28	0.037 – 0.515 (WD: 4 & WD: 7)	0.2542	0.1176	Between WD-5 & 6: 135	TW: 4	0.108 – 0.251	0.153
62	23	0.073 – 0.446 (WD: 6 & WD: 3)	0.2617	0.1182	-	-	-	-
74	25	0.069 – 0.392 (WD: 2 & WD: 4)	0.2365	0.0955	WD-4: 80	WD-4: 7	WD-4: 0.142 – 0.196	0.163
80	12	0.092 – 0.568 (WD: 7 & WD: 7)	0.271	0.1120	-	-	-	-
180	7	<0.003 – 0.093 (WD: 9 & WD: 6)	0.031	0.0330	WD-4: 350	WD-4: 3	WD-4: 0.012 – 0.061	0.032

**Source:** Hassan, 2003.

Figures in the parentheses indicate the Ward number. Here WD stands for the administrative ward.