

THE NATURE AND EXTENT OF ARSENIC-AFFECTED DRINKING WATER IN BANGLADESH

Seth H. Frisbie^{*†}, Donald M. Maynard^{*}, and Bilqis A. Hoque[‡]

^{*} The Johnson Company, Inc.
100 State St.
Montpelier, VT 05602, USA

[‡] Environmental Health Programme
International Centre for Diarrhoeal Disease Research, Bangladesh
GPO Box 128
Dhaka-1000, Bangladesh

[†] To whom correspondence should be addressed (shf3@cornell.edu).

1. SUMMARY

The people of Bangladesh used to rely on surface water for drinking, which was often infected with cholera and other life-threatening diseases. To reduce the incidences of these diseases, millions of tubewells were installed in Bangladesh over the last 27 years. This recent transition from surface water to groundwater has significantly reduced deaths from water-borne pathogens; however, recent evidence suggests disease and death from arsenic and potentially other metals in groundwater are impacting large areas of Bangladesh.

In this preliminary assessment the areal and vertical distribution of arsenic and other inorganic chemicals in the groundwater was mapped throughout Bangladesh. The study suggests that a major source of this arsenic may be one or more phosphate minerals containing arsenate as an impurity. Evidence for other potentially toxic heavy metals in groundwater was also discovered. Several appropriate treatment technologies were evaluated.

2. INTRODUCTION

2.1. Geographic, Demographic, and Economic Overview of Bangladesh

The Peoples' Republic of Bangladesh is a relatively small, intensely populated, and poor country. Bangladesh is located at one of the largest river deltas in the world. The Ganges, Brahmaputra, and Meghna rivers flow through Bangladesh to the Bay of Bengal. Very little of the country is more than 12 m (40 feet) above sea level, and in a normal monsoon season one-third of its cultivated land is flooded. Bangladesh has 120,000,000 people living on 144,000 square kilometers; this is equivalent to having one-half the population of the United States living in an area the size of Wisconsin. The infant mortality rate is 115 per 1,000 live births. There is one doctor per 5,200 people; by comparison the United Kingdom has one doctor per 650 people. The adult literacy rate is 43% for men and 22% for women. The average annual income is equivalent to US \$220 per capita. The life expectancy is 55 years (Monan, 1995).

Bangladesh is an agricultural country with the vast majority of people involved in food production. Rice is grown during the rainy season, and is primarily used for domestic consumption. In irrigated areas, a second rice crop is possible, followed by wheat and vegetables in the short, dry winter from November to February. Bangladesh is the world's leading producer of jute, a strong natural fiber used in the carpet and sacking industries. The principle exports of Bangladesh from largest to smallest are garments, jute and its products,

shellfish, tea, and leather (Monan, 1995).

2.2. Project Overview

Much of the surface water of Bangladesh is microbially unsafe to drink. Since independence in 1971, approximately 2,500,000 tubewells have been installed to supply microbially safe drinking water to the people of Bangladesh. Unfortunately, vast areas of this 120,000,000 person country contains groundwater with arsenic concentrations above the World Health Organization (WHO) drinking water standard of 0.01 mg/L. Chronic arsenic poisoning attributed to groundwater ingestion was first diagnosed in 1993.

The Government of Bangladesh with funding from the United States Agency for International Development and technical support from The Johnson Company and the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B) implemented the following study to determine the nature, extent, and treatment of arsenic-affected groundwater in Bangladesh. The purposes of this eight week study in Bangladesh were to:

- provide technical training,
- evaluate analytical chemistry capability,
- determine the extent of arsenic-affected groundwater,
- hypothesize the source of arsenic in groundwater, and
- identify potential options for water treatment.

See USAID (1997) for an extensive discussion of this entire project.

3. MATERIALS AND METHODS

3.1. Groundwater Sampling and Analyses

Groundwater samples were collected from approximately 120 villages throughout Bangladesh. Typically 4 to 6 tubewells per village were sampled. These villages were as evenly distributed throughout the country as possible, given the limited access due to seasonal flooding (see Figure 1). The latitude and longitude of all sample locations were determined using the Global Positioning System.

All groundwater samples were collected (from July 22 to August 14, 1997), preserved, stored, and analyzed using procedures described in Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, and WEF, 1995). All analyses were performed at the ICDDR,B Laboratory, unless otherwise stated. Approximately 600 samples were analyzed for total arsenic by the silver diethyldithiocarbamate method and ferrous iron by 1,10-phenanthroline (see Figure 1). Approximately 100 samples were analyzed for chloride by mercuric thiocyanate, phosphate by amino acid, sulfate by barium turbidity, sulfide by methylene blue, and total iron by 1,10-phenanthroline. Approximately 75 samples were analyzed immediately after collection for pH by glass electrode, oxidation-reduction potential by electrode, dissolved oxygen by membrane electrode, specific conductivity by electrode, temperature by thermocouple, and nitrate by cadmium reduction.

3.2. Soil Leaching Study

A total of 31 surface soil samples (0 to 1.2 m or 0 to 4 feet below ground surface, bgs) were collected from random locations throughout Bangladesh from July 22 to August 6, 1997. These samples were stored in coolers packed with ice from the moment of collection until the samples were processed at the ICDDR,B Laboratory between 3 and 5 days later. Each soil sample was homogenized and analyzed for moisture content by evaporation to a constant mass at 105°C. Following desiccation a mass of field-moist soil equivalent to 100 grams of oven-dried soil was delivered to a clean sample jar, distilled water was added to the jar to

make the final mass of water equal to 200 grams, and the contents of the jar were mixed for 5 minutes. For example, if a 12 gram sample of field-moist soil weighed 10 grams after drying, then 120 grams of field-moist soil (this initial condition is equivalent to 100 grams of oven-dried soil and 20 grams of water) was delivered to a clean sample jar with 180 grams of distilled water (this final condition is equivalent to 100 grams of oven-dried soil and 200 grams of water; however, the composition of the soil being leached was never altered by oven-drying). After 6 days a 50 mL aliquot of water was removed, filtered through a standard glass fiber filter used to remove total suspended solids (APHA, AWWA, and WEF, 1995), and submitted for total arsenic analysis.

3.3. Bench-Scale Treatability Study for Arsenic Removal from Groundwater

Tubewell water was collected and used immediately for this treatability study without the addition of sample preservatives. The tubewell water was fortified with arsenic to yield 2.0 mg of As(III)/L. One liter aliquots of fortified tubewell water were delivered to 1 L borosilicate glass beakers. Chlorinated lime (a locally available oxidant, $aCa(OCl)_2, bCaCl_2, cCa(OH)_2, dH_2O$) was added at rates of 4, 6, 10, 15, and 20 mg/L. The solutions were mixed for 1 minute. Ferric chloride hexahydrate (an effective coagulant, $FeCl_3 \cdot 6H_2O$) was added at rates of 100, 150, 200, and 250 mg/L. Each solution was mixed for 1 minute, allowed to settle for 24 hours, then the water column above the precipitate was analyzed for total arsenic.

4. RESULTS AND DISCUSSION

4.1. Evaluation of Analytical Chemistry Capability and Evidence that Other Potentially Toxic Metals are Widely Distributed in Groundwater

Accurate laboratory results are imperative to understanding and solving the problem of arsenic-affected drinking water in Bangladesh; therefore, a major goal of this project was to determine accuracy and precision of the analytical chemistry results generated by various laboratories studying this problem.

The ICDDR,B Laboratory performed exceptionally well during this study (see Table 1). The recoveries from the blind analysis of all independently prepared standards were within the $100 \pm 25\%$ range considered acceptable for routine analytical laboratories (USEPA, 1994). An analytical interference for the determination of ferrous iron in undiluted groundwater by the 1,10-phenanthroline method was identified from suppressed matrix spike recovery (see Table 1). This interference was defeated by diluting all ferrous iron samples 10 times with distilled water before color development. Similarly, all samples submitted for total iron analysis by the 1,10-phenanthroline method were diluted 10 times with distilled water before acidic digestion to defeat this interference; despite this precaution, 24 of 89 samples (27%) failed to develop proper color. Some of these samples generated a whitish colloidal precipitate upon the addition of 1,10-phenanthroline. This analytical interference coupled with the results shown on Figure 8 suggests that one or more of the following potentially toxic metals are widely distributed in groundwater throughout Bangladesh: chromium, zinc, cobalt, nickel, bismuth, cadmium, mercury, and/or silver (APHA, AWWA, and WEF, 1995).

The recovery of independent standards and sample matrix spikes were used to assess other laboratories in Bangladesh (see Table 2). The arsenic results from Laboratory 1 are systematically high by approximately a factor of 4; therefore, a simple calibration error was likely generating results which incorrectly suggest that the arsenic problem is 4 times worse than reality. Laboratories 2 and 3 only recovered approximately 50% of the arsenic from independent standards, such results underestimate the significance to the arsenic problem by a factor of 2.

4.2. The Nature and Extent of Arsenic, Chloride, Phosphate, Sulfate, Sulfide, and Total Iron in Groundwater

This preliminary evaluation of the nature and extent of arsenic and other inorganic chemicals in groundwater is based on the limited number of samples that could be collected during our three-week field program. Samples were collected from only 600 of 2,500,000 tubewells in 120 of 68,000 villages; therefore, more extensive studies are required to support or disprove the hypotheses presented in this article.

The concentrations of various inorganic chemicals throughout Bangladesh were mapped to identify areas impacted by arsenic and other toxins, to determine the potential source of arsenic, and to identify possible water treatment requirements. Contour maps of chemical concentration show the aerial extent of arsenic, chloride, phosphate, sulfate, and total iron in groundwater (see Figures 2, 3, 5, 6, 7, 8, and 10). These contour maps were drawn using the average chemical concentration in tubewell water from each village, unless otherwise stated (recall that 4 to 6 tubewells per village were sampled). The vertical distribution of arsenic was evaluated by separating samples collected from "shallow" and "deep" tubewells. Shallow tubewells were arbitrarily assigned a depth less than 30.5 m (100 feet) bgs, and deep tubewells were arbitrarily assigned a depth greater than 30.5 m (100 feet) bgs. This separated the samples into two groups with each group containing approximately 300 samples.

The contour maps of average arsenic concentration in water from shallow and deep tubewells are shown in Figures 2 and 3, respectively. The detection limit for the arsenic method was 0.028 mg/L (defined as the concentration of the most dilute standard used for calibration); therefore, quantitation to the WHO drinking water standard of 0.01 mg/L was not attempted and these contour maps are based on the Bangladesh drinking water standard of 0.05 mg/L. Approximately 50% of the aerial extent of Bangladesh contains groundwater from shallow tubewells with an average arsenic concentration greater than the national drinking water standard (see Figure 2). Approximately 32% of the aerial extent of Bangladesh contains groundwater from deep tubewells with an average arsenic concentration greater than the national drinking water standard (see Figure 3). This wide-spread aerial and vertical distribution suggests the dominant source of the arsenic appears to be one or more geologically deposited minerals. The superimposition of Figures 2 and 3 suggests that drilling deeper tubewells may access water with less arsenic in some locations and drilling shallower tubewells may access water with less arsenic in other locations.

The comparison of 10 adjacent pairs (< 100 m or < 328 feet apart) of "very deep" (67.1 to 290 m bgs or 220 to 950 feet bgs) and shallow (< 30.5 m or < 100 feet bgs) tubewells shown in Figure 4 suggests the source of arsenic is hundreds of feet thick in many areas of Bangladesh. This wide-spread aerial and vertical distribution suggests the dominant source of the arsenic appears to be one or more geologically deposited minerals.

The success rate of drilling deeper tubewells was estimated using Figure 4. These results suggest that drilling deeper tubewells provided access to water with markedly less arsenic in only 2 of 10 cases; however, this frequency may increase by installing even deeper tubewells. The 2 "very deep" tubewells which yielded this improvement were significantly deeper (244 and 290 meters bgs, or 800 and 950 feet bgs) than the remaining 8 "very deep" (67 and 137 meters bgs, or 220 to 450 feet bgs) tubewells. Only 1 of these 2 "very deep" tubewells successfully accessed drinking water with arsenic concentrations less than the 0.05 mg/L national standard. A more extensive study of arsenic concentrations in adjacent "shallow" and "very deep" tubewells should be done to better estimate the success rate of drilling deeper tubewells to access safe drinking water.

A correlation coefficient matrix for a variety of tubewell water parameters is shown in Table 3 for informational purposes. Interpretation of this data should be performed with caution as it represents the entire country and is probably scale dependant. That is, these correlations may not apply on the district, thana, or village scale.

The contour map of average chloride concentration in water from shallow tubewells is shown in Figure 5. The spacial relationship between chloride and arsenic (see Figures 5 and 2) in connate water (water associated with deposition, Ravenscroft, 1997) suggests the arsenic-leaching mineral or minerals were likely deposited in an estuarine environment. An alternative hypothesis is that the release of arsenic from the solid phase is facilitated by chloride or another component of historical seawater.

Phosphate is commonly used as a fertilizer; therefore, the possibility of this agrochemical impacting groundwater must be considered before comparing the spacial relationship between phosphate and geologically deposited arsenic. Phosphate fertilizer forms difficultly soluble iron, aluminum, calcium, and magnesium compounds that do not readily leach from most soils (Brady, 1984); however, the phosphate concentration ranged from 1 to 20 mg/L in all 11 groundwater samples collected at greater than 122 m (400 feet) bgs. Like phosphate, nitrate is associated with agricultural activity. Unlike phosphate, nitrate readily leaches from soils; however, nitrate was detected above 1 mg of NO_3^- -N/L in only 5 of 90 groundwater samples. All 5 of the samples with detectable concentrations of nitrate were from wells not greater than 122 m (400 feet) bgs. Four of these 5 samples were from a small area of northwestern Bangladesh (Dinajpur, Phulbari, and Gobandaganj) which had relatively low concentrations of phosphate in groundwater. These findings suggest that the dominant source of phosphate in the groundwater of Bangladesh is geological, not an agricultural leachate.

The contour map of average phosphate concentration in water from shallow tubewells is shown in Figure 6. The spacial relationship between phosphate and arsenic (see Figures 6 and 2) suggests the arsenic-leaching mineral or minerals might contain arsenate isomorphically substituted for phosphate; that is, the major source of arsenic in the groundwater of Bangladesh may be a phosphate or phosphates which have arsenate as an impurity. This hypothesis should be confirmed or disproved by a detailed mineralogical evaluation of a statistically significant number of soil samples.

An alternative hypothesis that arsenic is being released from arsenopyrite (FeAsS) or an iron pyrite (FeS_2) has been proposed for the situation in nearby West Bengal, India (Mallick, and Rajagopal, 1995). This hypothesis suggests that arsenic is initially associated with a difficultly soluble pyrite mineral that is underwater in a reducing environment, and the arsenic is released when the pyrite is aerated by lowering the water table during groundwater pumping. This hypothesis is supported by the detailed mineralogical evaluation of one soil sample from West Bengal which suggested that arsenic is associated with iron pyrite (Das, Basu, Chowdhury, and Chakraborty, 1995). If this hypothesis is true for the general situation in Bangladesh, then the concentrations of inorganic sulfur and arsenic should be correlated; however, the concentrations of sulfate and arsenic, and sulfide and arsenic in groundwater from Bangladesh are not correlated (see Table 3).

The contour map of average sulfate concentration in water from shallow tubewells is shown in Figure 7. The spacial relationship between sulfate and arsenic (see Figures 7 and 2), and that between sulfide and arsenic (not shown) suggests the principal arsenic-leaching mineral or minerals in Bangladesh are not associated with inorganic sulfur in contrast to the presumed situation in West Bengal. If the arsenic-leaching mineral or minerals are not associated with inorganic sulfur, then the hypothesis that groundwater depression from

irrigated agriculture facilitates the release of arsenic by aerating arsenopyrite or another pyrite might not represent the general situation in Bangladesh. Nevertheless, the occurrence of sulfate and sulfide in groundwater at the West Bengal / Bangladesh border (see Figure 7) does suggest that pyrites may be an important source of arsenic in West Bengal and limited areas of Bangladesh.

Even if the principal source of dissolved arsenic in West Bengal is pyrites, the general situation in Bangladesh may differ because these two regions have very different geologies. Both West Bengal and Bangladesh receive sediment from the Ganges river basin, but Bangladesh also receives sediment from the Brahmaputra and Meghna Rivers. Each river has different sources of sediment, and most likely different proportions of arsenic, sulfur, and phosphate-bearing minerals. Moreover, Bangladesh is further than West Bengal from the presumed source of pyrites in the Ganges river basin. For these reasons, the percentage of arsenic-containing pyrites in Bangladesh aquifers is likely to differ from, and possibly be much less than that in West Bengal. Furthermore, the environments in which the aquifer sediments were deposited are different in West Bengal and Bangladesh; therefore, the oxidation-reduction conditions, sulfur concentrations, and other important aquifer chemistry parameters are likely different as well. The depositional environments of Bangladesh aquifers commonly include deltaic, estuarine, and riverine sediments, while most of the West Bengal aquifers contain only riverine sediments. Because there are so many substantial differences between the geologies of West Bengal and Bangladesh, it should not be assumed without further study that the source of arsenic in groundwater is the same in both regions.

The composition of all minerals leaching arsenic into the groundwater of Bangladesh should be determined from a detailed evaluation of a statistically significant number of soil samples.

If arsenic is released from arsenopyrite or a pyrite, then alternative groundwater management practices should be evaluated and the treatment of drinking water by aquifer oxygenation may prove to be inappropriate. Aquifer oxygenation is the injection of compressed air or oxygen around a well screen to precipitate arsenic and other metals before they are pumped above ground; however, if pyrites are present, then this process may facilitate the release of arsenic to groundwater. Knowledge of the composition of minerals leaching arsenic into groundwater is relatively unimportant if one is only concerned with treating water after it has been pumped above ground.

The contour map of average total iron concentration in water from shallow tubewells is shown in Figure 8. The spacial relationship between total iron and arsenic (see Figures 8 and 2), and the general excess of total iron relative to arsenic suggests that ambient iron might be used to coagulate (coprecipitate) arsenic in a low-input water treatment system (Faust and Ally, 1983). The distribution of analytical interference (see Table 1) for the determination of iron (located on the map with the letter "E") suggests that one or more of the following potentially toxic metals are widely distributed in groundwater throughout Bangladesh: chromium, zinc, cobalt, nickel, bismuth, cadmium, mercury, and/or silver (APHA, AWWA, and WEF, 1995).

Cobalt, nickel, and silver ores are often codeposited with arsenic (Mason and Berry, 1968), and each of these 3 metals are a potential interference to the 1,10-phenanthroline method; therefore, any limited resources available to investigate the occurrence of metals other than arsenic in this water should first include this subgroup of 3 metals (cobalt, nickel, and silver). Subsequent investigation should include the entire group of 8 metals (chromium, zinc, cobalt, nickel, bismuth, cadmium, mercury, and silver). Additional analytes beyond this group of 8 metals should be added as resources allow.

4.3. The Leaching of Arsenic from Surface Soils and its Potential Impact on Food Crops

The results of the Soil Leaching Study are shown in Figure 9. These results suggest that arsenic readily leaches from many Bangladesh surface soils. Arsenic can be up taken by crops (Brady, 1984); therefore, this human exposure pathway should be evaluated. Rice is often grown in flooded soils analogous to the conditions of this experiment, is the major staple of Bangladeshi diet, and is grown primarily for domestic consumption (Monan, 1995); therefore, the ingestion of arsenic from domestic rice should be specifically evaluated as a potential human exposure pathway. Unfortunately, the sample preparation equipment required to determine the concentration of metals in biological samples is not currently available in Bangladesh.

4.4. The Potential of Groundwater Monitoring to Reduce the Need for Arsenic Treatment

The contour map of minimum arsenic concentration in water from all (both shallow and deep) tubewells is shown in Figure 10. This contour map was drawn using the lowest ("cleanest") arsenic concentration from the 4 to 6 tubewells sampled in each village. The shaded regions of this map represents areas where no tubewell had an arsenic concentration less than the Bangladesh drinking water standard. Approximately 15% of the aerial extent of Bangladesh contains groundwater with a minimum arsenic concentration greater than the national drinking water standard and will require treatment. This result also suggests that 85% of the aerial extent of Bangladesh has access to groundwater that does not require treatment for arsenic removal prior to drinking. An intensive groundwater monitoring program identifying suitable drinking water wells within each village would significantly reduce the need for arsenic treatment for the majority of this 120,000,000 person country.

4.5. Implications of the Expected Nature of Arsenic in Groundwater on Treatment

The graphs of arsenic concentration versus oxidation-reduction potential and arsenic concentration versus pH are shown in Figures 11 and 12, respectively. The increase in arsenic concentration at relatively low oxidation-reduction potentials and moderate pH values suggests that soluble As(III), rather than difficultly soluble and potentially colloidal As(V), was the dominate form in the most highly affected tubewells (Ferguson and Gavis, 1972). If the arsenic is in the soluble As(III) oxidation state, then oxidation to difficultly soluble As(V) followed by coagulation, filtration, or sorption is required for effective treatment (Faust and Aly, 1983).

4.6. The Results of the Bench-Scale Treatability Study for Arsenic Removal from Groundwater

The effect of chlorinated lime (a locally available oxidant) and ferric chloride hexahydrate (an effective coagulant) on the removal of arsenic from groundwater was evaluated at the bench-scale (see Table 4). The tubewell water used in this experiment was fortified to 2.0 mg of As(III)/L, approximately 3 times the total arsenic concentration of the most severely impacted tubewell found during this project. The results shown in Table 4 suggest that oxidation followed by coagulation can reduce relatively large arsenic concentrations in tubewell water to below the WHO drinking standard. The addition of water treatment chemicals can yield pH values outside of the 5.5 to 8.5 drinking water range recommended by WHO (1984); therefore, pH adjustment may be required after coagulation. Limestone (CaCO_3) offers inexpensive and effective pH control after coagulation, often without the need of expensive dosing equipment.

4.7. The Conceptual Design of a Pilot-Scale Treatment System for Removing

Arsenic and Other Potentially Toxic Metals from Groundwater

The ideal water treatment system for the economic and demographic situation in Bangladesh will effectively remove arsenic and other toxic metals, be inexpensive to build and operate, and be simple to use. Such a system might use atmospheric oxygen as the oxidant and ambient iron as the coagulant; therefore, the long-term expense of purchasing water treatment chemicals would be avoided. Atmospheric oxygen delivered by waterfall or bubble aeration has been routinely used to oxidize As(III) to As(V) in water treatment systems, and should be evaluated in future studies (Faust and Aly, 1983). Ambient iron without the addition of another coagulant might adequately separate precipitated arsenic and other toxic metals from water in a large settling tank or an inclined-plate clarifier. Excellent guidance for the construction of low-input water treatment systems for the developing world is provided by the International Reference Centre for Community Water Supply and Sanitation (1988) and Heber (1985).

The apparent reduction in arsenic concentration from 0.16 to <0.002 mg/L shown in Table 5 supports the hypothesis that aeration followed by settling without the addition of coagulant can remove arsenic in tubewell water to below the WHO drinking standard. The apparent increase oxidation-reduction potential suggests that the water was aerated when pumped into the storage tank. The apparent decrease in pH, conductivity, and arsenic concentration suggests that ambient iron was oxidized, hydrolyzed water, and precipitated as a ferric hydroxide coagulant of arsenic. The water pump supplying this large tank does not operate at night due to the diversion of electricity to the capital; therefore, coagulated arsenic has many hours of relatively turbulent-free water to settle each evening.

5. CONCLUSIONS AND RECOMMENDATIONS

An appropriate quality assurance and quality control program should be implemented to determine the accuracy and precision of all analytical results associated with the problem of metal-affected drinking water in Bangladesh. This program should include the routine and blind analysis of independent standards, sample matrix spikes, field duplicates, laboratory duplicates, and blanks. The ICDDR,B Laboratory generated an excellent quality of results during this study; this is especially impressive because the metal analyses were completed without the benefit of an atomic absorption spectrophotometer (see Table 1). The other three laboratories evaluated in this study would presumably benefit from a more rigorous quality assurance and quality control program (see Table 2).

Drinking water should be routinely tested for arsenic and other toxic compounds. Approximately 50% of the aerial extent of Bangladesh contains groundwater from shallow tubewells with an average arsenic concentration greater than the national drinking water standard (see Figure 2). Approximately 32% of the aerial extent of Bangladesh contains groundwater from deep tubewells with an average arsenic concentration greater than the national drinking water standard (see Figure 3). The major source of this arsenic in the Groundwater of Bangladesh is potentially a phosphate mineral or minerals deposited in an estuarine environment. This source appears to be hundreds of feet thick in some areas. The analytical interference for the determination of iron by the 1,10-phenanthroline method (see Table 1) coupled with the results shown on Figure 8 suggests that one or more of the following potentially toxic metals are also widely distributed in groundwater throughout Bangladesh: chromium, zinc, cobalt, nickel, bismuth, cadmium, mercury, and/or silver (APHA, AWWA, and WEF, 1995).

Food crops should also be tested for arsenic and other toxic compounds. Arsenic readily leaches from many Bangladesh surface soils and can be up taken by crops (Brady, 1984). Arsenic exposure from the ingestion of rice and other domestically produced food crops

should be evaluated as a potential human exposure pathway.

Field testing kits for the rapid and inexpensive measurement of toxins in drinking water should be immediately developed. Approximately 15% of the aerial extent of Bangladesh contains groundwater with a minimum arsenic concentration greater than the national drinking water standard; therefore, it is hypothesized this is the smallest area of Bangladesh that will require groundwater treatment for arsenic removal prior to drinking (see Figure 10). An intensive groundwater monitoring program identifying suitable drinking water wells within each village would significantly reduce the need for arsenic treatment in this 120,000,000 person country.

An appropriate treatment systems for toxin removal should be developed for areas without access to safe drinking water. Ideally these systems should be effective, inexpensive, and easily operated by an illiterate person. These systems will likely require an oxidant to convert soluble As(III) to difficultly soluble As(V), and a process to allow the settling, filtration, or sorption of arsenic from solution.

6. REFERENCES

- American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF). (1995). *Standard Methods for the Examination of Water and Wastewater*, 19th ed. (Washington, DC: APHA).
- Brady, N.C. (1984). *The Nature and Properties of Soils*, 9th ed. (New York: Macmillian Publishing Company).
- Das, D., Basu, G., Chowdhury, T.R., and Chakraborty, D. (1995). Bore-hole soil-sediment analysis of some arsenic affected areas. *International Conference on Arsenic in Ground Water: Cause, Effect, and Remedy*. School of Environmental Studies, Jadavpur University, Calcutta, India - 700032.
- Faust, S.D., and Aly, O.M. (1983). *Chemistry of Water Treatment* (Boston: Butterworths).
- Ferguson, J.F., and Gavis, J. (1972). A review of the arsenic cycle in natural waters. *Water Res.* *June*, 1259-1274.
- Heber, G. (1985). *Simple Methods for the Treatment of Drinking Water* (Braunschweig/Wiesbaden: Friedr. Vieweg & Sohn).
- International Reference Centre for Community Water Supply and Sanitation (1988). *Small Community Water Supplies* (New York: John Wiley & Sons).
- Mallick, S., and Rajagopal, N.R. The mischief of oxygen on groundwater. *International Conference on Arsenic in Ground Water: Cause, Effect, and Remedy*. School of Environmental Studies, Jadavpur University, Calcutta, India - 700032.
- Mason, B., and Berry, L.G. (1968). *Elements of Mineralogy* (San Francisco: W.H. Freeman and Company).
- Monan, J. (1995). *Bangladesh the Strength to Succeed* (Oxford, UK: Oxfam).
- Ravenscroft, P. (1997). *An Overview of the Hydrogeology of Bangladesh* (Unpublished, British Geological Society).

USAID. (1997). Report of the Impact of the Bangladesh Rural Electrification Program on Groundwater Quality (Prepared by the Bangladesh Rural Electrification Board. Funded by US Agency for International Development, Contract Number: US AID RE III 388-0070) (Washington, DC: USEPA).

USEPA. (1994). USEPA Contract Laboratory Program National Functional Guidelines for Inorganic Data Review (EPA 540/R-94/013) (Washington, DC: USEPA).

WHO. (1984). Guidelines for Drinking Water Quality Vol. 1 Recommendations (Geneva: WHO).

7. ACKNOWLEDGMENTS

This study was performed for the Rural Electrification Board of Bangladesh. It was funded by the United States Agency of International Development (contract number US AID RE III 388-0070). The contract was implemented by National Rural Electric Cooperative Association (NRECA) International, Ltd. of Arlington, Virginia with personnel from The Johnson Company, Inc. of Montpelier, Vermont, USA and the Environmental Health Program of the International Center for Diarrhoeal Disease Research, Bangladesh. The project team offers our sincere thanks to Mr. James Ford of NRECA for providing invaluable leadership and management during the implementation of this ambitious contract. The principal investigators offer our deepest thanks to the dozens of talented and motivated Bengali scientists, engineers, and support staff who made this work a reality - the future of Bangladesh and West Bengal is bright indeed.

Table 1. The percent recoveries of independent standards and sample matrix spikes analyzed by the ICDDR,B Laboratory (Results are reported as means \pm standard deviations).

Analyte	Independent Standard Recovery	Sample Matrix Spike Recovery
Arsenic (As)	83%	89 \pm 11%
Ferrous iron (Fe ²⁺)	93 \pm 10%	34 \pm 23% without dilution 96 \pm 13% with 1 to 10 dilution
Total iron (Fe)	95%	120 \pm 12% with 1 to 10 dilution
Sulfate (SO ₄ ²⁻)	106%	106 \pm 20%
Chloride (Cl)	114%	90 \pm 15%
Phosphate (PO ₄ ³⁻)	88%	84 \pm 2%

Table 2. The performance of some other laboratories that are evaluating arsenic in Bangladesh.

Sample Description	Independent Laboratory	Result (mg/L)
Standard solution = 1 mg As/L	Laboratory 1	4.891
Distilled water = 0 mg As/L	"	0.002
Sample A (0.25 mg As/L)	"	1.101
Sample A (Blind duplicate)	"	1.035
Sample A (Blind triplicate)	"	0.266
Sample A plus 6.3 mg As/L	"	24.126
Sample B (0.31 mg As/L)	"	1.109
Standard solution = 1 mg As/L	Laboratory 2	0.533
Sample B (0.31 mg As/L)	"	0.397
Sample B plus 3.3 mg As/L	"	0.884
Standard solution = 1 mg As/L	Laboratory 3	< 0.5
Sample B (0.31 mg As/L)	"	0.30
Sample B plus 7.1 mg As/L	"	> 1.0

Table 3. Correlation coefficient matrix for a variety of tubewell water parameters.

	Arsenic	Sulfate	Sulfide	Chloride	Phosphate	Depth	Total Iron
Arsenic	1.00	-0.078	0.059	0.24	0.27	-0.19	0.44
Sulfate		1.00	0.41	0.051	-0.060	-0.14	0.16
Sulfide			1.00	0.062	0.19	-0.097	0.23
Chloride				1.00	0.10	0.028	0.38
Phosphate					1.00	0.16	0.073
Depth						1.00	-0.19
Total Iron							1.00

Table 4. The effect of oxidant [chlorinated lime, $a\text{Ca}(\text{OCl})_2 \cdot b\text{CaCl}_2 \cdot c\text{Ca}(\text{OH})_2 \cdot d\text{H}_2\text{O}$] and coagulant [$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$] on the removal of 2.0 mg of As/L.

Oxidant (mg/L)	Coagulant (mg/L)	Final arsenic concentration (mg/L)
4	250	0.075
6	250	0.037
10	250	0.006 ^a
15	250	0.003 ^a
20	250	< 0.002 ^a
20	100	0.06
20	150	0.03
20	200	0.02 ^a
20	250	< 0.002 ^a

^a The method detection limit for arsenic could not be determined in the time allotted for this project; therefore, all arsenic concentrations less than the most dilute standard used for calibration (0.028 mg/L) are estimated.

Table 5. The influent and effluent water quality of a 1.8 m (6 feet) tall by 4.6 m (15 feet) by 6.1 m (20 feet) water storage tank at the Kishorganj Rural Electrification Board facility that provides drinking water to approximately 300 people.

Parameter	Influent	Effluent
Arsenic (mg/L)	0.16	< 0.002 ^a
Oxidation-reduction potential (millivolts)	-38	19
pH	7.06	6.47
Conductivity (microseman)	514	344
Temperature (°C)	27.2	28.2
Total iron (mg/L)	NA ^b	1.4
Sulfate (mg/L)	NA	< 1
Sulfide (mg/L)	NA	< 0.02
Chloride (mg/L)	NA	16
Phosphate (mg/L)	NA	1.3

^a All arsenic concentrations less than the most dilute standard used for calibration (0.028 mg/L) are estimated.

^b NA = not analyzed.

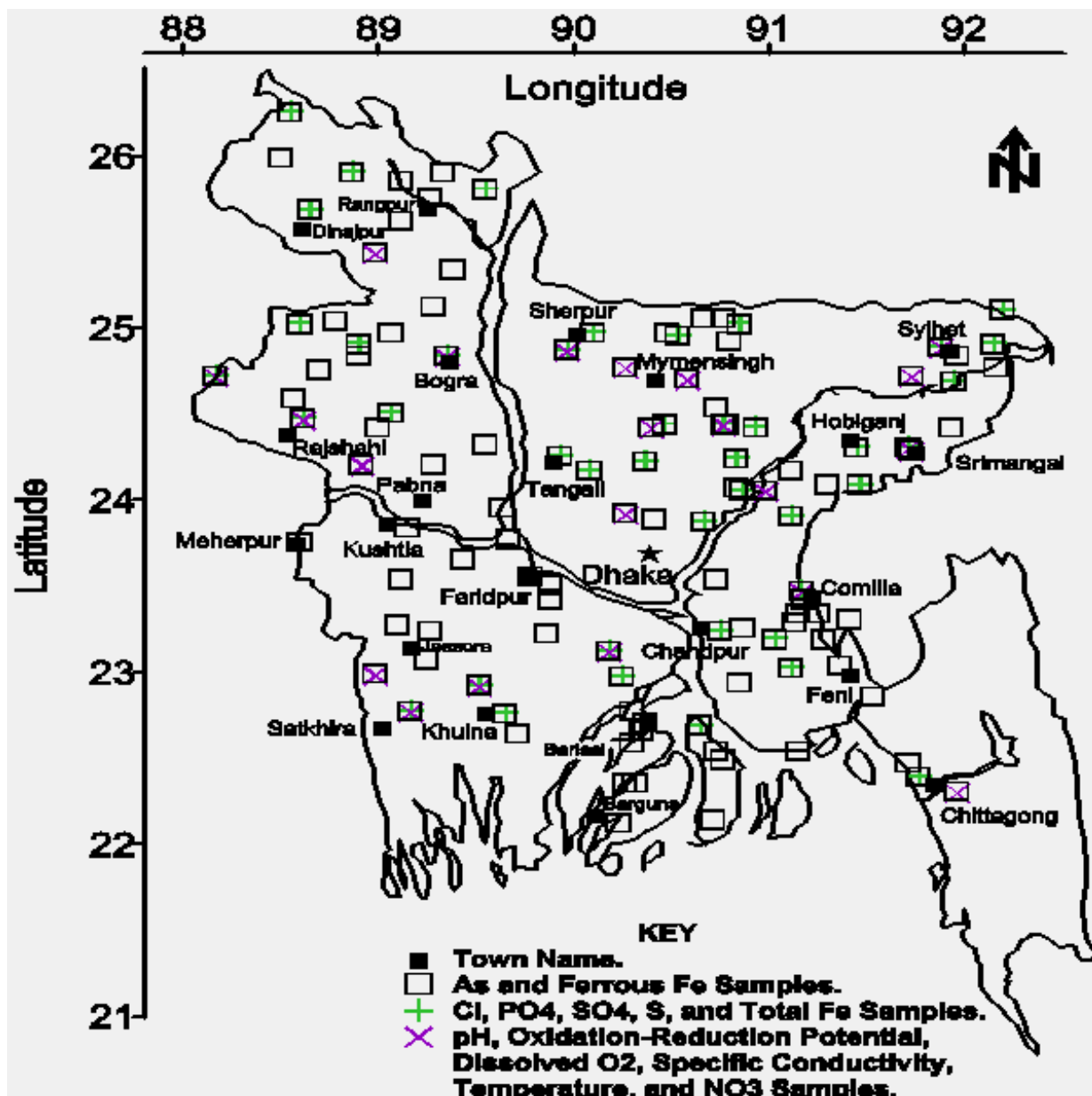


Figure 1. Locations where groundwater samples were collected from tubewells.

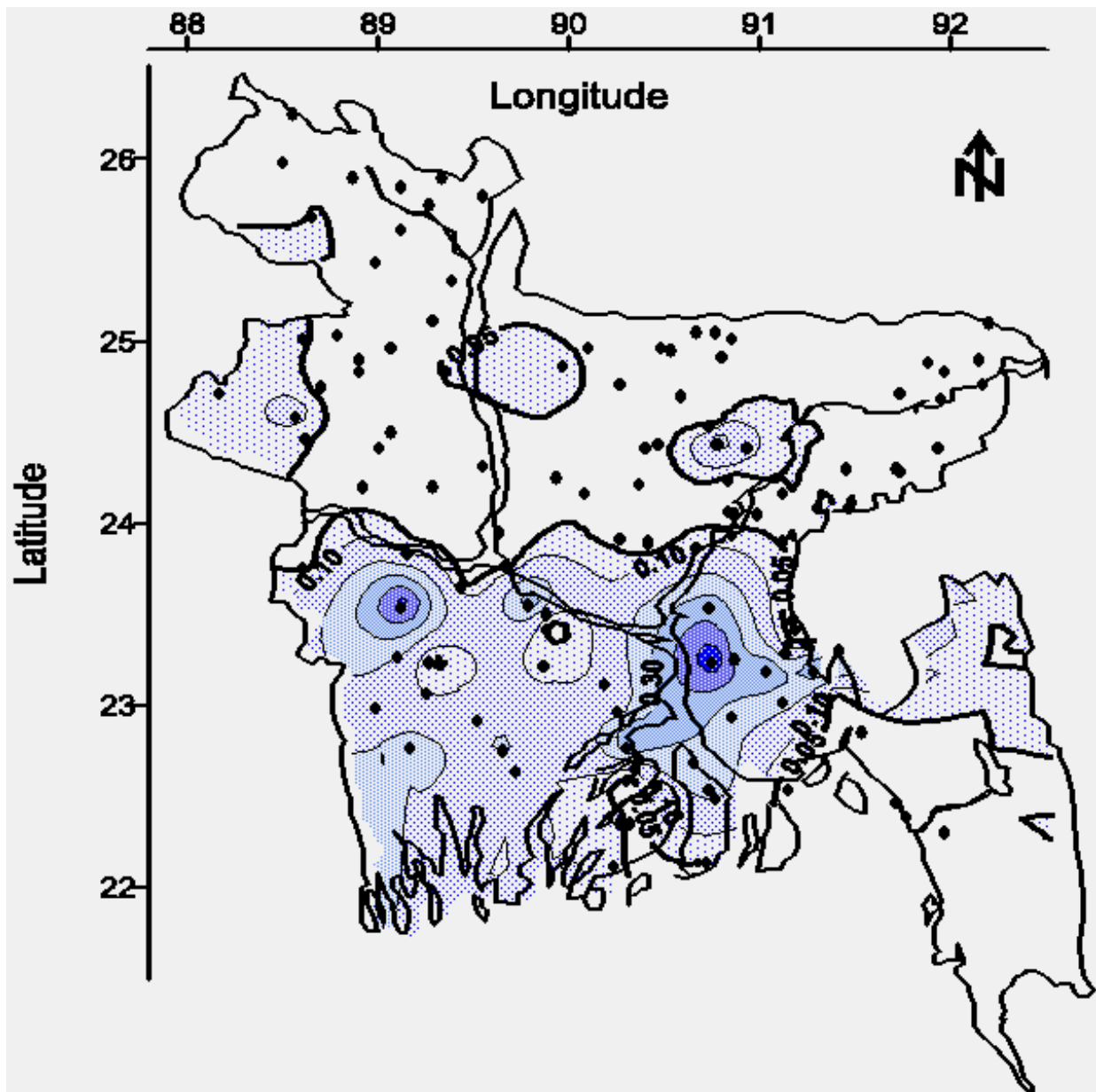


Figure 2. Map of the average arsenic concentration (mg/L) in water from tubewells less than 30.5 m or 100 feet bgs (• = village location).

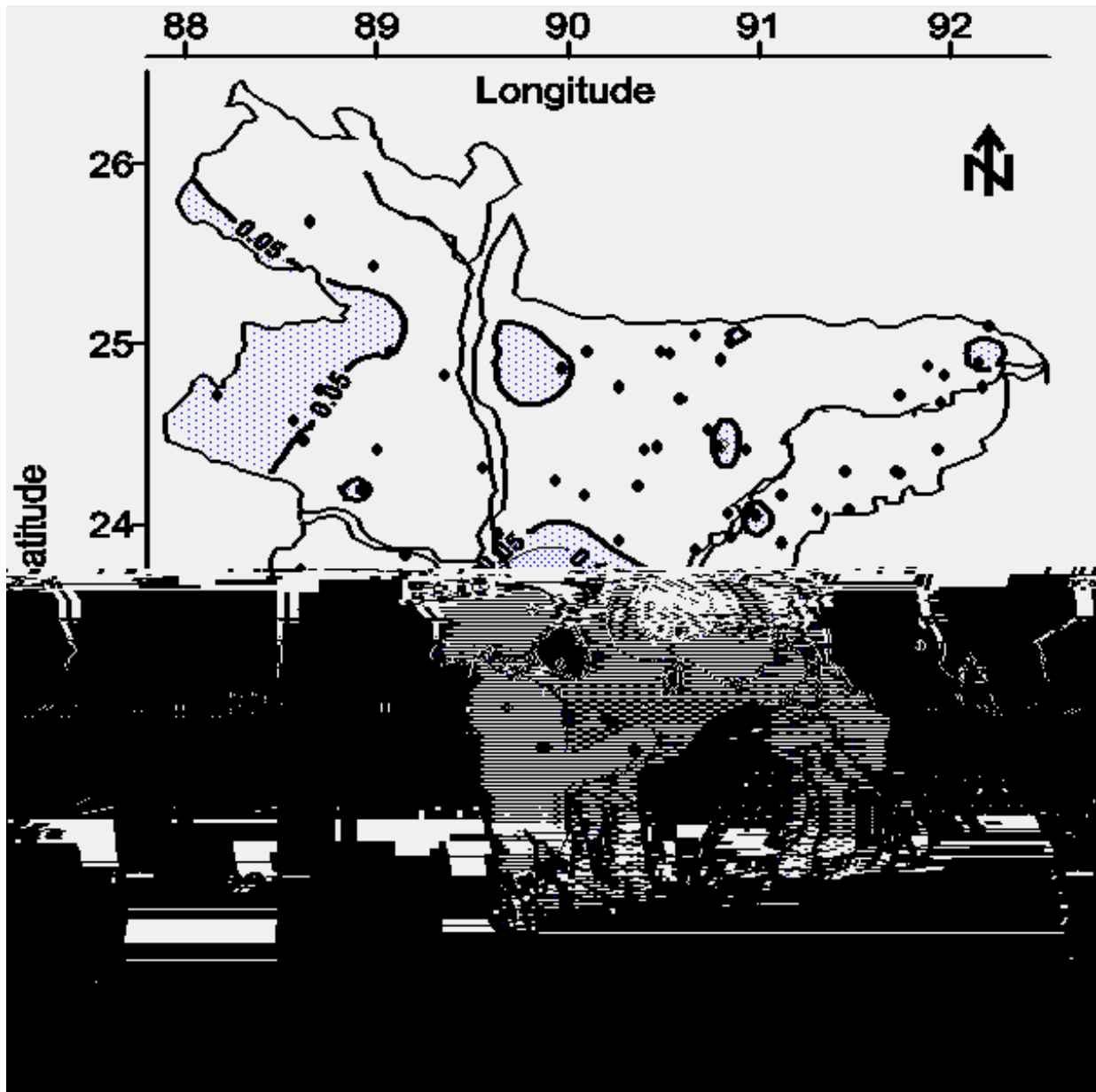


Figure 3. Map of the average arsenic concentration (mg/L) in water from tubewells greater than 30.5 m (100 feet) bgs.

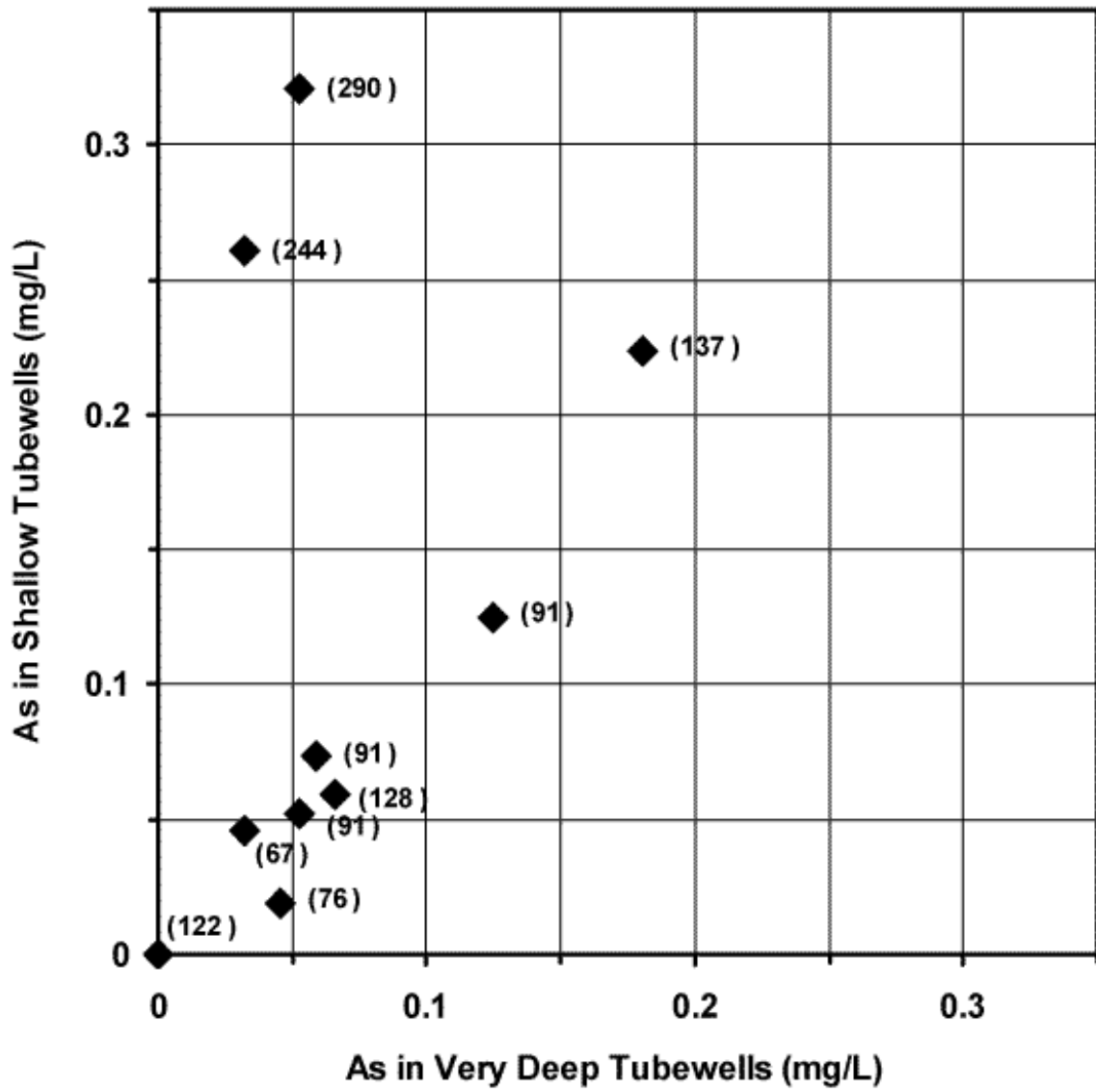


Figure 4. The vertical distribution of arsenic in groundwater.

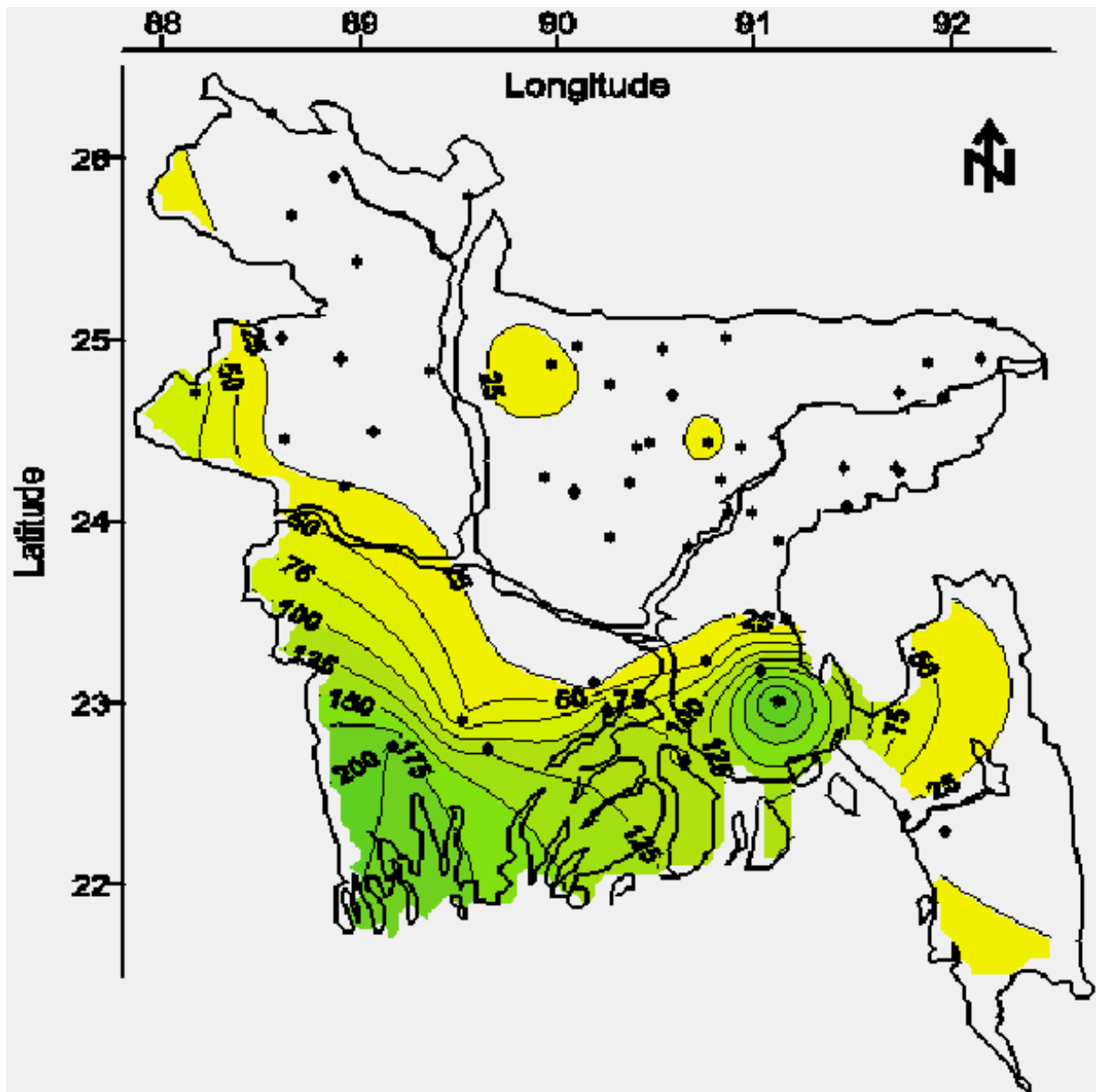


Figure 5. Map of the average chloride concentration (mg/L) in water from tubewells less than 30.5 m (100 feet) bgs.

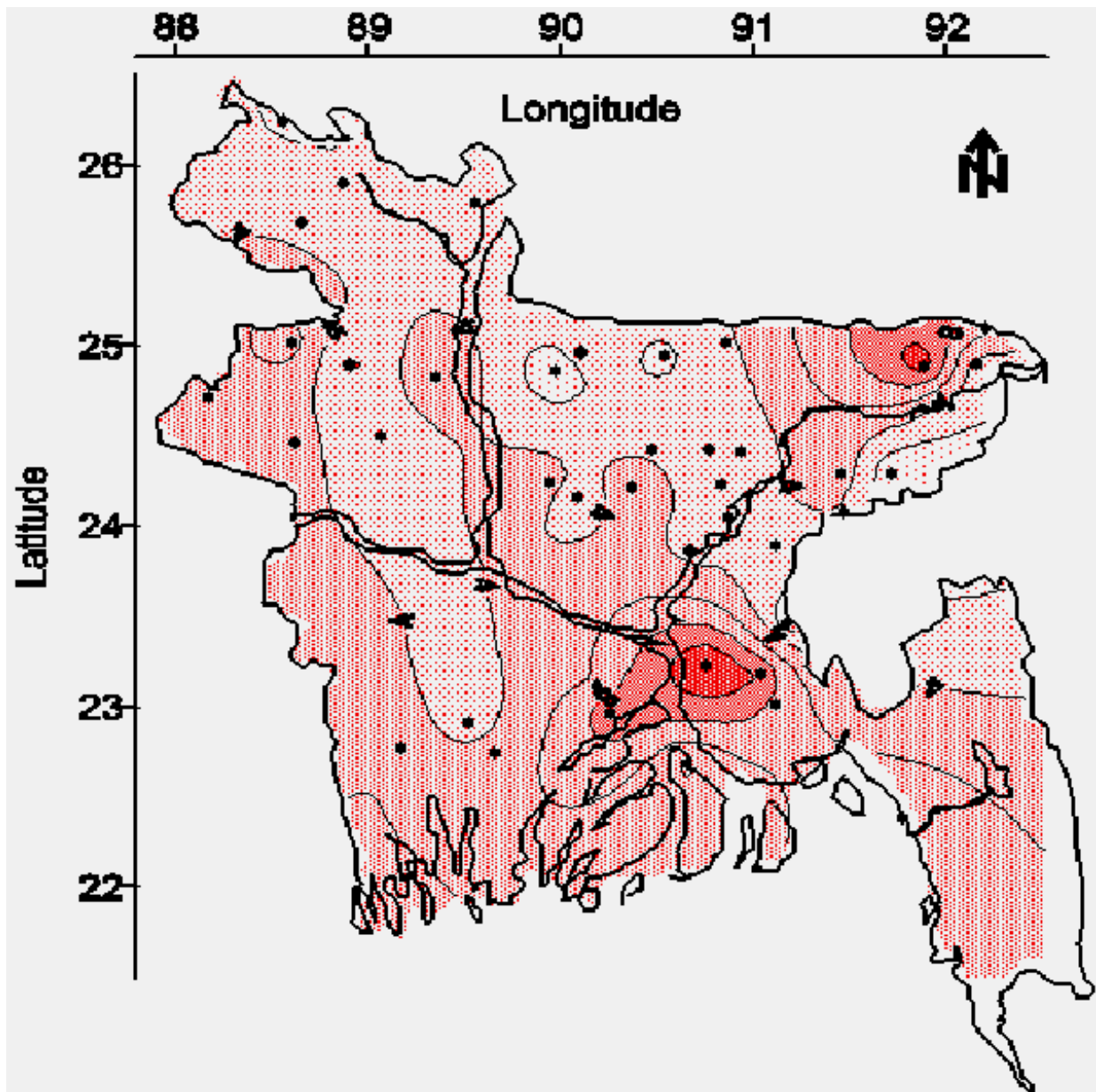


Figure 6. Map of the average phosphate concentration (mg/L) in water from tubewells less than 30.5 m (100 feet) bgs.

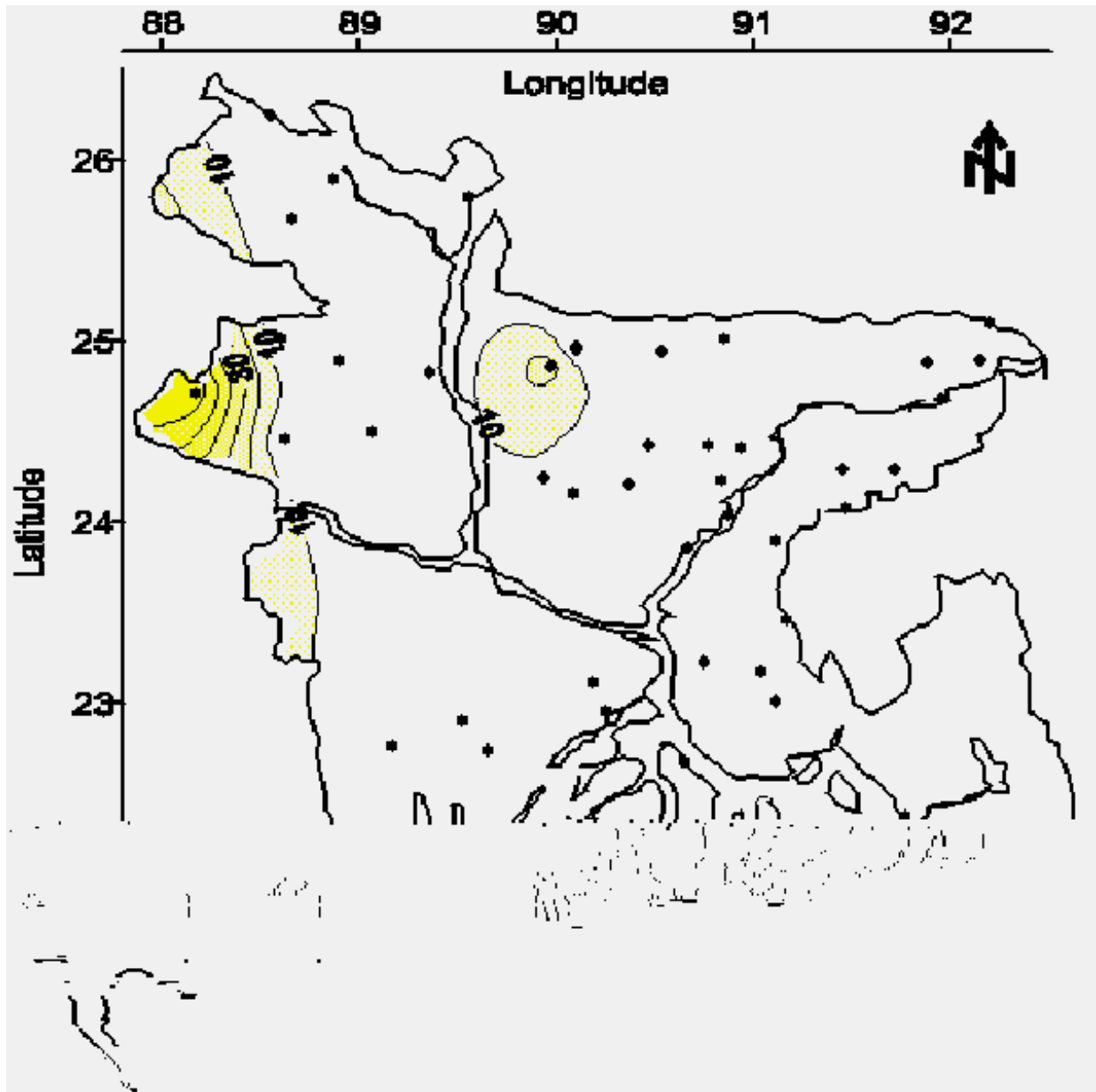


Figure 7. Map of the average sulfate concentration (mg/L) in water from tubewells less than 30.5 m (100 feet) bgs.

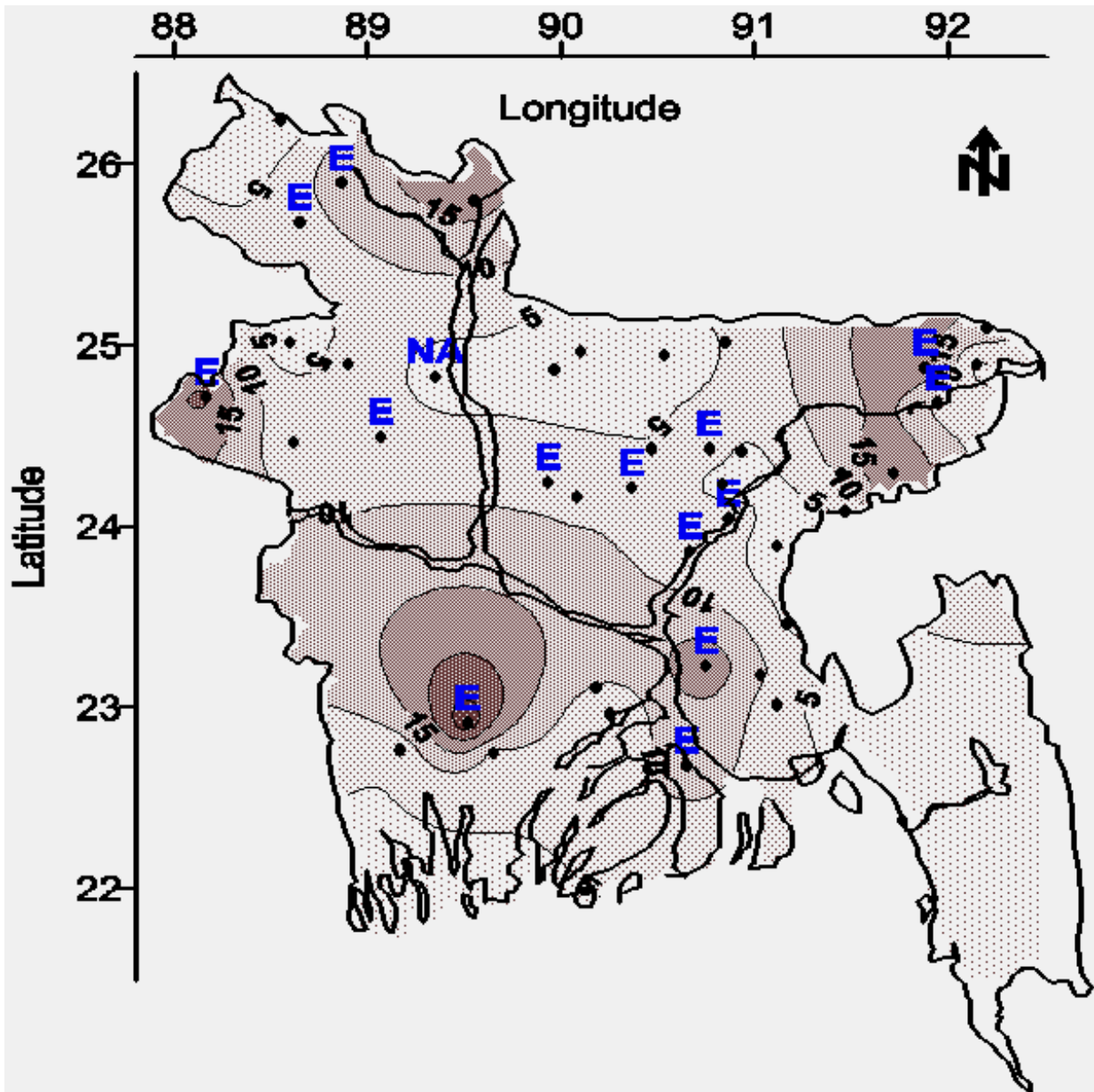


Figure 8. Map of the average total iron concentration (mg/L) in water from tubewells less than 30.5 m (100 feet) bgs.

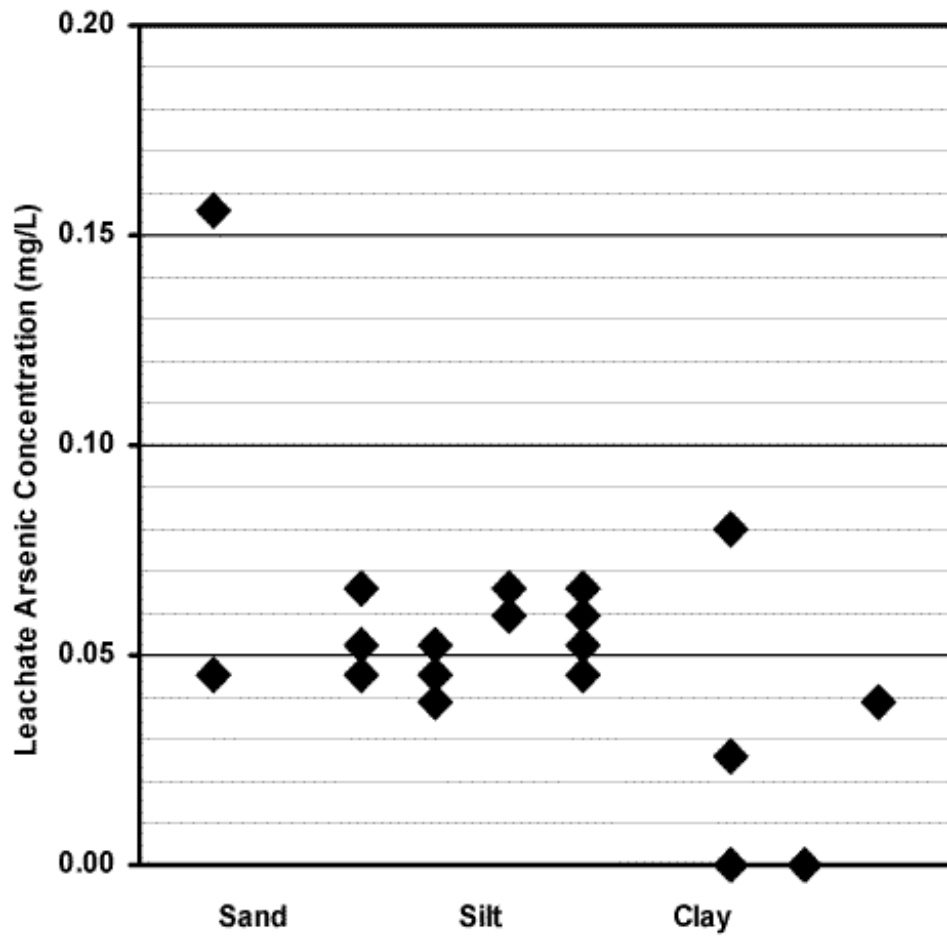


Figure 9. The concentration of arsenic (mg/L) leached into 200 mL of distilled water from 100 grams of surface soil after 6 days.

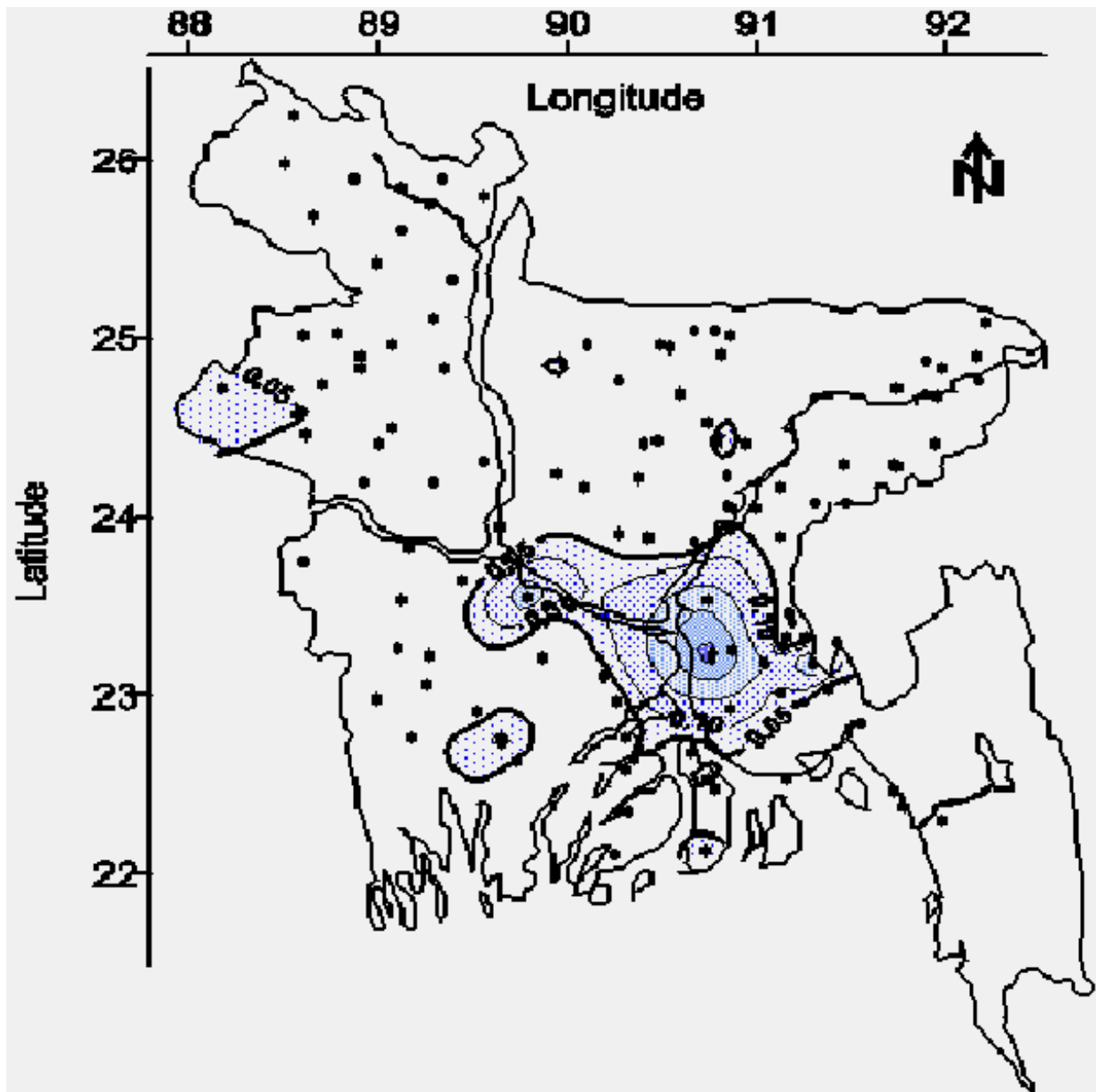


Figure 10. Map of the minimum arsenic concentration (mg/L) in water from all tubewells regardless of depth.

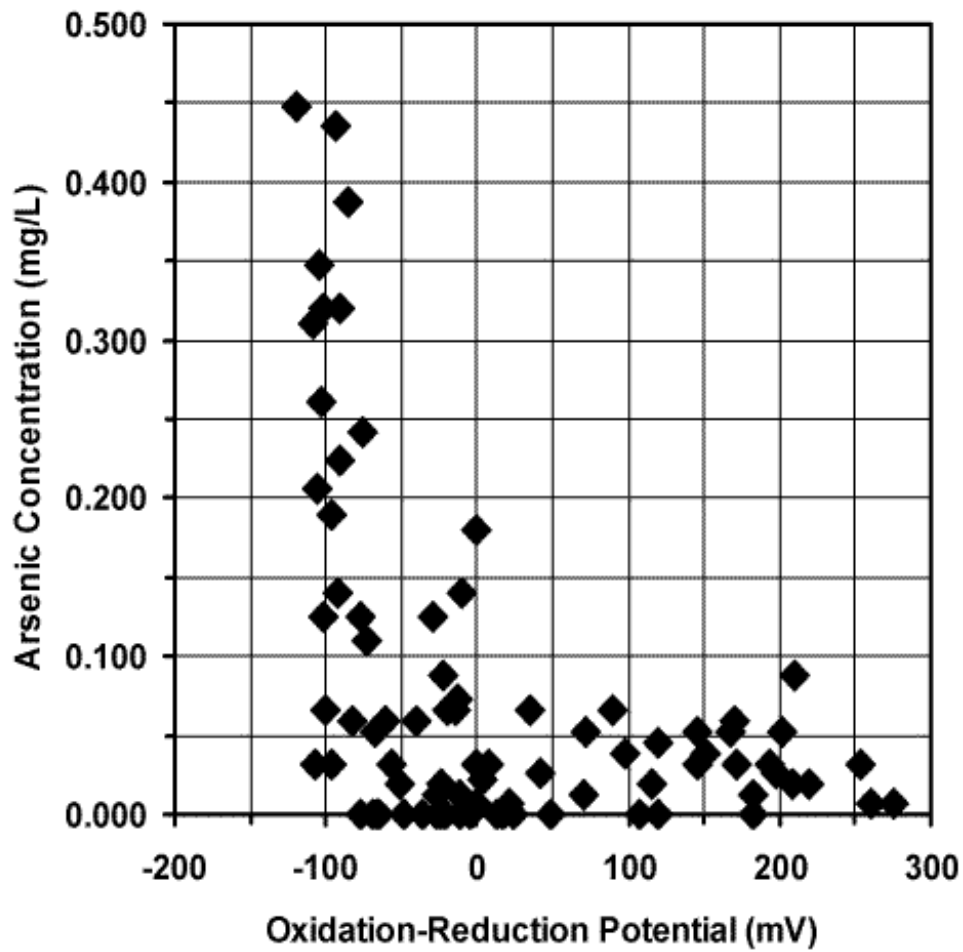


Figure 11. Graph of arsenic concentration (mg/L) versus oxidation-reduction potential in water from all tubewells regardless of depth.

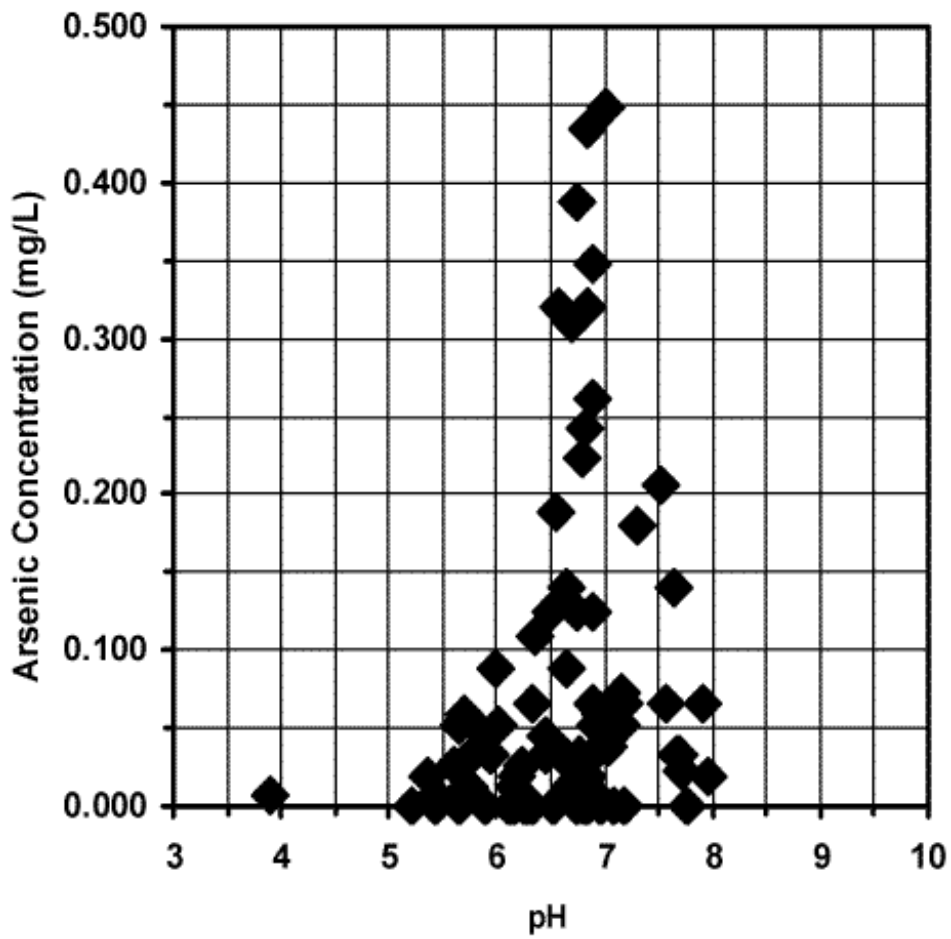


Figure 12. Graph of arsenic concentration (mg/L) versus pH in water from all tubewells regardless of depth.