Environmental Forensics, 9:1–11, 2008

ISSN: 1527–5922 print / 1527–5930 online
DOI: 10.1080/15275920801888400

Contributed Articles

A Forensic Look at Groundwater Arsenic Contamination in Bangladesh

Sayma Rahman[1] and Faisal Hossain[2]

[1]*Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA*
[2]*Faisal Hossain, Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, TN, USA*

A comprehensive forensic analysis of AS contamination in Bangladesh was undertaken using geographic information system (GIS), univariate, and bivariate statistics. The assessment provided the background needed for fine-tuning emerging/evolving methods of spatial mapping based on nonlinear deterministic dynamics and multivariate factorial analyses. Data were derived from a nation-wide AS survey completed in 1999 by the British Geological Survey (BGS) in collaboration with the Department of Public Health Engineering (DPHE) of Bangladesh. It was found that the standard deviation of arsenic concentration is highest along the river flood plains of the major rivers. The distribution of arsenic concentration was found to be symmetric in regions of very high mean concentration, while the regions of low and moderate contamination reveal a highly skewed distribution, suggesting the need for data transformation at these points prior to spatial interpolation. The mean value of Ca and Mg concentrations showed a strong spatial similarity in the southwest region of Bangladesh. This spatial similarity was also reflected in terms of skewness of the data. It was inferred that the mapping of AS concentrations at nonsampled locations on the basis of multivariate factorial or regression models may not require the dual presence of both Ca and Mg parameters; hence, one of them is redundant. Both the skewness and kurtosis of the distribution of Si concentration appeared very similar and highly heterogeneous in space suggesting that Si data requires careful transformation prior to modeling only in the smaller scale but not for country-wide/regional purposes. The age of wells was found to be nonlinearly correlated in the southeast region. The correlation of AS with Fe appeared strongest in the southwest region indicating that the oxidation–reduction hypothesis may be more appropriate as a release mechanism in the southwest region. In another regard, the sulphate concentration was found to be more correlated to AS in the northwest Pleistocene region of Bangladesh, suggesting that the pyrite oxidation hypothesis may be appropriate. Overall, our forensic analysis using GIS revealed useful findings for data transformation and selection of parameters towards spatial mapping based on multivariate factorial and nonlinear deterministic models in the resource-poor settings of developing countries.

Keywords: arsenic, Bangladesh, groundwater, forensics, GIS, univariate and bi-variate statistics, spatial mapping

Introduction

The large-scale AS contamination in the groundwater aquifers of Bangladesh needs no renewed introduction. Since its discovery in 1993, numerous studies have steadily improved our understanding of the contamination scenario in the following areas: 1) the spatial extent, mapping, and management (Biswas et al., 1998; Burgess et al., 2000; Mukherjee and Bhattacharya, 2002; Q1 Hossain and Sivakumar, 2006; Hossain et al., 2006; in press); 2) probable mechanisms of contamination (Harvey et al., 2002; van Q2 Geen et al., 2003a, 2003b; McArthur et al., 2001, 2004; Nickson et al., 1998); 3) effect on public health (Yu et al., 2003), and 4) Q3 the socioeconomic effect (Nahar et al., in press). It is now estimated that at least 50% of the country's population is affected by this large-scale contamination with the most vulnerable victims being the villagers (Ahmed, 2003).

When it comes to spatial mapping for cost-effective management, and probable mechanisms of contamination, a significant amount of uncertainty or lack of consensus among scientific researchers continues to exist in current literature. For example, it has been reported that the widespread application of geostatistical techniques such as kriging for the spatial mapping of AS contamination results in an interpolated 'field' subject to greater uncertainty at nonsampled locations due to measurement and sampling errors of in situ tests (Hossain et al., 2006; in press). In a recent assessment of ordinary kriging, Hossain et al. (in press) reported that the probability of successful prediction of safe wells is 72% (for WHO safe limit—10 ppb) and 78% (for Bangladesh safe limit—50 ppb). Their findings from this study exemplified that, while mainstream geostatistical approaches (e.g., ordinary kriging) may not provide the most accurate prediction of mean

Received July 24, 2006; accepted March 17, 2007.
Address correspondence to Faisal Hossain, Assistant Professor, Department of Civil and Environmental Engineering, Tennessee Technological University, 1020 Stadium Drive, Box 5015, Cookeville, TN 38505-0001, USA. E-mail: fhossain@tntech.edu

AS concentration at non-sampled locations, they can identify an approximate strategy for management of AS contaminated shallow groundwater if applied carefully.

Similarly, the actual causes of high AS concentration in the groundwater of Bangladesh have not yet been clearly pinpointed. Among the few hypotheses initially proposed to explain the possible mechanism of AS release, the scientific community appears to have converged on two major hypotheses: 1) *pyrite oxidation hypothesis* (Kinniburg and Smedley, 2001)—oxidation of AS mineral 'arsenopyrite' (FeAsS) or AS-rich 'pyrite' resulting in release of AS in groundwater, and 2) *oxy-hydroxide reduction hypothesis* (Nickson et al., 1998)—reduction of AS-rich Fe-Q4 oxihydroxides leaching the AS that remains at adsorbed state on its surface. In a recent e-mail survey conducted among experts to identify the prevailing views on the possible mechanism of AS release, 58% of the respondents supported the oxyhydroxide reduction hypothesis, 33% supported the pyrite oxidation hypothesis, and 75% of the respondents believed that overextraction of groundwater had some relationship with the contamination of AS in groundwater in Bangladesh (Akmam, 2002).

Given the prevailing uncertainty that currently exists on the probable causes of contamination and the limitations of mainstream geostatistical methods for spatial mapping and management, the recent collective works of Hossain et al. (2006; in press), Hossain and Sivakumar (2006) and Hill et al. (in press) have argued for the adoption of more enhanced and value-added techniques to derive cost-effective strategies for management of the contaminated groundwater resources. For example, Hossain and Sivakumar (2006) have argued that the geostatistical treatment of AS contamination in space as a regionalized (stochastic) random variable constitutes an incomplete analysis of its spatial variability. Because Bangladesh is essentially a riverine (dendritic) country with numerous 'small' floodplains (see Figure 1 for the network of major rivers), and further because the geology shows presence of pockets of Holocene-like and Pleistocene-like deposits scattered throughout the country, there is adequate reason to anticipate chaotic (nonlinear deterministic dynamic) behavior in the spatial pattern of AS contamination. Their study indicated correlation dimension (CD) values (Grassberger and Procaccia, 1983) ranging anywhere from 8 to 11 depending on the region, suggesting that the AS contamination in space, from the chaotic point of view, is a medium- to high-dimensional problem. In a follow-up study, Hill et al. (in press) demonstrated, using logistic regression, possible physical connections between the nonlinear deterministic CD value and the mathematical modeling of risk of AS contamination in groundwater. They reported that the uncertainty associated with prediction of wells as safe and unsafe by logistic regression model declines systematically as the total number of influencing variables increases from 7 to 11, suggesting that CD can act as a rapid proxy to improve spatial mapping of contamination under a resource-limited scenario.

In this study we have therefore attempted to undertake comprehensive forensic analysis of AS contamination in Bangladesh using Geographic Information System (GIS), univariate and bivariate statistics. Although our assessment is entirely data-based and mostly qualitative, we believe that such type of analyses—which has not been reported yet in literature to the best of our knowledge—can develop the knowledge base necessary for cost-effective techniques on spatial mapping. For example, the use of correlation dimension analyses in deterministic modeling requires improved understanding of geochemical parameters that co-exist with AS contamination. Hence, prior knowledge of the spatial variation of correlation coefficient would be beneficial. Similarly, the use of enhanced (i.e., value-added and more complex) geostatistical techniques such as factorial kriging (Goovaerts, 1997) requires knowledge of cross-correlation among geochemical parameters responsible for AS contamination (Lin et al., 2006).

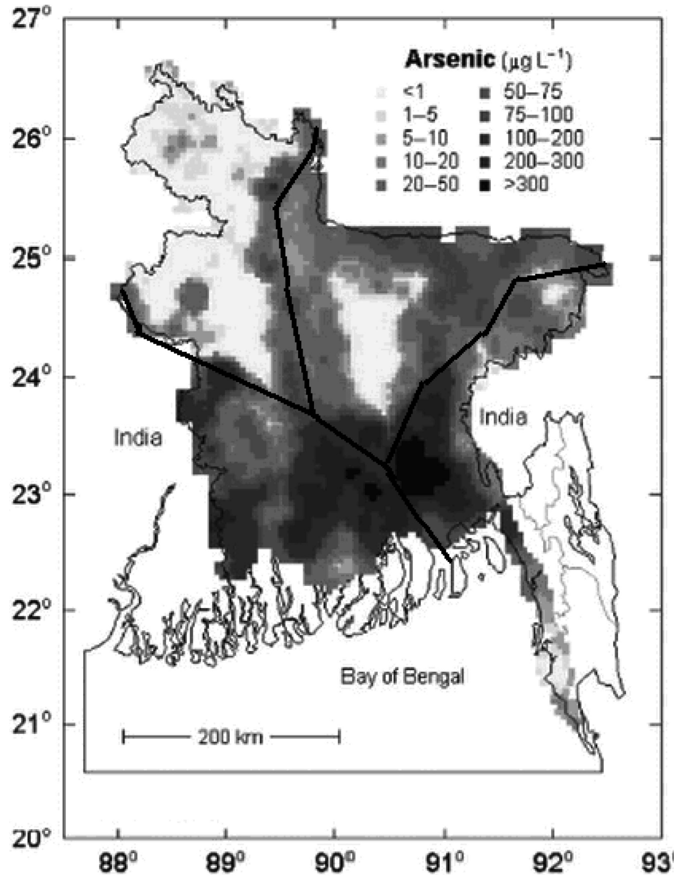

Figure 1. Study region showing the mean AS concentrations based on the British Geological Survey–Department of Public Health Engineering (BGS-DPHE, 2001) data. The solid dark line represents the approximate longitudinal axis of majors rivers and flood plains in Bangladesh.

It is important to highlight at this stage that, prior to the advent of easy-to-use GIS tools, such an analysis over a broad region (a country) would have been almost difficult, if not impossible, to carry out to gain the 'big picture' snap shot on the preliminary forensic status of contamination. To the best of our knowledge, such a GIS-based assessment that aims to search for 'connections' among contamination variables from a data-based yet 'forensic' perspective is absent in literature as far the AS contamination of groundwater in Bangladesh is concerned.

Q5 While the study presents only a baseline (i.e., "a ball-park") on the forensic nature without a clear revelation on the physics of the AS contamination, the findings from such an assessment along with the limitations that may be revealed, can only justify further the need for more detailed physically based studies involving GIS, forensic tools and contamination theory to advance spatial mapping tools for developing countries.

The objectives of our study are therefore as follows:

1. To compare the univariate statistical behavior of pertinent geochemical parameters with AS concentrations and thereby establish qualitative connections on the type of data transformations needed prior to spatial mapping.
2. To qualitatively analyze the bivariate statistical behavior of pertinent geochemical parameters with AS and thereby establish connections on the choice of variables for multivariate modeling (such as logistic regression or factorial kriging etc.).

We expect our findings to provide the background needed for fine-tuning the emerging/evolving methods of spatial mapping based on nonlinear deterministic dynamics, multivariate factorial analyses. This article is organized as follows. In the following section, we describe the data used for the study, followed by a description of the tools and methods. In the results and discussion section, we present our forensic findings on univariate and bivariate analyses and discuss their implications. Finally, in the conclusion we present the major findings of our study and the suggested extensions of our work.

Study Region, Data, and Methods

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. Our dataset on AS concentration of groundwater was derived from the BGS-DPHE (2001) study comprising 3,534 wells (Figure 1). The dataset was available at: http://www.bgs.ac.uk/arsenic/Bangladesh.html
Q6 (accessed). In the overall scheme of our investigation, the BGS-DPHE (2001) survey currently represents the most quality-controlled database of AS measurements available for any kind of country-wide forensic and GIS analyses. AS measurements of BGS-DPHE 2001 survey were based on the atomic absorption spectrophotometric method, which is currently considered a reliable method used for AS testing (Rahman et al., 2002; Hossain et al., 2006; Goovaerts et al., 2006). In another regard, even though the Bangladesh Arsenic Mitigation Water Supply
Q7 Project (available at: www.bamwsp.org (accessed) is host to an extensive archive on the status of approximately two to three million wells, this larger dataset is not amenable to forensic analyses due to the following two reasons: 1) use of semiquantitative field kits with very large measurement errors (Hossain et al., 2006); and 2) lack of geospatial information on individual wells that were sampled (Project Director of National Arsenic Mitigation Council – NAMIC, Bangladesh, personal communication,).

We assumed the in situ (field measured) data on AS concentration and pertinent geochemical and hydrologic variables to be Q8 reasonably stationary at the time scales of intermediate management efforts (i.e., 5–6 years) for which the improved schemes on spatial mapping are intended in developing countries. This is an acceptable assumption until a more structural solution is devised for the AS problem in Bangladesh. While the incorporation of a dynamic contaminant transport model would undoubtedly be relevant for our investigation (Davis et al., 2004), there are several limitations to spatial mapping of the dynamic AS field that the current state-of-the-art on AS data measurement protocols and scientific know-how can not address. These are: 1) mechanism of AS release in the groundwater for the shallow aquifers of Bangladesh is not well understood and actively debated by the greater scientific community (see for example, Harvey et al., 2002; van Geen et al., 2003; McArthur et al., 2004); Q9 2) groundwater flushing rates are insignificant in Bangladesh given its flat terrain (in the timescales of millennia; refer to the report by BGS-DPHE, 2001); 3) there are no country-wide well-monitoring programs that record the temporal fluctuations of AS concentration in groundwater. In fact, to the best of our knowledge, a second measurement of AS concentration at a cluster of wells on a regional basis has not been performed due to the prohibitive costs involved. We further justify our assumption of stationarity based on Goovaerts et al. (2005) who reported an absence of a trend or seasonality for naturally occurring AS concentration in southeast Michigan over a period of 10 years. Davis et al. (2004) has also argued against fitting standard contaminant process models without a scientific basis in the absence of mechanistic understanding of field scale variability of AS could be dangerous.

Table 1 shows the potential list of 'culprit' parameters that Q10 were analyzed in this study. These variables were co-sampled by BGS-DPHE (2001) along with AS concentration in well water. The minimum (i.e., basically detection limits) and maximum values of these variables (Table 1) indicate the range of variability across Bangladesh. The parameters chosen were (in mg/L): 1) Fe; 2) Mg; 3) Ca; 4) SO4; 5) Si; 6) Na; and 7) Zn. Additional parameters of 'age' (in years) and depth (in meters) of wells were also selected (not shown in Table 1). Our choice of variables is primarily dictated by literature reports on the causes of

Table 1. *The geochemical parameters for forensic analysis. (Note: 'Depth' and 'age' are not shown herein as they are not geochemical parameters)*

Variable	Mean	Minimum (∼ Detection Limit)	Maximum
Ca (mg/L)	51.590	0.100	366.000
Fe (mg/L)	3.353	0.005	61.000
Mg (mg/L)	20.750	0.040	305.000
Na (mg/L)	88.936	0.700	2700.000
Si (mg/L)	20.519	0.030	45.200
SO_4 (mg/L)	5.917	0.200	753.000
As (ppb)	55.205	0.500	1660.000

4C/Art

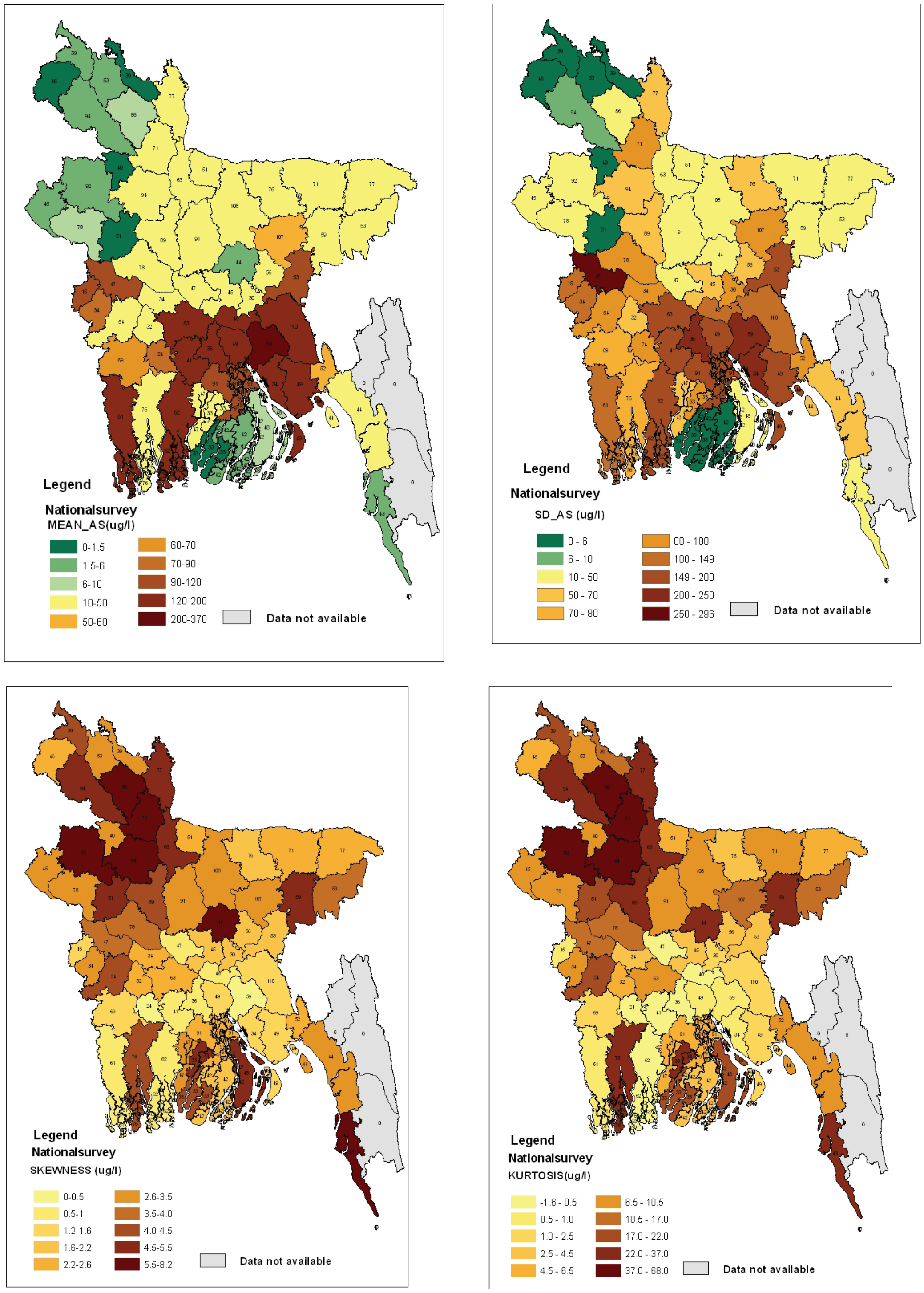

Figure 2. Univariate statistical behavior of AS concentration in terms of four central moments: 1) mean (top left), 2) standard deviation (top right), 3) skewness (bottom left), and 4) kurtosis (lower right). SD, standard deviation.

AS mobility (e.g., Welch et al., 2000; Harvey et al., 2002; van
Q11 Geen et al., 2003a; McArthur et al., 2004; Zheng et al., 2004), the availability of accurate data and the suitability for spatial mapping (see Lin et al., 2006).

For GIS analysis we used the software ArcGISTM (Ormsby et al., 2004) that has built-in capability to produce univariate and bivariate statistics of geo-located data and graphical presentation. For univariate statistics, we analyzed the data for: 1) Q12
mean; 2) standard deviation; 3) skewness, and 4) kurtosis (i.e., excess kurtosis). For bi-variate statistics we basically derived correlation measures for 1) Pearson's measure, and 2) Spearman's rank correlation. We were particularly interested in rank

4C/Art

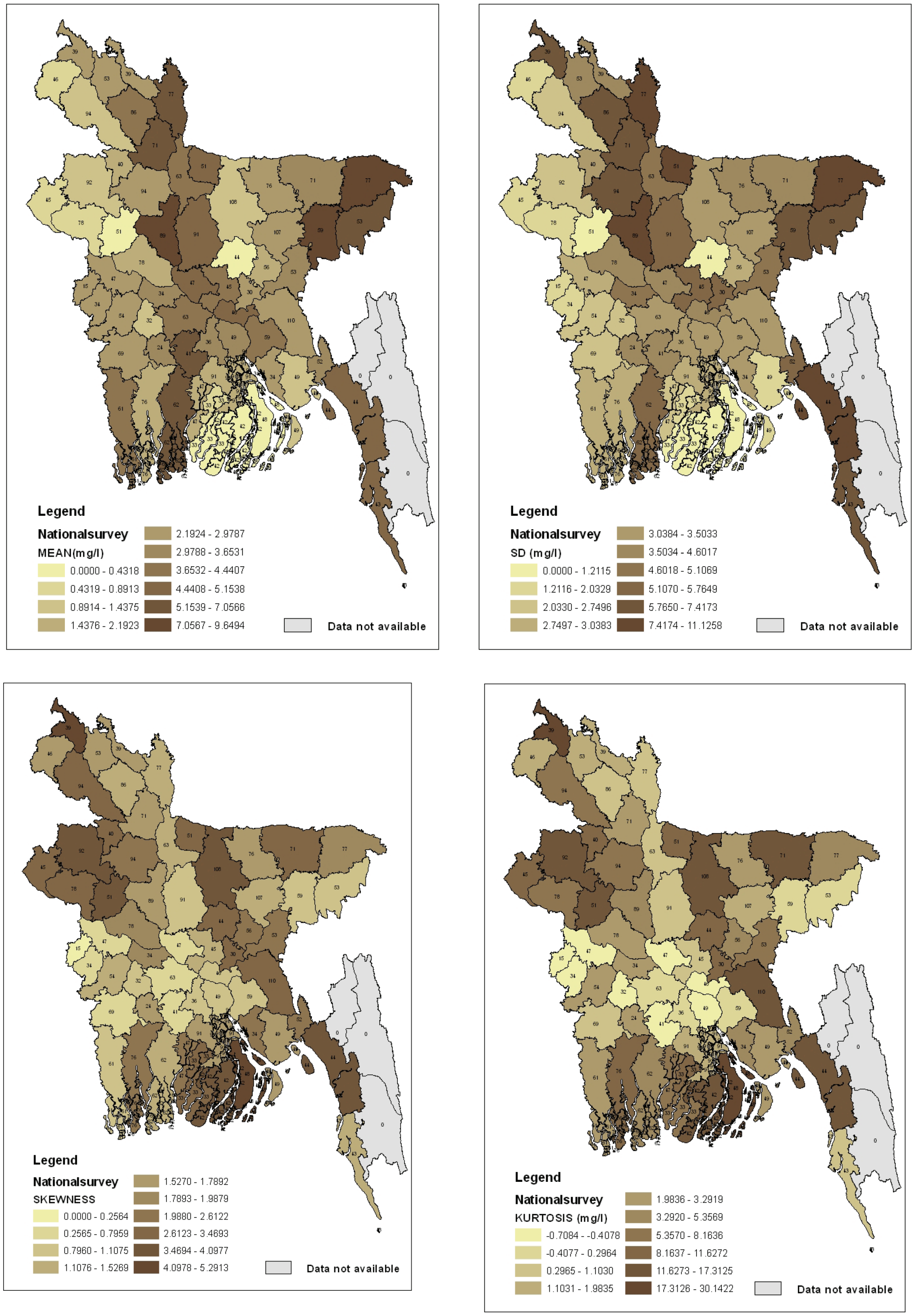

Figure 3. Univariate statistical behavior of Fe concentration in terms of four central moments: 1) mean (top left), 2) standard deviation (top right), 3) skewness (bottom left), and 4) kurtosis (bottom right).

correlation because of its ability to identify nonlinear covariation that is not usually detectable by the Pearson's measure. Unfortunately, ArcGISTM does not automatically yield the level of significance of the statistical analyses; hence they could not be reported in the herein study. However, such levels of confidence are important and should be reported in future work. Because the statistical measures we quantified are commonly used and available in any standard textbook on statistics, their theoretical definition is avoided herein. The statistical analyses were conducted for each district using all the individual well data within

4C/Art

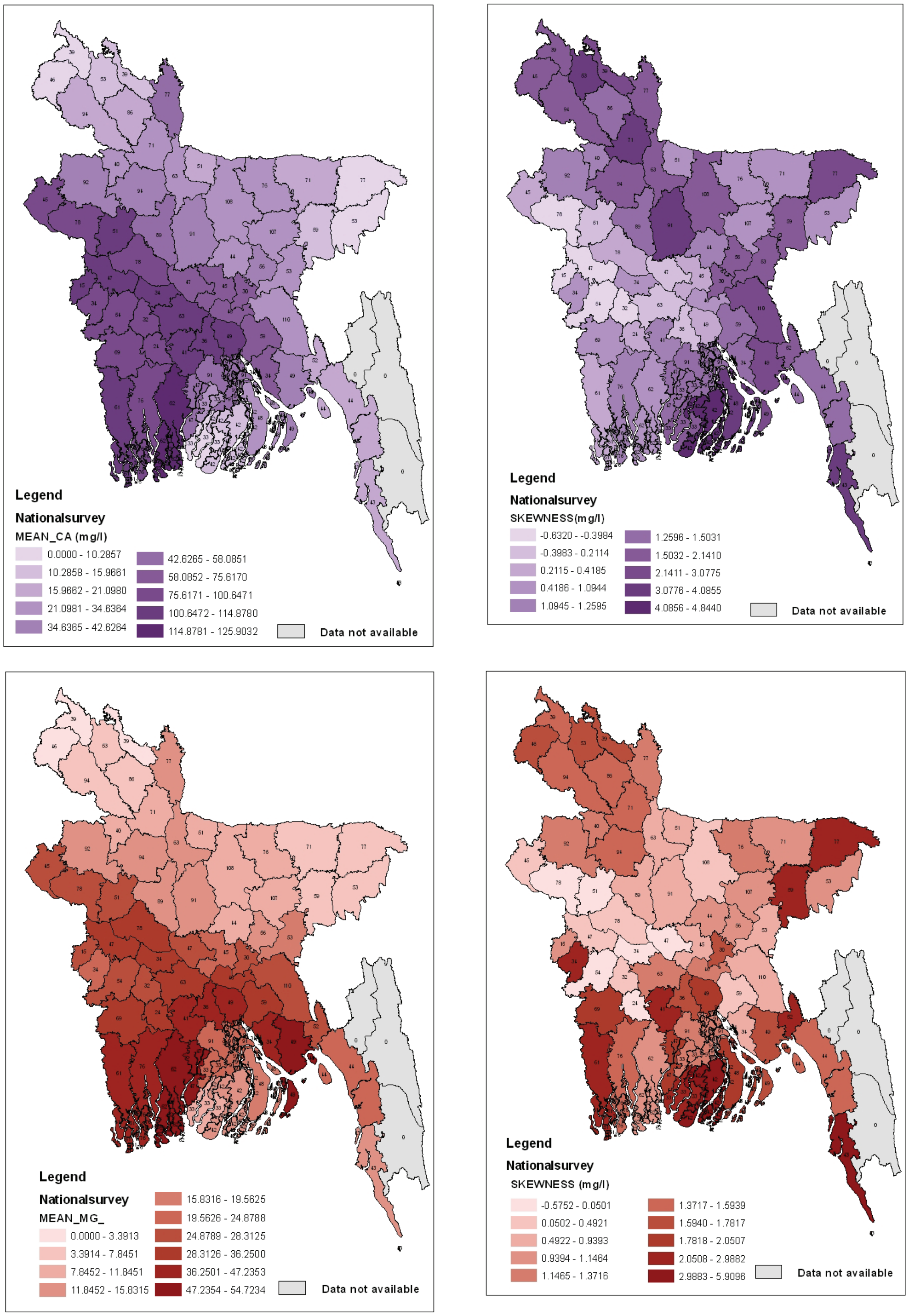

Figure 4. Univariate statistical behavior of Ca (top panels) and Mg (bottom panels) in terms of: 1) mean (left panels), and 2) skewness (right panels).

that administrative unit. For example, the computation of the mean or the standard deviation yielded one singular value reported for each district based on an average of approximately 40–100 data points. The sensitivity of these statistical analyses to sample size, while no doubt important, could not be evaluated due to the inherent paucity of data.

Results and Discussion

Univariate Analyses

As part of univariate analyses, we first show the statistical behavior of AS concentration in space in terms of the four moments: mean, standard deviation, skewness, and kurtosis (Figure 2).

4C/Art

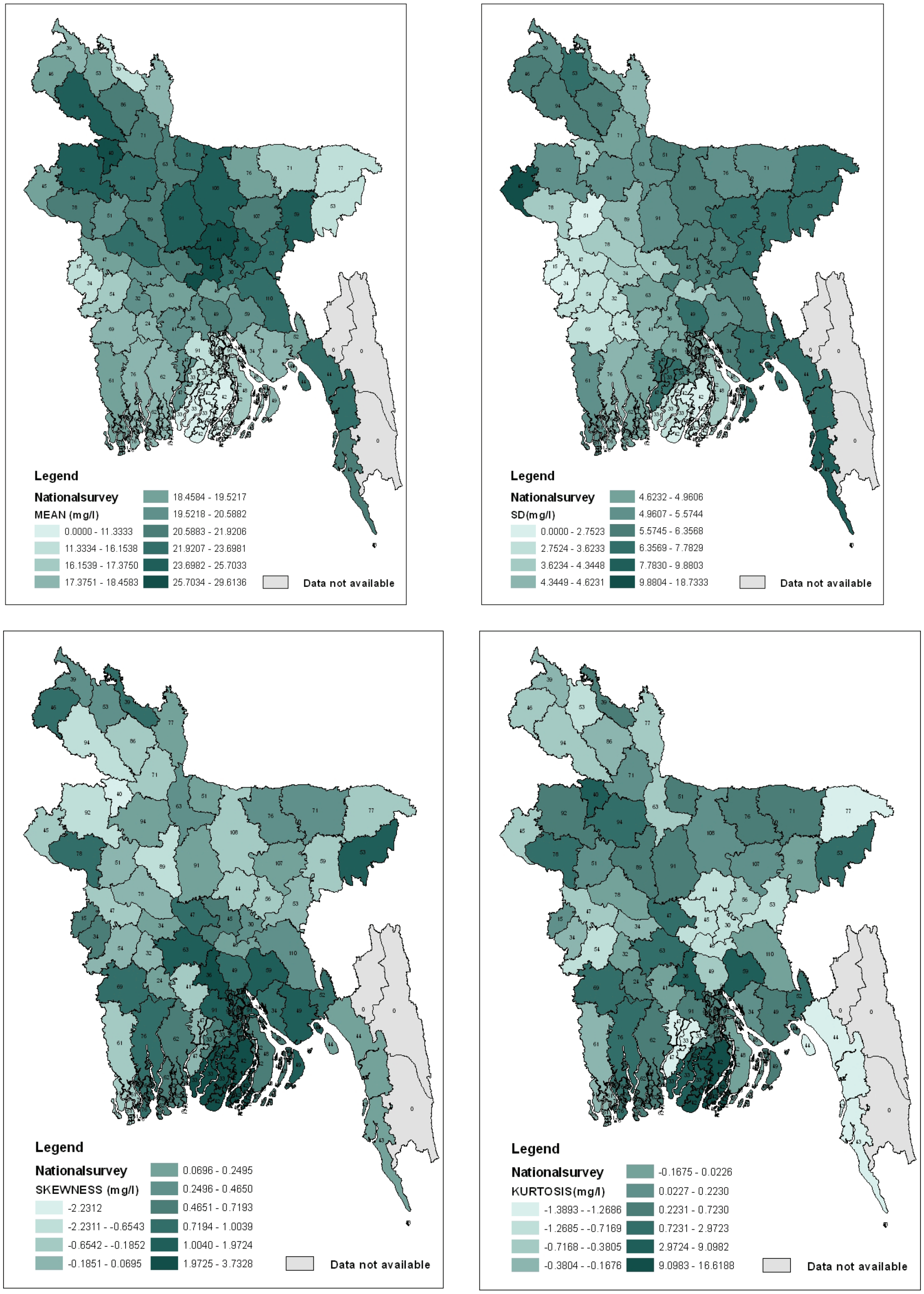

Figure 5. Univariate statistical behavior of Si in terms of: 1) mean (top left), 2) standard deviation (top right), 3) skewness (bottom left), and 4) kurtosis (bottom right).

The mean AS concentration (Figure 2, top left panel) indicates the already-known phenomenon that AS contamination is geologically dependent, with the highest and lowest concentrations abounding in the Holocene southcentral and Pleistocene Northwest regions, respectively. However, a look at the standard deviation reveals that slightly more refined picture where the variability is highest along the river flood plains of the Brahmaputra and Ganges rivers (Figure 2, top right panel). Although the skewness and kurtosis maps appear qualitatively similar, we observe that the distribution of AS concentration is symmetric usually in regions of very high mean concentration (Figure 2, compare bottom left panel with top right panel), while the regions of low

4C/Art

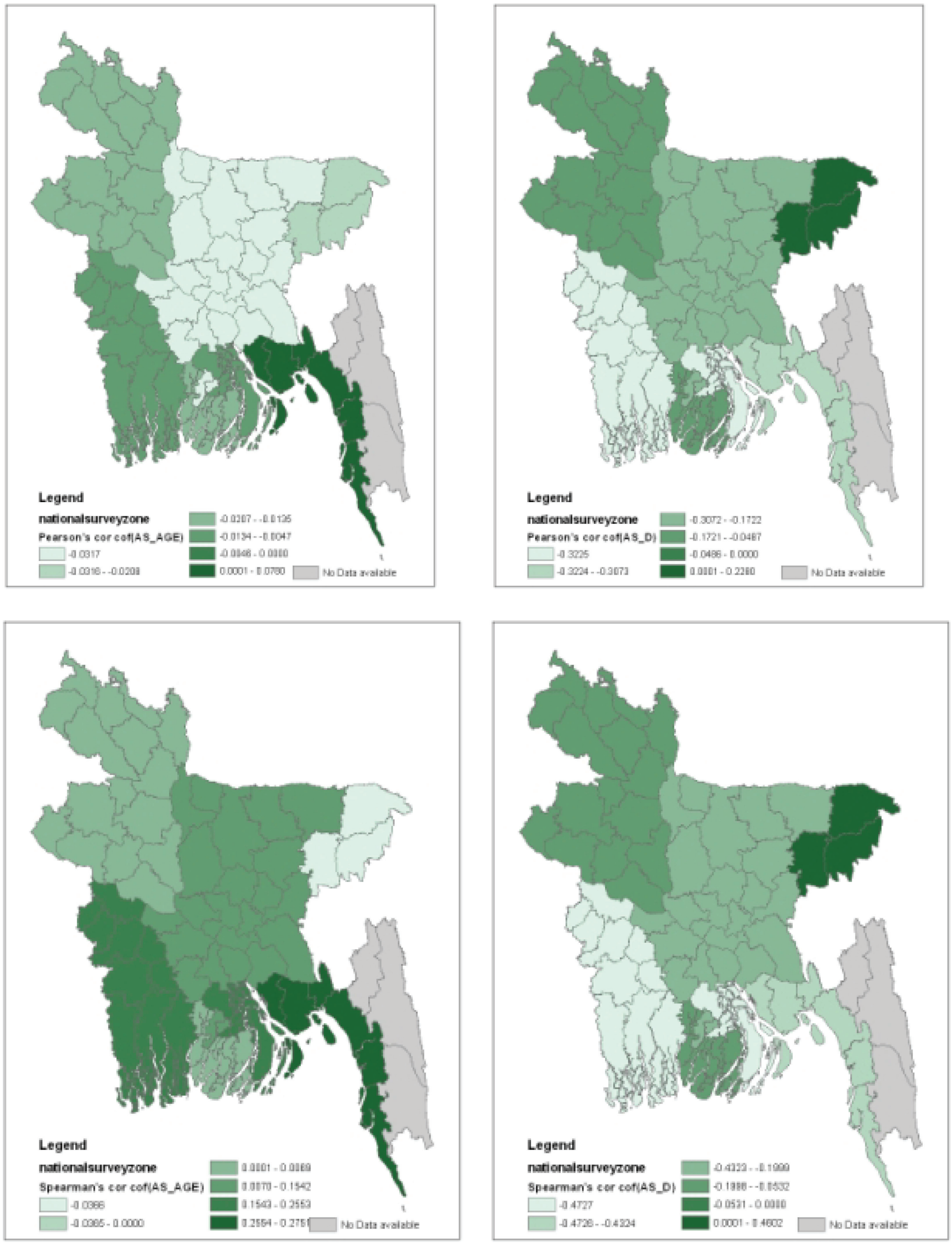

Figure 6. Bivariate statistical behavior of arsenic with age (left panels) and depth (right panels) of wells in terms of: 1) Pearson's correlation coefficient (top panels), and 2) Spearman's rank correlation (bottom panels).

and moderate contamination usually reveal a highly skewed distribution. This indicates the need for data transformation in those regions prior to the use of spatial mapping techniques such as kriging (Hossain et al., in press).In another regard, the AS distribution tends to flatten in regions of high contamination. This may be an indication of the presence of a uniform distribution.

Figure 3 shows the univariate statistical behavior of Fe in groundwater. This parameter is physically important in furthering our understanding of AS release mechanism hypothesis based on oxidation–reduction. In general, the mean Fe concentration appears to be high in regions with high AS concentration (Figure 3, top left panel) although there is no overwhelming similarity observed. However, the spatial map of skewness and kurtosis appears very similar to that for AS (Figures 2 and 3, compare bottom panels). This indicates that Fe concentration data may require similar kind of transformation as

4C/Art

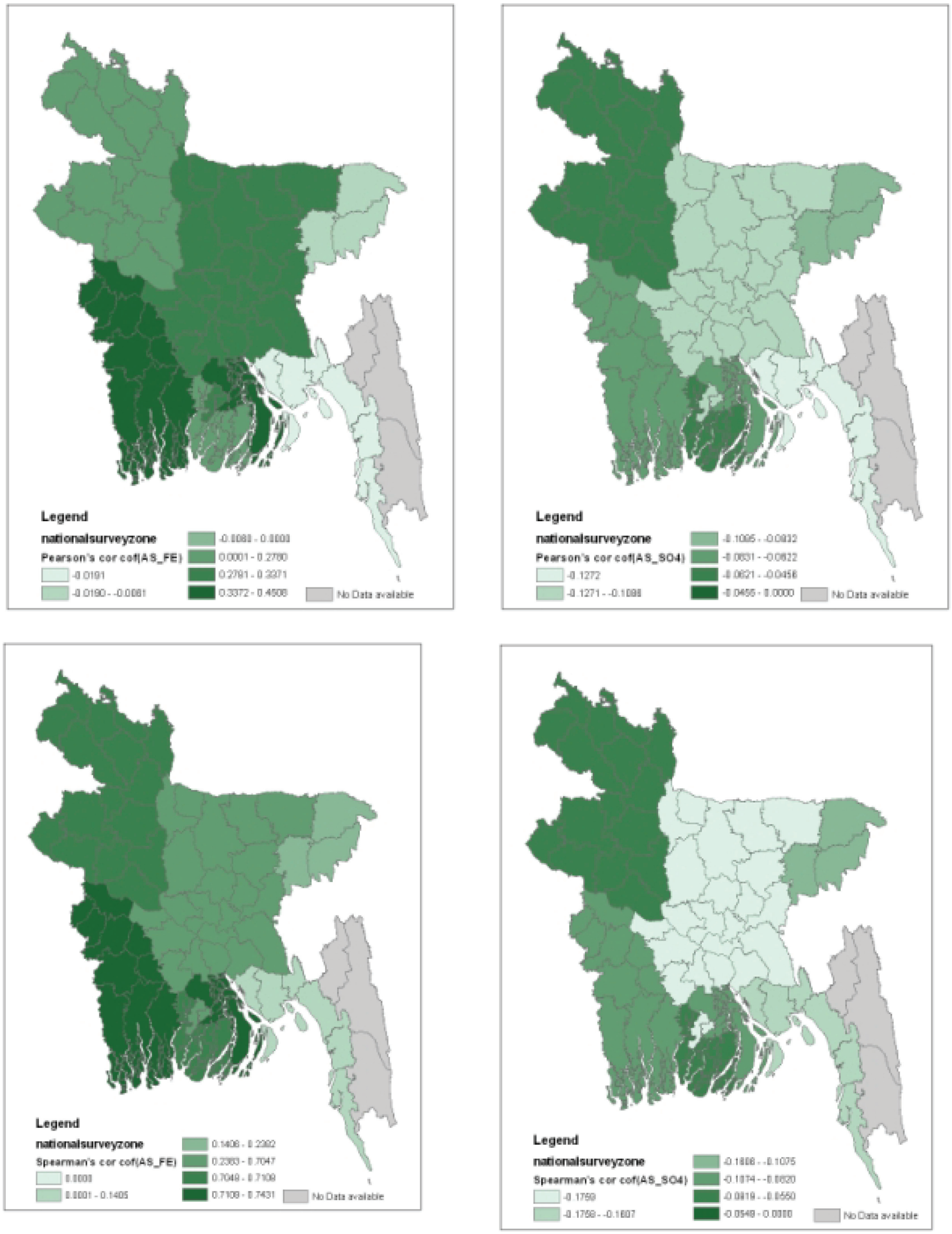

Figure 7. Bivariate statistical behavior of AS with Fe (left panels) and sulphate (right panels) of wells in terms of: 1) Pearson's correlation coefficient (top panels), and 2) Spearman's rank correlation (bottom panels).

AS prior to application of geostatistical or nonlinear mapping techniques.

The mean value of Ca and Mg concentrations shows a strong spatial similarity (Figure 4, left panels) in the southwest region of Bangladesh. This spatial similarity is also reflected in terms of skewness of the data (Figure 4, right panels), although the kurtosis values were not found to be as similar (not shown herein). We infer that the mapping of AS concentrations at nonsampled locations on the basis of multivariate factorial or regression models may not require the dual presence of both Ca and Mg; hence, one of them is redundant. We failed to observe any tangible behavior in the statistical behavior of Na and Zn in space and hence they are not reported herein. Finally, Figure 5 shows the univariate statistical behavior of the parameter Si, which is as important as Fe in the analyses of hypotheses of AS release. Although the mean Si concentration appears to exhibit little similarity with AS concentration, an interesting pattern emerges on the univariate statistical behavior. Both the skewness and kurtosis of the distribution appear very similar yet highly heterogeneous in space. This may be an indication that Si data will require careful transformation prior to any nonlinear or multivariate modeling only in the smaller scale but not for country-wide/regional assessment (Figure 5).

Bivariate Analyses

Based on preliminary univariate analyses (reported in the preceding section), we performed covariance analyses among the following pairs of parameters: 1) AS with age of wells; 2) AS with depth of wells; 3) AS with Fe; and finally 4) AS with sulphate. Furthermore, we present our bivariate findings in terms of correlation statistics of Pearson's (for linear correlation) and Spearman's rank (for nonlinear correlation), and finally in terms of administrative regions of Bangladesh. These larger administrative regions are called *divisions*.

In Figure 6, the correlation of AS with depth (right panels) and age of wells (left panels) are shown. It appears that only the northeast and southeast regions are noticeably correlated. In particular, the age of wells is only nonlinearly correlated in the southeast region while the rest of the country shows very weak correlation (Figure 6, left panels). The correlation of AS with Fe appears strongest in the southwest region (Figure 7, left panels), and this correlation appears more nonlinear (Figure 7, compare top left with bottom left panels). This possibly indicates that the oxidation–reduction hypothesis may be more appropriate as a release mechanism in the southwest region. In another regard, the sulphate concentration appears more correlated to AS in the northwest Pleistocene region of Bangladesh, suggesting that the pyrite–oxidation hypothesis may be more appropriate there (Figure 7, right panels). Overall, the Spearman's rank correlation coefficient appears to be a better alternative for screening dependent variables such as Fe and sulphate for multivariate modeling and factorial kriging.

Conclusion

A comprehensive forensic analysis of AS contamination in Bangladesh was undertaken using GIS, univariate and bivariate statistics. Our assessment provided the background needed for fine-tuning emerging/evolving methods of spatial mapping based on nonlinear deterministic dynamics and multivariate factorial analyses. The data were derived from the nation-wide AS survey completed in 1999 by the BGS in collaboration with the DPHE of Bangladesh. The study found that the standard deviation of AS concentration is highest along the river flood plains of the major rivers. The distribution of AS concentration was found to be symmetric in regions of very high mean concentration while the regions of low and moderate contamination reveal a highly skewed distribution. The mean value of calcium and magnesium concentrations showed a strong spatial similarity in the southwest region of Bangladesh. This spatial similarity was also reflected in terms of skewness of the data suggesting that the mapping of AS concentrations at nonsampled locations on the basis of multivariate factorial or regression models in Bangladesh may not require the dual presence of both Ca and Mg parameters and hence, one of them is redundant. Both the skewness and kurtosis of the distribution of Si concentration suggested that Si data would require careful transformation prior to any nonlinear or multivariate modeling only in the smaller scale but not for country-wide/regional assessment. The age of wells was found to be only nonlinearly correlated in the southeast region. The correlation of AS with Fe also appeared strongest in the southwest region indicating that the oxidation–reduction hypothesis may be more appropriate as a release mechanism in the southwest region.In another regard, the sulphate concentration was found to be more correlated to AS in the northwest Pleistocene region of Bangladesh, suggesting that the pyrite-oxidation hypothesis may be more appropriate. Overall, our forensic analysis has revealed a useful knowledge base for data transformation and selection of geochemical parameters towards spatial mapping based on multivariate factorial and nonlinear deterministic models.

Our study is not without limitations. Most of the inference is qualitative, and more definitive quantification would require the use of detailed mathematical methods (such as hypothesis testing). Furthermore, this study presents mostly from a data-based perspective without formulating physically based mechanistic hypothesis. Nevertheless, we believe the forensic findings from our study can be a useful first step towards developing more emerging spatial mapping techniques in light of uncertainty that exists on probable release mechanisms and mainstream geostatistical methods for mapping. Very recent work of Lin et al. (2006), Goovaerts et al. (2005), and Hill et al. (in press) reveal the importance of prior knowledge on data transformation, distribution analysis, principal components, and dominant variables for more accurate spatial mapping techniques based on factorial or nonlinear deterministic modeling.

Another limiting aspect of the study is that we have attempted to draw regional-level conclusions without looking closely in to the effect of spatial scale. For example, an open question remains as follows: What role do the spatial resolution and sampling of contamination data play in the statistical inferences on the forensics? The paucity of quality-controlled data (approximately 50 samples per district; see section discussing study region, data, and methods) makes it impossible to investigate if statistical analyses at scales smaller than the district level would significantly alter our forensic findings. Natural extensions of this work would therefore be: 1) significance testing of the univariate and bivariate statistical measures; 2) PCA; 3) establishment of connections between geochemical parameters based on mechanistic and physically based hypothesis; and 4) investigating the role of spatial scale (with respect to geologic variability) of AS contamination data on the univariate and bivariate statistical analyses. Some work has already begun along the suggested line and we hope to report them in the near future.

P1: FIZ
UENF˙A˙289007 ENF.cls February 12, 2008 16:35

References

Ahmed, M. F. 2003. Arsenic Contamination: Bangladesh Perspective. Q13 Dhaka, Bangladesh: ITN, BUET.

Akmam, W. 2002. *A Policy-Mix for Supplying Safe Water to Arsenic-Affected People in Bangladesh: With Special Reference to Meherpor District.* Q14 Doctoral thesis. Division of Agricultural and Forest Engineering, University of Tsukuba, Japan.

Biswas, B. K., Dhar, R. K., Samantha, G., et al. 1998. Detailed study report of Samta, one of the arsenic-affected villages of Jessore District, Bangladesh. *Current Science* 74: 134–145.

British Geological Survey–Department of Public Health Engineering (BGS–DPHE). 2001. Arsenic contamination of ground water in Bangladesh. In *British Geological Survey Report WC/00/19*, vol. 1–4, eds., Kinnburgh, D. G., and Smedley, P. L. Keyworth, UK: British Geological Survey. Available at: http://www.bgs.ac.uk/arsenic/Bangladesh (accessed January 13, 2008). Burgess, W. G., Burren, M., Perrin, J., Ahmed, K. M. 2000. Constraints on sustainable development of arsenic–bearing aquifers in southern Bangladesh. Part 1: A conceptual model of arsenic in the aquifer. In *Sustainable Groundwater Development*, eds., Hiscock, Q15 Rivett, and Davison. London, UK: Geological Society of London Special Publication 193: 145–163.

Davis, J. A., Yabusaki, S. B., Steefel, C. I ., et al. 2004. Assessing conceptual models for subsurface reactive transport of inorganic contaminants. *EOS—Transactions (AGU)*. 85(44): 449–455.

Goovaerts, P. 1997. *Geostatistics for Natural Resources Evaluation*., New York, NY: Oxford University Press.

Goovaerts, P., AvRuskin, G., Meliker, J., Slotnick, M., and Nriagu, J. 2005. Geostatistical modeling of the spatial variability or arsenic in groundwater of southeast Michigan. *Water Resources Research* 41: W07013.

Grassberger, P., and Procaccia, I. 1983. Measuring the strangeness of strange attractors. *Physica D* 9: 189–208.

Harvey, C. F., Swartz, C. H., Badruzzaman, A. B. M., et al. 2002. Arsenic mobility and ground water extraction in Bangladesh. *Science* 298: 1602–1606.

Q16 Hill, A. J., Hossain, F., and Sivakumar, B. In press. Is correlation dimension a reliable proxy for the number of dominant influencing variables for modeling risk of arsenic contamination in groundwater? *Stochastic Environmental Research and Risk Assessment*.

Hossain, F., Bagtzoglou, A. C., Nahar, N., Hossain, M. D. 2006. Statistical characterization of arsenic contamination in shallow tube wells of western Bangladesh. *Hydrological Processes* 20(7): 1497–1510.

Q17 Hossain, F., Hill, J., and Bagtzoglou, A. C. In press. Geostatistically based management of arsenic contaminated ground water in shallow wells of Bangladesh. *Water Resources Management*.

Hossain, F., and Sivakumar, B. 2006. Spatial pattern of arsenic contamination in shallow tubewells of Bangladesh: regional geology and nonlinear dynamics. *Stochastic Environmental Research and Risk Assessment* 20(1–2): 66–76.

Kinniburg, D. G., and Smedley, P. L., eds. 2001. Arsenic contamination of groundwater in Bangladesh, Ministry of Local Government, Rural Government and Cooperatives, Government of Bangladesh. *BGS Technical Report WC/00/19, vol 1*. Q18

Lin, Y.-B., Lin, Y.-P., Liu, C.-W., and Tan, Y.-C. 2006. Mapping of spatial multi-scale variation sources of groundwater arsenic on ChiaNan floodplain of Taiwan. *Science of the Total Environment*, 370: 168–181.

McArthur, J. M., Ravenscroft, P., Safiullah, S., and Thirlwall, M. F. 2001. Arsenic in ground water: testing pollution mechanisms for sedimentary aquifers in Bangladesh. *Water Resources Research* 37(1): 109–117.

Mukherjee, A. B., and Bhattacharya, P. 2002. Arsenic in ground water in the Bengal Delta plain: slow poisoning in Bangladesh. *Environmental Review* 9: 189–220.

Nahar, N., Hossain, F., and Hossain, M. D.In press. State of the art report on health and socio-economic effects of groundwater arsenic contamination Q19 in Bangladesh: new evidence from literature. *Journal of Environmental Health*.

Nickson, R. T., McArthur, J. M., Burgess, W., Ahmed, K.M., Ravenscroft, P., and Rahman, M. 1998. Arsenic poisoning of Bangladesh ground water. *Nature* 395: 338.

Ormsby, T., Napolean, E., Burke, R., Feaster, L., and Groessl, C. 2004. *Getting to Know ArcGIS Desktop*, 2nd ed., ESRI Press: Redlands, CA.

Rahman, M. M., Mukherjee, D., Sengupta, M. N., et al. 2002. Effectiveness and reliability of arsenic field testing kits: are the million dollar screening projects effective or not? *Environmental Science Technology* 36: 5385–5394.

van Geen A., Zheng, Y., Vesteeg, R., et al. 2003a. Spatial variability of arsenic in 6000 tube wells in a 25 km2 area of Bangladesh. *Water Resources Research* 39(5): 1140.

van Geen, A., Zheng, A., Stute, M., and Ahmed, K. M. 2003b. Comment on "Ground water arsenic and irrigation in Bangladesh" (II). *Science* 300: 584.

Welch, A. H., Westjohn, D. B., Helsel, D. R., and Wanty, R. B. 2000. Arsenic in ground water of the United States: occurrence and geochemistry. *Ground Water* 38: 589–604.

Yu, W. H., Harvey, C. M., and Harvey, C. F. 2003. Arsenic ground water in Bangladesh: a geo-statistical and epidemiological framework for evaluating health effects and potential remedies. *Water Resources Research* 39(6): 1146.

Zheng, Y., Stute, M., van Geen, A., et al. 2004. Redox control of arsenic mobilization in Bangladesh groundwater. *Applied Geochemistry* 19: 201–214.