The Spatial Pattern of Risk from Arsenic Poisoning: a Bangladesh Case Study

M. Manzurul Hassan,
Department of Geography, and Environment, Jahangirnagar University, Savar, Dkaka-1342, Bangladesh

Peter J. Atkins and Christine E. Dunn
Department of Geography, Durham University, Durham, UK

This is an early draft. For the published paper see:
Journal of Environmental Science and Health Part A, Toxic/Hazardous Substances & Environmental Engineering A38, 1 (2003), 1–24, DOI: 10.1081/ESE-120016590 1093-4529

ABSTRACT

Arsenic poisoning in Bangladesh has been one of the biggest environmental health and social disasters of recent times. About seventy million people in Bangladesh are exposed to toxic levels of arsenic (0.05 mg/L) in drinking water. It is ironic that so many tubewells have been installed in recent times to provide drinking water that is safe from water-borne diseases but that the water pumped is contaminated with toxic levels of arsenic. Along with the clinical manifestations, some social problems have also emerged due to arsenic toxicity. Analysing the spatial risk pattern of arsenic in groundwater is the main objective of this paper. Establishing the extent of arsenic exposure to the people will facilitate an understanding of the health effects and estimating the population risk over the area. This paper seeks to explore the spatial pattern of arsenic concentrations in groundwater for analyzing and mapping 'problem regions' or 'risk zones' for composite arsenic hazard information by using GIS-based data processing and spatial analysis along with state-of-the-art decision-making techniques. Quantitative data along with spatial information were employed and analyzed for this paper.

INTRODUCTION

Groundwater is purportedly the main source of safe drinking water in Bangladesh and yet presently much of it is contaminated by arsenic. Arsenic is a metalloid chemical element notorious for its toxicity that is naturally found as a main component of arsenopyrite[1] present in different rocks and soils. Arsenic occurs in the environment both in inorganic (trivalent or arsenite) and organic (pentavalent or arsenate) forms, with different degrees of toxicity.[2,3] Inorganic arsenic is dissolved in groundwater and is more harmful to human health than the organic arsenic present in food. Arsenic is necessary as a nutrient for humans in very small quantities, but ingesting excessive amounts can be toxic. Cancers occur chronically after a long-time exposure to even a small amount of daily arsenic intake.[4–6]

The arsenic hazard gives Bangladesh a new dimension to its existing plethora of natural calamities, such as floods and cyclones. At present two-thirds of the population are at risk of arsenic contamination from groundwater.[7–13] The scale of arsenic toxicity is greater than any environmental disaster seen before, it is beyond the accidents at Bhopal, India in 1984 and Chernobyl, Ukraine in 1986.[14] A health impact of ingesting arsenic from groundwater has been found in the study area and will be explored as the basis of risk characterization.

After the detection of the first arsenic contamination of groundwater in Bangladesh in 1993 by the Department of Public Health Engineering (DPHE), extensive contamination was confirmed in 1995 when chronic arsenicosis (an arsenic related disease) was diagnosed by health professionals. In 1996, arsenic contamination was detected in only seven districts but this had extended to 48 districts in the middle of 1997; while at present, 59 districts out of 64 are said to be affected. This paper seeks to explore the arsenic magnitudes in the study area using geostatistical interpolation methods. In addition, the spatial pattern of arsenic risk will be analyzed in order to identify composite arsenic 'hazard zones' in the study area.

DATA AND METHODS

Our investigation of arsenic concentrations in groundwater, and its toxic nature and risk pattern employed multiple methods. This strategy provided a mix of quantitative data (spatial and attribute information) with a questionnaire survey providing breadth of coverage. The research design was composed mainly of problem formulation, quantitative data collection procedures, data manipulation, analysis and interpretation, and geographical analysis with a GIS (Geographic Information System).

The Study Area

Since the Ganges delta is highly contaminated with arsenic, a study site close to the Indian (West Bengal) border was chosen on the basis of existing arsenic information, absence of municipal water supply facilities, and ease of access. The last point corresponds to Miles and Huberman's 'feasibility' attribute[15] and 'frontend-management'.[16] Ghona Union (the 4th order local government administrative unit in Bangladesh) of Satkhira District was selected for the study (Fig. 1). This has about a kilometre of international border with West Bengal, India, and is located 20 kilometres west of the Satkhira District Headquarters, between 22°41′ and 22°45′ north latitude and 88°57′ and 89°00′ east longitude. The study area consists of 5 mauzas (the lowest level administrative territorial unit having separate jurisdiction list numbers (JL No) in the revenue records) and nine administrative wards, having an area of 17.26 km^2 (1726 hectres) and a population of about 11,000 in 1991.[17] Physiographically the area is a part of Ganges Plain.[18] The Mahmudpur Khal (canal) and the British Khal are the two main rivers flowing through the study area.

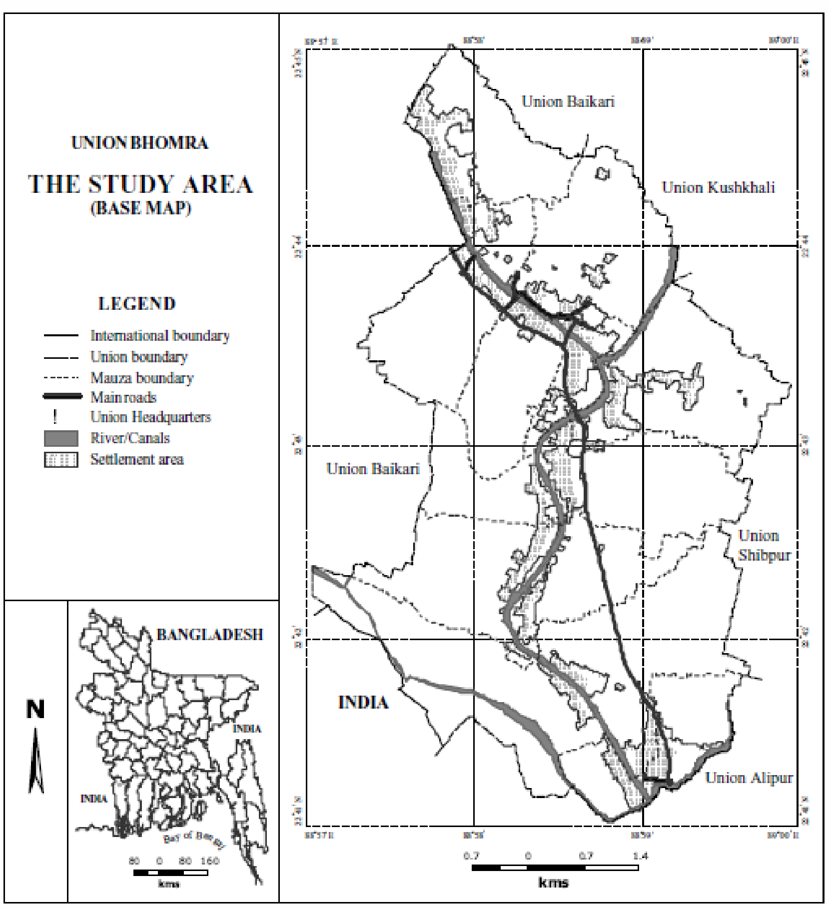

Figure 1. Location and characteristics of the study area.

Sampling Strategy

Tubewell screening is an important priority work for arsenic data collection. Which tubewells will be sampled and how many? This question is a very important issue since arsenic concentrations in groundwater are highly uneven in both space and time. In determining the 'actual' arsenic concentrations and magnitudes, all of the tubewells in the study area were screened rather than attempting to follow a representative sampling strategy widely used in quantitative inquiry.

Arsenic Data

For arsenic information a minimum detection limit (MDL) is essential for establishing 'safe' and 'risk zones' of arsenic, and we have used the DoE maximum contamination limit (MCL) of 0.05 mg/L.[19] The methods and analyses of arsenic in groundwater are well known and have been described in the literature.[3] The use of field test kits (FTK) is one approach and the E-Merck kit, ANN-NIPSOM modified kit, AQUA-Consortium kit and others are well-established in Bangladesh. The FTKs are easy to use and are cost-effective, but their results are less reliable and less accurate than laboratory methods. 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 collected water samples from 375 tubewells (in January 2001) and these were analyzed using the method of Flow Injection Hydride Generation Atomic Absorption Spectrometry (FI-HG-AAS) at the laboratories of SOES, Jadavpur University, Kolkata, India. The results mainly address the concentrations of inorganic arsenic in the groundwater.

In order to analyse the 'risk factor' and 'risk characterization' we needed to measure the effects on health of chronic exposure. Professional medical diagnosis revealed 11 patients with different levels of arsenicosis, including one family all of whose members were affected. All of the identified patients were ingesting arsenic with more or less similar toxicological levels. No patients were identified as having cancer symptoms.

Spatial Data

The data for spatial analysis with GIS operation are categorised as: (a) vector spatial data and (b) descriptive attribute data. The vector spatial data assigned to the display of points (tubewells, schools etc.); lines (boundary information, roads, rivers etc.); and polygons (administrative units, land use, topography etc.) are allocated by means of X, Y coordinates; while the attribute data are stored as records (rows) in a relational database. The attribute data of different map features (i.e., tubewell identification number, depth, arsenic magnitude, ownership, etc.) were collected from primary sources. Tubewell locations were plotted on the mauza maps (scale 1:3960) manually and the locations were transformed into real world co-ordinates in ArcGIS.

Data Analysis

Spatial Interpolation and Geostatistics

Thematic maps were developed to define the pattern of arsenic magnitudes and its spatial variation by using spatial interpolation methods. Interpolation is the process of estimating the value of parameters at unsampled points from a surrounding set of measurements.[20] When the local variance of sample values is controlled by the relative spatial distribution of these samples, geostatistics can be used for spatial interpolation.[21] Geostatistical approaches rely on both statistical and mathematical methods, which can be used to create surfaces and assess the uncertainty of the predictions.[22] Geostatistics represent one of the most powerful procedures for producing contour maps for regionalized variables.[23,24]

The spatial pattern of arsenic magnitudes was analyzed and interpolated in a GIS environment (ArcGIS-version 8.1) by using the Kriging method. This is a stochastic and optimal point interpolation method for the unbiased estimation of field variables.[20,21,25–29]

The method is based on the theory of regionalized variables.[30–33] Kriging is a means of local estimation in which each estimate is a weighted average of the observed values in the neighbourhood.[26,34] It is a distance weighting estimation method that takes into account the spatial characteristics of the local structure through a variogram function.[30,35] The advantage of Kriging is that the estimated values at observation sites are equal to the actual measurements.[25]

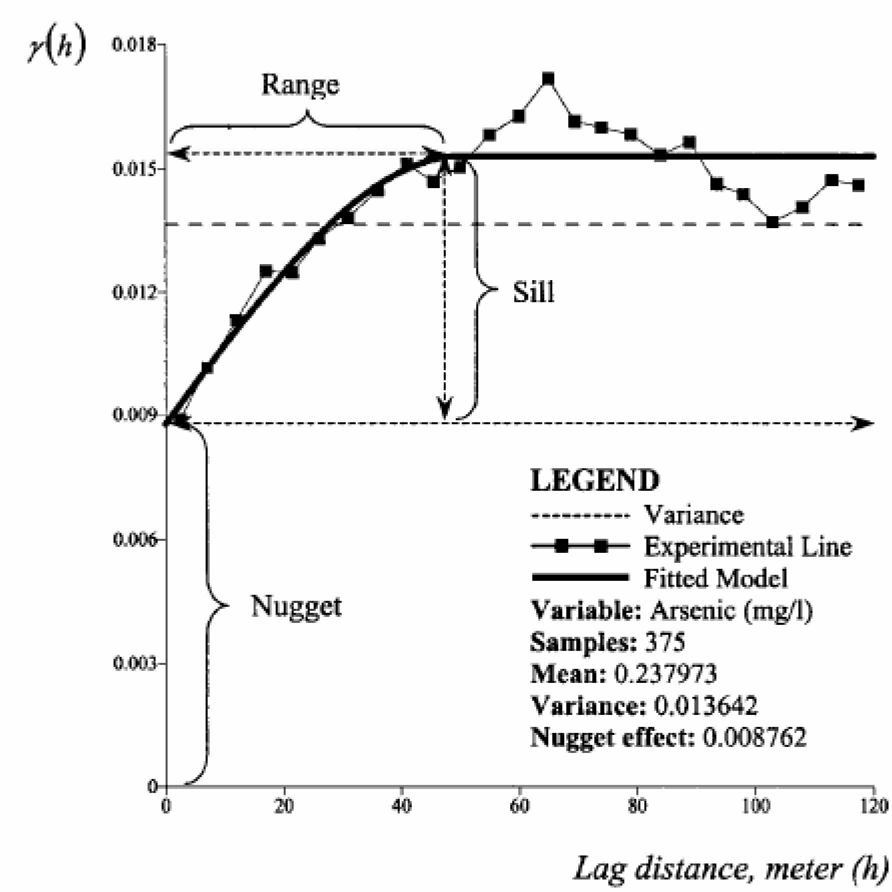

Figure 2. Spherical semivariogram for arsenic concentrations.

The arsenic interpolation map produced by Kriging is constrained by the spherical semivariogram fits (Fig. 2). The experimental variogram was computed from the raw data and a mathematical model[36–38] was fitted to the arsenic concentration values by weighted least-squares approximation, using ArcGIS. The parameters of the variogram model for arsenic concentrations were used with their values for estimating their concentrations over the area. The semivariogram, yðhÞ, is half the average squared difference between pairs of data $Z(x_i)$ and $Z(x_i+h)$ separated by a given distance h (lag). An estimate of the semivariogram with $N(h)$ the number of sampling pairs separated by a distance of h is given by the following equation[39]:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left\{ Z(x_i + h) - Z(x_i) \right\}^2 \qquad (1)$$

The semivariogram for the arsenic data illustrates a number of common features[33, 40]: (a) $\gamma(h)$ increases from smaller to larger lags but a limiting 'sill' is always found; (b) $\gamma(h)$ approaches the small lags, suggesting a large 'nugget effect'; and (c) the spherical semivariogram model gives good and acceptable fits to $\gamma(h)$. Ordinary Kriging was used in this study since arsenic concentrations in groundwater are high uneven. Ordinary Kriging, which is the most widely used type of Kriging to estimate values when data point values vary or fluctuate around a constant mean value.[35] It is applied for an unbiased estimate of the spatial variation of a component.[31]

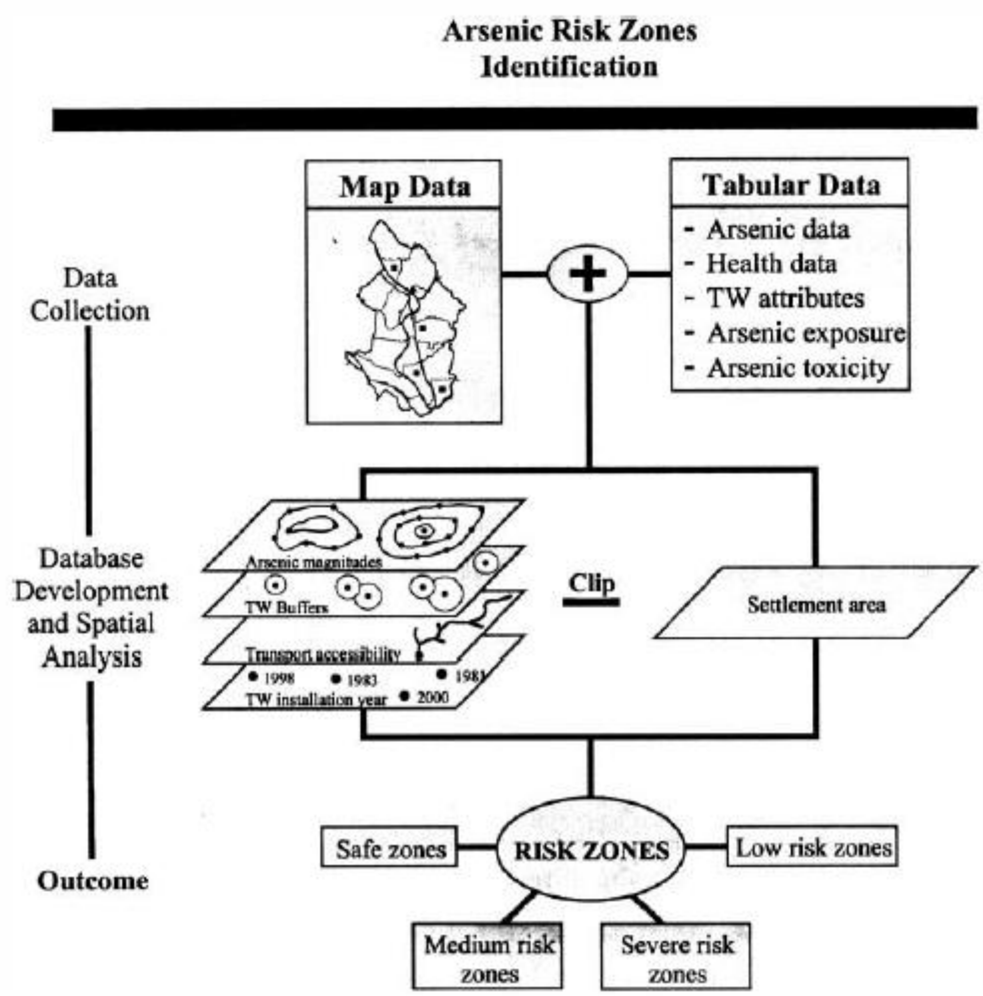

Figure 3. The GIS methodological procedure in identification of arsenic risk zones.

Spatial Analysis and Mapping in GIS

The spatial analytical capabilities of GIS were used to identify a spatial arsenic risk pattern (Fig. 3). 'Iso-arseno' value lines were developed to identify the arsenic magnitudes which were predicted through Kriging. In addition, buffer generation was used in mapping the proximity area of arsenic and spatial GIS overlay capabilities allow different map data to be combined in determining suitable sites for different risk zones of arsenic. Reclassification allows the transformation of attribute information; it represents the 'recoloring'[41] of features in the map. Thus, a map of spatial arsenic concentrations may be classified into categories such as 'safe zones' 'contaminated zones' or 'severely contaminated zones' without reference to any other information. Arsenic risk zones were identified by creating buffer zones around each tubewell, and in this case, the buffer distances were calculated according to the threshold limit (distance walked by the users) of a particular tubewell. The threshold limits or influence zones were identified during the field survey in 2001.

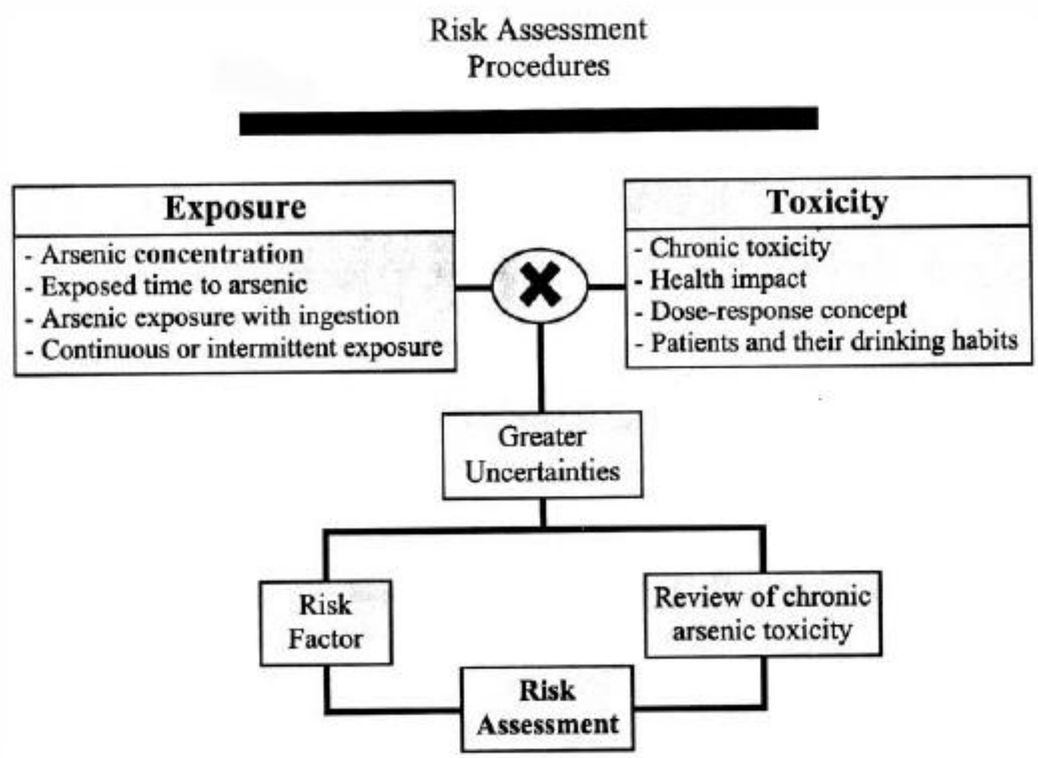

Figure 4. Risk assessment procedure: exposure assessment and toxicity assessment.

Risk Assessment

There is growing concern about levels of arsenic in the environment because of its toxicity to the human body. To answer the questions relating to the safety of tubewell water, requires performing a toxicological risk assessment, with an exposure assessment and a toxicity assessment (Fig. 4). How much arsenic is an individual or population exposed to? The answer to this question denotes the exposure assessment, which depends on: (a) how much arsenic is present in the groundwater; (b) how long people have been exposed to arsenic; (c) whether arsenic exposure was continuous or intermittent; and (d) how the people were exposed. In measuring chronic exposure to arsenic, we analyzed arsenic concentrations in the groundwater. We also established how long tubewells had been in each location and determined how many people were exposed. The route of exposure (ingestion) was then determined and the amount that people consumed was estimated. In our example, if groundwater that is used for drinking and cooking purposes is found to have arsenic at 0.05 mg/L, a person (60 kg body weight) who drinks 2 liters of water and cooks with 2 liters of water each day will have an exposure of 12 mg/day from this source. This figure is always changing, so, an exposure assessment is stated in terms of likelihood.

How much arsenic causes what kind of harm? Toxicity assessment can provide the answer to this question by investigating the potential for arsenic to cause harm. Toxicity to humans is not usually measured directly. Arsenic is toxic in quantity, but the mere presence of arsenic does not automatically imply harm. This is why toxicity assessment is concerned with the type and degree of harm caused by differing amounts of arsenic. Chronic effects happen only after repeated long-term exposure. The dose-response concept is the basis of all toxicity assessments: as the dose (exposure) increases, the response (toxicity) increases. In determining exactly how high a dose causes a particular kind of a response, the smaller the dose needed to cause an effect, the more potent (toxic) the substance is. We have examined the relationships between arsenicosis patients, their habits of consuming water, and the length of exposure to arsenic contaminated drinking water.

In addition, descriptive statistical techniques along with generalized linear models were employed in analyzing the arsenic data.

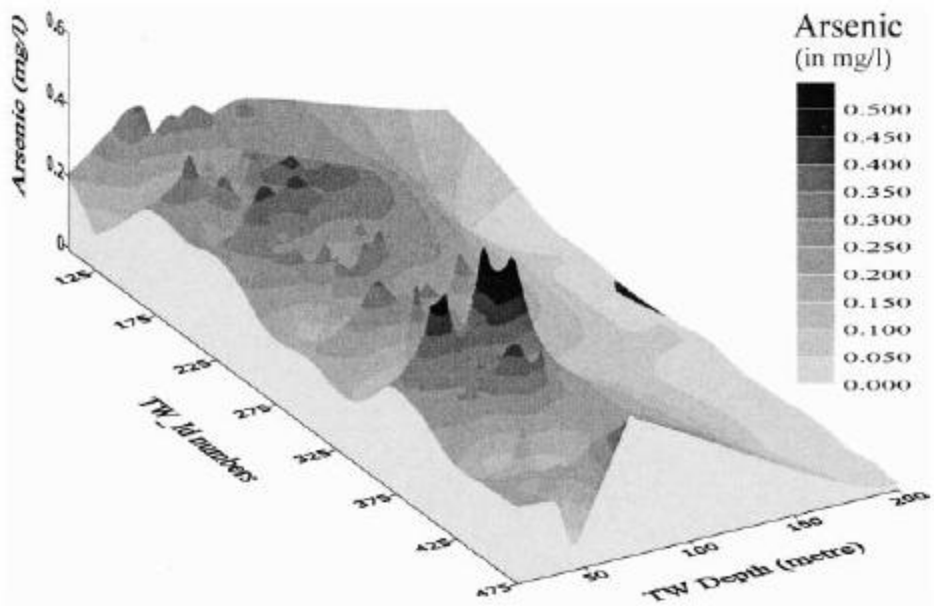

Figure 5. Three-dimensional view of arsenic concentrations in the study area.

SPATIAL ARSENIC MAGNITUDES

In order to determine which tubewells are safe and which are contaminated, data from the collected TW samples (n = 375) were analyzed by spatial interpolation. The spatial pattern of arsenic concentrations in the study area is highly uneven: some tubewells are heavily contaminated with arsenic and some are less so; some areas are worse than others (Fig. 5). Arsenic concentrations in the study area range between <0.003 mg/L and 0.600 mg/L. The mean arsenic concentration is 0.238 mg/L and the standard deviation is 0.117 mg/L (Table 1).

Table 1. Statistical properties of arsenic data from 375 TWs water in the study area.

Descriptive Statistics	Overall	Safe Level	Contamination Level
Frequency	375 (100%)	17 (4.53%)	358 (95.47%)
X-minimum	<0.003 mg/L	<0.003 mg/L	0.057 mg/L
X-maximum	0.6 mg/L	0.043 mg/L	0.6 mg/L
Mean	0.238 mg/L	0.022 mg/L	0.248 mg/L
Variance	0.014 mg/L	0.000144 mg/L	0.011881 mg/L
Std. deviation	0.117 mg/L	0.012 mg/L	0.109 mg/L

Figures in the parentheses indicate the net percent of the sample TWs.
(The arsenic data are calculated by descriptive statistical procedures).
Source: Field Survey, 2001.

Arsenic concentrations in groundwater can be classified into different categories based on arsenic magnitudes and statistical procedures, but here, we classified concentrations based on different permissible limits (Table 2 and Fig. 6): (a) the WHO permissible level (<0.01 mg/L); (b) the Bangladesh standard maximum contaminant level—MCL (<0.05 mg/L); (c) a moderate contamination level (0.05–0.1 mg/L); (d) a high contamination level (0.1–0.3 mg/L); and (e) a severe contamination level (>0.3 mg/L). These figures can be framed into two different broad categories on the basis of the official Bangladesh standard daily maximum tolerable limit of 0.05 mg/L (Fig. 6e). These are:

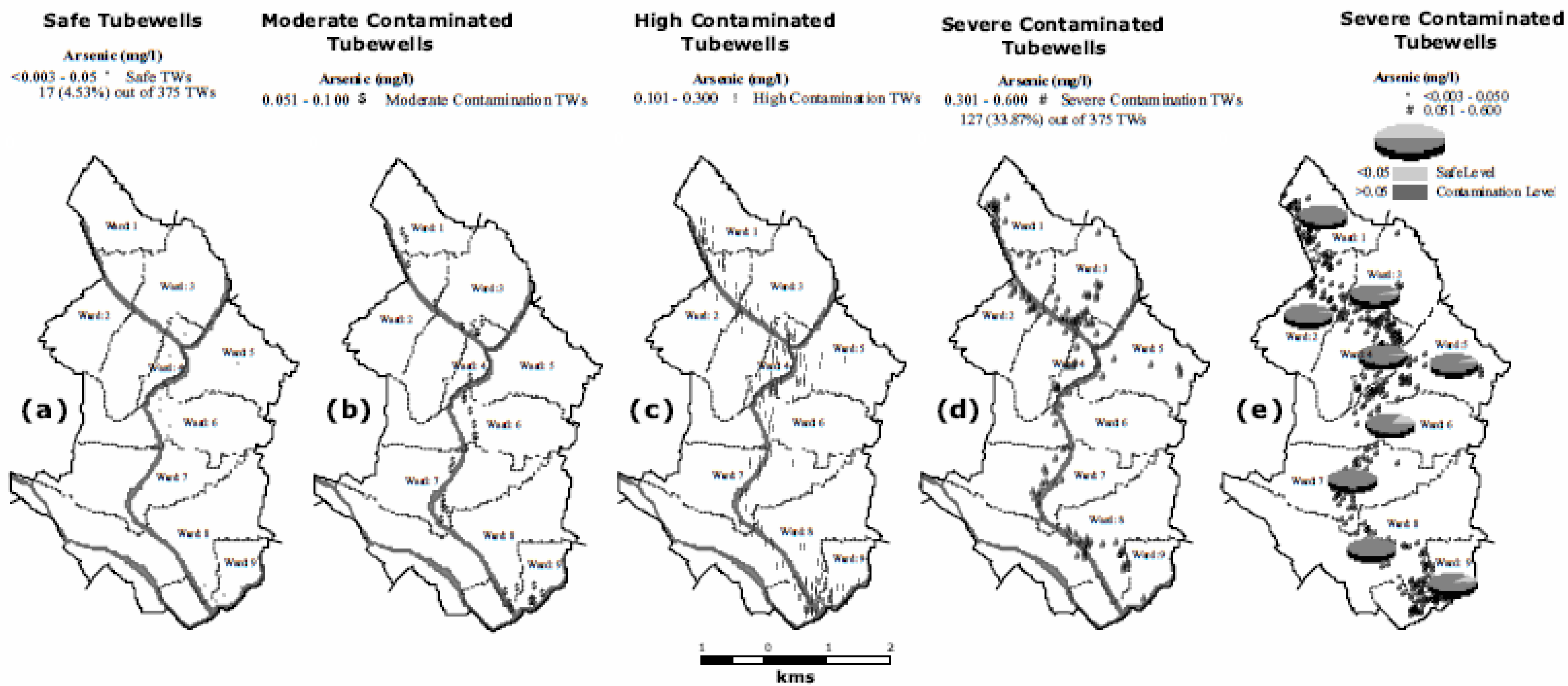

Figure 6. Classifications of arsenic concentrations in the study area: (a) Safe TWs; (b) Moderate contamination TWs; (c) High contamination TWs; (d) Severe contamination TWs; and (e) Two broad categories—safe and contamination TWs.

(a) a safe level (<0.05 mg/L); and (b) a contamination level (>0.05 mg/L).

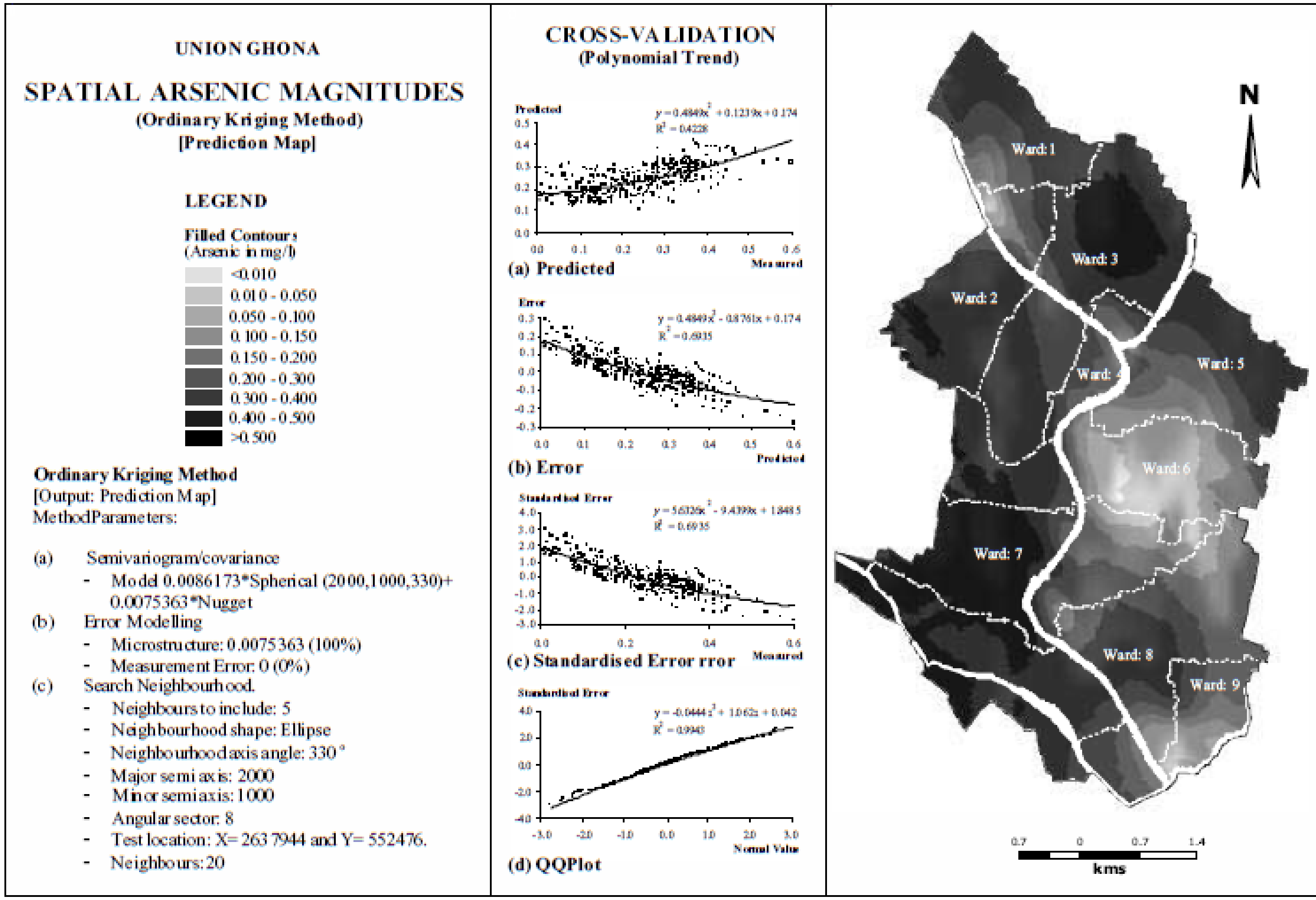

Figure 7. Spatial arsenic magnitudes in the study area.

Table 2. Geographical distribution of arsenic concentrations in groundwater.

Major Groups	Arsenic Magnitudes (mg/L)	Detailed Classification	Number of TWs[a]	Area Covered (Kriging Method)[b]
Safe level	<0.01	WHO permissible limit	4 (1.07)	8.4 (0.49)
	0.01–0.05	Bangladesh standard limit	13 (3.47)	42.9 (2.49)
Contamination level	0.05–0.1	Moderate contamination	32 (8.53)	173 (10.02)
	0.1–0.3	High contamination	200 (53.33)	587 (34.00)
	>0.3	Severe contamination	126 (33.60)	915 (53.00)

[a]Figures in parentheses indicate the net percent of the sample TWs.
[b]Figures in the parentheses indicate the percent of respective distribution area (hectare). (The dataset is classified on the basis of different permissible limits of daily arsenic ingestion and the interpolated area has been calculated by ArcGIS).
Source: Field Survey, 2001.

(a) a safe level (<0.05 mg/L); and (b) a contamination level (>0.05 mg/L).

The kriged prediction shows the isoline maps of estimated arsenic magnitudes and reveals lower arsenic concentrations mainly in the central zone and in some parts of the northern and southern zones of the study area; while higher magnitudes are recognisable in the west and northeast part of the study area (Fig. 7). The safe areas identified in the kriged estimation are especially in Wards 6 and 9 and these safe zones cover about 2.97% (51.30 hectare) of the total study area (Table 2 and Fig. 7).

Only 4.50% of the tubewells (17 out of 375) conform to this safe level. The arsenic concentration present in this broad band ranges between <0.003 mg/L in Ward-9 and 0.043 mg/L in Ward-2 and the mean ($\bar{X}$) arsenic concentration lies at 0.022 mg/L; while the standard deviation (δ_n) is 0.012 mg/L (Table 1). In the safe band, only 4 tubewells (1.07%) meet the WHO standard level (<0.01 mg/L) and 13 tubewells (3.47%) qualify at the Bangladesh Standard Permissible Limit (<0.05 mg/L). There is no safe tubewell in Wards 1 and 7 (Fig. 6). The arsenic-free tubewells in the safe band occur in the south, middle and northern part of the study area along the British Khal (Canal), within the Ganges alluvial plain (Fig. 6).

The kriged estimation map shows the increasing pattern of arsenic concentration from east to west, especially beyond the west bank of the British Khal (Fig. 7). In addition, the northeast parts of the study area are contaminated. Along with the northern part of Ward-3, the contaminated zones cover the western part of Wards 2, 3, 6, 7, and 8. High and severe contamination zones cover about 87% of the study area; while zones of moderate contamination cover about 10.03% (Table 2).

It has been calculated from the field database that about 95.50% (358) of tubewells are contaminated with arsenic. The arsenic concentrations in the contamination category range from 0.057 mg/L in Ward-3 to 0.6 mg/L in Ward-7 and the mean ($\bar{X}$) arsenic concentration is 0.248 mg/L; while the standard deviation (δ_n) in this broad category is 0.109 mg/L (Table 1). It is noteworthy that the mean arsenic concentration in this category is 5 times higher than the Bangladesh standard limit and 25 times higher than the WHO permissible limit.

In the contamination band, only 32 tubewells (8.53%) belong to the range of moderate contamination level (0.05–0.1 mg/L); 200 tubewells (53.33%) are highly contaminated (0.1–0.3 mg/L) level; while the remaining 126 tubewells (33.60%) are in the severe contamination (>0.3 mg/L) band (Table 2). The arsenic-contaminated tubewells in this category occur mainly in the south (Wards 8 and 9) as a cluster; the high arsenic levels are found in the northern, middle and southern portion of the study area; while all tubewells in the severe contamination category occur from north to south along the British Khal within the zone of the Ganges alluvial plain (Fig. 7). All of the tubewells in Wards 1 and 7 are contaminated with arsenic (Fig. 6e).

Arsenic concentration in groundwater is highly uneven over space. The pattern of arsenic magnitudes varies considerably and unpredictably over distances of a few meters, which results in large nugget variances (0.008762) of the spherical variogram (Fig. 2). In the study area, about 46% of tubewells are located within 25 meters of each other, but within this distance there are remarkable variations.

The overall pattern of arsenic concentrations in groundwater shows a broad band of low contamination running along the right bank of the British Khal and the areas near the Ghona UP (Upazila Parishad) Headquarters. Safe zones are mainly concentrated in the north, central and south part of the study area in a scattered manner (Fig. 7); while the contaminated zones are concentrated into the west, northeast and eastern sides. The south and southwest regions have some safe zones with some local variability. The contaminated zones are found everywhere in the study area but with a decrease in the degree of contamination from west to east. The central part of the study area has low contamination—in the area roughly corresponding to the Ganges alluvial floodplain. The west and northeast of the study area then are generally more contaminated; while the southwest part of the study area is contaminated in a highly irregular pattern (Fig. 7).

CHRONIC ARSENIC EXPOSURE AND HEALTH EFFECTS

What kind of health impacts are posed by arsenic? The most deceptive and dangerous aspect of arsenic toxicity is its very slow and insidious development. Chronic exposure to low levels of arsenic causes different skin lesions in the form of melanosis, leuco-melanosis and keratosis.[42–46] Moreover, non-malignant health effects such as diabetes,[46–48] peripheral neuropathy,[49] cardiovascular diseases,[50] ischemic heart disease,[51,52] hypertensive heart disease,[53] and bronchitis[54] can result from arsenic exposure. It is not clear from the literature how much ingestion of arsenic causes what types of skin lesions. This study identified four affected patients with melanosis of whom two had been ingesting arsenic <0.05 mg/L for around 12–15 years and another two between 0.05 mg/L and 0.1 mg/L for the last 20 years. Moreover, five patients were found to be affected with keratosis, having ingested arsenic at more than 0.1 mg/L for 15–20 years.

If arsenic builds up to higher toxic levels, organ cancers, neural disorders, and organ damage—often fatal—can result. Cancer risks from inorganic arsenicals in drinking water have been proved and reported.[55–61] A few years of continued exposure to low levels of inorganic arsenicals causes different skin lesions, and after a latency period of 20–30 years, internal cancers, particularly of the bladder and lung, can appear.[62] We found one patient with serious skin lesions, in particular hyperkeratosis, who had been ingesting arsenic at 0.446 mg/L for around 18 years and one person was also identified with gangrene having been ingesting the poison at 0.353 mg/L for 26 years.

RISK CHARACTERIZATION

There are many equivocal concepts regarding terminologies of risk, hazard, and toxicity.[63] Risk can be considered as the possibility of suffering harm from a hazard, and a hazard in this case the harm from arsenic to human health; while toxicity refers to the inherent potential of arsenic to cause systemic damage.[63] The term hazard is not a synonym for toxic. Risk assessment in the present context refers to the process of estimating the magnitude of risk to human health posed by exposure to arsenic as an environmental hazard in the study area. The assessment of environmental health risk is based on a combination of information on the amount of arsenic people were exposed to and its toxicity; while spatial risk assessment concerning arsenic toxicity involves mapping the areas of affected people and those likely to be affected in future as a result of ingesting different levels of arsenic.

Arsenic Risk Pattern

Risk characterization combines information on exposure and toxicity to estimate the type and magnitude of arsenic risk faced by the exposed population. Combining the evaluation of arsenic toxicity with estimates of how much people are exposed to leads to an assessment of the risk pattern. In addition, the combination of different arsenic data in relation to the installation year of tubewells and the number of people who ingest water from the tubewells helps to identify exposure patterns to arsenic from tubewell water as a factor of risk assessment (Fig. 4).

It is clear from this discussion that combining the uncertainties of toxicity assessment with the uncertainties of exposure assessment will lead to an overall risk assessment with greater uncertainty than that associated with either the toxicity or the exposure estimates. Thus, it is not possible to describe the pattern of exact risk, but we can assess how high and how low it could possibly be. The estimation of environmental health risk with uncertainties is described within a range of probabilities and should be seen as a 'best guess,' rather than an irrefutable statement of fact.

(a) The risk ratio, found by comparing the occurrence of arsenicosis symptoms with different toxic levels of arsenic, can be described as the process of estimating the environmental health risk from arsenic (Table 3). A risk ratio close to 1 suggests that there is no health effect from arsenic; a risk ratio of >1 suggests that the characteristic increases the risk of arsenicosis; and a risk ratio of <1 indicates that the characteristic protects against arsenicosis. 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 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 (Table 3).

Table 3. Risk ratio/pattern of arsenic in the study area.

Ingesting Arsenic (mg/L)	Identified Patients	Exposure Year	Cumulative Frequency	Risk Ratio
<0.01	1	17	1	—
0.01–0.05	1	20–25	2	2/1 = 2
0.05–0.1	2	20	4	4/1 = 4
0.1–0.3	2	15–20	6	6/1 = 6
>0.3	5	>20	11	11/1 = 11

Source: Field survey, 2001.

(b) In identifying the arsenic risk, we need to consider the chronic impact of arsenic and to review the opinions or theories concerning the ingestion of arsenic-contaminated drinking water and the associated health risks. A low to moderate level of environmental exposure to inorganic arsenic (0.02–0.05 mg/L) from drinking water does not have any dose-response relationship for arsenic and cancer.[64] From the study area we found that even low exposures to inorganic arsenic (<0.05 mg/L) in drinking water can be the cause of arsenicosis symptoms and can increase health risk if the dose level contains <0.05 mg/L for a lifetime.

(c) In analyzing arsenic data from a study in an arsenicosis-endemic area of Taiwan,[65–67] Morales et al concluded that although the shape of the exposure–response curve is uncertain at low levels of arsenic exposure, over a lifetime, one out of every 100–300 people who consume drinking water containing 0.05 mg/L arsenic may suffer an arsenic-related cancer (lung, bladder, or liver cancer) death.[68] Smith et al. predicted similar levels of arsenic risk.[69] Despite the considerable uncertainties in the underlying data, the risks are ‘‘sobering.’’[68] Morales et al. suggested that the lifetime risk of death 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.[68] In view of this argument, it can be said that in our study area there is a chance of about 95 people dying with arsenicosis if they consume arsenic at 0.05 mg/L for a lifetime or, 157 people at 0.1 mg/L.

(d) The lifetime risk of dying from cancer while drinking 1 litre of water a day containing arsenic at a concentration of 0.05 mg/L could be as high as 13 per 1000 people exposed.[69] Using the same methods for Ghona, the risk estimate for 0.1 mg/L of arsenic in drinking water would be 26 per 1000 people. 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.

(e) Astolfi et al.[70] pointed out that a regular intake of drinking water containing >0.1 mg/L of arsenic leads to clearly recognisable signs of arsenic toxicity and ultimately in some cases to skin cancer. In view of this, the risk estimate for >0.3 mg/L of arsenic in drinking water could be as high as 4 per 1000 people exposed for a life time.

(f) Tsuda et al. claim that exposure for 5 years to a high dose of arsenic (>0.1 mg/L) can cause skin signs of chronic arsenicism and subsequent cancer development.[71] By reviewing the present findings, we may suggest that there is a probability of 0.20% (20/1000) of cancer symptoms appearing within 20 years if the exposure level exceeds 0.5 mg/L. But it is noted that no cancer patient was identified during the fieldwork as having exposure to arsenic at >0.5 mg/L for about 5 years.

Spatial Arsenic Risk Zones

Arsenic risk zones were mainly identified in a vector-base data analysis process by using GIS technology. A GIS was used as a platform enabling the management of the ‘criterion data’[72] for the spatial risk zoning. GIS applications have frequently been used in producing new information, both by combining data from different sources and by the spatial analysis of existing data bases. Geographic information system technology has been applied to a wide range of environmental risks.[73–77]

A point-in-polygon operation through kriged interpolation methods was performed to analyse the spatial arsenic concentrations of different magnitudes. A cartographic model was developed in which the arsenic exposure data layer was created by combining the arsenic magnitudes map data, buffer area data of TW users, and the map data layer for TW installation years. The exposure data layer was then overlaid with the map data of the settlement area to yield a characterization of different risk zones (Fig. 8). On the basis of this method, the author developed the risk zones into four categories: (a) safe zones; (b) low risk zones; (c) medium risk zones; and (d) high risk zones. The four categories of risk zones were developed by poly-lines and they were converted to polygons using GIS in order to perform statistics. Note that the agricultural land was not accounted for in the spatial risk zoning.

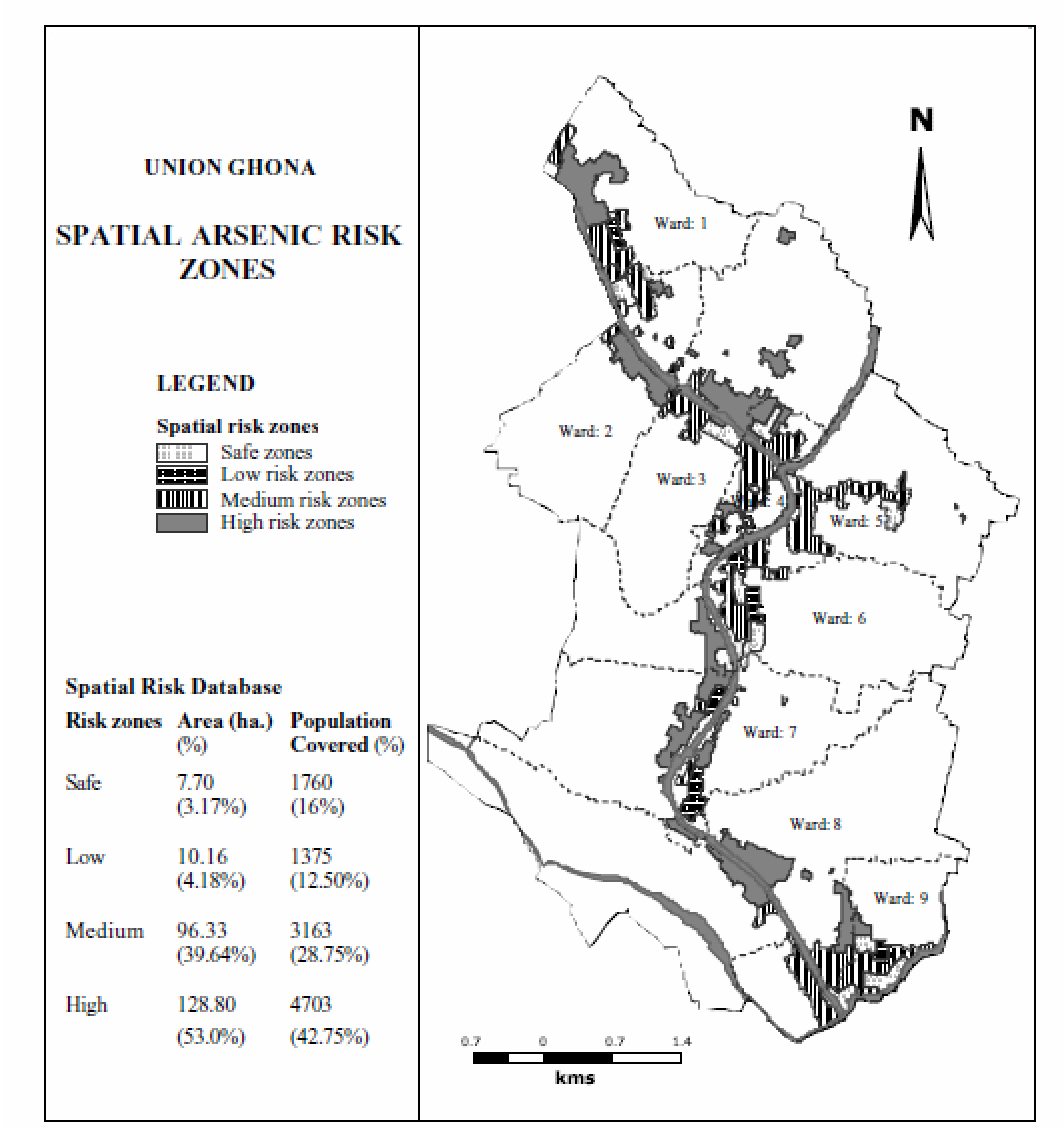

Figure 8. The pattern of spatial arsenic risk zones.

(a) Safe zone. Here are the areas having concentrations of arsenic of <0.05 mg/L. The bounded isolines for this zone cover about 3.17% (7.70 hectares) of the total settlement area. The safe zones are located in the central (Ward-6) and southern (Ward-9) part of the study area (Fig. 8). Only 10 TWs are found in this category. A total of about 1760 people (16%) collect water from the TWs located in this category all the year. During the summer, all of these 10 TWs contain water and most of the people collect water from these TWs.

(b) Low risk zone. Areas having arsenic concentrations between 0.05 and 0.10 mg/L and the installation years between 1981 and 2000 are categorized into this zone. The low risk zones are located in the northern (Wards 1 and 2), central (Wards 5 and 6) and southern (Wards 8 and 9) part of the study area (Fig. 8). The low risk zones cover about 4.18% (10.16 hectares) of total settlement area. A total of 12.50% (1375) of people collect water from 32 TWs in this category. The author identified two arsenic affected patients from this low risk zone.

(c) Medium risk zone. Areas with concentrations of arsenic from 0.10 to 0.30 mg/L and an installation year after 1981 are classed into this category. This risk zone is distributed from north to south along the middle of the study area. This medium risk zone covers about 39.64% (96.33 hectares) of the total settlement area. About 28.75% (3163) of the total population collect water from the 200 TWs in this category. The author did find two arsenic affected patients in this category. Both are in the primary stage of arsenicosis symptoms.

(d) High risk zone. Areas in which arsenic concentrations range from 0.30 mg/L to 0.60 mg/L and in which the TWs date from between 1950 and 1996 are classed as high risk zones. About 53% (129.00 hectares) of the total settlement area covers this category. The zones are mainly located in the west and northeast part of the study area. About 42.75% (4703) of the population use severely contaminated water from 126 TWs located in the high risk zone. The author found five people to be arsenicosis patients.

CONCLUDING REMARKS

This study has identified the spatial magnitudes of arsenic (Fig. 7), impact of arsenic on health with risk characterization, and the spatial risk zoning (Fig. 8). We examined the capability and functionality of GIS in identifying spatial arsenic risk zoning in the light of the existing micro level arsenic data and other tubewell attributes. A geostatistical approach in term of the Ordinary Kriging method was used for spatial interpolation.

In reviewing the literature, we have focussed on the pattern of arsenic magnitudes in the form of safe and contaminated tubewells, rather than especially proliferated spatial magnitudes. Arsenic is distributed everywhere in the study area, but with different degrees of magnitude. The spatial pattern of arsenic magnitudes shows variations of arsenic concentrations in different aspects. The literature shows that the pattern of arsenic magnitudes is usually described using concentrations of arsenic in individual tubewells rather than by the interpolation of values and production of isoline maps for the distribution pattern of arsenic magnitudes. Isoline mapping for this study gives a picture of arsenic concentrations with spatial characteristics. Isoline mapping with a geostatistical approach identified those zones with safe and low to high concentrations of arsenic.

It is found from published sources that arsenic, in recent times, in Bangladesh and West Bengal (India) is considered to be a 'natural calamity' because of its toxic nature. [9–11,56,78] The identified risk factors, risk assessment, and spatial risk zoning for this study show that, without any immediate mitigation action or awareness campaign, the people of the study area will be affected by mass poisoning and exposure to fatal disease. If people in the study area continue to ingest arsenic from the groundwater, they are likely to develop arsenicosis symptoms and in some cases cancer. Although the estimation of health risk in exposure to arsenic is uncertain, a low level of exposure to inorganic arsenic causes chronic toxicity in the body and will be related to health risks.

ACKNOWLEDGMENT

The senior author would like to express his sincere thanks to Professor Diponkor Chakrabarti of the SOES, Jadavpur University, Kolkata, India for his cooperation in analyzing the arsenic data.

REFERENCES

1 DeSesso, J.M.; Jacodson, C.F.; Scialli, A.R.; Farr, C.H.; Holson, J.F. An assessment of the developmental toxicity of inorganic arsenic. Reproductive Toxicology 1998, 12 (4), 385–433.

2 Basu, A.; Mahata, J.; Gupta, S.; Giri, A.K. Genetic toxicology of a paradoxical human carcinogen, arsenic: a review. Mutatation Research 2001, 488 (2), 171–194.

3 Irgolic, K.J.; Stockton, R.A.; Chakraborti, D. Determination of arsenic and arsenic compounds in water supplies. Environmental Perspectives 1987, 5 (1987), 282–308.

4 Goldsmith, J.R.; Deane, M.; Thom, J.; Gentry, G. Evaluation of health implications of elevated arsenic in well water. Water Research 1972, 6, 1133–1136.

5 Harding, B. What is the status of arsenic as a human carcinogen. In Arsenic: Industrial, Biomedical Environmental Perspectives; Lederer, W.H., Fensterheim, R.J., Eds.; Van Nostrand Reinhold: London, 1983; 203–209.

6 Morton, W.; Starr, G.; Pohl, D.; Stoner, J.; Wagner, S.; Weswig, P. Skin cancer and water arsenic in Lane County Oregon. Cancer 1976, 37, 2523–2532.

7 Ahmed, M.F. Water Supply Options in Arsenic Affected Rural Areas. Paper presented at the National Conference on Co-ordinated Action for Arsenic Mitigation, Dhaka: Department of Public Health Engineering,

1999.
8 Alam, M.K. Probable provenances of arsenic in the rocks, sediments and groundwater in Bangladesh and surrounding areas. Paper Presented at the International Conference on Arsenic Pollution of Groundwater in Bangladesh, Dhaka, Dhaka Community Hospital, 1998.
9. Bearak, B. New Bangladesh Disaster: wells that pump poison. The New York Times, Nov 1998 [http://www.nytimes.com/library/worl.../111098bangladeshwater.htm] (accessed May 2001).
10. Chowdhury, Q.I. Arsenic alert-40 million at risk: needed awareness campaign. The Daily Star, July 20, 1997.
11. Dhar, R.K.; Biswas, B.K.; Samanta, G.; Mandal, B.K.; Chakraborti, D.; Roy, S.; Jafar, A.; Islam, A.; Ara, G.; Kabir, S.; Khan, A.W.; Ahmed, S.K.; Hadi, S.A. Groundwater arsenic calamity in Bangladesh. Current Science 1997, 73, 48–59.
12. Hussain, A.Z.M.I. Effects of arsenic contamination of drinking water on health and its management. Paper Presented at the National Conference on Co-ordinated Action for Arsenic Mitigation, Department of Public Health Engineering, Dhaka, 1999.
13. Nickson, R.T.; McArthur, J.M.; Ravenscroft, P.; Burgess, W.G.; Ahmed, K.M. Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. Applied Geochemistry 2000, 15 (2000), 403–413.
14. Smith, A.H.; Lingas, E.O.; Rahman, M. Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bulletin of the World Health Organization 2000, 78 (9), 1093–1103.
15. Miles, M.; Huberman, A. Qualitative Data Analysis; Sage: London, 1994; 31–42.
16. Wainwright, D. Can sociological research be qualitative, critical and valid? The Qualitative Report 1997, 3 (2): 1–12; (http://www.nova.edu/ssss/QR/QR3-2/ wain.html) (accessed Jan 2002).
17. BBS (Bangladesh Bureau of Statistics). Bangladesh Population census, 1991: Thana Statistics. Dhaka: Bangladesh Bureau of Statistics, 1993; 327.
18. Rashid, H. The Geography of Bangladesh; UPL: Dhaka, 1991; 41–43.
19. DoE (Department of Environment). Environmental Quality Standards for Bangladesh; Government of Bangladesh: Dhaka, 1991.
20. Burrough, P.A.; McDonnell, R.A. Creating continuous surface from point data. In Principles of Geographic Information Systems, 1st Ed.; Oxford University Press: New York, 1998; 98–131.
21. Oliver, M.A.; Khayrat, A.L. A geostatistical investigation of the spatial variation of radon in soil. Computers and Geosciences 2001, 27 (8), 939–957.
22. Johnston, K.; Ver Hoef, J.M.; Krivoruchko, K.; Lucas, N. Using ArcGIS™ Geostatistical Analyst; Environmental System Research Institute (ESRI): Redlands, 2001; 49–80.
23. Beliaeff, B.; Cochard, M.L. Applying geostatistics to identification of spatial patterns of fecal contamination in a mussel farming area (havre de la vanle´ e, France). Water Research 1995, 29 (6), 1541–1548.
24. Badr, I.; Oliver, M.A.; Hendry, G.L.; Durrani, S.A. Determining the spatial scale of variation in soil radon values using a nested survey and analysis. Radiation Protection Dosimetry 1993, 49 (4), 433–442.
25. Rizzo, D.M.; Dougherty, D.E. Characterization of aquifer properties using artificial neural networks: neural kriging. Water Resource Research 1994, 30, 483–497.
26. Patgiri, D.K.; Baruah, T.C. Spatial variability of total porosity, air entry potential and saturation water content in a cultivated inceptisol II: estimation through kriging. Agricultural Water Management 1995, 27 (1), 11–16.
27. Isaaks, E.H.; Srivastava, R.M. An Introduction to Applied Geostatistics; Oxford University Press: New York, 1989; 278–322.
28. Phillips, D.L.; Marks, D.G. Spatial uncertainty analysis: propagation of interpolation errors in spatially distributed models. Ecological Modelling 1996, 91 (1–3), 213–229.
29. Tsanis, I.K.; Gad, M.A. A GIS precipitation method for analysis of storm kinematics. Environmental Modelling and Software 2001, 16 (3), 273–281.
30. Davis, J.C. Statistics and Data Analysis in Geology, 3rd Ed.; New York: Wiley, 2002; 45–78.

31. Wang, Y.; Ma, T.; Luo, Z. Geostatistical and geochemical analysis of surface water leakage into groundwater on a regional scale: a case study in the Liulin karst system, northwestern China. Journal of Hydrology 2001, 246 (1–4), 223–234.
32. Kalabokidis, K.D.; Omi, P.N. Isarithmic analysis of forest fire fuelbed arrays. Ecological Modelling 1995, 80 (1), 47–55.
33. Petkov, L.; Pieri, M.; Maselli, F.; Maracchi, G. Study and modelling of temperature spatial variability by NOAA-AVHRR thermal imagery. ISPRS Journal of Photogrammetry and Remote Sensing 1996, 51 (3), 127–136.
34. So¨ derstro¨ m, M.; Magnusson, B. Assessment of local agroclimatological conditions—a methodology. Agricultural and Forest Meteorology 1995, 72 (3–4), 243–260.
35. Sero´ n, F.J.; Badal, J.I.; Sabadell, F.J. Spatial prediction procedures for regionalization and 3-D imaging of Earth structures. Physics of the Earth and Planetary Interiors 2001, 123 (2–4), 149–168.
36. Persicani, D. Evaluation of soil classification and kriging for mapping herbicide leaching simulated by two models. Soil Technology 1995, 8 (1), 17–30.
37. Brooker, P.I.; Winchester, J.P.; Adams, A.C. A geostatistical study of soil data from an irrigated vineyard near waikerie, South Australia. Environment International 1995, 21 (5), 699–704.
38. Mapa, R.B.; Kumaragamage, D. Variability of soil properties in a tropical Alfisol used for shifting cultivation. Soil Technology, 1996, 9 (3), 187–197.
39. Lacaze, B.; Rambal, S.; Winkel, T. Identifying spatial patterns of Mediterranean landscapes from geostatistical analysis of remotely-sensed data. International Journal of Remote sensing 1994, 15 (12), 2437–2450.
40. Gerlach, T.M.; Doukas, M.P.; McGee, K.A.; Kessler, R. Soil efflux and total emission rates of magmatic CO2 at the Horseshoe Lake tree kill, Mammoth Mountain, California, 1995–1999. Chemical Geology 2001, 177 (1–2), 101–116.
41. Martin, D. Geographic Information Systems and their Socioeconomic Applications; Routledge: London, 1991; 12–19.
42. Cole, D.C.; Pengelly, L.D.; Eyles, J.; Stieb, D.M.; Hustler, R. Consulting the community for environmental health indicator development: the case of air quality. Health Promotion International 1999, 14 (1), 65–72.
43. Foster, F.; Craun, G.; Brown, K.G. Detection of excess arsenic-related cancer risks. Environmental Health Perspectives 2002, 110 (1), 12–13.
44. Jaafar, R.; Omar, I.; Jidon, A.J.; Wan-Khamizar, B.W.; Siti-Aishah, B.M.; Sharifah-Noor-Akmal, S.H. Skin cancer caused by chronic arsenical poisoning-a report of three cases. Medical Journal of Malaysia 1993, 48 (1), 86–92.
45. Mazumder, D.N.G.; Haque, R.; Ghosh, N.; De, B.K.; Santra, A.; Chakraborty, D.; Smith, A.H. Arsenic levels in drinking water and the prevalence of skin lesions in West Bengal, India. International Journal of Epidemiology 1998, 27 (5), 871–877.
46. Tondel, M.; Rahman, M.; Magnuson, A.; Chowdhury, I.A.; Faruquee, M.H.; Ahmad, S.A. The relationship of arsenic levels in drinking water and the prevalence rate of skin lesions in Bangladesh. Environmental Health Perspectives 2001, 107 (9), 727–729.
47. Lai, M.S.; Hsueh, Y.M.; Chen, C.J.; Shyu, M.P.; Chen, S.Y.; Kuo, T.L.; Wu, M.M.; Tai, T.Y. Ingested inorganic arsenic and prevalence of diabetes mellitus. American Journal of Epidemiology 1999, 139 (5), 484–492.
48. Rahman, M.; Tondel, M.; Ahmad, S.A.; Chowdhury, I.A.; Faruquee, M.H.; Axelson, O. Hypertension and arsenic exposure in Bangladesh. Hypertension 1999, 33 (1), 74–78.
49. Chiou, H.Y.; Huang, W.I.; Su, C.L.; Chang, S.F.; Hsu, Y.H.; Chen, C.J. Dose-response relationship between prevalence of cerebrovascular disease and ingested inorganic arsenic. Stroke 1997, 28 (9), 1717–1723.
50. Engel, R.R.; Smith, A.H. Arsenic in drinking water and mortality from vascular disease: an ecologic analysis in 30 counties in the United States. Archives of Environmental Health 1994, 49 (5), 418–427.
51. Chen, C.J.; Chiou, H.Y.; Chiang, M.H.; Lin, L.J.; Tai, T.Y. Dose-response relationship between ischemic heart disease mortality and long-term arsenic exposure. Arteriosclerosis, Thrombosis, and Vascular Biology 1996, 16 (4), 504–510.
52. Hsueh, Y.M.; Wu, W.L.; Huang, Y.L.; Chiou, H.Y.; Tseng, C.H.; Chen, C.J. Low serum carotene level and

increased risk of ischemic heart disease related to long-term arsenic exposure. Atherosclerosis 1998, 141 (2), 249–257.
53. Lewis, D.R.; Southwick, J.W.; Ouellet-Hellstrom, R.; Rench, J.; Calderon, R.L. Drinking water arsenic in Utah: a cohort mortality study. Environmental Health Perspectives 1999, 107 (5), 359–365.
54. Abernathy, C.O.; Liu, Y.P.; Longfellow, D.; Aposhian, H.V.; Beck, B.; Fowler, B.; Goyer, R.; Menzer, R.; Rossman, T.; Thompson, C.; Waalkes, M. Arsenic: health effects, mechanisms of actions, and research issues. Environmental Health Perspectives 1999, 107 (7), 593–597.
55. Brown, K.G.; Chen, C.J. Significance of exposure assessment to analysis of cancer risk from inorganic arsenic in drinking water in Taiwan. Risk Analysis 1995, 15 (4), 475–484.
56. Chatterjee, A.; Mukherjee, A. Hydrogeological investigation of ground water arsenic contamination in south Calcutta. The Science of the Total Environment 1999, 225 (3), 249–262.
57. Hsueh, Y.M.; Cheng, G.S.; Wu, M.M.; Yu, H.S.; Kuo, T.L.; Chen, C.J. Multiple risk factors associated with arsenic-induced skin cancer: effects of chronic liver disease and malnutritional status. British Journal of Cancer 1995, 71 (1), 109–114.
58. Gou, H.R.; Lu, F.J. Arsenic ingestion and internal cancers: a review. American Journal of Epidemiololy 1994, 139 (12), 1233–1234.
59. Mushak, P.; Crocetti, A.F. Risk and revisionism in arsenic cancer risk assessment. Environmental Health Perspectives 1995, 103 (7–8), 684–689.
60. Tseng, C.H.; Chong, C.K.; Chen, C.J.; Lin, B.J.; Tai, T.Y. Abnormal peripheral microcirculation in seemingly normal subjects living in blackfoot-diseasehyperendemic villages in Taiwan. International Journal of Microcirculation: Clinical and Experimental 1995, 15 (1), 21–27.
61. Woollons, A.; Russell-Jones, R. Chronic endemic hydroarsenicism. British Journal of Dermatology 1998, 139 (6), 1092–1096.
62. Byrd, D.M.; Roegner, M.L.; Griffiths, J.C.; Lamm, S.H.; Grumski, K.S.; Wilson, R.; Lai, S. Carcinogenic risks of inorganic arsenic in perspective. International Archives of Occupational and Environmental Health 1996, 68 (6), 484–494.
63. Kates, R.W. Hazard assessment: art, science, and ideology. In Perilous Progress: Managing the Hazards of Technology; Kates, R.W., Hohenemser, C., Kasperson, J.X., Eds.; Westview Press: Boulder, 1985; 53–79.
64. Buchet, J.P.; Lison, D. Mortality by cancer in groups of the Belgian population with a moderately increased intake of arsenic. International Archives of Occupational and Environmental Health 1998, 71 (2), 125–130.
65. Chen, C.J.; Kuo, T.L.; Wu, M.M. Arsenic and cancers (Letter). Lancet 1988, 2, 414–415.
66. Chen, C.J.; Chen, C.W.; Wu, M.M.; Kuo, T.L. Cancer potential in liver, lung, bladder and kidney due to ingested inorganic arsenic in drinking water. British Journal of Cancer 1992, 66, 888–892.
67. Wu, M.M.; Kuo, T.L.; Hwang, Y.H.; Chen, C.J. Dose-response relation between arsenic concentration in well water and mortality from cancers and vascular diseases. American Journal of Epidemiology 1989, 130, 1123–1132.
68. Morales, K.H.; Ryan, L.; Kuo, T.L.; Wu, M.M.; Chen, C.J. Risk of internal cancers from arsenic in drinking water. Environmental Health Perspectives 2000, 108, 655–661.
69. Smith, A.H.; Hopenhayn-Rich, C.; Bates, M.N.; Goeden, H.M.; Hertz-Picciotto, I.; Duggan, H.M.; Wood, R.; Kosnett, M.J.; Smith, M.T. Cancer risks from arsenic in drinking water. Environmental Health Perspectives 1992, 97, 259–267.
70. Astolfi, E.; Maccagno, A.; Fernandez, J.C.G.; Vaccara, R.; Stimola, R. Relation between arsenic in drinking water and skin cancer. Biological Trace Element Research 1981, 3, 133–143.
71. Tsuda, T.; Babazono, A.; Yamamoto, E.; Kurumatani, N.; Mino, Y.; Ogawa, T.; Kishi, Y.; Aoyama, H. Ingested arsenic and internal cancer: a historical cohort study followed for 33 years. American Journal of Epidemiology 1995, 141 (3), 198–209.
72. Store, R.; Kangas, J. Integrating spatial multi-criteria evaluation and expert knowledge for GIS-based habitat suitability modelling. Landscape and Urban Planning 2001, 55 (2), 79–93.

73. Berry, J. Cartographic modelling: the analytical capabilities of GIS. In Environmental Modelling with GIS, 1st Ed.; Goodchild, M., Parks, B., Steyaert, L., Eds.; Oxford University Press: New York, 1993; 58–74.
74. Carver, S. Integrating multi-criteria evaluation with geographical information systems. International Journal of Geographical Information Systems 1991, 5 (3), 321–339.
75. Dow, K. Exploring differences in our common future(s): the meaning of vulnerability to global environmental change. Geoforum 1993, 23 (3), 417–436.
76. Emani, S. GIS applications in hazard assessment and management: a review. In Applications in Hazard Assessment and Management: Explorations in Geographic Information Systems Technology, 1st Ed.; Emani, S., Ed.; Nations Institute for Training and Research (UNITAR): Geneva, 1996; Vol. 6, 1–48.
77. Newkirk, R.T. Extending geographic information systems for risk analysis and management. Journal of Contingencies and Crisis Management 1993, 1 (4), 203–206.
78. Das, D.; Samanta, G.; Mandal, B.K.; Chowdhury, T.R.; Chanda, C.R.; Chowdhury, P.P.; Basu, G.K.; Chakraborti, D. Arsenic in groundwater in six districts of West Bengal, India. Environmental Geochemistry and Health 1996, 18 (1), 5–15.