Arsenic in groundwater in Bangladesh: A geostatistical and epidemiological framework for evaluating health effects and potential remedies

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[1] This paper examines the health crisis in Bangladesh due to dissolved arsenic in groundwater. First, we use geostatistical methods to construct a map of arsenic concentrations that divides Bangladesh into regions and estimate vertical concentration trends in these regions. Then, we use census data to estimate exposure distributions in the regions; we use epidemiological data from West Bengal and Taiwan to estimate dose response functions for arsenicosis and arsenic-induced cancers; and we combine the regional exposure distributions and the dose response models to estimate the health effects of groundwater arsenic in Bangladesh. We predict that long-term exposure to present arsenic concentrations will result in approximately 1,200,000 cases of hyperpigmentation, 600,000 cases of keratosis, 125,000 cases of skin cancer, and 3000 fatalities per year from internal cancers. Although these estimates are very uncertain, the method provides a framework for incorporating better data as it becomes available. Moreover, we examine the remedy of drilling deeper wells in selected regions of Bangladesh. By replacing 31% of the wells in the country with deeper wells the health effects of drinking groundwater arsenic could be reduced by approximately 70% provided that arsenic concentrations in deep wells remain relatively low. *INDEX TERMS:* 1831 Hydrology: Groundwater quality; 6309 Policy Sciences: Decision making under uncertainty; 6304 Policy Sciences: Benefit-cost analysis; 1829 Hydrology: Groundwater hydrology; *KEYWORDS:* arsenic, Bangladesh, geostatistics, health effects, risk assessment, mitigation

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1. Introduction

[2] Dissolved arsenic in groundwater poses a health problem in various parts of the world. Concentrations higher than the World Health Organization's acceptable limit of 10 μg/L have been found; e.g., in Bangladesh, West Bengal, Taiwan [*Tseng et al.*, 1968], northern China [*Wang*, 1984], Vietnam [*Berg et al.*, 2001], Argentina [*Hopenhayn-Rich et al.*, 1998], Mexico [*Del Razo et al.*, 1990], Chile [*Smith et al.*, 1998], and parts of the United States [*Welch et al.*, 2000]. The most widespread arsenic poisoning is in Bangladesh; indeed, it may be the largest case of natural poisoning ever to occur.

[3] Millions of groundwater wells have been drilled in Bangladesh during the past several decades to provide pathogen-free drinking water, and these wells supply water to 97% of the population. Under this circumstance, it is tragic that much of the groundwater in Bangladesh contains high concentrations of arsenic. The adverse health effects for the people of Bangladesh due to ingesting the arsenic have been widely reported [e.g., *Smith et al.*, 2000; *Karim*, 2000; *Rahman et al.*, 2001, *Anawar et al.*, 2002]. To date we estimate that about 50% of the groundwater wells in Bangladesh have arsenic concentrations greater than 10 μg/L and about 28% have concentrations greater than 50 μg/L, and as a consequence that about 46 million people are exposed to concentrations greater than 10 μg/L and about 28 million people to concentrations greater than 50 μg/L.

[4] The first cases of arsenic poisoning from drinking arsenic-contaminated groundwater in the Bengal Basin were diagnosed in 1983 [*Saha*, 1995]. Dissolved arsenic in well water in Bangladesh came to public attention in 1993 when the Bangladesh Department of Public Health Engineering (DPHE) tested wells in western Bangladesh after groundwater arsenic was discovered in West Bengal. It is now documented that high concentrations of arsenic are widespread in Bangladesh [e.g., *BGS and DPHE*, 2001; *Abul et al.*, 2001a]. Also, it is generally agreed that the arsenic is

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geologic in origin, deriving from the sediments from the upland Himalayan catchments [e.g., *McArthur et al.*, 2001; *Nickson et al.*, 2000; *Harvey*, 2001; *Abul et al.*, 2001b; *Harvey et al.*, 2002]. These studies also indicate that the aquifers in Bangladesh do not contain high levels of solid arsenic but rather that the chemically reducing environment leads to high dissolved to solid ratios of arsenic. However, the specific geologic, hydrologic, and geochemical conditions and mechanisms are not yet known.

[5] The spatial variability of arsenic concentrations in Bangladesh is complex with both large differences between neighboring wells and regional trends. Research is just beginning to address the hydrologic and geochemical mechanisms that may explain this variability. *Paul and De* [2000] find a small statistically insignificant positive correlation between observed arsenic concentrations and shallow tube well density by district. The *BGS and DPHE* [2001] find that some differences in arsenic concentrations over large areas are consistent with geologic differences. Very little is known about changes in arsenic concentration over time as data have been collected for less than a decade. Most researchers have found no significant seasonal changes in arsenic concentration [*BGS and DPHE*, 2001].

[6] The observed health effects of exposure to groundwater arsenic are skin abnormalities and lesions: typically pigmentation changes (e.g., hyperpigmentation) on the upper chest, arms and legs, and keratoses of the palms and soles. Long-term exposure can result in skin cancer and in various types of internal cancer, predominantly cancer of the lung, bladder, and liver. Other types of health effects also have been reported; e.g., *Rahman and Azelson* [2001] report an increase in the prevalence of diabetes mellitus and hypertension in Bangladesh, and *Milton et al.* [2001] report an increase in respiratory effects in Bangladesh.

[7] In the first part of this paper, we characterize the distribution of groundwater arsenic concentrations using geostatistical methods. The analysis divides Bangladesh into geologic-geomorphic regions and includes depth trends for the regions. Then, in the second part we evaluate regional and national health effects due to exposure to groundwater arsenic. We do so by combining the geostatistical analysis with demographic data and dose response functions. We estimate the prevalences of arsenicosis (hyperpigmentation and keratosis) and skin cancer and the incidences of various types of internal cancer. We also estimate the health benefits of installing deeper wells in selected areas. Although the adverse effects of groundwater arsenic in Bangladesh are widely reported, detailed national estimates have not previously been reported for exposure to arsenic concentrations, or the national extent of the health effects of arsenic poisoning. Other researchers have combined geostatistical and epidemiological methods for other public health problems primarily in the U.S. [*Oliver et al.*, 1992, 1998; *Nicholson and Mather*, 1996; *Kitron et al.*, 1997; *Hwang et al.*, 1999; *Thomson et al.*, 1999; *Wakefield and Elliott*, 1999; *Glass et al.*, 1997; *Christakos and Serre*, 2000].

[8] The analysis in this paper is based upon a variety of survey data sets and prior analyses. The comprehensive surveys of groundwater arsenic concentrations by *BGS and DPHE* [2001] and *Department of Public Health Engineering, Government of Bangladesh et al.* [1999] (hereinafter referred to as *DPHE et al.* [1999]) enables us to characterize arsenic concentrations throughout Bangladesh. The epidemiological survey by *Mazumder et al.* [1998b] in West Bengal enables us to estimate dose response functions for arsenicosis. This paper is the first to report dose response functions for arsenicosis in Bangladesh. And the epidemiological surveys in southwest Taiwan by *Tseng* [1968, 1977] and *Chen et al.* [1992] enabled *Brown et al.* [1989] and the *National Research Council* (*NRC*) [1999] to estimate the dose response functions for arsenic-induced cancers that we use here.

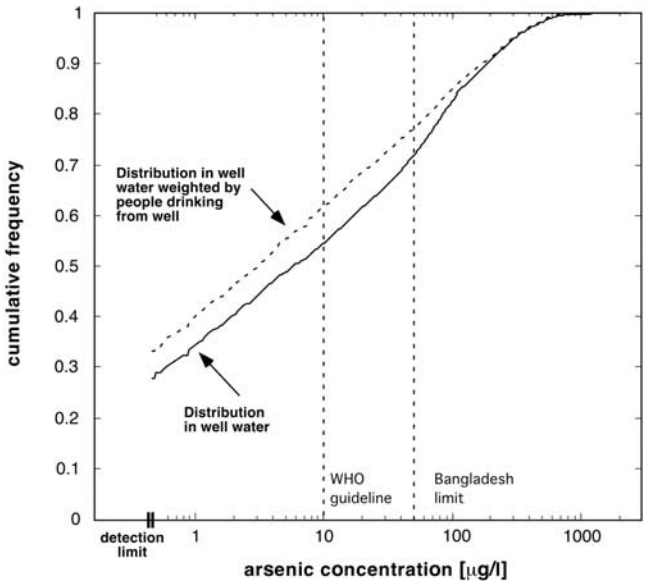

Figure 1. Cumulative arsenic distributions over wells and over people. A concentration of 0.1 μg/L is assigned to the nondetection wells.

[9] The framework developed here produces point estimates of health effects. The uncertainty on these estimates is large, however. The most important sources can not be reasonably quantified from existing data. In the last section, we identify but do not quantify (as probability distributions) the uncertainty in the various estimated quantities from which the health evaluations are calculated. This discussion provides a reappraisal of the information and assumptions underlying the health evaluations. The discussion of uncertainty argues for further analysis of the source and mobility of arsenic in groundwater and for further epidemiological data in which arsenic intake and health effects are measured at the individual level. As better understanding of arsenic behavior in the environment and epidemiological data becomes available, it can be incorporated into this framework to provide more accurate health evaluations.

2. Distribution of Groundwater Arsenic

2.1. Arsenic Concentrations in Sample Wells

[10] The British Geological Survey and the Bangladesh Department of Health and Engineering [*DPHE et al.*, 1999; *BGS and DPHE*, 2001] report arsenic concentrations measured by atomic fluorescence spectrometry for 4,140 wells (including Special Survey areas) located throughout most of Bangladesh (The data set is available at http://www.bgs.ac.uk/arsenic/Bangladesh). Figure 1 shows the cumulative distribution of the sample arsenic concentrations. In partic-

ular, 73% of the sample wells have arsenic concentrations greater than the survey detection limit (reported to be 0.25 to 0.50 μg/L [*BGS and DPHE*, 2001]), 46% have concentrations greater than the WHO acceptable limit of 10 μg/L, 28% have concentrations greater than 50 μg/L, 18% have concentrations greater than 100 μg/L, and 2% have concentrations greater than 500 μg/L.

[11] The DPHE-UNICEF also collected a larger data set of 51,000 measurements using field kits that record arsenic values at discrete thresholds. However, the BGS and DPHE data set is more representative of the groundwater wells in Bangladesh because its sample wells are systematically selected, e.g., approximately 8 samples are selected per thana (there are 489 thanas, or administrative units, in Bangladesh) uniformly covering the entire country (see *DPHE et al.* [1999, pp. 3.1–3.7] for the sampling procedure). Moreover, field kit measurements tend to be inaccurate, especially below 100 μg/L [*BRAC*, 2000]. For these reasons (and since statistical inference depends on absolute number of samples and not on the sample size relative to the population size), we choose to use the survey data set.

[12] The BGS and DPHE data includes 1,127 wells (27% of the sample) with arsenic concentration measurements below the detection limit (reported to be 0.25 to 0.50 μg/L) [*BGS and DPHE*, 2001]. We assign an arsenic concentration of 0.10 μg/L to these nondetection wells. Wells with such low concentrations pose little health risk, and thus the estimates of health effects are not sensitive to the choice of a concentration for the nondetection wells. Moreover, we find that the results from the analysis of spatial variability below, that use log concentrations rather than concentrations, are not affected by the choice of the value assigned to the nondetection wells.

[13] Figure 2 maps the geographic distribution of arsenic concentration in the sample wells. The spatial distribution of arsenic concentration has both small-scale variability and large-scale trends. Concentrations can differ greatly in nearby wells, e.g., concentrations as high as 1,000 μg/L occur within hundreds of meters of concentrations as low as 1 μg/L. Despite this small-scale variability, regional patterns in arsenic concentrations are evident. For example, the south-central area near the confluence of the Ganges, Brahmaputra, and Meghna rivers has the highest concentrations while the southeastern hills and northwest piedmont plains generally have the lowest concentrations.

[14] For the analysis in the next subsections, we transform the BGS and DPHE data set to log concentrations, reducing the impact of outliers. The log data has a variance of 1.6 (log-μg/L)^2.

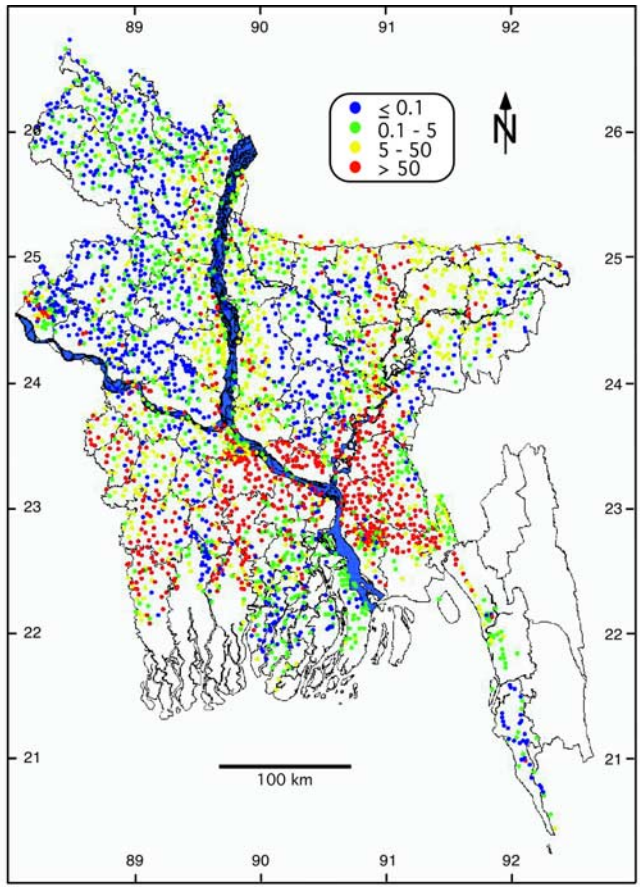

Figure 2. Geographic distribution of arsenic concentrations. Based on *DPHE et al.* [1999] data. Concentrations are in μg/L.

2.2. Variogram Analysis of Lateral Variation

[15] In general, a variogram measures variability between sample values as a function of their separation in 1, 2, or 3 dimensional space [*Journel and Huijbregts*, 1978; *Kitanidis*, 1997]. Here and in the next two subsections, we calculate experimental variograms $\gamma(h)$ that are defined by the formula:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i<j:d(i,j)=h} \left(\log_{10} x_j - \log_{10} x_i\right)^2 \qquad (1)$$

where $\gamma(h)$ [(log-μg/L)^2] denotes a variogram value, $d(i, j)$ [km] denotes the lateral separation between two sample wells i < j, $n(h)$ denotes the number of sample pairs i < j with lateral separation h, and x_i, x_j [μg/L] denote arsenic concentrations for the sample wells i, j.

[16] In a rough sense, a variogram value $\gamma(h)$ is the variance in log concentration for sample wells with lateral separation h. Typically, $\gamma(h)$ is increasing as a function of h. The variance of a data set can be shown to equal the weighted average of variogram values $\gamma(h)$ in which a weight is the fraction of sample pairs (i, j) having separation h. This property is a reason for using the function $\gamma(h)$, which is also-called a semi-variogram, instead of the function 2 $\gamma(h)$.

[17] The circles in Figure 3 plot the experimental variogram that we calculate from the BGS and DPHE data set. The three graphs are for different scales of lateral well separation. The 1-km variogram in Figure 3a characterizes the smallest scale of variability resolvable by the data set. The first circle shows that pairs of wells separated by a distance less than 100 m have a variance of about 0.36 (log-μg/L)^2. This value, called the nugget variance, represents the variability between nearby wells plus measurement error. In the work of *DPHE et al.* [1999, p. 14], it was found that for a random selection of 45 samples, replicate measurements were within 10% of original values in μg/L units. This calculation indicates that the measurement error variance is much smaller than 0.36 (log-μg/L)^2, and thus most of the nugget variance represents small-scale variability. This small-scale variability is consistent with *van Geen*

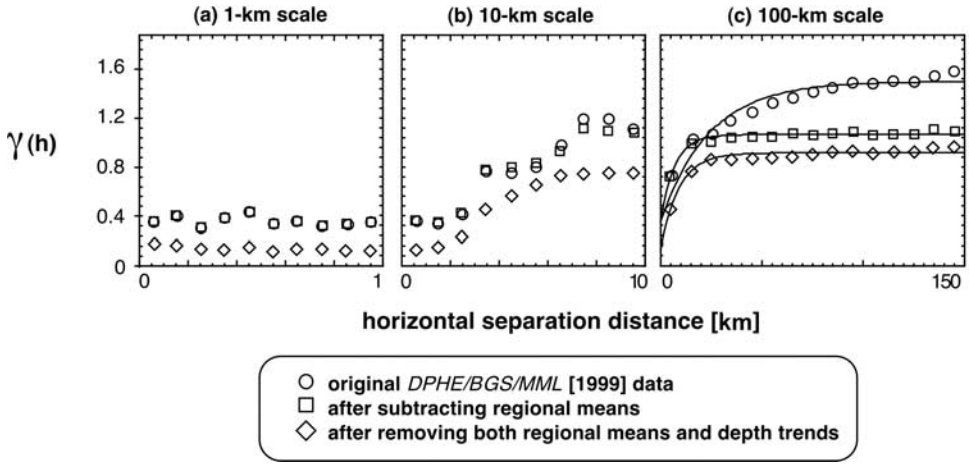

Figure 3. Experimental variograms for three spatial scales. Based on *DPHE et al.* [1999] data. Lateral separations h are in km, and variogram values $\gamma(h)$ are in (log-μg/L)^2.

et al.'s [2002] finding that 88% of wells with arsenic concentrations above the median are within 100 m of wells with arsenic below the median at their particular study site.

[18] For separation distances less than 3 km (all points in the 1-km variogram and the first three points in the 10-km variogram), the value of the variogram remains near the nugget variance. This feature suggests that little spatial structure exists between the 100 m and 3 km scales. For separation distances between 3 km to 100 km (the last 7 points in the 10-km variogram and all points in the 100-km variogram), the variogram value approaches 1.6 (log-μg/L)^2. This suggests that larger-scale (>3 km) features account for much of the variability in the data set.

[19] An experimental variogram can be fit by a negative-exponential model:

$$\gamma(h) = \sigma_n^2 + \sigma_c^2\left(1 - \exp\left(-\frac{h}{\lambda_h}\right)\right) \qquad (2)$$

with three parameters: the nugget variance σ_n^2 [(log-μg/L)^2], and the variance change σ_c^2 [(log-μg/L)^2] due to spatial structures with correlation scale λ_h [km].

[20] Table 1 reports parameter values σ_n^2, σ_c^2, λ_h estimated from experimental variograms by least squares calculations. The parameter values are for the 100-km variogram in Figure 3c obtained from the BGS and DPHE data set and adjusted data sets as described in the next subsections. We use the parameter values in Table 1 to evaluate the importance of national and regional geologic differences and regional vertical trends.

2.3. Geologic-Geomorphic Regions

[21] We examine how large-scale patterns in arsenic concentrations may be related to geologic and geomorphic regions. First, we divide the country into 24 geologic regions according to the geology map of *Alam et al.* [1990] that characterizes the underlying sediment. Then, we divide the country into 19 geomorphic regions according to the geomorphology map of *Food and Agriculture Organization* (*FAO*)/*United Nations Development Programme* (*UNDP*) [1988]. This map delineates both hydrologic and physiographic regions; e.g., it delineates the Ganges, Brahmaputra and Meghna basins, then divides the Ganges basin into fluvial and tidal regions. Thus we obtain 108 intersection regions that are nonempty. Then, we combine certain of these regions to define 34 disjoint regions (Figure 4 and Table 2). *DPHE et al.* [1999] also found differences in arsenic concentrations between geologic and geomorphic regions, but considered geology and geomorphology separately.

[22] The reduction of 108 intersection regions to 34 regions is based on (1) hypothesis testing to determine whether the mean log concentrations in contiguous regions are statistically different and (2) geographic separation of intersection regions. Contiguous regions are joined if a t test at the 95% confidence level fails to show that mean log concentrations differ and are kept separate otherwise. For example, we reject with a high degree of confidence ($p < 0.0001$) the hypothesis that the mean of 1.43 log-μg/L (27 μg/L) observed in the alluvial deposits in the Brahmaputra floodplains is statistically equivalent to the mean of 0.48 log-μg/L (3 μg/L) observed in the chandina deposits in the same floodplain.

[23] From the BGS and DPHE data, we construct a regionally adjusted data set by subtracting from each regional data set its mean log concentration. While the BGS and DPHE data has a variance of 1.6 (log-μg/L)^2, the adjusted data set has a variance of only 1.0 (log-μg/L)^2. Random separations of the data into 34 equal-size subsets serving as the 34 regions reduces the variance much less, to about 1.58 (log-μg/L)^2. Hence the 34 geologic-geomorphic regions most likely explain much of the large-scale variability in arsenic log concentrations in Bangladesh.

Table 1. Data Variances, Experimental Variograms, and Exponential Variograms

Data Set, log-μg/L	Data Variance[a]	Experimental Variogram Plotted in Figure 3	Exponential Variogram[a]		
			σ_n^2	σ_c^2	λ_h
BGS and DPHE data	1.6	circles	0.36	1.14	24.1
Regionally adjusted data	1.0	Squares	0.36	0.7	6.9
Regionally and depth adjusted data	0.9	diamonds	0.14	0.78	9.2

[a]Data variances and σ_n^2, σ_c^2 are in units of (log-μg/L)^2, and λ_h is in units of km.

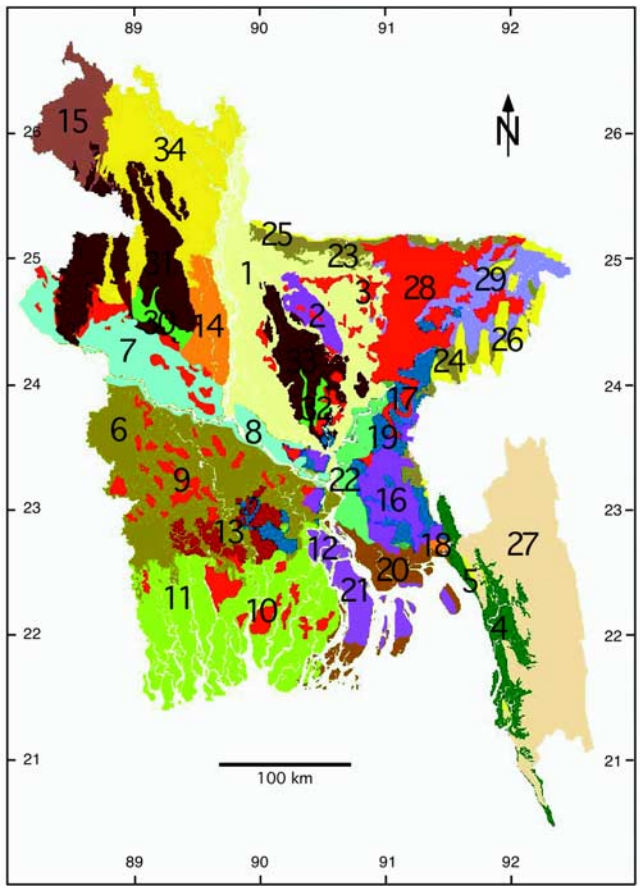

Figure 4. Thirty-four geologic-geomorphic regions. Based on geology map of *Alam et al.* [1990] and geomorphology map of *FAO/UNDP* [1988]. The regions are numbered as in Table 2.

[24] The squares in Figure 3 plot the calculated variogram after the regional averages have been subtracted, and Table 1 reports the resulting estimated 100-km scale exponential variogram parameters. In this exponential variogram, the nugget variance σ_n^2 is the same, but the variance change σ_c^2 due to large-scale structures is reduced from 1.14 (log-μg/L)^2 to 0.71 (log-μg/L)^2, and the correlation scale λ_h is reduced from 24.1 km to 6.9 km. Moreover, the graph of the variogram is horizontal beyond separation distances of about 10 km. Thus the geologic-geomorphic regions appear to account for spatial structures larger than about 10 km.

[25] The reductions in the variance change σ_c^2 due to large-scale structures and the correlation scale λ_h suggest that the geology and geomorphology of Bangladesh contribute significantly to the large-scale pattern of dissolved arsenic concentrations. This result is important for evaluations of health effects for two reasons: (1) It provides a rationale for partitioning the data into regions to consider concentration patterns with depth, and (2) It enables us to approximate the distribution of arsenic concentration in parts of a region where measurements do not exist.

[26] Some differences among regions are well known; e.g., the Pleistocene Madhupur and Barind terraces underlying Dhaka have low arsenic concentrations. However, other differences among regions are not well known; e.g., the average arsenic concentration of 38 μg/L in the marsh and clay deposits in the Ganges River floodplain is significantly lower than the average arsenic concentration of 105 μg/L in the surrounding deltaic deposits in the same floodplain. The sharp boundaries between these two regions would not be maintained in a kriging or moving average approximation of arsenic concentrations. Presumably, the arsenic concentrations in the regions differ because of differences in sediment type or in biogeochemical and hydrologic conditions.

2.4. Trends of Arsenic Concentration With Depth

[27] One potential remedy for the health problem caused by elevated dissolved arsenic is to drill deeper wells. In the BGS and DPHE data set, 94% of the wells deeper than 150 m have arsenic concentrations less than 10 μg/L while only 50% of the wells less deep than 150 m have concentrations less than 10 μg/L. Figure 5 plots log concentration versus depth for the 4,140 sample wells. The data pairs are clustered into a large group of shallow wells with higher arsenic concentrations and a smaller group of deep wells with lower arsenic concentrations. This clustering may be due to the presence of an aquitard that was deposited during a Holocene marine transgression and that is thought to separate two sandy aquifers in many areas of the country [*Umitsu*, 1993; *Goodbred and Kuehl*, 2000].

[28] A linear regression (depth trend function) of arsenic log concentration on depth for the BGS and DPHE data gives a national depth slope of −0.0036 (log-μg/L/m). While the r^2 is only 0.04, we can reject the hypothesis that the national depth slope equals zero with a high degree of confidence ($p < 0.0001$). In other words, the data has substantial scatter, but a sufficient number of data exist to indicate a trend of decreasing arsenic concentration with depth.

[29] We also examine depth trends for each geologic-geomorphic region. Table 2 reports that arsenic concentrations are estimated to decrease with depth for 24 regions and to increase with depth for the other 10 regions. Table 2 also shows that for 17 regions (one-half of the regions), the depth slope is statistically significant, i.e., the p-value is small enough to reject the hypothesis of a zero depth slope. For the other regions, a trend may not be evident either because there is no trend or because the number of sample wells, particularly deep wells, is insufficient to infer a trend. Although the data collection scheme of the BGS and DPHE was to sample a uniform proportion of deep wells throughout Bangladesh, some geologic-geomorphic regions contain few deep sample wells.

[30] A regionally and depth adjusted data set is constructed by the following steps. For each of the 17 regions whose depth slopes are statistically significant, we use its depth trend to calculate for each well an expected log concentration that we subtract from the well's measured log concentration. And for each of the other 17 regions, we subtract for each well only the regional mean log concentration from the well's measured log concentration (as in section 2.3). In this data set, each regional average equals zero. While the regionally adjusted data has a variance of 1.0 (log-μg/L)^2, the regionally and depth adjusted data set has a variance of 0.9 (log-μg/L)^2.

[31] The diamonds in Figure 3 plot the variogram calculated from the regional and depth adjusted data, and Table 1

Table 2. Geologic-Geomorphic Regions

Region[a]	Sample Wells	Mean, μg/L	SD, μg/L	Slope, log-μg/L/m	Slope p Value	Population (thousands)	Exposed Population,[b]	% Pop Density[c]	Arsenicosis[d]	Skin Cancer[d]	Internal Cancers[e]
1, Brahmaputra FP (alluvium)	411	27	56	−0.0023	0.309	13,584	71	1129	96,990	4,780	110
2, Brahmaputra FP (chandina)	28	3	12	−0.0005	0.931	1,205	48	747	1,010	40	0
3, Brahmaputra FP (clays)	73	25	46	−0.0050	0.265	3,141	73	1487	18,230	860	20
4, Chittagong Coast (alluvium)	65	24	58	−0.0030	0.002	5,437	95	1078	32,740	1,850	40
5, Chittagong Coast (sandstone/shale)	16	6	17	−0.0048	0.237	1,325	65	1146	1,070	40	0
6, Ganges River FP (deltaics)[f]	528	105	160	−0.0063	<0.0001	14,381	86	830	435,910	29,970	780
7, Ganges River FP west (alluvium)[f]	304	70	265	−0.0107	0.086	5,867	47	927	60,810	5,420	170
8, Ganges River FP east (alluvium)	123	104	164	−0.0018	0.356	1,996	98	1060	63,970	3,910	100
9, Ganges River FP (clays/peat)	66	38	81	−0.0036	0.089	1,558	54	825	17,140	990	20
10, Ganges Tidal FP (clays/peat)[f]	39	77	155	−0.0051	0.001	952	76	399	19,100	1,390	40
11, Ganges Tidal FP (deltaics)	244	46	111	−0.0058	<0.0001	7,112	71	470	95,190	6,250	160
12, Ganges Tidal FP (estuarine)[f]	19	64	167	−0.0047	0.004	561	80	727	10,100	770	20
13, Gopalganj-Khulna Bils[f]	29	71	88	−0.0083	0.003	710	79	592	15,300	820	20
14, Karatoya-Bangali FP	93	37	73	0.0027	0.574	2,122	93	743	25,060	1,430	30
15, Old Himalayan Fan	119	2	7	0.0195	0.014	2,778	42	638	1,850	70	0
16, Old Meghna Estuarine FP (chandina)[f]	378	148	158	−0.0088	<0.0001	4,838	99	1287	273,790	19,410	500
17, Old Meghna Estuarine FP (clays/peat)[f]	38	97	122	−0.0089	0.001	1,288	90	910	37,980	2,320	60
18, Old Meghna Estuarine FP (deltaics)[f]	33	120	122	−0.0085	<0.0001	757	90	841	25,750	1,540	40
19, Old Meghna Estuarine FP (alluvium)[f]	113	147	195	−0.0133	<0.0001	4,876	80	1400	207,600	15,270	400
20, Meghna Estuarine FP (delts/alluv)[f]	101	94	145	−0.0069	<0.0001	1,683	97	1331	36,140	2,000	50
21, Meghna Estuarine FP (estuarine)	54	25	122	−0.0048	<0.0001	2,375	91	634	18,130	1,690	50
22, Meghna River FP[f]	89	252	209	−0.0089	<0.0001	2,725	99	1187	220,480	17,210	460
23, N Piedmont P/N Hills (alluvium)	91	37	53	0.0098	0.001	2,427	81	629	23,690	1,140	30
24, E Piedmont P/N Hills (alluvium)	61	11	19	0.0019	0.567	1,877	78	877	5,900	250	10
25, N Piedmont P/N Hills (sndst/shale)	33	28	32	0.0108	0.167	810	68	676	6,050	260	10
26, E Piedmont P/N Hills (sndst/shale)	28	5	20	0.0032	0.636	812	45	615	1,670	80	0
27, South Hills	38	8	45	−0.0017	0.260	2,741	49	159	8,430	510	10
28, Surma/Sylhet Basin (clays/peat)	92	54	51	0.0054	0.005	2,267	96	482	37,100	1,780	40
29, Surma/Sylhet Basin (alluvium)	91	28	41	0.0063	0.017	2,719	86	674	20,530	930	20
30, Terraces West (alluvium)	32	4	17	−0.0019	0.924	878	36	761	1,280	60	0
31, Terraces West (clays)	201	1	2	−0.0042	0.213	4,472	37	641	1,260	50	0
32, Terraces East (alluvium)	21	1	2	0.0010	0.742	3,212	28	4782	1,690	60	0
33, Terraces East (clays)	80	4	18	−0.0039	0.052	9,962	12	2797	3,820	170	0
34, Tista FP	409	11	48	0.0063	0.076	11,485	56	901	38,240	2,270	60
Bangladesh	**4,140**	**63**	**140**	**−0.0036**	**<0.0001**	**124,933**	**68.3**	**818**	**1,864,000**	**125,590**	**3,250**

[a]Region names are formatted as geomorphologic region (geologic type).
[b]Exposed population in an area is defined as those people drinking dissolved arsenic above detection limit.
[c]Units are numbers of people per km^2.
[d]Units are numbers of cases; arsenicosis is defined as the sum of hyperpigmentation cases and keratosis cases.
[e]Units are fatalities per year; internal cancers are defined as the sum of bladder, lung, and liver cancers.
[f]One of the 11 regions selected for deep wells in the deep-well remediation.

reports the resulting 100-km scale exponential variogram. Here, the nugget variance σ_n^2 has been reduced from 0.36 to 0.14 (log-μg/L)^2. The variogram is shifted downward by about 0.2 (log-μg/L)^2 for all separation distances without significantly changing the correlation scale λ_h or the variance change σ_c^2 due to large-scale spatial structure. Thus much of the differences in arsenic concentrations between neighboring wells, as characterized by the nugget variance, is due to differing well depths coupled with depth trends.

[32] The 34 regions show a strong correspondence between greater mean log concentrations and more negative depth slopes. Of the 13 regions with the greatest mean log concentrations (greater than 50 μg/L) and the 16 regions with the most negative slopes (less than −0.004 (log-μg/L/m), 11 regions are in both categories. Hence, in areas where the arsenic problem is the worst the estimated trend of decreasing arsenic with depth is generally the most negative. Furthermore, most of the 11 regions show statistically significant decreasing trends—linear regressions for 10 of the 11 regions resulted in p-values on the slope that were less than 0.005.

[33] Table 2 indicates the 11 selected geologic-geomorphic regions. In section 5.2, we use this group of regions to examine a strategy of replacing shallow wells with deeper wells in order to reduce arsenic-induced health effects.

3. Population Exposure to Dissolved Arsenic

[34] We estimate for each geologic-geomorphic region the numbers of people who are exposed to various concentrations of groundwater arsenic by combining the above geostatistical modeling with demographic information obtained from the 1991 census conducted by the *Bangladesh Bureau of Statistics* (*BBS*) [1996]. This document reports data for 489 thanas throughout Bangladesh. Based on this data, the population of Bangladesh is estimated to be about 125 million people comprised of 51.48% males and 48.52% females, and average ages are estimated to be 23.10 yr. for males and 22.23 yr. for females. The *Central Intelligence Agency* (*CIA*) [2001] estimates the 2001 national population to be 131 million people with a population growth rate of 1.59% per year. However, 2001 population numbers for each of the 489 thanas are currently unavailable, and thus the demographic estimates based on 1991 data are used here.

[35] The BGS and DPHE survey data provides for each sample well: (1) the thana in which the well is located and

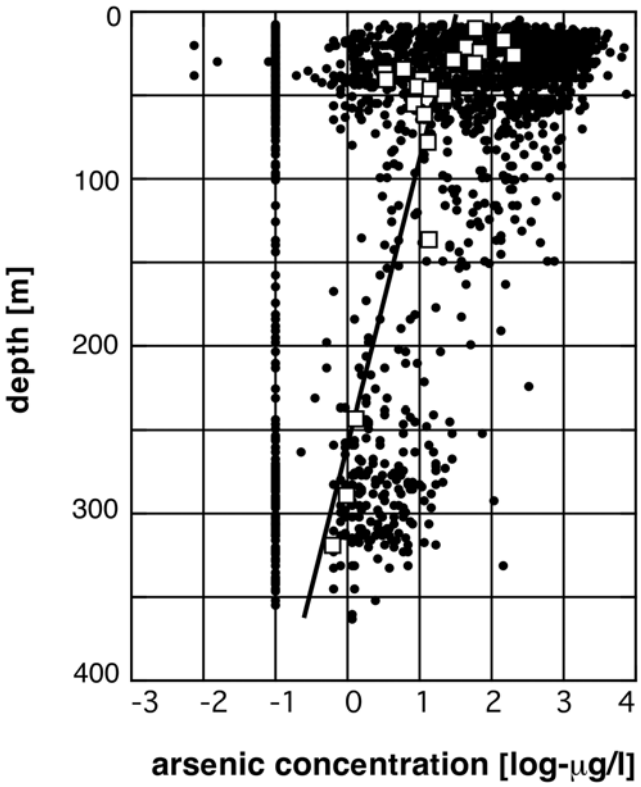

Figure 5. Groundwater arsenic concentrations versus depth. Based on *DPHE et al.* [1999] data. Squares represent averages over 200 wells. The linear fit is [log-μg/L] = 0.876 − 0.0036 [m].

(2) a GPS latitude-longitude reference that we have used to identify the geologic-geomorphic region in which the well is located. The BBS census data provides the population size of each thana. Based on this information, we use the steps below to assign each person in Bangladesh to a sample well and thus to a region. The following apply for each thana.

[36] 1. If there are sample wells in the thana (as in 433 of the 489 thanas), then we assign an equal number of people in the thana to each sample well. If every sample well in the thana lies in the same geologic-geomorphic region, then everyone is assigned to that region. And if the sample wells in the thana lie in several regions, then people are assigned to those regions based on the proportion of sample wells in each region.

[37] 2. If there are no sample wells in the thana (as in 56 of the 489 thanas), then we identify the geologic-geomorphic region in which the thana is located, and we assign an equal number of people in the thana to each sample well in the region. Thus we assume that the distribution of arsenic concentration in the unsampled thana is the same as the distribution of arsenic concentration in the geologic-geomorphic region as a whole.

[38] By steps 1 and 2, we calculate for each region the numbers of people who are exposed to the various sample arsenic concentrations in the region. Then, we estimate a finite distribution of concentration to which the national population is exposed by summing the regional distributions. We estimate that that about 46 million people are exposed to concentrations greater than 10 μg/L and about 28 million people to concentrations greater than 50 μg/L. *BGS and DPHE* [2001] estimate 57 million and 35 million people exposed to concentrations of 10 μg/L and 50 μg/L respectively using disjunctive kriging. Furthermore, *BGS and DPHE* [2001] also estimate 46 million and 28 million by multiplying the percentage of contaminated wells in a thana by the population of the thana. Since most thanas are found within a geologic-geomorphic region, our exposure estimates coincide closely with this approach.

[39] Figure 1 shows two cumulative distributions of arsenic concentration: that over the sample wells and that over the Bangladeshi population. The distribution over wells has a mean of 63 μg/L and a standard deviation of 140 μg/L while the distribution over people has a mean of 56 μg/L and a standard deviation of 123 μg/L. Thus the sample well distribution would not be accurate for calculating health effects. The distributions differ largely because of the high population density in Dhaka and to a lesser extent because of a nonuniform spacing of the sample wells.

[40] The two cumulative graphs in Figure 1 can be compared as follows. For the interval of arsenic concentrations below the detection limit (0.25–0.50 μg/L), the fraction of arsenic over people (32%) is greater than the fraction of arsenic over wells (27%). This discrepancy is due primarily to the dense population of Dhaka, located in the clay and alluvium regions (32 and 33) of the Eastern Terraces. As reported in Table 2, these regions contain 4,782 people/km^2 and 2,797 people/km^2 and contain mostly nondetection wells. For concentrations between the detection limit and 50 μg/L, the fractions of people are approximately equal to the fractions of wells, and thus the cumulative graphs are approximately parallel. For concentrations between 50 μg/L and 100 μg/L, the fractions of people are less than the fractions of wells, and thus the cumulative graph for wells rises to meet that for people. And for concentrations above 100 μg/L, the two distribution graphs are very close. Therefore, although the sample well distribution would not be accurate for calculating health effects, it would not be grossly different than that using the distribution over people since the main difference is for concentrations below 100 μg/L.

[41] Table 2 reports for each of the 34 selected regions the estimated number and percent of people who obtain drinking water from wells with arsenic concentrations above the detection limit. In sections 5.1, 5.2, we estimate regional health effects by estimating the health effects for these regional subpopulations. This approximation is suitable since the estimated health effects of exposure to arsenic concentrations below the detection limit are negligible. Note that as the number of wells in Bangladesh increases, our distributions of exposure are unchanged. This assumes that the depth distribution of wells does not change over time.

[42] The national population of people who use wells with arsenic concentrations above the detection limit consists of about 85 million people (68% of the entire population of Bangladesh). The distribution of arsenic concentration over this national subpopulation has a sample mean of 82 μg/L and sample standard deviation

of 142 μg/L. This sample distribution of exposure is used in section 4.3 for the estimation of arsenicosis dose response functions.

4. Arsenic Health Risk Assessment

4.1. Surveys of Arsenicosis in Bangladesh and West Bengal

[43] The most common health effects due to drinking water with dissolved arsenic are skin abnormalities and lesions. Typically, they are diagnosed as hyperpigmentation and keratosis. Hyperpigmentation is characterized by a freckled "raindrop" pattern of discolored spots or diffuse melanosis that is pronounced on the trunk and extremities. In advanced stages, depigmentation may occur. Keratosis is a later feature of arsenical dermatosis and is characterized by a bilateral thickening of the palms and soles, with or without raised nodules. The thickening can be painful and can make walking and fetching water difficult. Hyperpigmentation and keratosis are the two types of arsenicosis to be evaluated in this study.

[44] Surveys of arsenicosis in Bangladesh include those by *Asia Arsenic Network* (*AAN*) [1999], *Ahmad et al.* [1999], *Ahsan et al.* [2000], *Biswas et al.* [1998], *BRAC* [2000], *Chowdhury et al.* [2000, 2001], *Dhar et al.* [1997], *Milton and Rahman* [1999], *Quamruzzaman et al.* [2000], *Rahman and Tondel* [1999], *Smith et al.* [2000], *School of Environmental Studies/Dhaka Community Hospital* (*SOES/DCH*) [2000], and *Tondel et al.* [1999]. Surveys of arsenicosis in West Bengal include those by *Chakraborty et al.* [1999], *Chakraborty and Saha* [1987], *Chowdhury et al.* [2000, 2001], *Das et al.* [1994, 1995, 1996], *Mandal et al.* [1996, 1997], *Mazumder et al.* [1998a, 1998b], *Pandey et al.* [1999], *Saha* [1984, 1995], and *Subramanian and Kosnett* [1998].

[45] These surveys signal the extensive occurrence of arsenicosis in Bangladesh and West Bengal. For example, as part of the 500-Village Rapid Assessment Project, *Quamruzzaman et al.* [2000] surveyed 818,924 people in Bangladesh who were drinking water from 61,631 wells in the southern deltaic regions. These wells had high concentrations of dissolved arsenic, e.g., 52% of the sampled wells had arsenic concentrations greater than 100 μg/L. They found that 2327 people (0.28%) had symptoms of arsenicosis. They also found a weak correlation between the fraction of wells in a village with high arsenic concentrations (>100μg/L) and the prevalence ratio of arsenicosis in the village. Other surveys found much higher prevalence ratios; e.g., the *SOES/DCH* [2000] surveyed 17,896 people from 214 arsenic-affected villages and found that 3688 (21%) had arsenical skin lesions, and *Tondel et al.* [1999] interviewed and examined 1481 patients in four villages and found that 430 (29%) of the patients had skin lesions.

[46] The discrepancies in reported prevalence ratios may be due to differences in such factors as: the arsenic concentrations in the surveyed region, the quantity of contaminated water ingested, the duration of exposure, the age cohorts surveyed, the nutrition of the people surveyed, the procedure to recruit participants, and the diagnostic criteria for arsenicosis. Even though the reported prevalence ratios in the Bangladesh and West Bengal surveys vary widely, these surveys establish a relationship between the ingestion of arsenic and the occurrence of arsenicosis.

4.2. Surveys of Arsenic-Induced Cancer in Southwest Taiwan

[47] Adequate data to estimate dose response functions for skin or internal cancers has not yet been collected in Bangladesh or West Bengal. The reason is that most wells were installed within the last 20 years, and latency periods for arsenic-induced cancer are typically more than 20 years. However, several surveys conducted in southwest Taiwan in the 1960s provide data on cancer due to ingesting arsenic contaminated well water. The surveys covered large numbers of participants who were exposed to groundwater arsenic over long periods. The epidemiological data consists of frequency counts on the prevalence of skin cancer in which the health endpoint is morbidity and on the incidence of three types of internal cancer (lung, bladder, and liver) in which the health endpoint is fatality. The Taiwanese surveys provide much of our information on the relationship of cancer to arsenic ingestion; in particular, they provide the basis for recent studies of health effects on the U.S. population [*U.S. Environmental Protection Agency* (*U.S. EPA*), 2001; *NRC*, 1999, 2001; *Brown*, 1998].

[48] For skin cancer, the epidemiological data is from an ecological study by *Tseng et al.* [1968] and *Tseng* [1977] covering 40,421 persons in the southwest coastal area of Taiwan. In this area, wells with high arsenic concentrations had provided drinking water for more than 60 years. The types of skin cancer observed are intraepidermoid, epidermoid, and basal cell. Other studies also have found that ingesting groundwater arsenic is associated with skin cancer [*Wu et al.*, 1989; *Chen and Wang*, 1990; *Cuzick et al.*, 1992; *Hopenhayn-Rich et al.*, 1996; 1998, *Smith et al.*, 1992, 1998].

[49] For internal cancers, the epidemiological data is from an ecological study covering 898,806 person-years from 1973 to 1986 in the same region of southwest Taiwan. *Chen et al.* [1985] and *Wu et al.* [1989] describe the survey. The types of internal cancers observed are lung, bladder, liver, and kidney. Other studies also have found that ingesting groundwater arsenic is associated with internal cancers [*Steinmaus et al.*, 2000; *Chen and Wang*, 1990; *Guo et al.*, 1997; *Hopenhayn-Rich et al.*, 1996, 1998; *Smith et al.*, 1992, 1998; *Cuzick et al.*, 1992; *Tsuda et al.*, 1995; *Bates et al.*, 1995].

[50] Estimating dose response functions from the Taiwanese data is difficult because the studies do not provide individual risk assessments (e.g., a list of ingested arsenic concentration, age, and gender for each participant). Moreover, arsenic concentrations are measured only in some of the wells used by participants (223 wells in the skin-cancer data and 155 wells in the internal-cancer data). For most villages, concentration is measured in only one well, and the measured value is a proxy for the exposure of individuals who obtain drinking water from any well in the village. But when concentrations are measured in more than one well within a village, the values show extreme variability within the village, much like the variability observed in Bangladesh.

[51] *Brown and Chen* [1995] and *Brown et al.* [1997a, 1997b, 1989] discuss these and other limitations of the Taiwanese skin and internal cancer data. They show, e.g.,

that it is extremely difficult to use the data to extrapolate dose response functions to low arsenic concentrations. The dose response models obtained from the Taiwanese data should provide better estimates of cancer rates in Bangladesh, where arsenic concentrations are high, than in the US where cancer rates must be extrapolated to low arsenic concentrations. Other researchers have also examined weaknesses in dose response models based on the Taiwanese data; e.g., *Morales et al.* [2000] show that dose response functions of different parametric forms can lead to quite different estimates of cancer incidence, and *NRC* [1999] shows that risk estimates are sensitive to how the data is grouped and to which arsenic concentrations are included in the data.

4.3. Dose Response Functions for Arsenicosis

[52] Here, we estimate for each gender dose response functions that relate prevalence ratios of hyperpigmentation and keratosis to arsenic concentration. To our knowledge, these are the first reported parametric dose response models for arsenicosis. We use data from the survey by *Mazumder et al.* [1998b] that covers 7683 participants in West Bengal and which is the only survey of arsenicosis that provides data stratified by arsenic concentration and age for a wide range of ages (survey by *Tondel et al.* [1999] in Bangladesh only considers individuals over 30 years of age). Observed prevalence ratios are reported for each combination of the following: two types of arsenicosis (hyperpigmentation and keratosis), gender, eight intervals of arsenic concentration, and seven intervals of age.

[53] For each type of arsenicosis and gender, the prevalence ratios are increasing with arsenic concentration for any fixed age. To illustrate, the age-adjusted prevalence ratios of keratosis for males increase from 0.2% for concentrations less than 50 μg/L to 10.7% for concentrations more than 800 μg/L and for females increase from 0% to 8.3% over the same concentration intervals. However, the prevalence ratios do not increase with age for fixed concentrations; the greatest prevalence ratios occur for intermediate age intervals. Rather than estimating nonmonotonic dose response functions, we use age-adjusted data and estimate prevalence ratios as a function of arsenic concentration alone. For each type of arsenicosis and gender, we estimate a dose response function of the quadratic-exponential form:

$$p(c) = 1 - \exp\left(-\left(q_1 c + q_2 c^2\right)\right) \tag{3}$$

where $p(c)$ denotes the fraction (prevalence ratio) of the gender with the type of arsenicosis, c [μg/L] denotes arsenic concentration, and the parameters q_1, q_2 are nonnegative.

[54] Table 3 reports estimated parameter values q_1, q_2 for the two types of arsenicosis and the two genders. The parameter values were calculated by minimizing the sum over the intervals of arsenic concentration of the squared deviations between a calculated prevalence ratio implied by the parameters q_1, q_2 and an age-adjusted prevalence ratio reported in Mazumder et al.

[55] To obtain calculated prevalence ratios for the eight intervals of arsenic concentration used in the Mazumder et al. data set, we first estimate a distribution of arsenic concentration in each of the intervals. Rather than estimating the distribution in an interval by a point concentration, we estimate it by a conditional distribution. We define the conditional density function $f_{a,b}(c)$ for arsenic concentration in an interval from a to b as:

$$f_{a,b}(c) = f(c) / \int_a^b f(c)dc \tag{4}$$

where $f(c)$ is the unconditional density function for arsenic concentration. Then, the estimated prevalence ratio for an arsenic-concentration interval is the expected value of the prevalence ratio with respect to the conditional density function (4) for the interval, that is:

$$\int_a^b p(c) f_{a,b}(c)dc = \int_a^b p(c) f(c)dc / \int_a^b f(c)dc \tag{5}$$

To use (4), (5), we need to model the density function $f(c)$ for the distribution of arsenic concentration over the 7,683 participants in the Mazumder et al. survey. Since the Mazumder et al. the survey does not report this distribution, we approximate it by the sample distribution of exposure for Bangladesh as defined in section 3.1 (which excludes areas such as Dhaka with its nondetection wells). For computational tractability, we fit the sample distribution of exposure by a lognormal distribution, and we define $f(c)$ as the density function for this parametric distribution. From the mean and variance of the sample distribution, we calculate for $f(c)$ the parameter values $\mu = 1.6100$ log-μg/L and $\sigma = 0.5123$ log-μg/L.

[56] A dose response function for hyperpigmentation or for keratosis for both genders is a weighted average:

$$p(c) = 0.515\, p_m(c) + 0.485\, p_f(c) \tag{6}$$

where $p_m(c)$ and $p_f(c)$ are the dose response functions for males and females and the weights are calculated from the *BBS* [1996] census as described in section 3.1.

[57] In applying dose response functions (3) and (6) to Bangladesh, we assume the following: (1) The exposure periods in West Bengal, i.e., the numbers of years since groundwater wells were installed, are approximately the same as the present exposure periods in Bangladesh, roughly 0–30 years (section 5.1 discusses the issue of estimating arsenicosis prevalence ratios for lifetime exposure.), (2) All cases of arsenicosis are due to drinking groundwater with dissolved arsenic (e.g., arsenic from food is negligible), (3) There is no threshold concentration below which arsenicosis does not occur, and (4) The susceptibility to arsenicosis is about the same for people in Bangladesh as for people in West Bengal.

Table 3. Parameter Values for Hyperpigmentation and Keratosis

	q_1	q_2	MSE[a]
	Hyperpigmentation		
Male	2.678×10^{-4}	0	2.82×10^{-3}
Female	1.217×10^{-4}	0	1.16×10^{-3}
	Keratosis		
Male	1.223×10^{-4}	0	6.81×10^{-4}
Female	6.416×10^{-5}	2.717×10^{-9}	4.19×10^{-5}

[a]MSE is the sum of squared differences between the observed and predicted prevalence ratios divided by eight arsenic concentration intervals.

[58] Mazumder et al. found participants with both hyperpigmentation and keratosis. Most people with some type of arsenicosis had only hyperpigmentation, fewer had only palmar/plantar keratosis, and far fewer had both (Hoque, personal communication, 2001). For summary purposes, we measure arsenicosis cases as the sum of hyperpigmentation cases and keratosis cases.

4.4. Dose Response Functions for Arsenic-Induced Cancers

[59] *Brown et al.* [1989] and the *U.S. EPA* [1988] have estimated dose response functions for skin cancer. They use data from the study by *Tseng et al.* [1968, 1977] in Taiwan to estimate for each gender the prevalence ratio of skin cancer as a function of arsenic concentration and age.

[60] *Chen et al.* [1992] and *NRC* [1999, 2001] have estimated dose response functions for internal cancers. They use data from the Taiwanese study described by *Chen et al.* [1985] and *Wu et al.* [1989] to estimate incidence rates of arsenic-induced internal cancers (fractions of people who die of the type of cancer per year). Chen et al. estimate lung, bladder, liver, and kidney cancers while the NRC estimate only the first three types of internal cancers.

[61] Here, we apply to Bangladesh the dose response functions for skin cancer estimated by Brown et al. and the dose response functions for lung, bladder, and liver cancers estimated by the NRC. In both cases, the survey data shows that the risk of cancer is increasing with age and the dose response functions are modeled as functions of age as well as arsenic concentration.

[62] Brown et al. estimate for each gender a dose response function that predicts the prevalence ratio of arsenic-induced skin cancer as a function of arsenic concentration and age. They use a multistage dose response model of the parametric form:

$$p(c,t) = 1 - \exp\left(-(q_1 c + q_2 c^2)\cdot (t-m)^k H(t-m)\right) \qquad (7)$$

where $p(c, t)$ denotes a fraction of people with skin cancer, c [μg/L] denotes arsenic concentration, and t [yr] denotes age. Here, H denotes the Heaviside function, namely, $H(t - m) = 0$ for $t < m$ and $H(t - m) = 1$ for $t \geq m$, and the parameters q_1, q_2, k, m are nonnegative.

[63] The NRC estimates for lung, bladder, and liver cancer and each gender a dose response function that predicts the incidence rate of arsenic-induced cancer as a function of arsenic concentration and age. They use a dose response model related to (7) of the form:

$$h(c,t) = k\left(q_1 c + q_2 c^2\right)(t-m)^{k-1} H(t-m) \qquad (8)$$

where $h(c, t)$ denotes an incidence rate and the variables and parameters are defined as in (7).

[64] Table 4 shows the parameter values q_1, q_2, k, m in (7) that Brown et al. estimate for skin cancer for each gender and the values q_1, q_2, k, m in (8) that the NRC estimates for lung, bladder, and liver cancers for each gender. Both studies use estimated or observed cancer frequencies for categories defined by intervals of arsenic concentration and age and use a maximum-likelihood model with point estimates for the distributions of concentration and age in the data intervals.

Table 4. Parameter Values for Skin and Internal Cancers[a]

	q_1	q_2	k	m
		Skin Cancer		
Male	7.936×10^{-10}	1.640×10^{-12}	2.950	6.873
Female	6.291×10^{-11}	3.265×10^{-13}	3.231	9.000
		Lung Cancer		
Male	1.4672×10^{-11}	0	3.9195	21.4946
Female	0	6.1194×10^{-14}	3.5137	17.0978
		Bladder Cancer		
Male	0	7.3394×10^{-17}	5.1306	14.7025
Female	0	2.2225×10^{-13}	3.4732	33.0365
		Liver Cancer		
Male	3.6947×10^{-14}	4.9984×10^{-13}	2.9054	16.8998
Female	2.8015×10^{-8}	4.9395×10^{-13}	2.7282	25.9420

[a]Estimated by *Brown et al.* [1989] and *NRC* [1999, 2001].

[65] We obtain dose response functions of arsenic concentration (but not age) by averaging a dose response function (7) or (8) over the distribution of ages in Bangladesh for males or females. We model an age distribution as an exponential distribution with parameter λ, and thus the age-adjusted dose response functions are:

$$p(c) = \int_0^\infty p(c,t)\lambda\exp(-\lambda t)dt, \quad h(c) = \int_0^\infty h(c,t)\lambda\exp(-\lambda t)dt \qquad (9)$$

Based on the 1991 BBS census, the average ages of males and females are 23.10 yr. and 22.23 yr., and thus $\lambda = 0.04329$ for males and $\lambda = 0.04498$ for females. A dose response function for both genders is a weighted average of age-adjusted dose response functions (9) as described in (6).

[66] Brown et al. assume a zero background prevalence of skin cancer in the survey area of southwest Taiwan. Evidence in support of this assumption is a survey reported by *Tseng et al.* [1968] of 7500 people on an island near the survey area who were not exposed to groundwater arsenic and who showed no cases of skin cancer. However, the NRC estimate dose response functions for the background incidence of internal cancers and for the total incidence at a given arsenic concentration. They obtain function (8) by subtracting a background dose response function from a total dose response function. It is in this sense that function (8) estimates the incidence of an arsenic-induced internal cancer.

[67] In applying to Bangladesh dose response functions for cancers based on the Taiwanese data, we make the following assumptions: (a) The susceptibility of the detection-level population in Bangladesh to arsenic-induced cancers at a specific arsenic concentration is approximately equal to that of the survey population in southwest Taiwan, (b) The Taiwanese population was exposed to arsenic concentrations that were constant over time, and (c) The Bangladeshi population will continue to be exposed to present arsenic concentrations.

[68] The major difference between the situation in southwest Taiwan at the time the surveys were conducted there and the situation in Bangladesh at present is that the Taiwanese had been exposed to groundwater arsenic over a long period, throughout their lifetimes for most people

Table 5. Health Effects in Bangladesh for Nonintervention[a]

	Male	Female	Both
Prevalence of arsenicosis (numbers of persons)			
Hyperpigmentation	870,500 (1.35%)	381,200 (0.63%)	1,251,700 (1.00%)
Keratosis	406,700 (0.63%)	205,600 (0.34%)	612,300 (0.49%)
Prevalence of skin cancer (numbers of persons)	98,800 (0.15%)	26,800 (0.04%)	125,600 (0.10%)
Incidence of internal cancers (fatalities per year)			
Lung cancer	1,410 (2×10^{-3} %/yr)	430 (7×10^{-4} %/yr)	1,840 (1×10^{-3} %/yr)
Bladder cancer	520 (8×10^{-4} %/yr)	380 (6×10^{-4} %/yr)	900 (7×10^{-4} %/yr)
Liver cancer	400 (6×10^{-4} %/yr)	110 (2×10^{-4} %/yr)	510 (4×10^{-4} %/yr)
Three types (totals)	2,330 (4×10^{-3} %/yr)	920 (2×10^{-3} %/yr)	3,250 (3×10^{-3} %/yr)

[a]Percents shown in parentheses.

while the Bangladeshis have been exposed over a limited period, less than 20 years for most people. Thus the dose response functions that we apply evaluate the prevalence and incidence of cancers for the scenario of lifetime exposure. In section 5.1, we discuss the extent to which these evaluations may overestimate the prevalence and incidence of cancers for the scenario of present exposure.

5. Evaluation of Health Effects

5.1. Evaluation of Health Effects for Nonintervention

[69] Here, we evaluate the health effects of exposure to groundwater arsenic in its present concentrations. The measurement units and health effects are: population prevalence amounts (numbers of people) of hyperpigmentation, keratosis, and skin cancer, and population incidence rates (fatalities per year) of lung, bladder, and liver cancers. First, we evaluate the health effects for each gender and for both genders for each of the 34 geologic-geomorphic regions (Table 2), and second we evaluate the same quantities for all of Bangladesh by summing the regional evaluations (Table 5).

[70] Each regional evaluation is calculated as follows. Section 3.1 estimates for each of the 34 geologic-geomorphic regions a finite distribution of exposure to groundwater arsenic. For a region, suppose that c denotes a sample arsenic concentration and n_c denotes the estimated number of people who are exposed to that concentration. We combine this distribution with a dose response function $p(c)$ or $h(c)$ to estimate a prevalence amount or an annual incidence rate for the region, that is:

$$\text{prevalence amount} = \Sigma_c n_c p(c), \quad \text{incidence rate} = \Sigma_c n_c h(c) \tag{10}$$

Then, as mentioned above each national evaluation is calculated by summing regional evaluations over the 34 regions.

[71] The estimates of health effects in Tables 2 and 5 are the pivotal results for public policy in this paper. We estimate for Bangladesh about 2 million cases of hyperpigmentation and keratosis (arsenicosis), about 125,000 cases of skin cancer, and 3000 deaths per year from internal cancers. Health outcomes of all types are about twice as frequent for males as for females.

[72] The evaluations of health effects are point estimates. Below, we identify the assumptions that underlie the estimates, and in section 6.1 we discuss these and other sources of uncertainty as to the veracity of the estimates.

[73] 1. The future geographic distribution of arsenic concentration in Bangladesh will be the same as that found by *DPHE et al.* [1999] and *BGS and DPHE* [2001]. Of concern here is the possibility that dissolved arsenic concentrations may change in ways and for reasons that are presently unknown. For instance, agricultural practices or lower groundwater tables could possibly result in different arsenic concentrations in the future.

[74] 2. The demographics of Bangladesh are those reported by the Bangladesh Bureau of Statistics [*BBS*, 1996] based on the 1991 census of Bangladesh. As future demographic information becomes available on the level of the thanas, it can be used in place of the 1991 BBS census data to estimate the distribution of arsenic concentration over people in each of the 34 regions. As the rural population of Bangladesh increases, more people will be exposed to arsenic for a fixed geographic distribution of arsenic concentration.

[75] 3. The durations of exposure to arsenic at the present time in Bangladesh is the same as the durations of exposure in the West Bengal population surveyed by *Mazumder et al.* [1998b]. The dose response functions for hyperpigmentation and keratosis that we estimate from the Mazumder et al. survey are intended to predict prevalence ratios due to present exposure to arsenic (i.e., exposure from well installation to the present time). Prevalence ratios due to lifetime exposure most likely are greater. We conjecture that prevalence amounts of hyperpigmentation and keratosis due to present exposure are almost as much as those due to lifetime exposure. The reason is that latency periods for arsenicosis seem to be years rather than decades. Latency periods for arsenicosis as short as 6 months have been reported in China [*Lianfang and Jianzhong*, 1994] and as long as 5–10 years in Bangladesh [*Mazumder et al.*, 1998b; *Milton and Rahman*, 1999].

[76] 4. Lifetime exposure in Bangladesh is the same as the durations of exposure in the southwest Taiwan population surveyed by *Tseng et al.* [1968, 1977], *Chen et al.* [1985], and *Wu et al.* [1989].

[77] As mentioned in section 4.2, people in the Taiwanese survey areas had ingested arsenic from groundwater wells for at least 60 years and most likely over their lifetimes. The dose response functions for arsenic-induced skin and internal cancers that *Brown et al.* [1989] and *NRC* [1999] estimate from the surveys are intended to predict cancer frequencies due to lifetime exposure to arsenic. Groundwater wells in Bangladesh have been installed during the past 30 years, and thus frequencies of cancers due to the present exposure most likely are not as great.

[78] We conjecture that unlike the case of arsenicosis there is a substantial difference between the frequencies of arsenic-induced cancers for lifetime exposure and for present exposure. The reason is that that the latency periods for cancers (especially internal cancers) can be decades [*Alain*, 1993]. Under this conjecture, the prevalence of skin cancer and the incidences of internal cancers will increase over time and approach the frequencies evaluated for lifetime exposure.

5.2. Evaluation of Health Effects for the Deep-Well Remedy

[79] The BGS and DPHE survey data indicates that deeper wells may have much lower arsenic concentrations, especially in areas of high concentrations, and thus drilling deeper wells in selected areas of Bangladesh may reduce arsenic concentrations in well water by substantial amounts. This notion is widely believed in Bangladesh, and shallow wells with high arsenic concentrations are being replaced by deep wells (~150 m) on an ad-hoc, privately financed basis, at least in the Munshiganj district where we have worked.

[80] As an example of a public health policy of installing deeper wells, consider the following deep-well remedy. In each of the 11 geologic-geomorphic regions selected in section 2.4, every well less deep than 150 m and with an arsenic concentration above the detection limit is to be replaced by a well screened at a depth of 150 m. We estimate that this policy would mean replacing 76% of the wells in the 11-region area (31% of the wells in Bangladesh) and that the policy would affect 29.25 million people (75% of the area population and 31% of the national population).

[81] We estimate reductions in health effects for the deep-well remedy by the following steps. First, we estimate the arsenic concentration in each deeper well by using the estimated arsenic trend with depth for the region in which the well is located. Then, we recalculate the distribution of arsenic concentration over people for each of the 11 regions, and we use the modified distributions to recalculate health effects under the deep-well remedy. The resulting estimates assume that demographics and arsenic concentrations remain constant over time.

[82] Table 6 reports evaluations of health effects for the deep-well remedy, and Table 7 reports the consequent reductions (benefits) in health effects as compared to the nonintervention policy. Table 7 shows that the deep-well remedy could substantially reduce the health effects due to dissolved arsenic in groundwater wells. As compared to the nonintervention policy, using deep wells in the 11 selected regions provides reductions in every type of health effect: an 87% to 94% reduction in the 11 regions with the deep wells, and a 63% to 74% reduction nationally.

Table 6. Health Effects for the Deep-Well Remedy[a]

	11 Regions	National
Prevalence of arsenicosis[b]	168,400 (0.44%)	689,400 (0.55%)
Prevalence of skin cancer[c]	7,300 (0.02%)	36,800 (0.03%)
Incidence of internal cancers[d]	150 (4×10^{-4} %/yr)	860 (7×10^{-4} %/yr)

[a]Data are for both genders. Percents of 11 regions or national population are in parentheses.
[b]Hyperpigmentation plus keratosis. Units are numbers of persons.
[c]Units are numbers of persons.
[d]Lung, bladder, and liver. Units are fatalities per year.

Table 7. Reductions in Health Effects for the Deep-Well Remedy[a]

	11 Regions	National
Reductions in arsenicosis[b]	1,174,600 (87%)	(63%)
Reductions in skin cancer[c]	88,800 (92%)	(71%)
Reductions in internal cancers[d]	2,390 (94%)	(74%)

[a]Data are for both genders. Percents of reductions are in parentheses.
[b]Hyperpigmentation plus keratosis. Units are numbers of persons.
[c]Units are numbers of persons.
[d]Lung, bladder, and liver. Units are fatalities per year.

[83] For the deep-well remedy, we estimate monetary cost per case prevented as follows. *Ahmed* [2002] estimates an average cost of $790 to install a deep well to 250–300 m. To install a well to 150 m would cost approximately $500 (Ahmed, personal communication). The average number of persons using a well is estimated by *Shafique* [1998] as 37 and by *Quamruzzaman et al.* [2000] as 11. Based on our experiences in Munshiganj, we believe that the average number of users per well is somewhere between these two estimates.

[84] Consider the health effect of arsenicosis. In the 11-region area, there are 29,250,000 people using wells that are to be replaced, i.e., wells less than 150 m having arsenic concentrations above the detection limit (calculated from Table 2), and the deep-well remedy will prevent 1,174,600 cases of arsenicosis among this population (Table 7). Thus each person in the population has a probability of 1,174,600/29,250,000 = 0.04 of avoiding arsenicosis because of the deep-well remedy. It follows that the cost per arsenicosis case prevented is between $500/(37 \times 0.04) = \$340$ and $500/(11 \times 0.04) = \$1,130$. These amounts are the cost per benefit, excluding cancers prevented, for the deep-well remedy as compared to the nonintervention policy. Cost per benefit amounts can also be calculated for other potential remedies, e.g., rainwater harvesting and home filter units.

[85] In spite of these cost-benefit assessments, the use of deep wells as a remedy should be considered with caution. One concern is that deep wells must be installed properly. If a well bore is not adequately sealed, shallower water is likely to be drawn down through the annulus around the casing, thereby directly transporting arsenic dissolved in the water into deeper regions or introducing chemical and biological constituents that could mobilize solid-phase arsenic from deep sediments. However, most wells in Bangladesh are installed by indigenous methods; e.g., expanding clays such as those used in western countries are not readily available and thus often are not used, and cement often is not used. A second concern is that arsenic concentrations could increase in deep aquifers after the wells have been installed. Conceivably, increased pumping could draw arsenic into deeper aquifers or could cause geochemical changes that would mobilize arsenic. These issues should be understood before undertaking a national program.

[86] The deep-well remedy should be regarded as a simple version of such remedies in that it involves replacing all the wells in the 11-region area by wells screened at 150 m. Other versions could be proposed in which only some wells in the 11 regions are replaced and perhaps wells in other regions are also considered for replacement. Such a partial deep-well remedy could be combined with the

remedy suggested by *van Geen et al.* [2002] of changing the behavior of Bangladeshi villagers so that they obtain drinking water from the well in their village having the lowest arsenic concentration.

5.3. Local Data on Arsenicosis and Arsenic-Induced Cancers

[87] The estimated prevalence ratio of 1.49% for arsenicosis in Bangladesh (Table 5) can be compared with those reported in other studies from Bangladesh and West Bengal. Table 8 shows 11 such prevalence ratios listed according to the number of participants in the study. The first 3 studies have more than 100,000 participants and the other 8 studies have fewer than 20,000. The prevalence ratios range from 0.13% to 0.28% in the 3 large-participant studies and range from 10.0% to 99.0% in the 8 small-participant studies. Thus the prevalence ratio of arsenicosis that we estimate is between the two clusters of prevalence ratios reported in these field studies.

[88] The large prevalence ratios of arsenicosis reported by the small-participant studies may be due to the surveys being conducted in arsenic-affected villages where the problem was known to be severe. And the small prevalence ratios of arsenicosis reported in the large-participant studies may be due to difficulties in field diagnosis; e.g., many villagers who had arsenical skin lesions may not have manifested symptoms sufficient to be diagnosed or may not have made themselves available for diagnosis.

[89] Comprehensive studies of arsenic-induced cancers in Bangladesh or West Bengal have not been conducted to date. Since internal cancers have the same appearance whether they are background or arsenic-induced, surveys of such cancers would need to be statistical. It should be possible, however, to diagnose cases of arsenic-induced skin cancer. The lack of confirmed cases might be due in part to the latency periods for cancer. The occurrence of arsenic-induced skin and internal cancers is well established in Taiwan where people were exposed to arsenic far longer than the people in Bangladesh were at present. Hence we expect that if present concentrations of arsenic persist in Bangladesh field studies there will show substantial occurrences of arsenic-induced cancers.

6. Uncertainty

[90] Here, we examine uncertainty in the point estimates of population prevalence amounts and population incidence rates that section 5.1 presents for the nonintervention policy and section 5.2 presents for the deep-well remedy. The discussion provides a reappraisal of the information and assumptions underlying the health evaluations. Just as we have exercised judgment in the choices of data and models, here we offer judgments as to the accuracy of the resulting evaluations. Many researchers have investigated methods to deal with uncertainties in risk and exposure assessments [*Bogen and Spear*, 1987; *Bogen*, 1995; *Brand and Small*, 1995; *Morgan and Henrion*, 1990]. However, most deal with risk assessment at a level of sophistication not possible with the available data for this problem (e.g., *Bogen* [1995] deals with combined probability distributions on exposure uncertainty and individual inter-variability).

[91] Each health evaluation is calculated from the following types of information: (1) physical distribution of arsenic concentration over the groundwater wells that are used for drinking water (present wells or present wells replaced in part by deep wells), (2) demographic distribution of arsenic concentration over the Bangladeshi population, and (3) dose response functions, each of which expresses the risk of a health effect for a gender or for both genders as a function of arsenic concentration. Below, we consider in turn each type of information 1–3.

Table 8. Prevalence Ratios of Arsenicosis Reported by Recent Studies[a]

Study	Number of Participants	Prevalence Ratio
Quamruzzaman et al. [2000]	818,294	0.28%
BRAC [2000], Sonargaon	165,000 (estimated)	0.15%
BRAC [2000], Jhikargachha	115,000 (estimated)	0.13%
SOES/DCH [2000]	17,896	20.6%
Chowdhury et al. [2000]	11,180	24.5%
Ahmad et al. [1999]	3,606	10.0%
Dhar et al. [1997]	1,630	57.5%
Tondel et al. [1999]	1,481	29.0%
Biswas et al. [1998]	600	55.0%
Ahsan et al. [2000]	167	21.6%
AAN [1999]	135	99.0%

[a]Listed by number of participants.

6.1. Concentrations of Arsenic in Well Water

[92] First, consider the nonintervention policy. The BGS and DPHE data set that we selected provides arsenic measurements in 4140 of the millions of existing wells. The accuracy in estimating the distribution of arsenic concentration in the population of existing wells from the concentrations in the sample wells depends on the degree to which the sample wells are representative of the existing wells and on the absolute number of sample wells but not on the relative number of sample wells. We judge that the number of sample wells is adequate and that the sample is representative based on the sampling strategy adopted by the BGS and DPHE [*DPHE et al.*, 1999].

[93] A much greater uncertainty, we believe, lies in the distribution of arsenic concentration over time. Have concentrations been constant over time or have they changed over time, perhaps in part as a consequence of recent introduction of massive irrigation pumping? We simply do not know whether hydrologic and geochemical processes may change arsenic concentrations in the future [*Harvey*, 2001; *Harvey et al.*, 2002; *Nickson et al.*, 1998; *McArthur*, 1999; *Acharyya et al.*, 1999; *Chowdhury et al.*, 1999]. The estimated health effects are based on the uncertain assumption that future concentrations (in the absence of a remedy) will be the same as those at present.

[94] Second, consider the deep-well remedy of replacing in 11 selected regions all wells less than 150 m deep by wells screened at 150 m. We estimate the arsenic concentration in a new, deep well as the concentration in the present, shallow well plus the regional depth slope times the change in-depth. Thus the uncertainty in arsenic concentration for a deep well is that for the shallow well plus that for the regional depth slope times the depth change. The concentration in the shallow well and the depth change are accurately measured whereas the regional depth slope is highly uncertain for several reasons: (1) There may be only a small number of sample wells in the region. (2) The depth trend at the shallow well may be appreciably different from

the regional depth trend. (3) The true dependence of arsenic concentration on depth in the region may be highly nonlinear, perhaps due to the presence of two overlapping aquifers in the region.

[95] There are yet other sources of uncertainty. Section 5.2 describes the problem of installing deep wells properly. If wells are not properly constructed or sealed, arsenic concentrations may or may not rise due to leakage of dissolved arsenic or other chemical constituents down the well bore. And there is the perplexing question of whether arsenic concentrations will change over time in the deep aquifer. Will the use of deeper wells, quite possibly the extracting of water from a deeper aquifer, cause the concentrations in these wells to increase over time? These questions are not yet answered.

6.2. Numbers of People Who Are Exposed to Various Arsenic Concentrations

[96] We estimate the numbers of people using the various groundwater wells in Bangladesh by combining the BGS and DPHE data with demographic data based on the Bangladesh census in 1991, the last year for which data on the level of thanas is available. Thus uncertainty in the estimates of exposure to groundwater arsenic is due to how well people are assigned to wells by the procedure described in section 3.1 and how well the census data describes the present and future populations of Bangladesh. Errors in assigning people to wells will tend to cancel one another, and thus the greater uncertainty is most likely due to the demographic estimates.

[97] The *CIA* [2001] estimates that Bangladesh has an annual growth rate of 1.6%. Assuming this growth rate throughout Bangladesh during the 11-year period 1991–2002, the population in 2002 has increased by about 20%, and thus the present health effects are 20% greater than those estimated. Moreover, the health effects will increase in the future if the population continues to increase. Uncertainty may lay not so much in the growth rate as in its geographic uniformity; for example, will most of the growth occur in Dhaka where arsenic concentrations are low and not in rural areas where concentrations are high?

6.3. Dose Response Functions for Health Effects

[98] Uncertainties in the dose response functions are distinct from and indeed are stochastically independent of uncertainties in the geographical distribution of dissolved arsenic in Bangladesh or in the exposure of people to the arsenic. We distinguish between two sources of uncertainty in a dose response function: (1) uncertainty regarding its accuracy for the sample population of West Bengal or Taiwan, and (2) additional uncertainty as to its accuracy for the target population of Bangladesh.

[99] Uncertainty of type 1 depends on the accuracy of measurements in a sample population, here the participants in a West Bengal or southwest Taiwan survey. *NRC* [1999, 2001], *Brown and Chen* [1995], and *Brown et al.* [1997a, 1997b, 1989] discuss limitations with the Taiwanese data set. In both cases, the data sets were frequency counts of people with or without a health effect in categories defined by gender and by intervals of age and arsenic concentration. More accurate measurements could be made by obtaining data sets of individual risk assessments. Such a data set could contain, e.g., a total number of participants together with distributional information on gender, age, and arsenic concentration (possibly not assumed to be independent) and for each participant with the health effect a record of gender and point values of age and arsenic concentration.

[100] The applicability of such an epidemiological study would be enhanced if it were conducted in Bangladesh. And such a study would be further enhanced if it searched for and included any arsenic-induced health effects not evaluated in this paper. For example, people in Bangladesh may be susceptible to noncancer health effects in addition to hyperpigmentation and keratosis (such as Blackfoot's disease [see, e.g., *Tseng et al.*, 1968; *Tseng*, 1977] and hypertension [see, e.g., *Rahman et al.*, 2001]), and they may be susceptible to internal cancers (such as kidney [see, e.g., *Chen et al.*, 1992; *Wu et al.*, 1989]) in addition to lung, bladder, and liver cancers. Moreover, there may be fatalities due to skin cancer; indeed, *Byrd et al.* [1996] state that about 10% of arsenic-induced, skin-cancer cases eventually result in fatality.

[101] Uncertainty of type 2, that is, uncertainty as to the applicability to Bangladesh of the dose response functions in sections 4.3, 4.4, will be due to differences in susceptibility between people in the West Bengal and Taiwan surveys and people in Bangladesh, e.g., differences in nutritional or genetic factors. For instance, for arsenicosis we use age-adjusted prevalence ratios reported in the Mazumder et al. survey. In doing so, we assume that the target population of Bangladesh has the same age distribution and the same susceptibility across this distribution as the sample population in West Bengal.

[102] *Smith* [2001] argues, however, that global differences in susceptibility to arsenic poisoning are small relative to other sources of epidemiological uncertainty. For example, are exposure pathways similar between the Bangladeshi population and those surveyed in West Bengal and Taiwan? *Naidu et al.* [2002] examine the various arsenic exposure pathways in Bangladesh and suggest that irrigation with arsenic contaminated groundwater may be an additional exposure pathway.

[103] The grouping of data from a sample population into intervals causes not only uncertainty in a dose response function but also uncertainty in its applicability to Bangladesh. Do the sample and Bangladesh populations have the same distribution of age or arsenic concentration in each of the age or arsenic concentration intervals that the data was grouped into? We expect that residual uncertainty of this type is less than the uncertainty caused by differences in susceptibility due to factors such as nutrition and genetic predisposition for which no data is available.

[104] We do not present error bars for the estimated parameters in the dose response functions. One reason is that uncertainty in the dose response parameters most likely has less influence on uncertainty in the health effects than other sources of uncertainty (e.g., arsenic changes over time). A second reason is that uncertainty in parameters does not fully determine uncertainty in the application of a dose response function. As has been discussed, applying dose response functions based on West Bengal and Taiwanese populations to a Bangladeshi population can be problematic. *NRC* [2001] highlights the difficulty of applying findings in Taiwan to the population in the U.S. However, the dose response functions estimated here should be far

more accurate when applied to Bangladesh, where arsenic concentrations are similar to those in the sample populations of West Bengal and Taiwan, than when applied to the U.S., where most arsenic concentrations are quite low and thus there is substantial extrapolation error.

6.4. Difficulties Quantifying Uncertainty

[105] The above discussion suggests that the most influential sources of uncertainty cannot be quantified by statistical analysis of existing data. Uncertainty about sources such as changes in arsenic concentration over time and the applicability of dose response functions cannot be quantified by statistical analysis of existing data on arsenic concentrations in Bangladesh or by analysis of parameters in existing dose response functions. We could report, e.g., confidence intervals for the mean and variance of the distribution of arsenic concentration in Bangladesh or error bars for the estimated parameter values in the dose response functions, but we believe that such confidence intervals and error bars would have a greater potential to be misleading than to provide insight, primarily because the random errors that they represent have far less influence on uncertainty in the estimates of health effects than the influence of the bias errors discussed above.

7. Conclusions

[106] This paper combines surveys of arsenic concentrations, census data, and epidemiological studies to estimate arsenic-induced health effects and to map the estimated health effects over Bangladesh. Moreover, we use this framework to evaluate the benefit of a potential remedy, that of drilling deeper wells in 11 selected geologic-geomorphic regions.

[107] The primary conclusions of the paper are as follows.

[108] 1. Most of the large-scale (>10 km) lateral structure in arsenic concentrations in Bangladesh is explained by differences in geology and geomorphology. We separate the country into 34 regions based on maps of the geology and geomorphology of Bangladesh and show that mean arsenic log concentrations in contiguous regions are statistically different. Subtracting regional means in arsenic log concentration from the BGS and DPHE data set reduces the variance in log concentration from 1.6 to 1.0 $(\log\text{-}\mu g/L)^2$, reduces the variance change due to large-scale structures from 1.14 to 0.71 $(\log\text{-}\mu g/L)^2$, and reduces the correlation scale from 24.1 to 6.9 km. These reductions are consistent with the notion that the geologic and geomorphic environments partially control the large-scale variability of arsenic concentrations observed.

[109] 2. For most regions, the BGS and DPHE data support the hypothesis that arsenic concentrations are less in deeper wells. However, some regions may lack sufficient data, particularly from deep wells, to show a vertical trend and other regions may in fact have zero or even a positive depth trend. The regions with significant negative depth trends are generally the same as those in which arsenic concentrations are highest (and thus a remedy could achieve the greatest reduction in health effects). In many parts of the country, the depth trend may be due to a shallow aquifer with high arsenic concentrations separated from a deep aquifer where concentrations are presently low.

[110] 3. A substantial part of the small-scale (<3 km) variability between wells is due to variations in well depth and to the presence of a depth trend, generally decreasing with depth. Removing the regional depth trends from the 17 regions in which they are significant reduces the nugget variance from 0.36 to 0.14 $(\log\text{-}\mu g/L)^2$ but has little effect on the shape of the variogram.

[111] 4. Significant spatial structure exists at an intermediate scale (between 3 km and 10 km) that is explained neither by vertical trends nor by differences among the geologic-geomorphic regions. The variance of the data after spatial and vertical trends are removed is 0.90 $(\log\text{-}\mu g/L)^2$, which is much larger than the nugget variance of 0.14 $(\log\text{-}\mu g/L)^2$.

[112] 5. If the demographics of Bangladesh as reported by the BBS and arsenic concentrations as reported by the BGS and DPHE continue into the future, the health effects of dissolved arsenic in well water will be severe: prevalences of about 2 million cases of arsenicosis and 125,000 cases of skin cancers, and incidences of several thousand deaths from internal cancers per year.

[113] 6. The deep-well remedy has the potential to reduce the health effects of dissolved arsenic by approximately 70%, and thus should be considered as a public policy. However, it entails large uncertainties, including the following: (1) Will the deep wells be installed to prevent seepage of high-arsenic water down the well bore, (2) will arsenic concentrations at 150 m remain as at present, and (3) will a better remedy become available?

[114] Whether the deep-well remedy is advisable as a policy depends not only on estimates and uncertainties regarding its benefits and on the manner in which it is implemented but also on the institutional processes by which it is chosen. If deep-wells are installed, and new information then warrants a change of policy, how will the parties involved respond? Will there be undue criticism of or adherence to the deep-well remedy, or will the parties adapt to the new situation while recognizing that the deep-well remedy was a reasonable choice at the time it was made.

[115] In summary, this paper provides a framework to incorporate future data and to evaluate what types of data would be most valuable to obtain. We hope that the framework can be helpful both in leading to better information and in leading to timely and effective remedies for the crisis posed by dissolved groundwater arsenic in Bangladesh.

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