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ORIGINAL ARTICLE

Geostatistically based management of arsenic contaminated ground water in shallow wells of Bangladesh

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Abstract This paper investigates the effectiveness of geostatistical approaches, specifically ordinary kriging, for regional management of arsenic contaminated shallow ground water in Bangladesh. The arsenic database for reference comprised the nation-wide survey (of 3534 drinking wells) completed in 1999 by the British Geological Survey (BGS) in collaboration with the Department of Public Health Engineering (DPHE) of Bangladesh. A Monte Carlo (MC) framework was devised for selection of randomly-sampled networks of wells from this reference database. Each randomly sampled network was assumed an equi-probable exploratory field campaign designed commensurably with the requirements of rapidity and cost-effectiveness in a rural setting. In general, the kriging method was found to underestimate the arsenic concentration at non-sampled locations. This underestimation exceeded the safe limits at the Holocene region of Southcentral Bangladesh. The probability of successful prediction of safe wells for this region was found to be 72% (WHO safe limit – 10 ppb) and 78% (Bangladesh safe limit – 50 ppb). For the Pleistocene Northwestern region of Bangladesh, the safe well prediction probability was in the ranges of 90%–97%. The relatively more contaminated Holocene region in Southcentral Bangladesh, on other hand, was found more amenable to accurate geostatistical prediction of unsafe wells. Findings from this study exemplify that, while mainstream geostatistical approaches (e.g., ordinary kriging) may not provide the most accurate prediction of mean arsenic concentration at non-sampled locations, they can delineate an approximate strategy for management of arsenic contaminated shallow ground water if applied carefully. The kriging methodology is applied to a test case in Bangladesh; the approach, however, is general and is expected to have application in rural settings for other developing countries where arsenic contamination of ground water is also widespread (e.g., parts of India, Vietnam, Taiwan and Mexico).

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1. Introduction

Patterns, or 'organized' distributions, of a contaminant variable of interest play an important role in groundwater management. One pertinent example on the need to identify such patterns for long-term monitoring of public health is the case of extensive ground water arsenic contamination in Bangladesh. It is currently estimated that more than half of the population in Bangladesh is at risk from arsenic poisoning (Yu *et al*., 2003). Since 1993, when it was first discovered that a vast proportion of the shallow wells (sunk at a depth <150 m) in Bangladesh were contaminated with arsenic, numerous studies have been conducted to better understand the contamination scenario (e.g., Biswas *et al*., 1998; Burgess *et al*., 2000; McArthur *et al*., 2000; Mukherjee and Bhattacharya, 2002; Harvey *et al*., 2002; Yu *et al*., 2003; McArthur *et al*., 2004; Hossain *et al*., 2006). A commonality among the studies that characterized the 'spatial' pattern of arsenic was the use of geostatistical tools centered around the kriging method. For example, the first country-wide study towards characterization of the arsenic calamity was conducted in 1999 by the British Geological Survey in collaboration with the Department of Public Health and Engineering (DPHE) of Bangladesh (hereafter, this survey is referred to as 'BGS-DPHE', 2001). The BGS-DPHE (2001) study characterized the spatial variability through modeling of the variogram and prediction of arsenic concentrations at non-sampled locations by kriging.

However, in geo-hydrologic practice, information becomes available over the course of time, so pattern filling techniques such as kriging cannot be done once and for all but will rather evolve with time (Rizzo and Dougherty, 1994). As new (and reliable) information becomes available from field observations, the variography and its parameters will need to be re-estimated (Massmann and Freeze, 1989). For contaminated ground water, this evolving nature of geo-spatial knowledge consequentially alters the planning of strategies for management. For developing countries, a clear understanding of the management practice as a function of incomplete (and evolving) geo-spatial knowledge is important due to the added constraints of limited resources and time. Bangladesh, being one such developing country with a dominant rural make-up, is an ideal example showcasing the need for such an understanding.

However, the management of contaminated ground water in Bangladesh, can be quite challenging. Of the 6–20 million shallow wells currently operational (*exact number unknown*) in rural Bangladesh, most remain largely unscreened for arsenic (Rahman *et al*., 2002; Hossain and Sivakumar, 2006). Only 2–3 million have been screened so far, yet the test results are questionable due to the use of the semi-quantitative field kits (Rahman *et al*., 2002; Hossain *et al*., 2006). Yu *et al*. (2003) estimated that by replacing 31% of the country's shallow wells with deep ones Bangladesh could potentially reduce the arsenic related health hazards by about 70%. Due to the high costs and long delays that will most likely be associated with implementation of such a remedial measure, one interim but cost-effective approach for management could be the geostatistical identification of safe/unsafe wells (or cluster of wells) at non-sampled location. Such an approach, on the basis of limited field data, could offer preliminary insights into the contamination scenario which could then be used to strategize subsequent sampling, monitoring and remediation efforts on the basis of more detailed field surveys. For example, a geostatistical approach could identify regions where uncontaminated shallow drinking wells are likely to abound, for continued domestic use by villagers, and simultaneously, predict regions where wells that are likely to be unsafe, and hence prioritize (those regions) as in greater need of remediation (Hossain *et al*., 2006). Recently, villagers have revealed that, walking to a safe, reliable and easily manageable water source once a day was more convenient and/or acceptable to them than operating and maintaining house-hold water treatment options (Hoque *et al*., 2004). Hence, while a more structural but time-consuming solution is no doubt necessary for Bangladesh (such as deep well drilling or aquifer remediation), a geostatistically based management strategy as delineated above has the potential to serve interim needs on a regional basis that may also be compatible with the social fabric of the rural regions.

The method of ordinary kriging is one such geostatistical tool that can predict a well as safe or unsafe at non-sampled locations reasonably conveniently without the need for complex contaminant transport modeling (Davis *et al*., 2004). Although, it is considered the most widely-used tool for such a purpose (Ma *et al*., 1999; Shieh *et al*., 2005; Yamamoto, 2005; Marchant and Lark, 2005), to the best of our knowledge, it has not been thoroughly assessed of its effectiveness for management of arsenic contaminated shallow ground water in Bangladesh in light of the additional constraints imposed due to a rural setting. Serre *et al*. (2003) reports that spatial interpolation of arsenic contamination in Bangladesh as challenging as most of the variability in arsenic concentration occurs within a distance of 2 km. Yu *et al*. (2003), on the other hand, has reported that much of the regional scale variability could be explained by geologic and geomorphologic differences In this paper, we investigate, the utility of kriging (hereafter called 'kriging') for making preliminary yet rapid decisions for regional management of arsenic contaminated ground water in Bangladesh. A scenario of a rapid decision for management could be, for example, flagging a non-sampled well with a risk factor via kriging (safe, unsafe, undetermined) and dispense remediation resources for that well or cluster in accordance with the associated contamination risk factor. We recognize that the approach we are testing, being based on best linear unbiased estimator principles, will tend to smooth out the results and provide an average pattern and as such has limitations. Geostatistical simulation methods (e.g., Smith and Freeze, 1979; Bagtzoglou and Ababou, 1997 among many others) and various non-linear estimation methods (Christakos and Lee, 1998, for example) could be a much better suited approach for this situation and is currently under investigation by our team. However, since the majority of the researchers dealing with arsenic contamination in Bangladesh have employed kriging techniques (such as, for example, BGS-DPHE, 2001; Yu *et al*., 2003), we opted to test our hypotheses management using this approach first.

The paper is organized as follows. Section 2 presents the study region and dataset while Section 3 describes the methodology for assessing kriging for contaminated ground water management. Section 4 describes the Monte Carlo (MC) stochastic framework devised for assessment of kriging effectiveness. Finally, Sections 5 and 6 present the discussion of results and the conclusions of the study, respectively.

2. Study region and data

Our study region was Bangladesh excluding the dense forests in the Southwest and Southeast (Figure 1). Geologically, the region is made up of mainly old oxic Pleistocene and relatively young anoxic Holocene deposits (Figure 1 upper right panel). Based on geologic differences and relative levels of severity of arsenic contamination, we classified our study region in to two categories: (1) Northwest Bangladesh (BD), defined as a Pleistocene region bound by 24.0°N–26.5°N latitude and 88.0°E–89.5°E longitude representing an area of about 37,500 km^2; (2) Southcentral BD, defined as a Holocene region bound by 22.0°N–23.5°N latitude

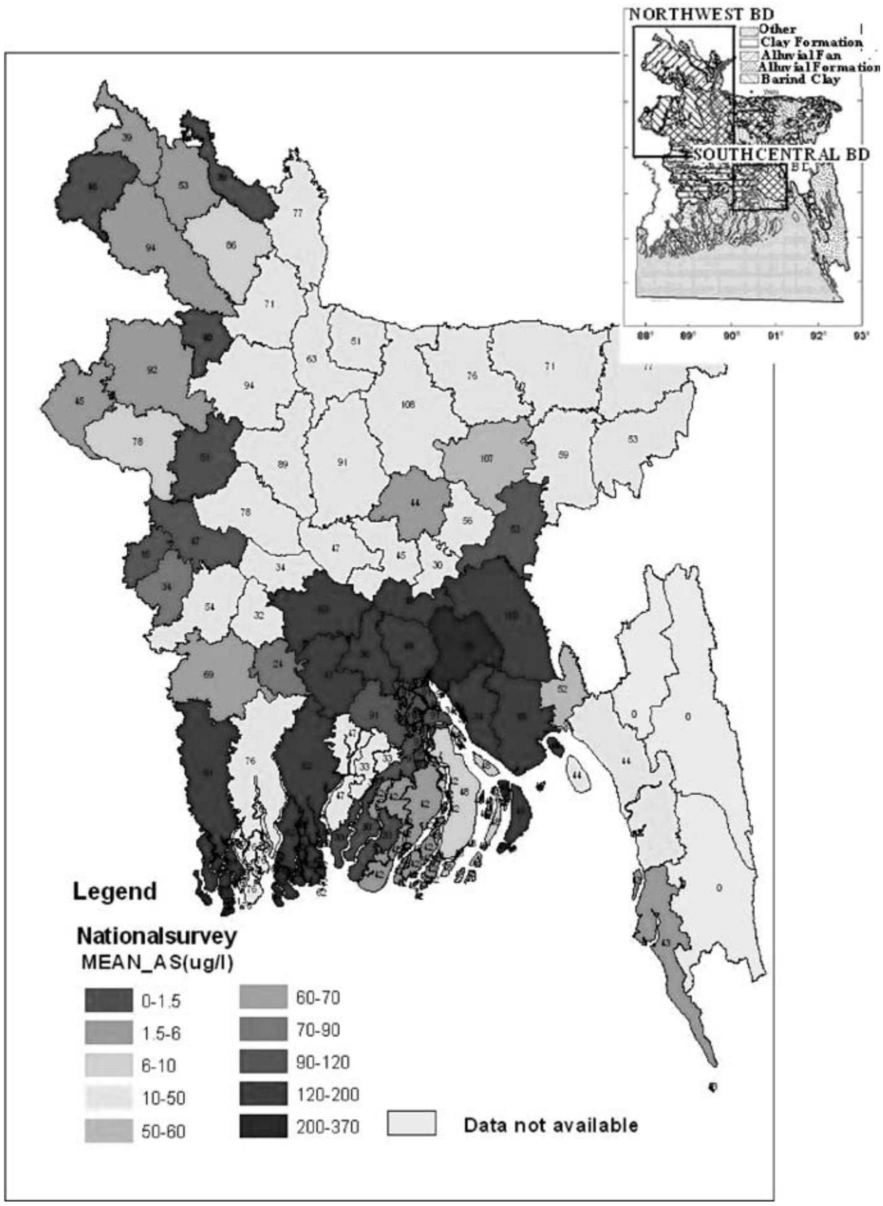


Fig. 1 Mean arsenic concentrations based on the BGS-DPHE (2001) data per *zila* or districts (i.e., typical large-scale administrative unit in Bangladesh). The number of wells tested by BGS-DPHE(2001) for each district are shown inside. The figure on the upper right corner shows the two main study regions for Bangladesh – Northwest and Southcentral. Broad geological classifications according to Alam *et al*. (1990) are also shown in the inset

and 90.0°E–91.5°E. The Pleistocene region of Northwest BD represented the relatively risk-free zone comprising oxic aquifers, while, for the Southcentral BD, the anoxic aquifers in Holocene deposits suffer from elevated levels of arsenic concentration in groundwater (Figure 1).

Arsenic data were obtained from the BGS-DPHE (2001) survey. This dataset comprised 3534 wells and is freely available through the internet at the website http://www.bgs.ac.uk/arsenic/Bangladesh. Sample wells were systematically selected uniformly with approximately one well per 37 km^2. In the overall scheme of our investigation, the BGS-DPHE (2001) survey currently represents the most quality-controlled database of arsenic measurements available for any kind of country-wide management analyses. Arsenic measurements of BGS-DPHE (2001) survey were based on the Atomic Absorption Spectro-photometric (AAS) method, which is currently considered the most reliable method typically used for arsenic testing (Rahman *et al*., 2002; Hossain *et al*., 2006; Goovaerts *et al*., 2006). On the other hand, even though the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP; www.bamwsp.org) is host to an extensive archive on the status of about 2–3 million wells, this larger dataset is not amenable to geostatistical analyses due to the following two reasons: (1) use of semi-quantitative field kits (FK) with very large measurement errors (Hossain *et al*., 2006); (2) lack of geospatial information on individual wells that were sampled (personal communication with Project Director of National Arsenic Mitigation Council – NAMIC, Bangladesh). Hence, while a sparse density of sampling of BGS-DPHE (2001) may raise concerns, which are understandable, we would also like to emphasize that there is no convincing reason to believe that the dataset should not be used. We admit that the BGS-DPHE (2001) may have its own limitations, but we believe that such potential limitations alone should not hamper our ability to investigate the usefulness of the kriging method, and particularly so when our intention is to primarily conduct a preliminary assessment on regional management. Recent work by Goovaerts *et al*. (2005) offer further credence to this philosophy where kriging has been used for modeling the spatial variability groundwater arsenic in southeast Michigan using a comparably sparse amount of data. More details on the study dataset, sampling protocols can be found in BGS-DPHE (2001; Volume 1).

3. Methodology

3.1. Data organization

In general, wells deeper than 75 m were neglected as the study focused on shallow wells that are the primary source of drinking water in rural Bangladesh (Ahmed, 2003). This is the depth up to which most of the drinking wells in rural Bangladesh can be drilled affordably. Previous studies have indicated that much of the spatial variability in arsenic contamination in drinking wells can be attributable to depth (Yu *et al*., 2003). The BGS-DPHE (2001) dataset itself indicates that, on the average, the highest arsenic concentrations are usually observed in the 15 m–75 m range. Hossain *et al*. (2006) also reported a similar depth range for a more recent field campaign in the Southwest region of Bangladesh. Hence, by assigning a cutoff depth of 75 m, our geostatistical analyses are assumed to be minimally affected by depth in influencing the spatial variability of arsenic concentration. A point to note herein is that the depth refers to the depth of the screen of the well and not to the depth of the groundwater table. We assumed an arsenic concentration of 1 ppb (1.0 μg L^{-1}) as the detection limit for current AAS measurement technology. The non-detection wells containing arsenic concentration

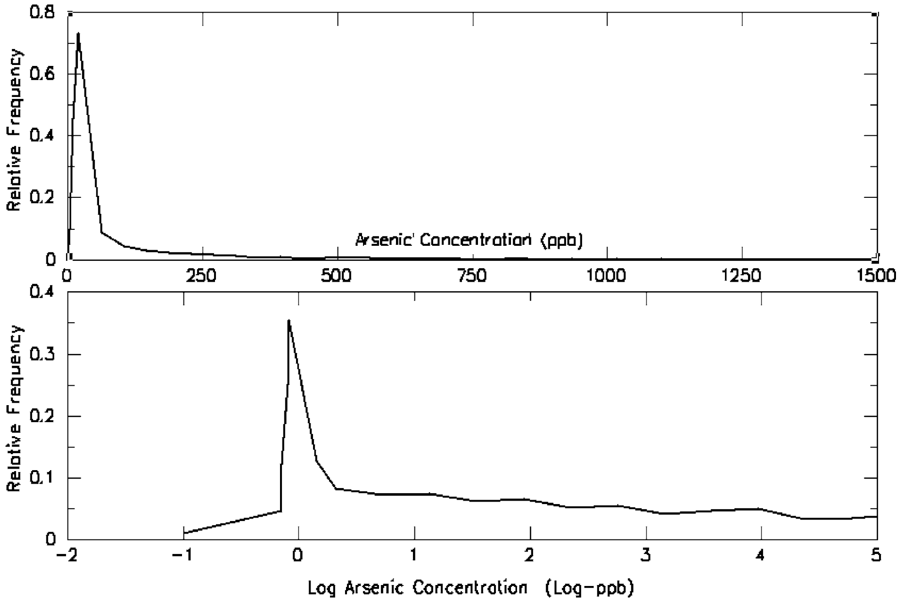


Fig. 2 Probability distribution of arsenic concentrations. Upper panel: for untransformed data; Lower panel: for log-transformed arsenic data

below this detection limit were therefore assigned a value of 1 ppb. The advantage of this adjustment is that it preserved the "sanity" of log-transformation of arsenic data, which is considered a necessary element, as arsenic concentrations are known to vary over 3–4 orders of magnitude in Bangladesh (seeFigure 2 upper panel). The log-transformation of arsenic concentrations resulted in a highly plausible Gaussian and symmetric distribution about a near-zero mean in log (ppb) (Figure 2 lower panel). This simple log-transformation consequently reduced considerably the need for any additional adjustments to achieve a 'perfectly' Gaussian univariate distribution, such as the normal score transform (Deutsch and Journel, 1998), that is necessary for application of ordinary kriging on multi-modal log-transformed data (Goovaerts *et al*., 2005). Finally, we mapped this transformed arsenic concentration for each well over a 5 km × 5 km grid to facilitate graphical representation of our spatial interpolation analyses on a regular grid system. Each grid within the study domain was represented by one well at the most. A point to note however, is that all pertinent variograms and kriging application were performed on individual well points *per se*. We use the grid overlay procedure primarily for gauging the value of kriging for GIS-based regional management at scales of 25 km^2 or higher.

3.2. Ordinary kriging

Ordinary kriging is a spatial interpolation estimator $\hat{Z}(x_0)$ used to find the best linear unbiased estimate of a second-order stationary random field with an unknown constant mean as follows:

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{1}$$

where $\hat{Z}(x_0)$: kriging estimate at location x_0; $Z(x_i)$: sampled value at location x_i; and λ_i: weighting factor for $Z(x_i)$.

The estimation error is

$$\hat{Z}(x_0) - Z(x_0) = R(x_0) = \sum_{i=1}^{n} \lambda Z(x_i) - Z(x_0) \tag{2}$$

where $Z(x_0)$: unknown true value at x_0; and $R(x_0)$: estimation error. For an unbiased estimator, the mean of the estimation error must equal zero. Therefore,

$$E\{R(x_0)\} = 0 \tag{3}$$

and

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{4}$$

The best linear unbiased estimator must have minimum variance of estimation error. The minimization of the estimation error variance under the constraint of unbiasedness leads to a set of simultaneous linear algebraic equations for the weighting factors, λ_i, which can be solved by an optimization routine and the method of Lagrange multipliers. For details on the ordinary kriging technique and its application to ground water or related problems, the reader is referred to works of Ma *et al*. (1999), Shieh *et al*. (2005), Yamamoto (2005), Marchant and Lark (2005) and Goovaerts *et al*. (2005). For specific details on the software routines used in this study, the reader is referred to the *Geostatistical Software Library (GSLIB) and Users Guide* (Deutsch and Journel, 1998).

4. Monte Carlo (MC) framework for assessment of kriging

A Monte Carlo (MC) framework was devised for design of an exploratory network comprising randomly selected wells. These random networks are considered analogous to equi-probable exploratory field campaigns that would need to be small-scale (i.e., limited sampling) during a remediation-cum-management exercise for requirements of rapidity and cost-effectiveness. We addressed two specific questions herein: (1) *How effective is kriging in modeling the spatial variability of arsenic contamination*? (2) *What role does geology play in dictating the effectiveness of the kriging method?* In particular, we assessed the accuracy of the kriging method in detecting safe and unsafe wells at non-sampled locations.

50% of the wells were selected randomly for each of the study regions: (1) Northwest BD and (2) Southcentral BD (Figure 1, upper right panel). Such a network of randomly selected wells would need to be screened for modeling the spatial variability of arsenic contamination during a field survey. The random selection of equi-probable exploratory networks was repeated 1000 times to derive the same number of ensembles of spatially interpolated (kriged) fields for each region. Figure 3 showsone such random selection of exploratory networks for each study region. For each realization, the empirical variogram was computed and subsequently modeled assuming the exponential correlation function. It is noteworthy to mention that the non-negligible nugget effect corresponded to about 30% and 20% of the experimental variance of the data for Northwest BD and Southcentral BD,

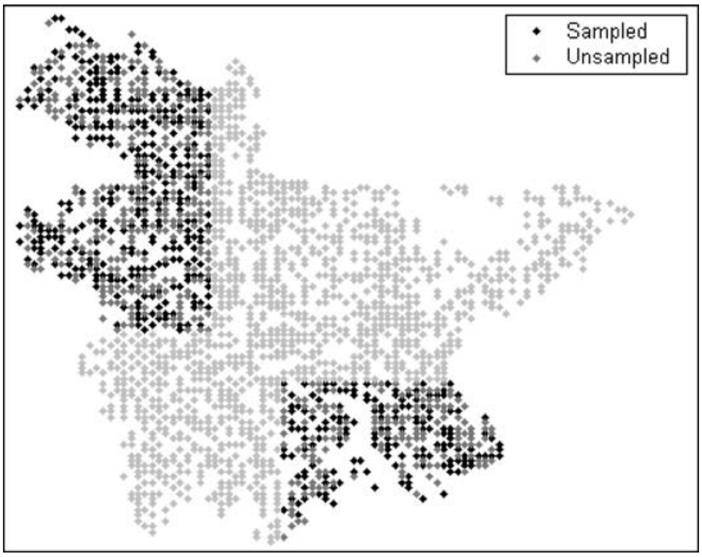


Fig. 3 An example of a randomly selected exploratory network for Northwest BD and Southcentral BD. The circles in black show the areal distribution of sampled wells, while the red stars indicate non-sampled well grids. Gray circles fall outside the study regions

respectively. Model parameters were estimated by the method of least squares. While there may exist considerable uncertainty associated with the variogram modeling for a sparsely sampled region (see for example, Marchant and Lark, 2005), we consider this uncertainty an unavoidable aspect for any remediation-cum-management exercise in a developing country due to cost concerns that limit the scale of any survey. Figure4 provides a flow-chart that summarizes the algorithmic operation of the MC framework involving kriging modules.

After each realization comprising: (1) random selection of wells for an equi-probable exploratory network; and (2) kriging, we assessed the effectiveness of the kriging method in terms of probability of successful detection of safe and unsafe wells along with the probabilities for false hopes (predicting an unsafe well grid as safe) and false alarms (predicting a safe well grid as unsafe) at the non-sampled well. The kriging method was cross validated only over those non-sampled wells that had measurements of arsenic concentration (not used in the variogram analysis). For a given management exercise, the kriged arsenic value for a non-sampled well may exhibit one of the four possible outcomes during assessment:

- Kriging predicts a non-sampled well to be safe when in reality its arsenic value is less than the safe limit (i.e., Successful Safe Well detection).
- Kriging predicts a non-sampled well to be safe when in reality its arsenic value is greater than the safe limit (i.e., False Hope).
- Kriging predicts a non-sampled well to be unsafe when in reality its arsenic value is less than the safe limit (i.e., False Alarm).
- Kriging predicts a non-sampled well to be unsafe when in reality its arsenic value is greater than the safe limit (i.e., Successful Unsafe Well detection).

The probabilities for successful detection of safe (outcome 1) and unsafe wells (outcome 4) and the probabilities for false hopes and false alarms (outcomes 2 and 3, respectively) can be quantified from the confusion matrix shown below:

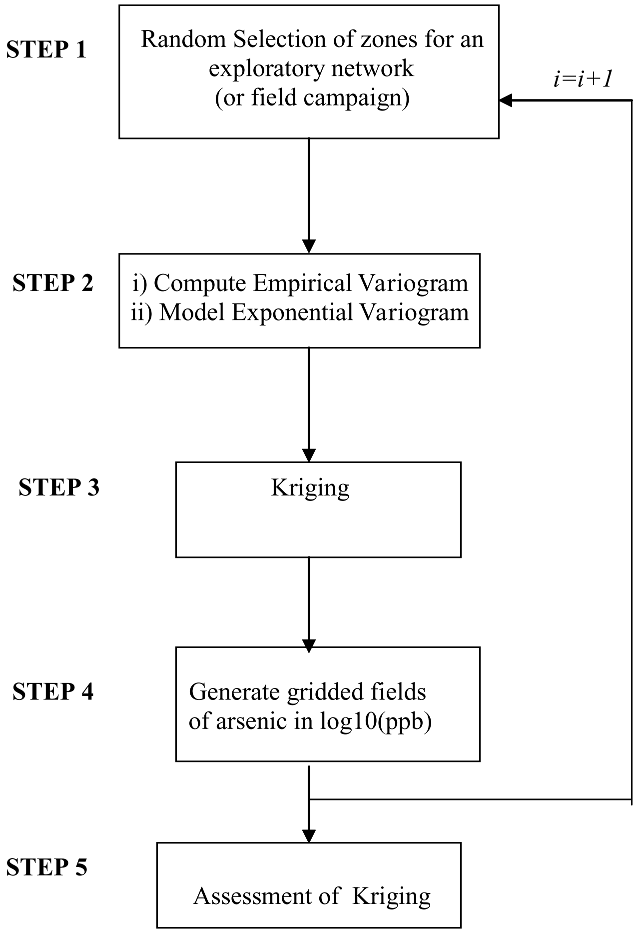


Fig. 4 Flow-chart summarizing the Monte Carlo (MC) framework used for assessment of ordinary kriging [i represents the index for a MC realization of a randomly-selected exploratory network, where $i = 1, 1000$]

Probability for Successful Safe Well Detection:

$$\frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} \frac{N_A}{N_A + N_B} \tag{5}$$

Probability for Successful Unsafe Well detection:

$$\frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} \frac{N_D}{N_C + N_D} \tag{6}$$

		Truth (from BGS-DPHE (2001))	
		Safe	*Unsafe*
Kriging Prediction	*Safe*	N_A	N_B
	Unsafe	N_C	N_D

Probability of False Hope:

$$\frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} \frac{N_B}{N_A + N_B} \tag{7}$$

Probability of False Alarm:

$$\frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} \frac{N_C}{N_C + N_D} \tag{8}$$

where, N_{MC} is the total number of MC realizations (= 1000).

5. Results and discussion

Figure 5a andb show an outcome of a kriging exercise from a typical randomly selected exploratory network of wells conducted for Northwest BD and Southcentral BD, respectively. The left panel denotes the wells (i.e., grids for pictorial representation) that were sampled (shown in red) during a hypothetical field campaign while the corresponding arsenic field that was derived from kriging is shown in the right panel. The corresponding semi-variograms associated with each kriging exercise are shown inFigure 6a and c. These arsenic predictions were validated over the non-sampled grids (shown in white in the left panels). Figure 7a andb show the (kriging) predicted minimized standard deviation of error of the kriged map (right panel) and the actual error, for Northwest BD and Southcentral BD, respectively. Herein, actual error is defined as the absolute value of the difference between kriging prediction and reference arsenic values. Reasonable qualitative consistency is observed between the error (minimum variance) map predicted by kriging and the actual error map for Northwest BD and Southcentral BD. Kriging in general appears to underestimate arsenic concentrations at non-sampled locations. −8.6 ppb for Northwest BD and −52.6 ppb for Southcentral BD. Thus underestimation is found to be more severe for Southcentral BD exceeding the Bangladesh safe limit of 50 ppb (see Table 1 a and b, last column).

Table 1 a and b show a summary of the effectiveness of kriging in terms of successful detection of safe/unsafe wells. Due to predominantly low arsenic concentrations in Pleistocene Northwest BD, the false alarm and successful detection of unsafe wells were found to be negligible. We thus show the probability of safe well detection (Equation 5) and the probability of false hope (Equation 7) for the Northwest BD (Table 1a). On the average itis

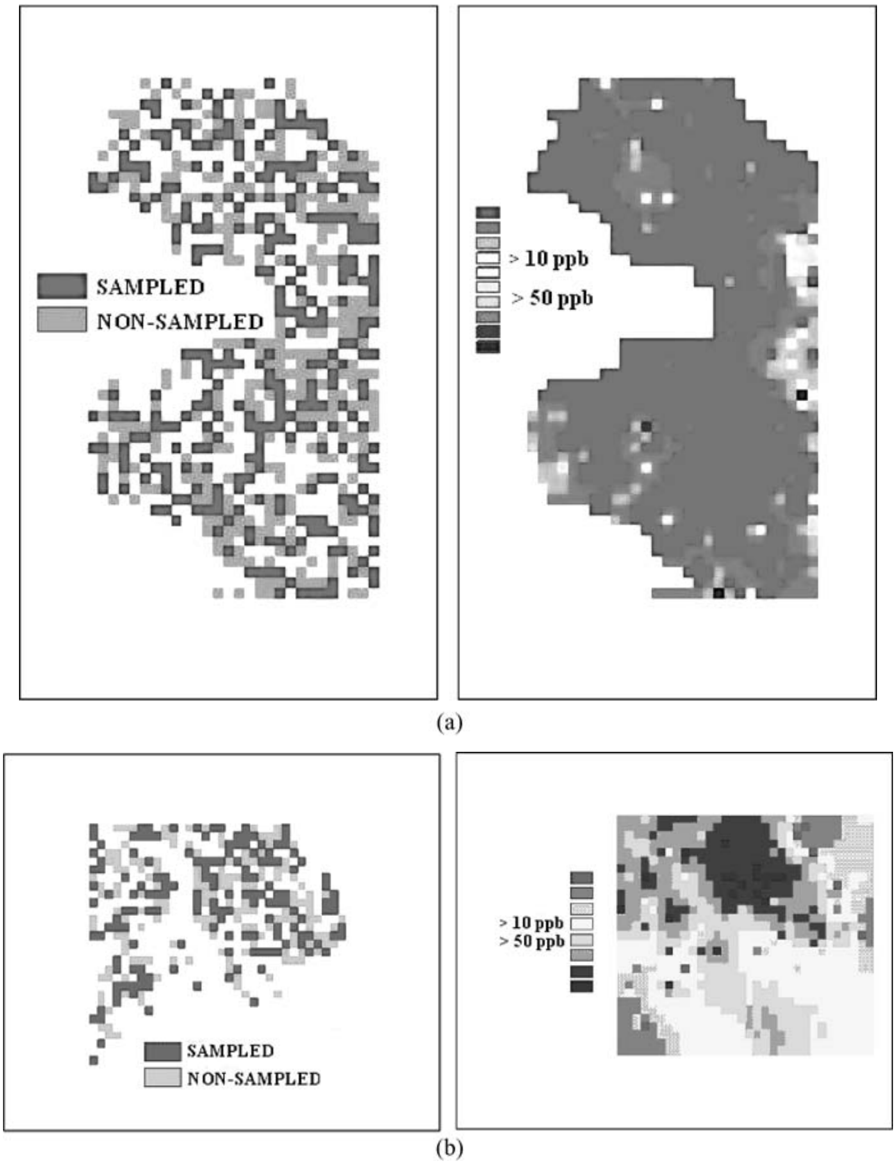
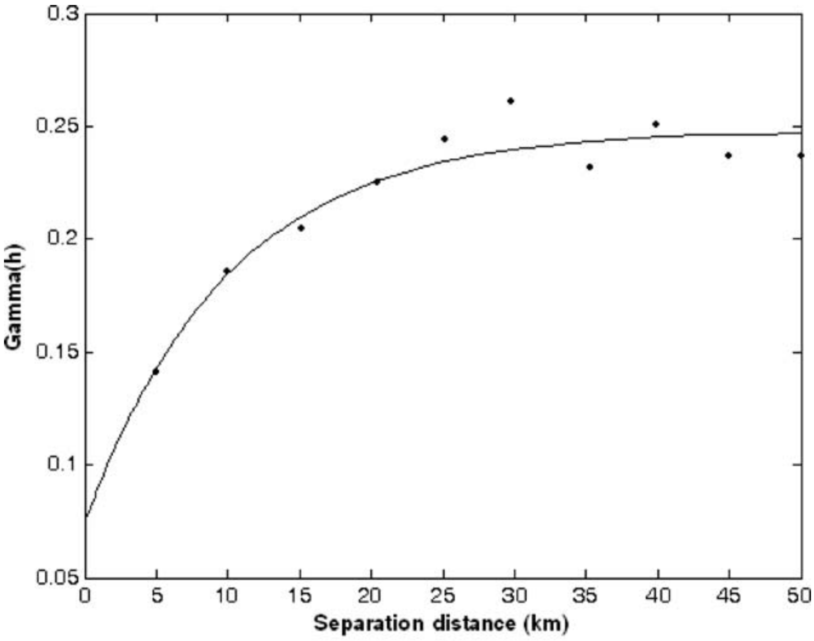
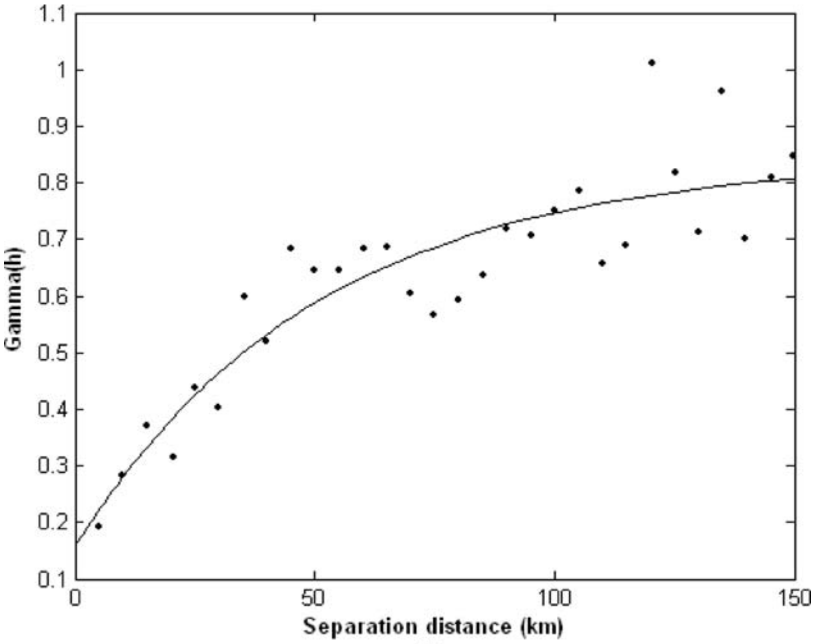


Fig. 5 (a) An example of spatial interpolation of arsenic concentrations by kriging for a large scale field campaign conducted over Northwest BD. *Left panel*: red pixels indicate the randomly selected zones comprising one given realization of an exploratory network; grey pixels are the non-sampled zones over which kriging effectiveness was evaluated. *Right panel*: the kriged arsenic concentration field. Yellow and cyan zones are predicted as being unsafe according to WHO and Bangladesh safe limits of 10 ppb and 50 ppb, respectively. (b) Same as (a): for Southcentral BD



(a)



(b)

Fig. 6 (a) Semi-variogram (empirical in circles; and modeled in solid line) produced from random sampling over the Northwest BD during the hypothetical field campaign of Figure 5a. The Gamma (h) herein refers to the semi-variance of the log (base *e*) arsenic concentrations of the sampled zones at separation distance of h km (x-axis). (b) Same as (a): For Southcentral BD

Table 1 Assessment of ordinary kriging for detection of safe and unsafe wells according to the WHO and Bangladesh safe limits

Safety limit	Confusion matrix numbers (1000 MC realizations)				Probability of false hope (%)	Probability of successful safe zone detection (%)	Probalility of false alarms (%)	Probability of successful unsafe well detection (%)	Mean error (ppb)
	N_A	N_B	N_C	N_D					
(a) for Northwest BD									
10 ppb									
Mean	279	30	2	2	9.8	90.2			
Min	260	17	0	0	6.2	93.8			−8.6
Max	291	44	15	9	15.4	84.6			
50 ppb									
Mean	304	10	0	0	3.0	97.0			
Min	296	3	0	0	1.0	99.0			−8.6
Max	310	18	2	1	5.5	94.5			
(b) for Southcentral BD									
10 ppb									
Mean	13	4	12	126	23.2	76.8	8.7	91.3	
Min	4	0	3	115	0	100.0	17.2	82.8	−52.6
Max	22	18	25	138	64.3	35.7	2.3	97.7	
50 ppb									
Mean	35	14	14	94	27.8	72.2	12.7	87.3	
Min	23	1	4	74	2.6	97.4	18.1	77.9	−52.6
Max	47	28	25	108	39.8	60.2	3.9	96.10	

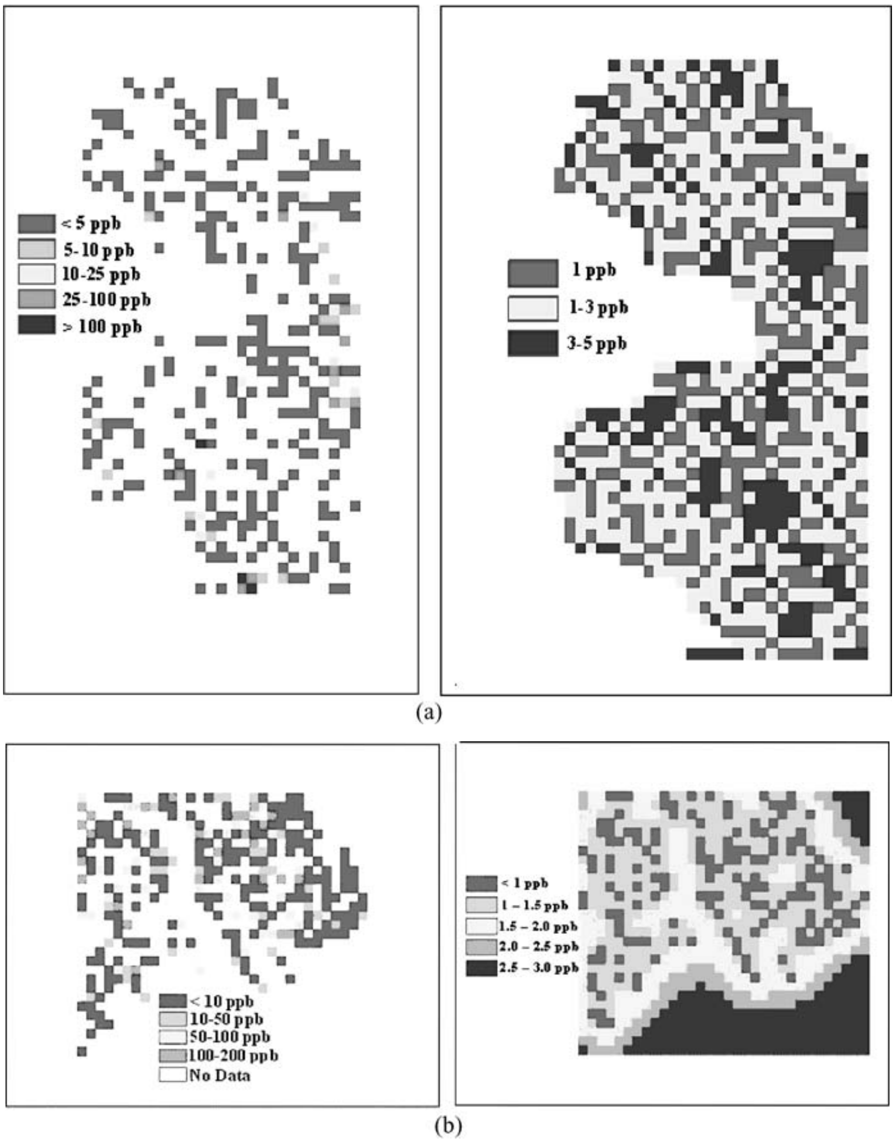


Fig. 7 (a) Error map for the given field campaign of Figure 5a (Northwest BD). Left panel- actual error map over non-sampled zones. *Right panel*: the map of standard deviation of estimation error produced during error variance minimization. (b) Same as (a): For Southcentral BD

observed that kriging can be accurate 90% of the time in successfully detecting (or predicting) a safe well at non-sampled locations according to the WHO limit of 10 ppb. The probability of false hope was found to be around 10%. For the Bangladesh safe limit of 50 ppb, we observe these probabilities to increase and decrease to 97% and 3%, respectively (Table 1a). Geologic dependency of the kriging effectiveness is manifested through the observed differences in probabilities of false hope and safe well detection between Northwest BD and Southcentral BD. The probability of safe well detection in the Holocene Southcentral

Bangladesh is found to be 72.2–76.8% (20% lower than Northwest BD). The probability of successful detection of unsafe wells is found to be higher ranging from 87.3–91.3%. This observed difference between Pleistocene and Holocene regions can be explained from the fact that the average arsenic concentration is considerably lower for the Northwest than the Southcentral Bangladesh.

An aspect that emerges from our analyses is that the effectiveness of kriging for regional management in terms of probabilities for prediction of safe wells and false hopes is strongly dependent on the dominant geologic regime that dictates arsenic variability in Bangladesh (Pleistocene vs. Holocene). In general, Northwest BD has relatively few unsafe wells ($\sim$10%) according to the WHO limit while none according to the Bangladesh safe limit. This explains the very small sample numbers observed for N_C and N_D in the confusion matrix for deriving the probabilities of successful detection of unsafe well (Equation 6) and false alarms (Equation 8). On the other hand, the probability of successful detection of safe wells decreases on the average by about 20% for the Holocene Southcentral region. The probability for unsafe well detection is noticeably high for the Holocene region. From the planning and management perspective, this translates to an approximate rule of thumb that a kriging based management approach is likely to be 20% less effective in detecting safe wells for the Southcentral region than the Northwest on the basis of a sparsely sampled field campaign. This therefore demands an equivalent 20% greater resources for management in Holocene aquifers in the Southcentral BD than the Northwest BD.

6. Conclusions

The effectiveness of a geostatistical approach (such as ordinary kriging) for making preliminary decisions on management of arsenic contaminated ground water in Bangladesh has been studied. In general, the kriging method was found to underestimate the arsenic concentration at non-sampled locations. This underestimation was more for the Holocene region of Southcentral Bangladesh which yielded a 72% and 78% probability of successful prediction of safe wells according to the WHO and Bangladesh safe limits, respectively. For the Pleistocene Northwest Bangladesh, the safe well prediction probability was found to be considerably higher and in the ranges of 90–97%. The relatively more contaminated Holocene region in Southcentral Bangladesh, on other hand, was found more amenable to accurate geostatistical prediction of unsafe wells.

Although our assessment of the kriging method has shed some tangible light on its utility under a resource-limited scenario (such as in Bangladesh), it is only fair herein to discuss the potential limitations of our approach for the benefit of the readers. Awareness of these limitations can potentially render a more critical yet useful assessment of the kriging method as a natural extension to our work. We articulate these limitations as follows:

1. *On log-transformation of data:* Log-transformation of data is justified for skewed data when the transformation yields a symmetric Gaussian distribution. Because kriging represents variability only upto the second order moment (covariance), the random field of the transformed contaminant variable must therefore be Gaussian to derived unbiased estimates at non-sampled locations. While we have shown strong possibility of honoring the skewed and Gaussian requirement, our assessment has only been qualitative. A more rigorous analysis involving normal score transform (Goovaerts *et al.*, 2005; Deutsch and Journel, 1998), translated log transformation, and assessing its implications on inducing any transformation-related bias to the kriging analyses may be necessary. Furthermore, a

log-transformation prior to kriging may necessitate a multiplicative correction based on Gaussian theory when reporting the kriged results as arsenic concentrations (Chiles and Delfiner, 1999).

2. *On classification of wells by kriging:* Kriging is based on a minimization technique that tends to smooth out results with respect to the data and to the fitted variogram. Hence, when such a linear kernel is assessed in terms of its ability to correctly classify a well as safe or unsafe based on a threshold, caution needs to be applied on the interpretation of kriging-based classification of wells when the sill variance is slow (as is the case for Northwest BD). With a 0.25 sill value (Figure 6a), the variance of the estimation error for Northwest BD is naturally low, resulting in minimal misclassification of wells from kriging. The converse is true for the Southcentral BD (Figure 6b).

A natural extension of our work would also be the investigation of geostatistical simulation methods (e.g., Smith and Freeze, 1979; Bagtzoglou and Ababou, 1997 among many others) for detailed assessment of management of arsenic contamination. Although the kriging methodology has been applied and assessed to a test case in Bangladesh, the specific approach formulated herein is general and is expected to have application in rural settings for other developing countries where arsenic contamination of ground water is widespread. For example, the health risk posed by dissolved arsenic in ground water has been reported in West Bengal (Mazumder *et al*., 1998), Taiwan (Tseng *et al*., 1968), Vietnam (Berg *et al*., 2001) and Mexico (Del Razo *et al*., 1990). These countries could conveniently assess the utility of a simple geostatistical technique such as ordinary kriging in a fashion similar to what was reported herein for deriving preliminary yet cost-effective management strategies of their ground water resources until a long-term structural solution in implemented.

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