

ARSENIC RISK MAPPING IN BANGLADESH: A SIMULATION TECHNIQUE OF
COKRIGING ESTIMATION FROM REGIONAL COUNT DATA

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ABSTRACT

Risk analysis with spatial interpolation methods from a regional database on to a continuous surface is of contemporary interest. Groundwater arsenic poisoning in Bangladesh and its impact on human health has been one of the ‘biggest environmental health disasters’ in current years. It is ironic that so many tubewells have been installed in recent times for pathogen-free drinking water but the water pumped is often contaminated with toxic levels of arsenic. This paper seeks to analyse the spatial pattern of arsenic risk by mapping composite ‘problem regions’ in southwest Bangladesh. It also examines the cokriging interpolation method in analysing the suitability of isopleth maps for different risk areas.

GIS-based data processing and spatial analysis were used for this research, along with state-of-the-art decision-making techniques. Apart from the GIS-based buffering and overlay mapping operations, a cokriging interpolation method was adopted because of its exact interpolation capacity. The paper presents an interpolation of regional estimates of arsenic data for spatial risk mapping that overcomes the areal bias problem for administrative boundaries. Moreover, the functionality of the cokriging method demonstrates the suitability of isopleth maps that are easy to read.

Keywords: Arsenic, cokriging, spatial interpolation, risk mapping, Bangladesh.

INTRODUCTION

The discovery of groundwater arsenic poisoning in Bangladesh has been characterised as the ‘worst mass poisoning in human history’ (1). The extensive presence of groundwater arsenic in water used for drinking and cooking threatens the health of many people around the world, including about 50 million in Bangladesh alone (2). More than 30 per cent of the 4.37 million tubewells analyzed have been found to be contaminated with arsenic and, so far, about 36,500 patients have been registered as suffering from the symptoms of arsenicosis (www.bamwsp.org). Cancers, for instance, occur after chronic exposure to even a small amount of daily arsenic intake (3, 4).

Inorganic arsenic is dissolved in groundwater and is a documented carcinogen. Numerous epidemiological studies from Taiwan, Chile and Argentina show consistently high mortality risks from lung, bladder and kidney cancers among populations exposed to arsenic through drinking water (5-7). It is evident that skin cancers can appear after a latency of about 10 years; internal cancers, particularly affecting the bladder and lung, can materialize after 30 years at a concentration of 0.05 mg/L of arsenic (8-10). In addition, long-term exposure to inorganic arsenic is also associated with non-carcinogenic and non-malignant health effects in the form melanosis, leuko-melanosis and keratosis (11).

Risk assessment examines the potential human health challenge due to exposure to toxic contaminants in various environmental media. Its purpose is to estimate the severity or magnitude of risk to human health posed by exposure to an environmental hazard (12-14). The potential for environmental damage and the resulting threats to human life from arsenic poisoning demand an assessment of spatial risk zoning and mapping. Risk mapping is the

process of estimating the spatial magnitude of risk to human health posed by exposure to hazardous arsenic.

Geographical Information Systems (GIS) and geostatistical approaches with cokriging interpolation can be applied to spatial risk mapping. GIS is the automated spatial decision-making system used in the mapping of geographically referenced information. It is especially powerful because of its mathematical and programming facilities (15, 16). A geostatistical approach relies on both statistical and mathematical methods which can be used to create surfaces and to assess the uncertainty of predictions for regionalised variables ((12, 17-19). Interpolation is the process of estimating the spatial arsenic concentrations at unsampled points from a surrounding set of measurements. When the local variance of sample values is controlled by the relative spatial distribution of these samples, geostatistics can be used for spatial interpolation and point interpolation is significant in GIS operation (20). Overlay and buffer analysis in GIS can also be used to generate maps of safe and risk zones. A threshold distance for collecting water from tubewells with different degrees of arsenic concentrations was employed in our research to generate buffer areas.

Risk assessment is the procedure of obtaining the level of risk measured with quantitative or qualitative computation. Risk assessments have traditionally focused on quantifying the probability of negative consequences from one or a number of identified or unknown sources (21). Much of the risk assessment literature has been focused on assessing potential impacts of chemicals on humans. Traditional non-spatial models as a means of risk characterization are thought to be unreliable and potentially misleading (19). The use of spatial techniques in analyzing spatial risk zoning is still uncommon; however, the techniques have the ability to overcome the error of non-spatial procedures. Such negative effects can be amended by

spatial risk assessment. Spatial risk mapping for arsenic toxicity involves plotting the areas of affected people and those likely to be affected in future as a result of ingesting different levels of arsenic concentrated in tubewells.

In view of increasing concerns about arsenic-related health risk issues, the present paper focuses on methodological issues of spatial arsenic risk mapping with interpolation of regional estimates of arsenic data. We seek to explore the spatial pattern of arsenic risk in order to identify composite 'risk zones' in southwest Bangladesh using the cokriging interpolation method. The assessment of arsenic risk is based on a combination of information on the amount of arsenic people are exposed to and its toxicity, while spatial risk assessment is involved in mapping the areas of affected people ingesting different levels of arsenic. Previously Hassan *et al* (22) identified different risk zones on the basis of spatial arsenic concentrations and exposure assessment, but the present paper is different because of its new methodological approach. In the previous paper arsenic concentrations were analyzed with ordinary kriging method, but this paper is focused on the methodological issues of using geostatistics with a cokriging interpolation. The functionality and suitability of GIS led buffer generation and overlay operation is analyzed. Overlay operation and buffer generation are the two main spatial analytical procedures used here in preparing spatial risk maps, but they were not applied in details in the previous paper.

MATERIALS AND METHODS

Exposure characterization is a central step in arsenic risk assessment. Arsenic concentration in drinking water is mainly considered for exposure characterization. A cartographic model was developed in which a data layer for arsenic risk zones was created by overlaying map

data of arsenic concentrations, a buffer area of tubewell users, and a data layer of tubewell installation years. The arsenic data layer was then overlaid with the map data of the settlement area to yield a characterisation of different risk zones (Figure 1).

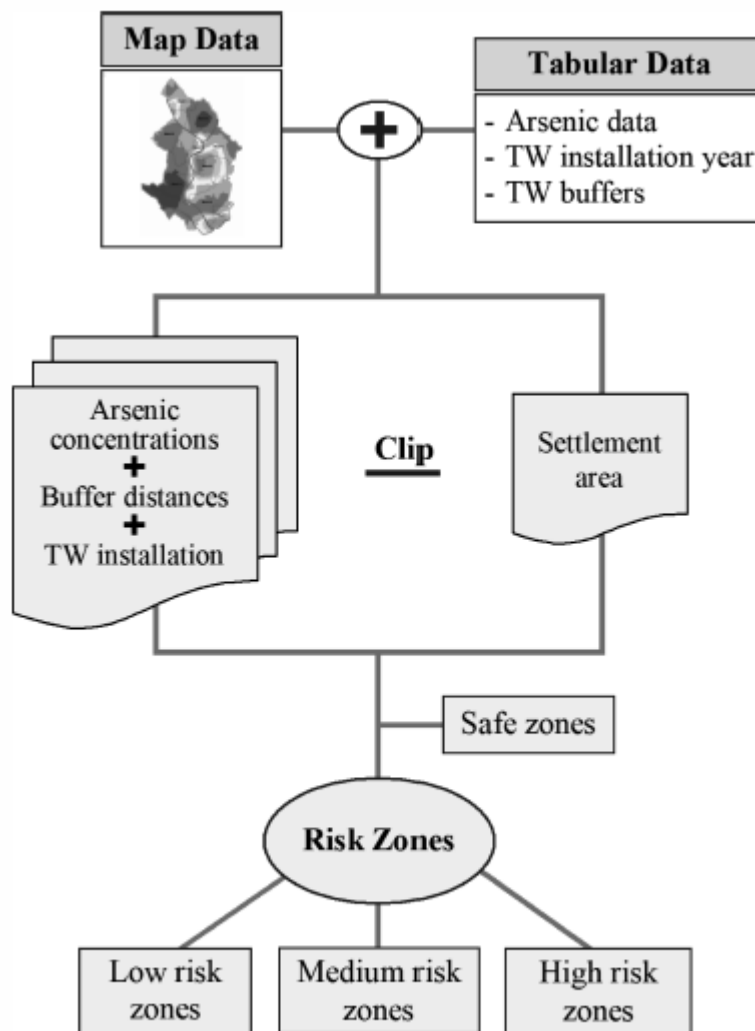


Fig. 1. Analysing the spatial arsenic risk zones.

Study Area and Arsenic Characterization

The relevant data for this study were collected from Ghona *Union* (the fourth order local government administrative unit in Bangladesh) of Satkhira District in the southwest Bangladesh near to the border with India (Figure 2). The study area comprises five *mauzas*

(the lowest level administrative territorial unit) and nine administrative wards (area 17.26 km²), with a population 13,287 in 1991 (23). The area has low levels of education and low income levels, and it is dominated by primary economic activities related mainly to a traditional agrarian economy. Physiographically, the study area is part of the Ganges alluvial and tidal plains.

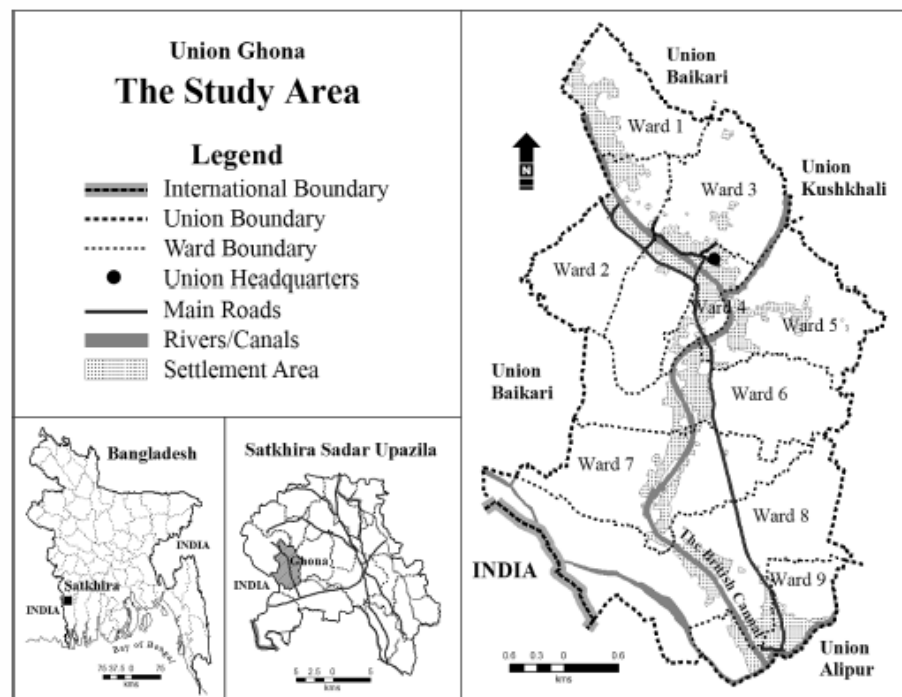


Fig. 2. The study area: Ghona Union of Southwest Bangladesh.

Arsenic concentration in groundwater is found to be uneven over space (Figure 3). Arsenic concentrations in the study area range between 0.003 mg/L and 0.600 mg/L, with a mean concentration of 0.238 mg/L and a standard deviation of 0.117mg/L. The study area is very badly affected by arsenic, with water from 99 per cent (371 out of 375) of tubewells contaminated at the WHO standard (0.01 mg/L) and about 96.50 per cent (358 out of 375) of tubewells contaminated at the Bangladesh standard daily permissible limit (0.05 mg/L) (24). The mean arsenic concentration in the study area is five times higher than the Bangladesh standard limit and 25 times higher than the WHO permissible limit. The pattern of

concentrations varies considerably and unpredictably over distances of just a few metres; most notably about 46 percent of tubewells are located within 25 metres of another well within the settlement area of the study site (24).

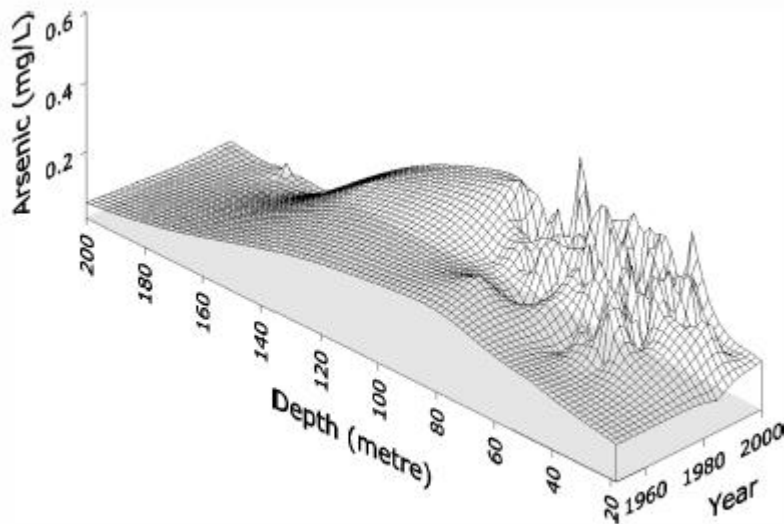


Fig. 3. A three-dimensional diagram of the pattern of arsenic concentration.

Low exposures to inorganic arsenic (<0.05 mg/L) in drinking water can be the cause of arsenicosis symptoms for a lifetime. Daily consumption of water with more than 0.05 mg/L of arsenic can lead to problems with the skin and circulatory and nervous systems (Das *et al*, 1996). Morales *et al* (25) conclude that the lifetime risk of dying from cancer is 1 in 100 from consuming 0.05 mg/L and 1 in 50 from consuming 0.1 mg/L of arsenic in drinking water. Hassan *et al* (22) show that people who ingest arsenic between 0.01 and 0.05 mg/L daily are twice as likely to get arsenicosis symptoms as people who ingest at the relatively safe level (<0.01 mg/L). Those who ingest arsenic at 0.05-0.1 mg/L daily are four times as likely to get arsenicosis symptoms, six times at between 0.1 and 0.3 mg/L, and eleven times at >0.3 mg/L. There is a chance of dying of 7 per 1000 people with arsenicosis if they consume arsenic at 0.05 mg/L for lifetime; while 12 per 1000 people will die with arsenicosis if they continuously intake arsenic for their lifetime at 0.1 mg/L. The assessed risk for 0.2 mg/L of

arsenic in drinking water would be 52 per 1000 people, rising to 130 per 1000 people if the concentration of arsenic in drinking water is 0.5 mg/L (22).

Arsenic, Spatial and Attribute Data

Arsenic data collection is important priority work, with a view to identifying the present scale of arsenic concentrations. Data quality is an important issue for this research and a minimum detection limit was also considered. The field test kits used in analysing arsenic concentrations are easy to handle, but their results are less reliable and less accurate than laboratory methods (26, 27). In addition, kit results are not accurate enough to permit testing at the WHO permissible limit and sometimes even at the Bangladesh Standard limit. The reliability of testing kits is not acceptable in the analysis of lower levels of arsenic concentrations (28, 29).

To assure reliable and accurate arsenic data, all of the collected water samples ($N = 375$) were analysed using a laboratory method of flow injection-hydride generation-atomic absorption spectrometry (FI-HG-AAS) at the School of Environmental Studies of Jadavpur University, Kolkata, India. In order to prevent adsorption losses, the collected samples were preserved by acidification with a drop of concentrated nitric acid in each 10 ml of water sample and placed in a refrigerator at a temperature below 4° C until the data were analysed. The method is characterised by high efficiency, low sample volume, low reagent consumption, improved tolerance of interference, and rapid determination (30, 31). With a 95 per cent confidence level, the minimum detection limit of the FI-HG-AAS method is 0.001 mg/L, and the quantification limit is 0.003 mg/L, which is excellent for arsenic research.

Spatial map features were mainly collected from the Department of Land Records and Survey, Local Government Engineering Department, Bangladesh Bureau of Statistics, and Survey of Bangladesh. The geographical location of each tubewell in the study area was plotted on large-scale *mauza* maps (1:3960) and spatial patterns generated of arsenic concentrations in the study area. Along with the arsenic content in water, two main attributes were collected for each tubewell: (a) tubewell installation year; and (b) users of a tubewell. All of the tubewell holders and some users were asked for information about these attributes of their tubewells through a questionnaire survey.

Patient Information

The arsenic-affected patient identification process for this study was conducted with a local medical doctor. This local physician had been trained on arsenic issues. At the initial stage, the first author identified the users of high and severe arsenic contaminated tubewells and the local physician then diagnosed 67 patients. This figure was doubtful due to infections from contaminated floodwater; a considerable number of people, especially children, were found to be affected with skin lesions. The first author then approached a second medical doctor with experience of arsenicosis diagnosis. He identified 8 patients out of the previously diagnosed 67 patients and also 3 other patients outside the list. This physician identified these patients as having health conditions resulting from different stages of arsenicosis.

Buffering and Overlay

In determining the risk zones, GIS often suggests a combination of buffer generation and overlay analysis. Buffer is a form of proximity analysis around coverage features and overlay

is the process of integrating different data layers (32). Buffer is a zone of a specified distance around coverage features and this analysis is used for identifying areas surrounding geographic features. In this paper, a buffer zone or ‘buffer’ is a polygon enclosing an area within a specified distance from a point, i.e. a tubewell. Different risk zones were analyzed with buffer areas of different tubewells, clipping them from agricultural land. In this case, buffer distances of tubewells were calculated based on the opinions of local people regarding the threshold distance in collecting water from the surveyed tubewells (Figure 4).

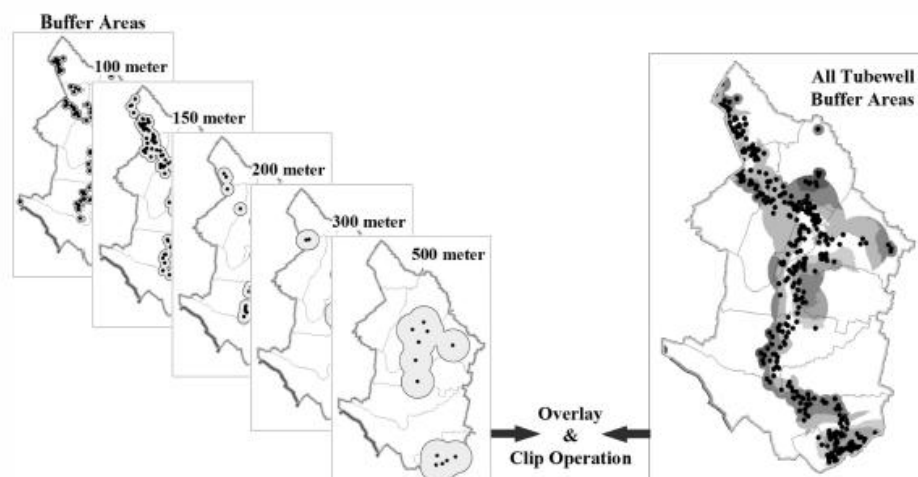


Fig. 4. Buffer distances of different tubewells.

Threshold distances of different tubewells were estimated on the basis of how far users are willing to travel to collect water from tubewells. Different people with different occupations and different levels of education had variable opinions about the threshold distance. Some 23 in-depth interviews and five focus-group discussions (farmers, school and madrasa teachers, NGO and health officials, political leaders and social activists, and elected administrators) were conducted in this regard. The poor and the marginal farmers were not interested in collecting arsenic-safe water from a long distance since arsenic was not a priority issue to them; but educated people, social activists and other elite groups showed their awareness in a

willingness to bring arsenic-safe drinking water from a longer distance – in one case as far as a kilometer. In addition, all the tubewell owners were asked about the users of their own tubewell and the threshold distance of collecting water from their tubewells.

Five different threshold distances were calculated for different tubewells using these different opinions of the local people and various arsenic concentrations: (a) deep tubewells, 500 metre buffer distance; (b) tubewells with concentration of arsenic $<0.05\text{mg/L}$, 300 metres; (c) tubewells with $<0.1\text{mg/L}$ of arsenic, 200 metres; (d) tubewells with $<0.3\text{ mg/L}$ of arsenic, 150 metres; and (e) with $<0.6\text{mg/L}$ of arsenic, 100 metre buffer distance. The threshold limits or influence zones were identified during the field survey (Figure 4). In addition, primary, secondary or tertiary buffers were also estimated on the basis of different arsenic contents and threshold distances. A problem with buffer and overlay techniques is risk zones that may exist outside such buffers.

GIS has strong spatial overlay capabilities that allow different map data to be combined in determining different ‘problem regions’ of arsenic pollution. Spatial overlay is accomplished by joining separate data sets that share all or part of the same geographical area. GIS enables the combination and evaluation of different map overlays to provide new risk information. Thus overlaying the settlement within the buffer zone facilitates the generation of information on arsenic ‘problem regions’ (Figure 5).

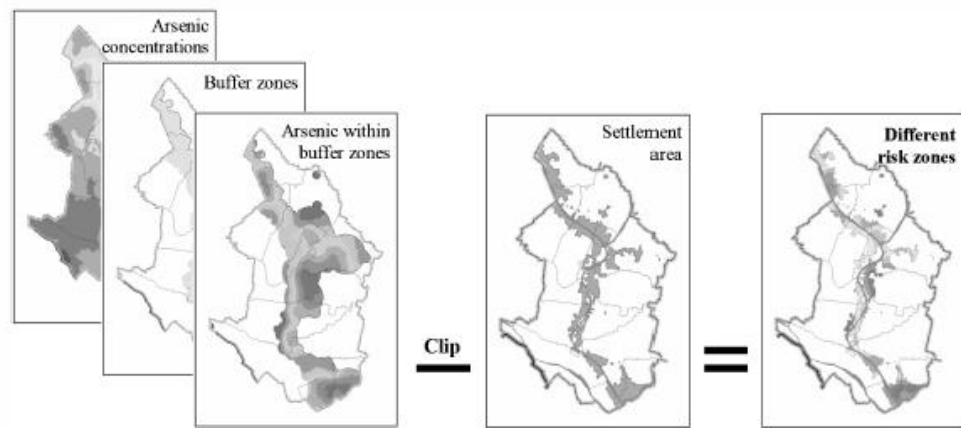


Fig. 5. Overlay operation for analyzing arsenic risk zones.

Cokriging Interpolation

A cokriging interpolation method was employed for spatial risk analysis. It is a mathematical interpolation and extrapolation tool that can be utilised when measurements have been made at scattered sampling points. Cokriging is an extension of kriging in which random variables are simultaneously predicted by utilizing their interrelationships and their spatial co-dependence (33-36). It is based on a theory of regionalized variables whose values vary from place to place (37, 38). Cokriging gives weights to data that minimize the estimation variance (cokriging variance) (35, 39-42). When more than one property has been measured, then cokriging will be preferred for spatial prediction through cross-variogram functions (43).

Variogram Estimation

Cokriging gives weights to data that minimize the estimation variance. When more than one property has been measured then cokriging will be preferred for spatial prediction 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 using the cokriging technique (44). Once the

cross-variogram has been derived, cokriging is a straightforward process. The cross-dependence between two variables, e.g. tubewell installation year Z_1 and arsenic concentrations Z_2 , can be described by the cross-semivariogram $\hat{\gamma}_{12}(h)$ with the estimator (45):

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

where $Z_1(x_i)$ and $Z_1(x_i + h)$ are the tubewell installation years 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-variogram estimation is based only on locations at which both variables are measured. The cross-variance is negative if the correlation between Z_1 and Z_2 is negative (45).

After obtaining the cross-variogram, 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 (36). Our groundwater arsenic interpolation map produced by the cokriging method was constrained by spherical cross-variogram fit by weighted least-squares approximation, using the geostatistics of ArcGIS. The spherical model was used to fit the raw semivariogram (46).

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

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 . The *nugget* is a measure of spatial discontinuity at small distances; a *sill* is an estimate of sample variances under the assumption of spatial independence; and a *range* is the distance at which sample data is spatially independent.

The cross-variogram of arsenic concentrations suggests spatial variation and it was fitted best by a spherical model. A graph of the cross-variogram for the arsenic data shows $\hat{\gamma}(h)$ as a function of lag distance h and the model illustrates features common to the arsenic semivariogram (47): (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 a large ‘nugget effect’; and (c) the spherical semivariogram model gives good and acceptable fits to $\hat{\gamma}(h)$. Weights in the cokriging approach are based not only on the distance between the measured points and the prediction location, but also on the overall spatial arrangement among the measured points and their values (48). The general equation for estimating the prediction value, $\hat{Z}(S_0)$, is given by (49):

$$\hat{Z}(S_0) = \sum_{i=1}^N \lambda_i Z(S_i) \quad (3)$$

Where, $\hat{Z}(S_0)$ = prediction value for location, S_0 ;

N = number of measured sample points surrounding the prediction location;

λ_i = the weight obtained from fitted variogram; and

$Z(S_i)$ = observed value at location S_i .

RESULTS AND DISCUSSION

Terminological Issues of Risk and Arsenic Concentrations

Which areas are at risk and which areas are safe? In an attempt to answer the question, we need to deal with the terminological issues of risk, hazard, and toxicity since there are conceptual uncertainties (13, 50). Risk can be considered as the possibility of suffering harm from a hazard; a hazard is a potential threat to humans; and toxicity refers to the inherent potential of arsenic to cause systemic damage (50). Hazards can be naturally occurring or human-induced processes or events, with the potential to create loss, that is, a general source of future danger; while risk is the probability of a hazard occurring and creating loss (51). A hazard, in this paper, is considered as the harm from arsenic to human health. The nature of risk depends on three elements: hazard, vulnerability, and exposure. If any of these three risk elements increases or decreases so does the pattern of risk (52).

The cokriging mapping interpolation shows that groundwater arsenic concentration in the study area is found to be uneven over space (Figure 6). The lowest arsenic concentrations are mainly in the central, northern and southern parts of the study area in a scattered manner; while higher concentrations are recognisable in the west and northeast, again with a highly irregular pattern. The contaminated zones in the study site cover about 92 per cent of the total study area; while the rest of the area (about 8 per cent) lies in safe zones.

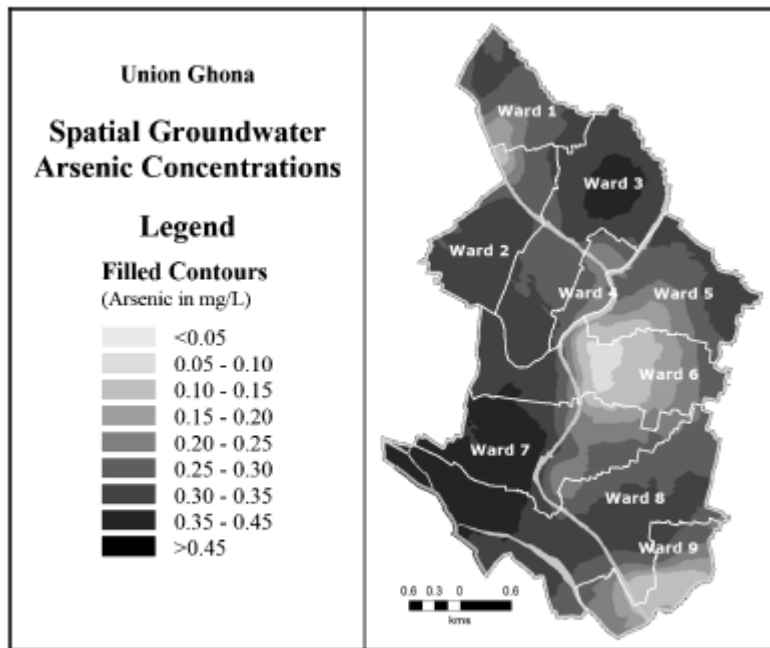


Fig. 6. Spatial arsenic concentrations in the study area.

Arsenic within Threshold Distances

The ‘threshold distance’ for arsenic analysis refers to the areas from which people collect their drinking water. Travel time and travel distance are the two main factors in determining the buffer distance or proximity areas of tubewells. Our field survey showed that most people are willing to collect their drinking water from a long distance if it comes from the safe hand-pump deep tubewells that the Government of Bangladesh has provided. But there are still many people who use contaminated tubewells within a very short distance. The buffer zones or proximity areas of tubewells were calculated from the threshold distances of tubewells having different degrees of arsenic magnitudes. The threshold distance of deep tubewells is estimated to be 500 metres, while tubewells with high level of arsenic concentrations have a much lower threshold distance. Accordingly, settlement areas within different buffer categories were calculated for risk zone quantification (Table 1).

Table 1. Buffer generation and area for assessing spatial risk of arsenic.

Buffer distance (metres)	Average arsenic (mg/L)	Tubewell frequency	Buffer area (hectares) ■	Buffer area (excluding overlapping) ●■	Settlement within each buffer (hectares) ■
500	0.025	12	464.30	464.30 (66.78)	145.55 (60.06)
300	0.032	7	137.99	26.64 (3.83)	17.53 (7.23)
200	0.08	30	207.97	58.20 (8.37)	24.58 (10.14)
150	0.198	200	430.96	105.09 (15.11)	39.96 (16.49)
100	0.366	126	222.16	41.07 (5.91)	14.72 (6.07)
			Total :	695.30	242.34

● People's preferences were given priority. They want to collect their drinking water from any arsenic-free tubewell.

■ Figure in the parentheses indicate the percent of buffer area in hectares.

In identification of the pattern of arsenic concentrations within buffer zones or proximity areas, GIS was used as an integration of the layers of arsenic concentrations and buffer zones of different threshold distances (Figure 7). An uneven concentration of arsenic was found within the buffer zones of tubewells in the study area. The cokriging prediction map confirms that the safe zones are mainly concentrated in the north, central and south part of the buffer areas in a scattered manner. The west and northeast part of the proximity areas are generally contaminated (Figure 7).

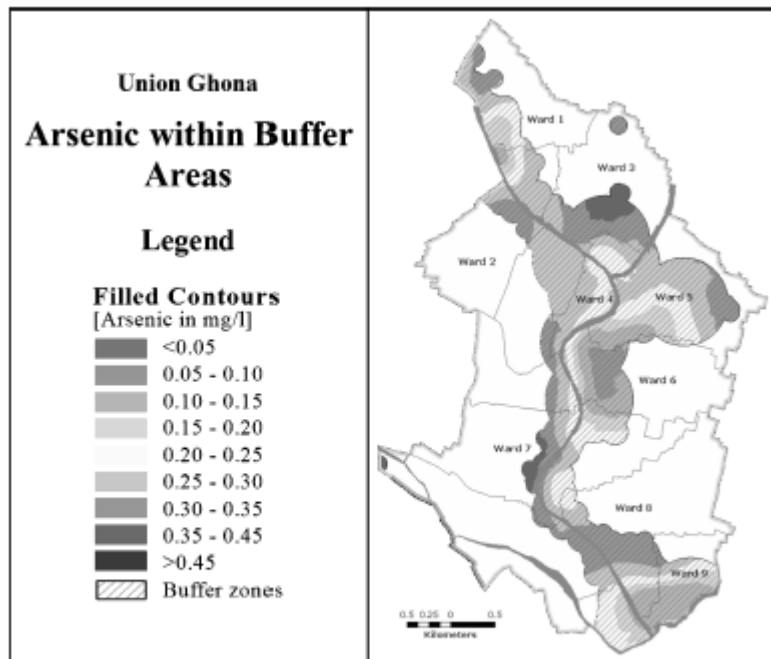


Fig. 7. Pattern of arsenic concentrations within the buffer areas. This isopleth map is based on the cokriging interpolation method.

Spatial Arsenic Risk Zones

Arsenic risk zones were mainly identified in a vector-base data analysis process by using GIS methods. A point-in-polygon operation through cokriged interpolation was performed in this regard. In a developed cartographic model, the data layer for arsenic risk zones was created by combining arsenic magnitudes with threshold distances of tubewells. A GIS was used as a platform enabling the management of the 'criterion data' (53) for the spatial risk zoning. In recent years the use of GIS methodologies in spatial environmental risk assessment has emerged and proliferated (54, 55). In addition, reclassification operations allow the transformation of attribute information, which represents the 'recolouring' (32) of risk features in the map. A map of spatial arsenic concentrations within the buffer zones can be analysed into different categories without reference to any other information.

Spatial arsenic risk zones can be classified into different categories based on spatial concentrations of arsenic measured with the cokriging interpolation technique, threshold distance of collecting arsenic-safe water, and pattern of arsenic exposure (Figure 8). The classified demarcated risk zones are: (a) low risk zones; (b) medium risk zones; and (c) high risk zones. The categories of risk zones were developed by poly-lines and these were converted to polygons in order to perform statistics. In addition, safe zones were also developed. It should be noted here that only the settlement areas were accounted for in the spatial risk zoning; the agricultural land was not considered in this regard.

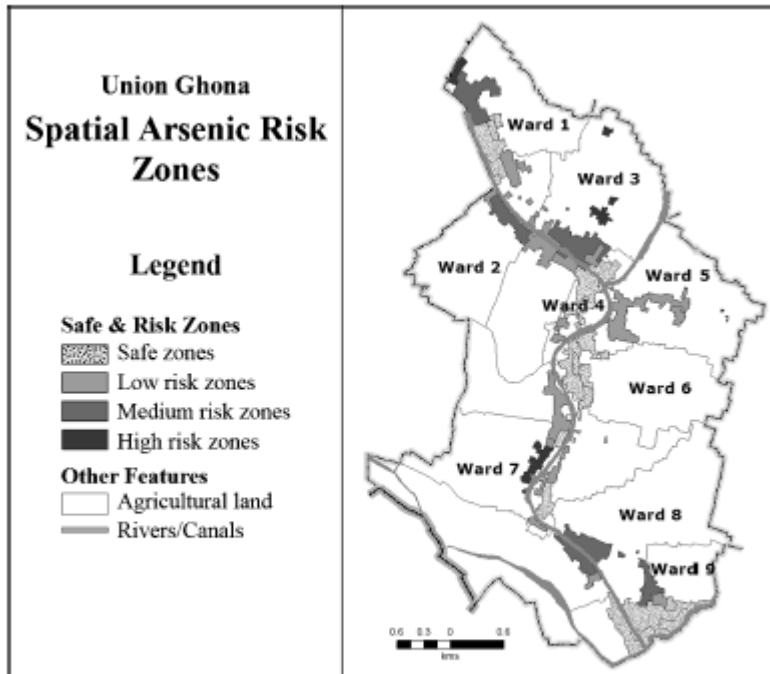


Fig. 8. Different risk zones and safe zones within the settlement area.

- (a) **Low risk zone.** Arsenic concentrations in this zone are mainly concentrated between 0.05 mg/L and 0.01 mg/L. The 200-metre buffer distance was considered for this category (Figure 4). The low risk zones cover about 27.88 per cent (67.57 hectares) of total settlement area and 3.92 per cent of the total study area. They are found mainly in the northern (Wards 2 & 3), central (Ward 5) and lower central (Wards 6 & 7) part of the study area (Figure 8). Some 9.68 per cent (1286) of the population live with low risk of arsenic contamination (Table 2). The first author identified two arsenic affected patients from this low risk zone.

Table 2. Spatial risk zones in the study area and population are at risk.

<i>Safe & risk zones</i>	<i>Area (hectares)</i>	<i>% against settlement</i>	<i>Net area (%)</i>	<i>Population at risk*</i>
Safe	98.22	40.53	5.69	6197 (46.64)
Low	67.57	27.88	3.92	1286 (9.68)
Medium	63.38	26.15	3.67	4216 (31.73)
High	13.17	5.44	0.76	1588 (11.95)
Total :	242.34	100%	14.04%	13,287

*Note: Figures in the parentheses indicate the percent of total population.

- (b) **Medium risk zone.** Arsenic concentrations in this zone are mainly concentrated between 0.1 mg/L and 0.3 mg/L. A 150-metre buffer distance was selected for identifying this risk zones. The medium risk zone covers slightly more than a quarter (63.38 hectares) of the total settlement area. About one-third (4216) of the total population live in this zone (Table 2). Two people in this zone were found with symptoms suggesting the primary stage of arsenicosis. This zone is distributed in the northern (Wards 1, 2 & 3) and southern (Wards 8 & 9) parts of the study area covering about 3.67 per cent of the total study area area (Figure 8).
- (c) **High risk zone.** In high risk zones, arsenic is concentrated above 0.3 mg/L, covering about 5.44 per cent (13.17 hectares) of the total settlement area and 0.76 per cent of the total study area. The average buffer distance of each tubewell was calculated as 100 metres. They are found in the northern (Ward 1), central (Ward 3) and southern (Ward 7) part of the study site (Figure 8). About one-eighth (1588) of the total population use arsenic-contaminated water from this high risk zone (Table 2). Five arsenicosis sufferers were found to be living in this zone.

(d) **Safe zone.** Areas having concentrations of arsenic <0.05 mg/L are classed as safe zones. Buffer distances of 300 metres and 500 metres for arsenic-safe shallow tubewells and arsenic-safe deep tubewells were used in identifying safe zones. The isopleth map for this zone covers slightly more than two-fifths (98.22 hectares) of the total settlement area, in the northern (Wards 1 & 2), central (Ward 4, 5 & 6) and southern (Ward 9) part of the study area (Figure 8). Arsenic-free tubewells are mainly concentrated in this zone. A total of 6197 people (46.46 per cent) collect their drinking water from tubewells here (Table 2).

CONCLUSION

The paper has analyzed arsenic spatial risk characterization along with the pattern of arsenic concentration. An attempt has been made to analyze spatial arsenic risk patterns with a geostatistical approach - the cokriging interpolation method in a GIS platform. Isopleth mapping based on the cokriging interpolation method for this study gives a picture of risk zones with spatial concentration patterns of arsenic within the tubewell proximity areas.

The paper has examined the capability and functionality of GIS and spatial interpolation methods in identifying spatial arsenic risk zones in the light of existing micro level arsenic data. GIS has been used in this study to produce smoothed cartographic models.

The pattern of arsenic concentrations is usually described using containing arsenic in individual tubewells rather than by the interpolation of values with isopleth mapping. Isopleth mapping with a geostatistical approach gives a picture of arsenic concentrations with spatial

characteristics within the proximity areas of different tubewells, and it has advantages over the simple point distribution technique.

This study has shown that about half of the people (46.67 per cent) in the study area are living within the safe zone; while more than half (53.33 per cent) are living in zones with different levels of risk. About one-third of the population (31.75 per cent) are living within the zone of medium risk and one-eighth (11.95 per cent) are living within the zone of high risk (Table 2). If they continue to ingest arsenic from the groundwater there is a likelihood of them developing symptoms of arsenicosis. Although the estimation of health risk in exposure to arsenic is uncertain, even a low level of exposure to inorganic arsenic causes chronic toxicity in the body and is related to health risks. The spatial risk zoning approach employed in this study could be used in planning and management for immediate arsenic mitigation and, coupled with an awareness campaign, it could be basis of significantly improved policy-making in Bangladesh.

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