Research Article

# Status of groundwater arsenic contamination in the state of West Bengal, India: A 20-year study report

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Since 1988 we have analyzed 140 150 water samples from tube wells in all 19 districts of West Bengal for arsenic; 48.1% had arsenic above 10 μg/L (WHO guideline value), 23.8% above 50 μg/L (Indian Standard) and 3.3% above 300 μg/L (concentration predicting overt arsenical skin lesions). Based on arsenic concentrations we have classified West Bengal into three zones: highly affected (9 districts mainly in eastern side of Bhagirathi River), mildly affected (5 districts in northern part) and unaffected (5 districts in western part). The estimated number of tube wells in 8 of the highly affected districts is 1.3 million, and estimated population drinking arsenic contaminated water above 10 and 50 μg/L were 9.5 and 4.2 million, respectively. In West Bengal alone, 26 million people are potentially at risk from drinking arsenic-contaminated water (above 10 μg/L). Studying information for water from different depths from 107 253 tube wells, we noted that arsenic concentration decreased with increasing depth. Measured arsenic concentration in two tube wells in Kolkata for 325 and 51 days during 2002–2005, showed 15% oscillatory movement without any long-term trend. Regional variability is dependent on sub-surface geology. In the arsenic-affected flood plain of the river Ganga, the crisis is not having too little water to satisfy our needs, it is the crisis of managing the water.

**Keywords:** Arsenic contamination in West Bengal / Arsenic in tube wells / Combating the arsenic crisis / Population at risk / Sub-surface geology

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## 1 Introduction

Groundwater arsenic contamination and its health effects in South-East Asian countries came to limelight during the last decade [1]. Bangladesh, India (School of Environmental Studies: www.soesju.org, Lex van Geen, Lamont-Doherty Earth Observatory, Columbia University: http://www.ldeo.columbia.edu/~avangeen/, Richard Wilson, Department of Physics, Harvard University: http://phys4.harvard.edu/~wilson/arsenic/arsenic_project_introduction.html, Dhaka Community Hospital: http://www.dchtrust.org/) and China [2] are the worse arsenic-affected nations. At present our preliminary survey for the last 20 years in India indicates that some areas of all the states (Uttar Pradesh, Bihar, Jharkhand, West Bengal) in Ganga plain are arsenic affected and thousands are suffering from arsenic toxicity and millions are at risk [3]. The first report of arsenic groundwater contamination and its health effects in the Ganga plain from West Bengal was published in 1984 [4]. Since 1988 our team has been surveying arsenic-affected villages in West Bengal. In 1988, when we commenced our first arsenic survey in West Bengal, we knew of 22 affected villages (As >50 μg/L) over 12 blocks in five districts. Now according to our latest survey in the state, the number of affected villages has increased to a staggering 3417 in 107 blocks in some nine districts. During the last 20 years, with every additional survey we have found an increasing number of contaminated villages and more affected people from nine arsenic-affected districts. We have reported our findings in national and international journals, monographs, and book, available in our SOES website (www.soesju.org). Most of our earlier publications

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**Abbreviations**: **FI-HG-AAS**, flow injection-hydride generation-atomic absorption spectrometry; **PHED**, Public Health Engineering Department were focused on bringing forth the issue of groundwater arsenic contamination and its subsequent health effects for the villages in the nine highly affected districts of West Bengal where some groundwater contained arsenic at concentrations of 300 μg/L and above. More studies by other researchers on arsenic contamination, the source of the arsenic, and the effects of arsenic on health in West Bengal are available ([5] and in some arsenic special issues [6–8]). UNICEF, in collaboration with the Public Health Engineering Department (PHED), Government of West Bengal, tested 132 262 government installed hand tube wells and private tube wells on demand by Ag-DDTC Spectrophotometric method for arsenic from eight arsenic-affected districts of West Bengal [9]: 57.9% of tested hand tube wells showed arsenic above 10 μg/L, while 25.5% had arsenic above 50 μg/L.

The present publication reveals a complete picture of groundwater arsenic contamination situation in the state of West Bengal for the first time. The information in this report mostly includes our recent unpublished data as well as that from our previously published data. Here, we mainly focus on: (a) arsenic groundwater contamination situation in all of the 19 districts of West Bengal, on the basis of analyses by flow injection-hydride generation-atomic absorption spectrometry (FI-HG-AAS) of some 140 150 water samples from hand tube well; (b) an estimation of total hand tube wells in arsenic-contaminated and uncontaminated areas of the state; (c) the relationship between arsenic, iron concentrations and depth of tube wells; (d) an estimation of the population exposed to various arsenic concentrations in the 8 highly arsenic-affected districts of the state and estimation of the population at risk from arsenic exposure above 10 μg/L; (e) the arsenic-contamination situation in tube wells of more than 100 m in depth, a depth considered and recommended for drinking water to be safe from arsenic in the affected districts; (f) the regional variability of arsenic concentration in groundwater in relation to subsurface geology of the state; and (g) an approach to combat the present arsenic crisis.

## 2 Materials and methods

### 2.1 Study area and sampling

West Bengal (area 88 750 km$^2$; population 80.2 million) is one of the 29 states of India. Its administrative structure consists of several districts; each district has several blocks/police stations; each block has several Gram Panchayets (GPs), which are cluster of villages. There are 19 districts, 341 blocks and 37 910 villages in West Bengal. We analyzed 140 150 water samples for arsenic from 7823 villages of 241 blocks from these 19 districts of the state. We collected water samples from both contaminated and safe areas, but more samples were collected from contaminated regions. At the beginning of 1988, until 2000, we mainly collected water samples from hand tube well from nine arsenic-affected districts. For last 7 years we have collected water samples from both contaminated and uncontaminated districts to determine the arsenic contamination situation over the whole state of West Bengal. For the last 20 years, on average six persons, 10 h/day, for 4 days a month, collected water samples from all 19 districts. Water collections were taken more frequently during the winter than during the rainy season and hot summer days.

Kolkata, one district of West Bengal, is at present the largest city (area 185 km$^2$ and nighttime population 4.6 million) of eastern India. For administrative purposes it is divided into 141 wards, we have analyzed water samples for arsenic from 100 wards.

### 2.2 Collection of samples

Tube well water samples were collected (after pumping for few minutes) without filtration in 10-mL polyethylene bottles that were pre-washed with nitric acid and water (1:1). After collection, 1 drop of concentrated nitric acid:water (1:1) per 10 mL of water sample was added as preservative. The modes of water sample collection and analytical procedures were reported earlier [10].

We also collected and analyzed water samples from two tube wells, in Ward No. 96, within 200 m of our laboratory in Jadavpur University, Kolkata on 325 and 51 different days, respectively, between 2002 and 2005 to determine the temporal change of arsenic concentration during the period. The distance between these two tube wells is about 25 m; both the tube wells are 33 m deep. Samples from these two tube wells were always analyzed within 30 mins of collection. The median arsenic concentrations were 43.5 and 277.5 μg/L, respectively.

### 2.3 Instrumentation

Arsenic analysis was performed by FI-HG-AAS. For iron analysis, the 1,10-phenanthroline method was used with a UV-visible spectrophotometer. Details of the instrumentation have been described elsewhere [10].

### 2.4 Quality assurance and quality control program

For quality control, inter-laboratory tests were performed on water samples [10]. Analysis of an EPA water standard for arsenic using our technique has been reported earlier [10].

### 2.5 Statistical analysis

Standard statistical techniques were applied to analyze and present the data. To test the presence of association, a Chi-square test was used. An ANOVA was applied to test the homogeneity of arsenic concentrations.

 

**Table 1.** District-wise distribution of arsenic concentration in West Bengal

| Districts | Area in km$^2$ | Population | Total no. of blocks | No. of blocks sur-veyed | No. of blocks with As >10 µg/L | No. of blocks with As >50 µg/L | No. of samples analyzed | Distribution of total samples in different arsenic concentration (µg/L) ranges | | | | | | | | | Max. As. conc. (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | ≤3 | 4–10 | 11–50 | 51–100 | 101–200 | 201–300 | 301–500 | 501–1000 | > 1000 | |
| **Highly affected** | | | | | | | | | | | | | | | | | |
| North-24-Parganas | 4094 | 8934286 | 22 | 22 | 22 | 21 | 54368 | 22221 | 3129 | 13001 | 6403 | 5531 | 2249 | 1308 | 477 | 49 | 2830 |
| South-24-Parganas | 9960 | 6906689 | 29 | 17 | 12 | 11 | 8333 | 4407 | 427 | 1141 | 743 | 741 | 327 | 305 | 212 | 30 | 3700 |
| Murshidabad | 5324 | 5866569 | 26 | 26 | 25 | 24 | 29668 | 11471 | 2244 | 8042 | 3267 | 2366 | 941 | 884 | 382 | 71 | 3003 |
| Nadia | 3927 | 4604827 | 17 | 17 | 17 | 17 | 28794 | 11431 | 2613 | 9810 | 2265 | 1520 | 630 | 360 | 152 | 13 | 3200 |
| Maldah | 3733 | 3290468 | 15 | 14 | 13 | 9 | 4449 | 1754 | 373 | 810 | 488 | 559 | 183 | 163 | 97 | 22 | 1904 |
| Haora | 1467 | 4273099 | 14 | 12 | 12 | 7 | 1471 | 889 | 226 | 192 | 87 | 41 | 22 | 12 | 1 | 1 | 1333 |
| Hugli | 3147 | 5041976 | 18 | 17 | 16 | 11 | 2212 | 1469 | 346 | 251 | 77 | 52 | 14 | 2 | 1 | | 600 |
| Kolkata | 185 | 4572876[a] | 141[b] | 100[b] | 65[b] | 30[b] | 3626 | 2224 | 855 | 345 | 85 | 75 | 27 | 10 | 5 | | 800 |
| Bardhaman | 7024 | 6895514 | 31 | 24 | 12 | 7 | 2634 | 2091 | 79 | 244 | 86 | 89 | 27 | 11 | 6 | 1 | 2230 |
| **Subtotal** | 38861 | **50386304** | 172 | 149 | 129 | 107 | 135555 | 57957 | 10292 | 33836 | 13501 | 10974 | 4420 | 3055 | 1333 | 187 | |
| **Mildly affected** | | | | | | | | | | | | | | | | | |
| Koch Bihar | 3387 | 2479155 | 12 | 5 | 4 | 1 | 474 | 403 | 57 | 13 | 1 | | | | | | 54 |
| Darjiling | 3149 | 1609172 | 12 | 4 | 3 | 0 | 562 | 502 | 50 | 10 | | | | | | | 19 |
| Dinajpur-North | 3140 | 2441794 | 9 | 7 | 6 | 2 | 990 | 817 | 57 | 112 | 4 | | | | | | 68 |
| Dinajpur-South | 2219 | 1503178 | 8 | 6 | 2 | 1 | 452 | 398 | 47 | 6 | 1 | | | | | | 51 |
| Jalpaiguri | 6227 | 3401173 | 13 | 7 | 4 | 0 | 445 | 355 | 74 | 16 | | | | | | | 27 |
| **Subtotal** | 18122 | **11434472** | 54 | 29 | 19 | 4 | 2923 | 2475 | 285 | 157 | 6 | | | | | | |
| **Unaffected** | | | | | | | | | | | | | | | | | |
| Bankura | 6882 | 3192695 | 22 | 17 | 0 | 0 | 279 | 279 | | | | | | | | | <3 |
| Birbhum | 4545 | 3015422 | 19 | 11 | 0 | 0 | 718 | 718 | | | | | | | | | <3 |
| Purulia | 6259 | 2536516 | 20 | 15 | 0 | 0 | 314 | 314 | | | | | | | | | <3 |
| Medinipur-East[c] | 14081 | 9610788 | 25 | 10 | 0 | 0 | 182 | 182 | | | | | | | | | <3 |
| Medinipur-West | | | 29 | 10 | 0 | 0 | 179 | 179 | | | | | | | | | <3 |
| **Subtotal** | 31767 | **18355421** | 115 | 63 | 0 | 0 | 1672 | 1672 | | | | | | | | | |
| **Total** | 88750 | **80176197** | 341 | 241 | 148 | 111 | 140150 | 62104 | 10577 | 33993 | 13507 | 10974 | 4420 | 3055 | 1333 | 187 | |

a) Nighttime population ≈4.6 million. It has no block but 141 municipal wards.
b) Number of wards instead of blocks.
c) Area and population are total of Medinipur East and Medinipur West.

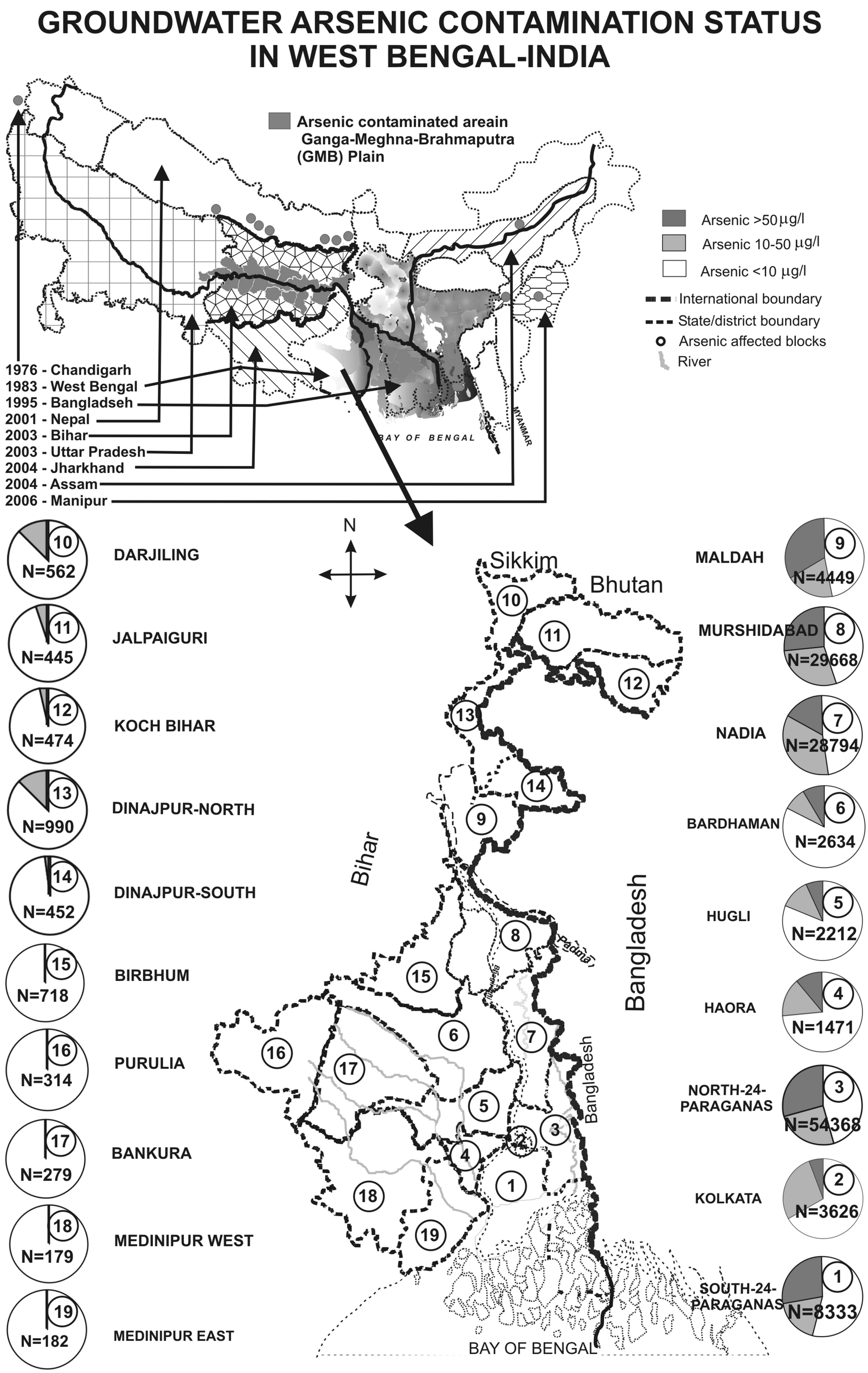


**Figure 1.** Present groundwater arsenic contamination situation in the state of West Bengal in India and in the inset the Ganga-Meghna-Brahmaputra plain.

## 3 Results and discussion

### 3.1 Groundwater arsenic contamination in West Bengal

Table 1 shows the district-wise distribution of arsenic concentrations from all the 19 districts of West Bengal based on analyses from 140 150 samples from hand tube well; 48.1% had arsenic concentrations above 10 μg/L and 23.8% above 50 μg/L. Importantly, 3.3% of the analyzed tube wells had arsenic concentrations above 300 μg/L, a concentration predicting overt arsenical skin lesions [3]. A total of 187 (0.13%) hand tube wells were found highly contaminated (>1000 μg/L). The maximum arsenic concentration (3700 μg/L) was found in Ramnagar village of GP Ramnagar II, Baruipur block, in South 24 Parganas district. This tube well was a private one and all nine members of the owners' family had arsenical skin lesions; seven other members with severe arsenical skin lesions had already died, four of them from cancer. Figure 1 demonstrates the groundwater arsenic contamination status of Ganga-Meghna-Brahmaputra plain and all 19 districts of West Bengal. Most of the highly arsenic-affected districts of West Bengal are on the eastern side of the Bhagirathi River (Fig. 1). Supporting Information Table S1 shows an overview of arsenic contamination and its health effects situation in West Bengal up to November 2007.

Based on the intensity of arsenic concentrations, we have demarcated West Bengal into three zones (Table 1): highly affected, mildly affected, and unaffected. Nine districts (Maldah, Murshidabad, Nadia, North-24-Parganas, South-24-Parganas, Bardhaman, Haora, Hugli and Kolkata), in which an arsenic concentration of >300 μg/L was found in some tube wells, are considered as highly affected. Out of 135 555 samples analyzed from these nine districts 67306 (49.7%) had arsenic concentrations above 10 μg/L, 33470 (24.7%) above 50 μg/L, and 4575 (3.4%) above 300 μg/L. Out of these nine highly affected districts, five (Maldah, Murshidabad, Nadia, North-24-Parganas, South-24-Parganas) are widely affected. In three districts (North-24-Parganas, Nadia, Murshidabad) more than 95% of the blocks had arsenic above 50 μg/L (Table 1). At present, of these nine highly arsenic affected districts, three (Haora, Hugly, Bardhaman) are on the western side of River Bhagirathi, but once the highly arsenic-affected blocks of these three districts lay on the eastern side of Bhagirathi River which then changed its couse. For this reason, these three districts are highly (particular blocks) but not widely affected.

Five districts (Koch Bihar, Jalpaiguri, Darjiling, Dinajpur-North and Dinajpur-South), showing concentrations mostly below 50 μg/L (only a few above 50 μg/L but none above 100 μg/L), are considered mildly affected. We analyzed 2923 water samples from these districts, 285 (9.8%) had arsenic concentration between 3 and 10 μg/L, 163 (5.7%) above 10 μg/L and 6 (0.2%) above 50 μg/L.

The five other districts (Bankura, Birbhum, Purulia, Medinipur East and Medinipur West) are unaffected or arsenic safe. All samples from these areas ($n = 1672$) had an arsenic concentrations below 3 μg/L (the minimum determination limit of our instrument with 95% confidence level). Our analysis of arsenic contamination in hand tube - wells from highly affected, mildly affected and unaffected districts may not be exhaustive but it is of reasonable size, and representative.

### 3.2 Groundwater arsenic in Kolkata City

Kolkata, the capital of West Bengal, is mainly an urban area. The present drinking water demand in Kolkata is around 1262 million liters per day (MLD). Metropolitan authority supply through pipeline 1209 MLD of which 1096 MLD is treated surface water and the rest is groundwater.

So far, we have analyzed 3626 samples from hand tube well water for arsenic from 100 out of 141 administrative wards in Kolkata. In 65 wards, tube wells had arsenic concentrations above 10 μg/L and in 30 wards above 50 μg/L (Table 1). We have depth information from 2034 tube wells. Out of 1057 wells deeper than 100 m, 220 (20.8%) showed arsenic concentration above 10 μg/L, 113 (10.7%) and 72 (6.8%) had arsenic above 50 and 100 μg/L, respectively. Out of 977 wells between 91 and 100 m, 149 (15.3%) had arsenic concentration above 10 μg/L, 30 (3.1%) and 13 (1.3%) had arsenic above 50 μg/L and 100 μg/L respectively; however, no tube well deeper than 300 m had arsenic above 50 μg/L. The maximum concentration was 800 μg/L at 20 m depth. Among 977 samples in the depth range 91–100 m, 771 were the roadside tube wells widely used by people for drinking water; most of these tube wells (734 out of 771) were installed by Kolkata Municipal Corporation (KMC). Our analysis shows out of 734 KMC wells 121 (16.5%) had arsenic above 10 μg/L, 26 (3.6%) above 50 μg/L and only 2 (0.2%) above 300 μg/L. The study shows that the southern part of Kolkata city is more contaminated than the northern and central parts.

### 3.3 Allowable temporal changes in arsenic concentrations

Analysis of variance of the data collected from two tube wells from Jadavpur, Kolkata, near our laboratory for 325 and 51 days during 2002–2005, confirmed the absence of any significant monthly, seasonal or annual variation. Although there were 17.5% and 14.6% oscillatory variation in arsenic concentrations in the surveyed tube wells, trend analysis (Supporting Information Fig. S1) shows an absence of any long-term trend in the data for the tube well we studied for 325 days during 2000–2005. This oscillatory variation includes 5% instrumental variation. The instrumental variations were calculated by injecting the same water sample 20 times (mean =50.28, SD =2.83, Min =46, Max =55.5 μg/L) and an EPA standard water sample (certified value 17.6 ± 2.,21 μg/L) 15 times (mean =17.6, SD =4.9, Min =16.2, Max =19.0 μg/L). We consider 15% oscillatory variation as an allowable variation. Usually, fine invisible arsenic-rich particles are present in tube well water samples [11]. The observed 15% oscillatory variation may due to the presence of these particles in tube well water. Keeping this in mind, it is necessary to rethink the coloring given to tube wells: red (unsafe) or green (safe) based on the criterion of an arsenic level of exactly 50 μg/L in West Bengal, Bangladesh and many other developing countries. Wrongly labeling a tube well may have adverse implications for the villagers when safe tube wells are marked red (unsafe) and *vice versa*.

### 3.4 Estimation of the number of highly arsenic-affected hand tube wells

During the field survey, we collected information regarding number of people using 37 833 of 131 929 tube wells in eight highly affected districts (area 38 676 km$^2$; population 45.8 million). We excluded the Kolkata district from the calculation, because it is a mainly urban area and the principal source of drinking water is treated Ganga river water supplied by city corporation authority. The estimated average number of people using each tube well is 34. Based on the number of people using a tube well and the population in each district, we calculated, following the procedure as described earlier [12] (method also described in Supporting Information), the total number of the tube wells in these eight arsenic-affected districts to be 1.33 million. A district-wise estimate is given in Supporting Information Table S2. Extrapolating the data, the total number of tube wells throughout West Bengal (excluding Kolkata) is expected to be 2.2 million (Supporting Information Table S2).

### 3.5 Relationships between arsenic and iron concentrations and depth of tube wells

We have depth information of 107 253 tube wells from all regions of the state of West Bengal. Arsenic concentration decreased with increasing depth and we did not find levels of arsenic >50 μg/L in wells deeper than 350 m. Most tube - wells (70%) had a depth of 10–40 m with an average of 34 m (SD 36 m). Figure 2 demonstrates that the probability of the arsenic concentration of water from a tube well exceeding a certain level decreases with increasing depth.

From West Bengal we analyzed 17 050 samples for both arsenic and iron. Supporting Information Table S3 shows data relating to iron concentration (mean: 3756 μg/L, median 3110 μg/L; SD 3592 μg/L). The maximum iron concentration 77 000 μg/L was recorded from Sonarpur block of South 24-Parganas district. However, no health-based guideline value for iron in drinking water has been proposed by WHO [13], but taste is usually unacceptable at iron concentrations above 300 μg/L, 93% of the samples were found above this limit.

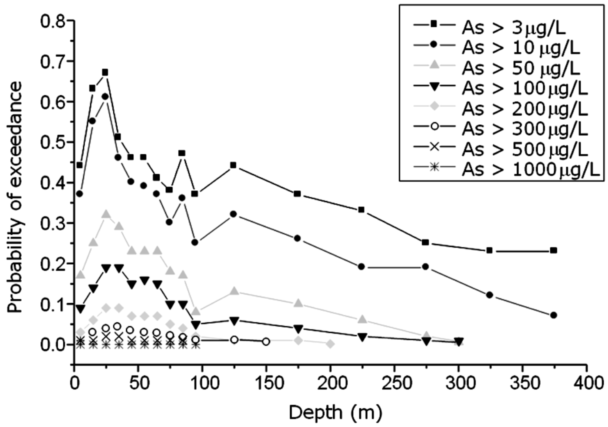


**Figure 2.** Probability of a tube well being arsenic contaminated above certain concentration limits by depth of the tube wells.

Bi-variate analysis shows a poor relationship between groundwater iron and arsenic ($r$= 0.24, $n$=17 050). The reason for the poor relationship is possibly that there are many processes by which iron may be removed from groundwater and that some of these do not also involve arsenic [14]. A negative correlation ($r$=–0.137, $n$=15 611) has been observed between depth of the tube well and iron concentration. Chi-square test ensures strong association ($\chi^2$ = 65.28) between arsenic concentration ranges and depth segments.

### 3.6 Estimating the number of people drinking arsenic-contaminated water and population potentially at risk from arsenic exposure above 10 μg/L

Based on the average number of users of a tube well ($n$=34) and the estimated number of tube wells contaminated with different arsenic concentration in blocks of each district (Supporting Information Table S2), the number of people who could be drinking arsenic contaminated water at various concentration levels was estimated. We report here only the arsenic-affected blocks in eight arsenic-affected districts that we surveyed. Table 2 shows the estimated population for the different districts who could be drinking arsenic contaminated water at different concentration levels. The calculation method has been described previously [12] and is presented in the Supporting Information. From Table 2, it is apparent that about 9.5 and 4.2 million people could be drinking water contaminated with arsenic levels above 10 and 50 μg/L, respectively, and an estimated 0.53 million drinking water with more than 300 μg/L arsenic, the concentration predicted to cause overt arsenical skin lesions. Throughout West Bengal, 26 million people could be poten-

**Table 2.** Population exposed to arsenic contaminated water above 10, 50, 100, 125, 200, 250, 300, 500 and 1000 μg/L in the surveyed affected blocks of the affected 8 districts of West Bengal

| Districts | Total population[a)] of affected blocks | Estimated[b)] population exposed to arsenic contamination (μg/L) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | >10 | >50 | >100 | >125 | >200 | >250 | >300 | >500 | >1000 |
| North-24-Parganas | 4290233 | 1921371 | 959377 | 568240 | 458595 | 244314 | 161979 | 106534 | 32898 | 3980 |
| South-24-Parganas | 2577369 | 854916 | 524922 | 340894 | 273083 | 168136 | 129625 | 90057 | 24257 | 3583 |
| Murshidabad | 5249116 | 2568707 | 1208863 | 692033 | 494444 | 292359 | 220726 | 152854 | 48437 | 8075 |
| Nadia | 3855122 | 2075328 | 589810 | 281406 | 216897 | 111853 | 77031 | 47579 | 13066 | 742 |
| Maldah | 2751151 | 971975 | 571224 | 366803 | 308535 | 168581 | 127124 | 104399 | 47975 | 8439 |
| Haora | 2437846 | 498312 | 201938 | 82256 | 67303 | 38667 | 27713 | 14609 | 2772 | 1801 |
| Hugli | 3272749 | 379311 | 82722 | 32669 | 25237 | 9156 | 4259 | 2820 | 301 | 0 |
| Bardhaman | 1860326 | 258808 | 112741 | 68240 | 47098 | 20407 | 11803 | 7593 | 3016 | 456 |
| Total | 26293912 | 9528728 | 4251597 | 2432541 | 1891192 | 1053473 | 760260 | 526445 | 172722 | 27076 |

a) Total population of those areas (villages and GPs) in those blocks from where we collected water samples for arsenic analysis and found arsenic contamination above 10 μg/L were considered in the estimation.
b) Assuming 34.3 persons using one tube well.

**Table 3.** Distribution of arsenic in deep tube wells (>100 m) from four districts of West Bengal, India

| Depth in meters | Mean | Max | Min | Distribution of deep tube well in different As conc. (μg/L) range | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | <10 | 10-19 | 20-29 | 30-39 | 40-49 | 50-99 | 100-299 | 300-499 | 500-1000 | >1000 | |
| 100–149 | 21.10 | 1100 | ≤3 | 1893 | 344 | 144 | 90 | 47 | 154 | 138 | 11 | 3 | 3 | 2827 |
| 150–200 | 18.24 | 550 | ≤3 | 1078 | 93 | 67 | 50 | 44 | 94 | 57 | 1 | 2 | | 1486 |
| 201–300 | 10.83 | 230 | ≤3 | 544 | 78 | 16 | 21 | 10 | 19 | 14 | – | | | 702 |
| 301–350 | 6.75 | 82 | ≤3 | 226 | 20 | 9 | 5 | 3 | 4 | – | – | | | 267 |
| 351–400 | 7.17 | 40 | ≤3 | 27 | 4 | 1 | 1 | 1 | – | – | – | | | 34 |
| > 400 | 3.32 | 10 | ≤3 | 21 | 1 | – | – | – | – | – | – | | | 22 |
| Total | | | | 3789 | 540 | 237 | 167 | 105 | 271 | 209 | 12 | 5 | 3 | 5338 |

tially exposed to arsenic-contaminated water at levels >10 μg/L. This was calculated by multiplying the population of the affected blocks (Supporting Information Table S1 and calculation procedure) of each district by percentage of hand tube well water samples above 10 μg/L.

## 3.7 Estimation of population at risk and the uncertainties involved

Arsenic concentration in drinking water hence ingestion per unit body weight is considered one of the measures of toxicity [15]. It may not be practically feasible to precisely assess arsenic exposure from drinking water in a population of the size of West Bengal (Table 2) until we have more information. First, we need to know the numbers of wells involved. However, tube wells are continuously being installed or re-drilled, and at different depths. Second, arsenic concentration in hand tube wells may change with time in some areas depending on sub-surface geology of the area [16–19]. Third, people acquire knowledge of the risk posed by arsenic, and change their pattern of water use. They may adopt safe water options, or may switch to an existing, private or community, safe-water source. Fourth, government water supply schemes may replace the use of contaminated tube wells. For all these reasons, plus the normal uncertainties about individual water consumption, only an estimate of arsenic exposure is possible.

## 3.8 Arsenic contamination in tube wells deeper than 100 m, the depth considered safe for drinking water in the affected districts

The common observation in arsenic-affected areas of West Bengal is that the concentration of arsenic in hand tube wells decreases with depth [20, 21]. A large number of hand tube wells was installed by PHED, Government of West Bengal, that had a depth 100 m or more to obtain arsenic-safe water in arsenic-affected villages. We have systematically collected water samples from 5338 hand tube wells at depth range of 100–651 m from the four highly and widely arsenic-affected districts of West Bengal (North 24-Parganas, Nadia, Murshidabad and South 24-Parganas) over the last 3 years. Table 3 shows the arsenic concentration at different tube well depths. From Table 3, it can be seen that arsenic levels of 50 μg/L (the Indian standard of arsenic in drinking water) are only always absent in water from hand tube well water deeper than 350 m. Therefore, we cannot say all tube wells deeper than 100 m would be arsenic safe.

From Table 3 it appears that out of 5338 tube wells of all depths, 54% tube wells are 100–149 m and 80.8% between 100 and 200 m deep. Only 19.2% tube wells are deeper than 200 m. In Kolsur GP (population 17 000) Deganga block of North 24-Parganas district, 64 tube wells that are deeper than 100 m have been installed by the PHED, Government of West Bengal. Of these tube wells, 58 are between 136 and 155 m and 6 deeper than 155 m. Most of the tube wells ($n = 43$) were of 151 m (500 ft) deep. We analyzed these 151 m tube wells three times during 2006 and 2007 (3 October 2006; 17 July 2007; 7 October 2007). The mean value was 45.8 μg/L with maximum arsenic concentration 189 μg/L. Of these 43 (151 m deep) tube wells, 81.4% and 34.9% had arsenic above 10 μg/L and 50 μg/L, respectively. We have reported [22] that, for the arsenic-affected region of Bangladesh, if deep safe aquifer under a thick clay barrier is tapped, arsenic safe water can be expected. We are also noticing the same trend in case of West Bengal.

Recently, the PHED, Government of West Bengal [23] supported our findings and reported "Hydrogeology of the districts of Murshidabad, Nadia, North-24-Parganas suggests that deeper aquifer tube wells will not be generally sustainable in these districts due to absence of a thick clay barrier separating the arsenic-affected aquifer and the deeper aquifer". However, a contradictory finding was reported by Cheng *et al*. [24], which was strongly criticized by Sengupta *et al*. [25] and Ravenscroft *et al*. [26].

In West Bengal and Bangladesh tapping deep aquifer is being portrayed as a panacea for crisis without proper consideration to the hydrogeological situations.

### 3.9 Regional variability in arsenic concentration in groundwater in relation to sub-surface geology of West Bengal

Lateral and depth-wise variations in the disposition of unconsolidated litho-units (cobbles, pebbles, gravels, sand, silt and clay) in the sub-surface quaternary sequence play major roles in the incidence and distribution of varied concentration of arsenic in groundwater of West Bengal (Bengal Delta). A detailed account of district-wise variations of pervious and impervious litho-units together with hydrgeological and hydrochemical behavior of aquifers within a depth of 300 m is given elsewhere [27]. Supporting Information Fig. S2 presents the 3-D sub-surface sediment depositional model for West Bengal.

In the extreme northern part of West Bengal, the 150–250-m-thick granular zone occurring as alluvial fans acts as the recharge zone for the unconfined aquifers with high permeability. This zone receives on an average 3000 mm rainfall annually. In most areas an underlying 2–10-m-thick clay layer separates it from confined aquifers that are found within 300 m depth. To the south of the fan zone, these deeper aquifers are hydraulically connected to the recharge zone and contain groundwater mildly affected by arsenic. High concentrations of arsenic are recorded in groundwater beneath the recent floodplains in Maldah district [28].

The geological features in the southern part of West Bengal, east of the Archaean shield area, show that the subsurface is similar to its northern counterpart except for the absence of cobbles and pebbles, and Pleistocene sediments cover almost half of the area. To the east it is overlapped by Holocene deltaic sediments. At the delta head, located in Murshidabad and Nadia districts, a 150–250-m-thick granular zone with a minor clay layer contains unconfined groundwater with high concentration of arsenic. It forms the recharge zone for the deeper aquifers down south. As in the Northern part, there are several clay layers, which thicken to the south, dividing the aquifers. A clay layer appears at the top of the sequence with thickness gradually increasing southward from 2 to 30 m, precluding direct rainfall recharge to the group of aquifers below the top clay. They constitute the confined aquifer system receiving water from the recharge area to the north as well as to the west formed by the weathered sections within the crystalline rocks in the shield area.

In and around Kolkata, besides the top clay layer, another 20–30-m-thick clay layer occurs at around 150 m depth, the thickness of which increases to 50–60 m further south. It is underlain by an alternating sequence of sand and clay layers down to a depth of about 300 m [28].

In parts of the delta and riverine flood plains, the intervening clay layers may be absent, connecting the aquifers at depth and providing avenues for polluted groundwater to migrate deeper [28].

This complex phenomenon seems to be responsible for the variation in arsenic content in groundwater on tapping the same aquifer within a short distance in the delta and flood plain deposits. Moreover, travel time required for transmission of arsenic contaminated groundwater from the recharge zones to the deeper aquifer system further south depends on the variation in composition of material through which groundwater moves. All these factors cause variations in arsenic concentration in groundwater from one location to the other. Seasonal change and/or temporal variation in arsenic concentration in groundwater are therefore, not an unexpected phenomenon.

## 4 Concluding remarks

To combat the present arsenic crisis, we urgently need the following: (1) From our analyses of 135 555 water samples from hand tube well in nine highly arsenic-affected districts of West Bengal, we found 49.7% had arsenic levels above 10 μg/L and 24.7% with 50 μg/L. Thus, about 75% and 50% of the hand tube-wells are safe to drink considering Indian Standard and WHO guideline value of arsenic in drinking water, respectively. We informed the heads of the village committee for most of the blocks about the arsenic levels in their tube wells and requested them to color the tube wells as safe and unsafe, and to make the villagers aware the danger of arsenic toxicity. All those dealing with arsenic contamination in West Bengal should immediately follow this strategy for both public and private tube wells. There are less public tube wells in arsenic-affected districts than private tube wells. (2) The Government should make and implement strict regulation for boring tube wells. At present, there is no groundwater withdrawal regulation in the state, and as farmers do not have to pay for water, they withdraw more water than they need for the crops. Drip water irrigation should be considered and those crops with minimum water requirement, like wheat should be promoted. We have evidence from West Bengal that some tube wells, the water of which was once safe to drink, are now becoming contaminated with arsenic [19]. Safe tube wells in contaminated areas should thus be regularly tested for arsenic for contamination. (3) As a permanent solution for providing arsenic-safe water we should consider using our vast traditional known safe water options like surface-water, dug wells, rain water harvesting, etc. However, these sources still need to be properly treated against bacterial and other chemical contamination before use. The mitigation approach needs to be location specific; a universal approach may not suit all the affected areas. Proper watershed management with peoples' participation is essential. (4) People should be made aware of arsenic calamity and they must be made to realize that it is not a curse of GOD or the consequences of the wraths of GOD. (5) An old Indian custom recommends that water be drunk after it has been allowed to stand overnight and then filtered through a piece of fine cloth. Our study showed that more than 70% of the arsenic in the water obtained from tube wells high in soluble iron could be removed by this procedure. The principle is that, on standing overnight, the iron in the water is precipitated as ferric hydroxide; any co-precipitating arsenic would also be removed. This procedure is recommended for those who have no available sources of arsenic safe tube well water and have not yet analyzed their tube well water. The procedure will not work where the water contains very small amount of iron and high degree of arsenic. A simple test to know whether tube well water contains a relevant level of iron is to pump out some water and let it stand for some time. If it contains such levels of iron, it will turn hazy and become a brownish in color. This is very common phenomenon in tube well water in the arsenic-affected districts. (6) As yet, there is no available medicine for chronic arsenic toxicity; safe water, nutritious food, vitamin and physical exercise are the only preventive measures to fight chronic arsenic toxicity. Plenty of seasonal fruits and vegetables rich in vitamins are available in West Bengal and Bangladesh all round the year. A large percentage of villagers are not aware that they can get better nutrition from local fruits and vegetables. Most villagers cook vegetables in such a way that their nutritional value is lost. We have to teach villagers how they can get nutritious food using local seasonal fruits and vegetables. It is not necessary to eat fish, meat, eggs, apples and grapes, which poor villagers cannot afford. (7) The scientific community and medical workers all over the world should come forward to find a solution to the problem that has put more than 100 million people at risk of arsenic contamination in west Bengal and Bangladesh alone.

In West Bengal and Bangladesh we have huge surface water resources of fresh water such as rivers, wetland, flooded river basin and Ox-Bow lakes. The surface water available per capita in Bangladesh is about 11 000 $m^3$. These two delta areas are known as the land of rivers and have approximately 2000 mm annual rainfall. Instead of using these resources, we are withdrawing groundwater without proper management. Proper watershed management and villagers' participation are needed to assist the proper utilization these huge bodies of water. In the arsenic-affected flood plain of the river Ganga, the crisis is not of having too little water to satisfy our need, but of managing the water. There is a current trend towards extracting more and more groundwater. Even during summer we extract groundwater through deep tube well for irrigation.

In India fluoride contamination of groundwater has been known since 1937. At present in India 62 million people are suffering from fluorosis, a crippling disease [29]. Although the groundwater in Bankura, Birbhum, and Purulia in the western part of West Bengal seems arsenic safe, there is fluoride contamination in these areas and thousands are suffering from fluorosis. The presence of U, B, Ni, Cr, Pb, Mn in groundwater of Bangladesh above WHO-prescribed limiting values has been reported [18]. Recent research suggests that groundwater with unsafe levels of Mn, Pb, Ni, and Cr extends beyond Bangladesh borders into adjacent state of West Bengal [30]. Should we take fluoride and arsenic in the groundwater as nature's preliminary warning about more dangerous toxins yet to come?

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