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Special Feature on Groundwater Management and Policy

Arsenic Contamination of Groundwater in Bangladesh

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High arsenic concentrations in groundwater were first detected in western Bangladesh in the early 1990s. The arsenic is of natural origin and is believed to be mobilized in the subsurface by a number of mechanisms that are not yet clearly understood. Estimates of the population in Bangladesh now exposed to concentrations over the national drinking water standard vary from 20 million to over 36 million people, with 57 million out of a population of over 140 million being exposed to levels higher than the World Health Organization standard. While a national survey has identified 38,430 chronic cases so far, at least one scientific study estimates that the prevalence of arsenicosis in Bangladesh annually could be up to two million cases if consumption of contaminated water continues. For skin cancer it could be up to one million cases, and the incidence of death from arsenic-induced cancer could be 3,000 cases. In response to the problem, many initiatives have been launched both domestically and internationally to analyze and deal with the situation, including finding alternate sources of water and ways of treating it. By the middle of 2005, 1,851 deep tube wells had been installed to draw from the (so far) arsenic-free deep aquifer, with plans to put in 8,981 more. At the same time, 5,626 dug wells, 458 pond sand filters, and 2,606 household-scale rainwater-harvesting units have been installed, but there are still problems with these systems and other technologies to treat water, and Bangladesh's government is reviewing and certifying technologies that remove arsenic from water. This paper presents an overview of some of the important aspects of arsenic contamination of groundwater in Bangladesh, including an overview of the extent of contamination, current knowledge about the source of arsenic and the mechanisms governing its mobilization, as well as a summary of the present understanding of the impact of irrigating with arsenic-laden water on agricultural soil and the food chain. Several different arsenic removal technologies already in use or tested in Bangladesh are discussed, along with the results of the first phase of a certification process for arsenic removal technologies.

Keywords: Groundwater contamination, Arsenic, Bangladesh, Arsenic removal technology.

1. Introduction

The presence of elevated levels of arsenic in groundwater has become a major concern in Bangladesh, India, and several other countries. The contamination scenarios in Bangladesh and India's state of West Bengal appear to be the worst detected so far worldwide, both in terms of area and population affected. Arsenic contamination of groundwater is particularly challenging in Bangladesh, since water extracted from shallow aquifers is the primary source of drinking and cooking water for most of its population of over 140 million. The rural water supply is almost entirely based on groundwater supply through use of hand-pump tube wells;[1] an estimated ten million domestic wells constitute the backbone of rural water supply in the country. The urban water supply is also heavily dependent on groundwater.

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[1] The term *tube well* is generally used to describe a water well.

Arsenic contamination has primarily affected the shallow aquifer (usually less than 100 meters [m]), and there is a distinct regional pattern, with the greatest contamination in the south and southeast and least in the northwest (BGS and DPHE 2001; BAMWSP 2005). Out of 465 upazilas (sub-districts) in Bangladesh, 270 have been affected with significantly high concentrations of arsenic. According to the British Geological Survey (BGS) and Department of Public Health Engineering (DPHE) (BGS and DPHE 2001), 35 million people in Bangladesh are exposed to an arsenic concentration in drinking water exceeding the national standard of 50 micrograms per liter (μg/L), and 57 million people are exposed to a concentration exceeding the World Health Organization (WHO) guideline value of 10 μg/L. This has lowered the safe water coverage of the population to less than 80 percent from an impressive figure of nearly 98 percent. Arsenic toxicity has no known effective medicine or treatment, but drinking arsenic-free water and improving nutritional intake can help affected people to recover from some of the symptoms of toxicity. Therefore, there is an urgent need to provide safe water to the huge population in the arsenic-affected areas on a priority basis. Diagnosis of arsenicosis patients and their treatment and management remain a major challenge.

In Bangladesh, high arsenic concentration has been found throughout the floodplain and delta of the Ganges, Brahmaputra, and Meghan rivers, but the delta region of southern Bangladesh is the most contaminated (BGS and DPHE 2001). Arsenic present in groundwater is of natural origin and is believed to be mobilized in the subsurface by a number of mechanisms, which are not yet clearly understood and are the subjects of many ongoing scientific research studies.

The government of Bangladesh adopted a national policy for arsenic mitigation in 2004 and also developed an implementation plan for arsenic mitigation. A major focus of the national arsenic policy is to ensure access for all to safe water for drinking and cooking through implementation of alternative water supply options in the areas affected by arsenic contamination. The policy also focuses on the diagnosis of arsenicosis patients, their proper treatment and management, and assessment of possible impacts of arsenic on agriculture.

The options commonly suggested as possible alternatives to arsenic-affected groundwater can be broadly divided into the following categories: (1) alternate groundwater sources (e.g., deep tube wells and dug wells); (2) surface water sources (e.g., pond/river sand filter treatment); (3) rainwater harvesting; and (4) groundwater treatment for arsenic removal. A number of alternative water supply options have already been implemented in different arsenic-affected areas with mixed results. The government has established a technology verification process through which all proposed arsenic removal technologies must be verified before approval is given for marketing. The first phase of this technology verification process has been completed through which the performance of five arsenic removal technologies has been verified. The second phase of the verification process is expected to commence soon.

Besides domestic use, huge quantities of groundwater are also used for irrigation in Bangladesh during the dry season, mainly for the cultivation of dry-season rice (boro) and wheat; some other crops and vegetables are also grown with irrigation water. In fact, the volume of groundwater extracted for irrigation far exceeds that extracted for domestic use. A total of 925,152 shallow tube wells and 24,718 deep tube wells were used for irrigation during the 2004 dry season, and groundwater accounted for about 75 percent of total irrigation (BADC 2005). Ali et al. (2003a) estimated that over 900 metric tons (tonnes) of arsenic is cycled each year with irrigation water. Thus, accumulation of arsenic in root-zone soil, its introduction into the food chain, and possible impact of arsenic-bearing irrigation water on soil fertility and crop yield are major concerns.

This paper presents an overview of some of the important aspects of arsenic contamination of groundwater in Bangladesh, including an overview of the extent of contamination. Current understanding about the source of arsenic and the mechanisms governing its mobilization are summarized. An overview of the Bangladesh national policy and implementation plan for arsenic mitigation is presented. The paper provides an overview of the alternative water supply options that are currently being implemented for providing safe drinking and cooking water to people in different arsenic-affected areas of the country. It presents a discussion on different arsenic removal technologies used in Bangladesh and the results of the first phase of the technology verification process instituted by the government. Also summarized is the present understanding of the effect of arsenic-bearing irrigation water on agricultural soil and the food chain.

2. Extent of arsenic contamination

2.1. Distribution of arsenic in groundwater

Awareness about the presence of arsenic in Bangladesh has been growing since late 1993, when arsenic was first tested and detected in groundwater samples from the district of Chapai Nawabgonj bordering the state of West Bengal in India. Since then, higher levels of arsenic (exceeding the WHO standard of 10 microgram per liter [μg/L] and Bangladesh standard of 50 μg/L) have been detected in many regions of the country. Different organizations and research groups have carried out groundwater surveys to characterize the distribution of arsenic in Bangladesh’s groundwater. Many of these were small-scale studies focusing on a particular area or region (e.g., Nickson 1997; Badruzzaman et al. 1998; Safiullah 1998; Yokota et al. 2001; van Geen et al. 2003; Swartz et al. 2004). The NRECA surveyed around 570 tube wells spread around the country (NRECA 1997), and the DPHE and UNICEF jointly carried out a comprehensive nationwide survey (using field kits with a detection limit of 50 μg/L), which included 51,000 analyses up to October 1999 (BGS and DPHE 2001). The first, most comprehensive study on the distribution of arsenic in groundwater was carried out by the BGS along with the DPHE of the Bangladesh government (BGS and DPHE 2001). In this study, water samples from 3,534 tube wells in 61 out of 64 districts and from 433 out of the 496 upazilas were analyzed. More recently, the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP) carried out a very detailed screening of tube wells and a survey of arsenicosis patients in 270 of the most arsenic-affected upazilas of the country (BAMWSP 2005). In this study, every household was surveyed and all tube wells were tested using field-test kits. A total of 4,946,933 tube wells were screened for arsenic and over 66 million people were surveyed for arsenicosis.

Much of our understanding about the distribution of arsenic across Bangladesh comes from the comprehensive studies of the BGS and DPHE (2001) and BAMWSP (2005). The regional patterns of arsenic distribution obtained from these two surveys are very similar, with the greatest contamination in the south and southeast region (except in Chittagong and Chittagong Hill Tracts) and least in the northwest and the higher elevation areas of north-central Bangladesh. Figures 1 and 2 show the distribution of arsenic concentration in Bangladesh, based on the nationwide surveys. The data obtained from the BAMWSP survey are currently being analyzed by the National Arsenic Mitigation Information Centre (BAMWSP 2005). The survey by the BGS and DPHE (2001) provides a detailed assessment of different aspects of groundwater arsenic contamination. Arsenic concentration exceeding the Bangladesh standard of 50 µg/L was detected in 53 out of 61 districts and in 249 out of 433 upazilas sampled. Of the 3,534 samples analyzed in the BGS/DPHE study, only 9 percent were from deep tube wells (> 150 m) and the rest were from shallow wells. Of the shallow tube wells, 27 percent contained arsenic in excess of 50 µg/L (Bangladesh standard) and 46 percent in excess of the WHO guideline value of 10 µg/L. For the deep tube wells, the corresponding figures were 1 percent and 5 percent, respectively (BGS and DPHE 2001). It should be noted that since the deep tube wells tested are mainly in the coastal region and Sylhet in the northeast, they are not necessarily representative of deep wells elsewhere in the country. The survey results revealed some "hot spots" of high arsenic concentration in some of the least-contaminated regions (e.g., Chapai Nawabgonj in western Bangladesh), and it was recognized that the sample density in the BGS/DPHE survey was not sufficient to ensure detection of all such hot spots.

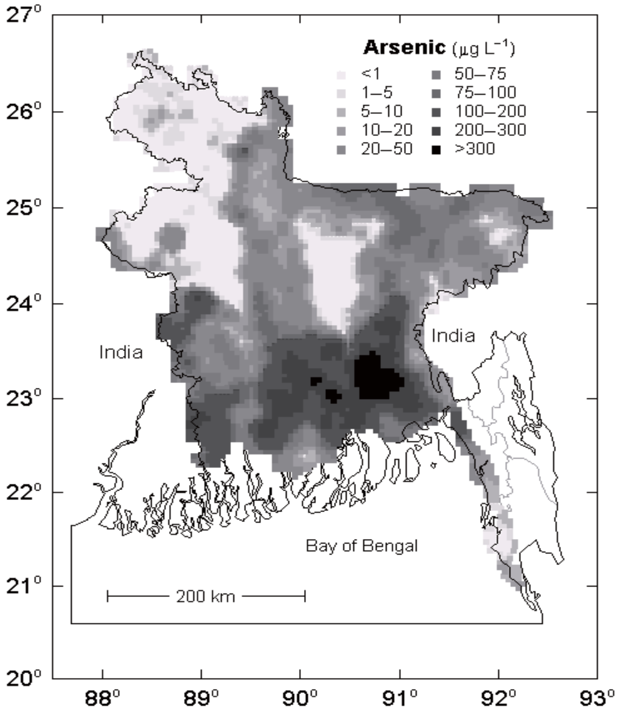

Figure 1. Distribution in Bangladesh of arsenic contamination in groundwater

Source: BGS and DPHE 2001.

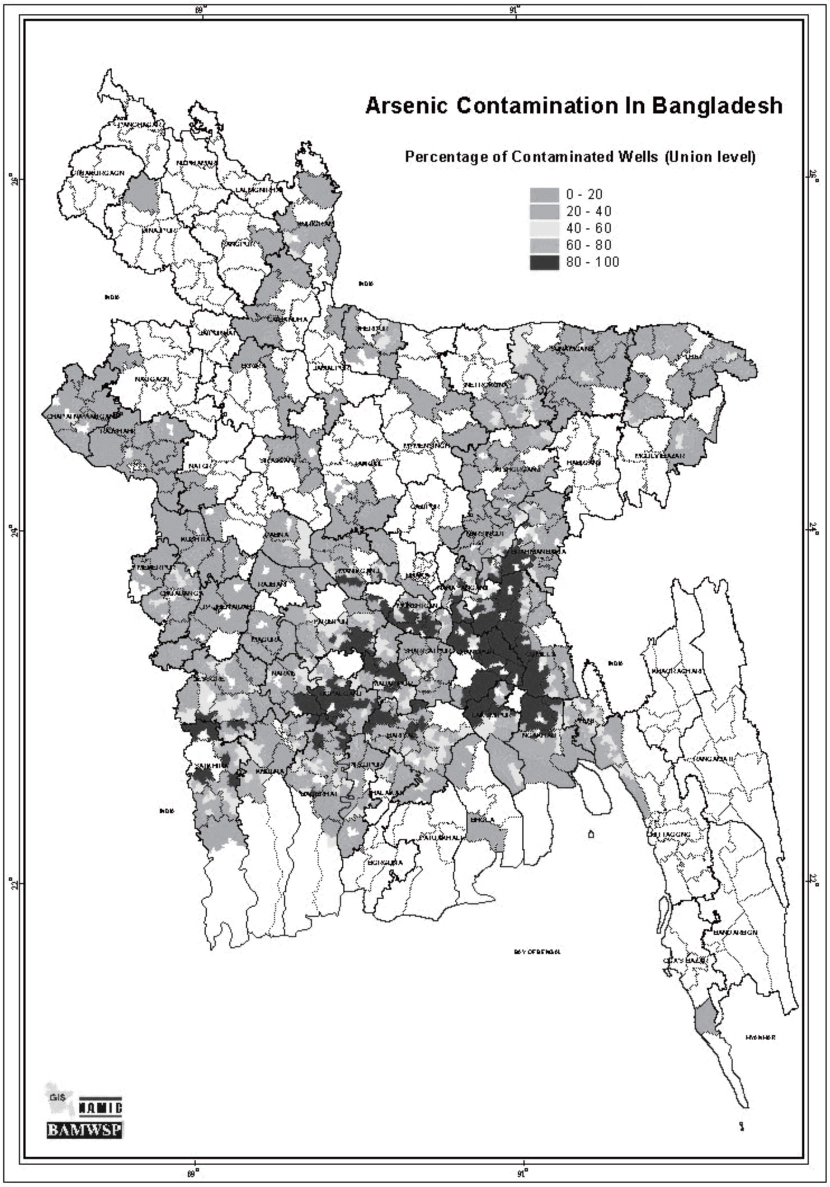

Figure 2. Percentage of wells in Bangladesh with arsenic concentration exceeding 50 μg/L

Source: BAMWSP 2005.
Note: As per the National Screening Program 2002–03.

An important observation from this and other arsenic surveys is the significant variation of arsenic concentration in well waters within short distances of each other. Arsenic concentrations were found to be extremely patchy over small scales. Neighboring wells within the same village were found to contain quite different concentrations of arsenic and other water quality parameters (BGS and DPHE 2001). In the vertical dimension, high concentrations were detected within tens of meters of low concentrations. The BGS and DPHE (2001) reported a "bell-shaped" depth profile for average arsenic concentration, with the maximum average concentration found in the interval of 15–30 m. It is interesting that a similar bell-shaped pattern has been reported in a number of specific sites (e.g., Harvey et al. 2002; McArthur et al. 2004; van Geen et al. 2003). Figure 3 shows the vertical profile of dissolved arsenic concentration at a study site (Harvey et al. 2002) in Mushiganj, 30 kilometers south of Dhaka.

According to the BGS and DPHE (2001), the patchiness of arsenic distribution reflects the large amount of local variation in sediment characteristics and hydrogeological regimes, both laterally and vertically. Harvey et al. (2005a) contend that understanding the effects of flow and transport is important for understanding the behavior of dissolved arsenic; the usual close spacing (tens and hundreds of meters) of discharge areas (e.g., irrigation wells and rivers) and recharge areas (e.g., ponds, rice fields, rivers) drives groundwater flow through a complex, transient three-dimensional system of flow paths that also have spatial scales of tens and hundreds of meters. Harvey et al. (2005a) suggest that the complex nature of recharge and discharge areas could provide a potential explanation for the spatial complexity of arsenic distribution in the subsurface.

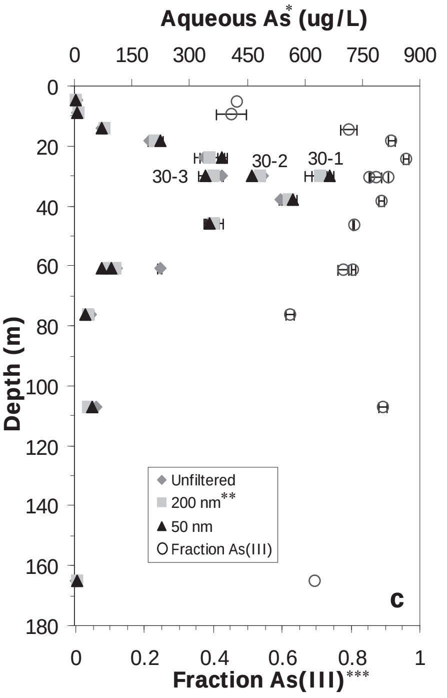

Figure 3. Vertical profile of dissolved arsenic concentration at a study site in Mushigonj

Source: Harvey et al. 2002.

*As = the chemical symbol for arsenic

**nm = nanometer (one billionth [10^{-9}] of a meter).

***As(III) = arsenic present in trivalent form.

Note: Study conducted by the Massachusetts Institute of Technology (MIT), University of Cincinnati, and the Bangladesh University of Engineering and Technology (BUET), with funding from the National Science Foundation (NSF), USA.

2.2. Population affected by arsenic contamination

Estimates of population exposed to a concentration of arsenic above the Bangladesh drinking water standard of 50 μg/L vary from about 20 million to over 36 million people (DPHE, BGS, and MML 1999; EES and DCH 2000; Begum 2001; BGS and DPHE 2001). According to the BGS and DPHE (2001), 35 million people are exposed to an arsenic concentration in drinking water exceeding the national standard of 50 μg/L and 57 million people are exposed to a concentration exceeding the WHO standard of 10 μg/L.

The most commonly reported symptoms (often referred to as arsenicosis) of chronic exposure to arsenic are hyperpigmentation (dark spots on the skin), hypopigmentation (white spots on the skin), and keratosis (skin hardens and develops raised wart-like nodules). Sometimes, hyperpigmentation and hypopigmentation are commonly referred to as melanosis. Chronic exposure to arsenic can also cause skin cancer, internal cancers, and a wide range of other health problems (e.g., abdominal pain, nausea, vomiting, diarrhea, anemia). The most commonly manifested disease in Bangladesh so far is skin lesions (melanosis and keratosis).

Yu et al. (2003) estimated that the prevalence of arsenicosis in Bangladesh annually could be up to two million cases if consumption of contaminated water continues. For skin cancer it could be up to one million cases, and the incidence of death from arsenic-induced cancer could be 3,000 cases. In a survey conducted in 270 villages of Bangladesh, more than 7,000 arsenicosis patients were identified (Rahman et al. 2000). In the nationwide screening program carried out by the BAMWSP (2005), over 66 million people in every household of 270 arsenic-affected upazilas were surveyed for arsenicosis patients, and a total of 38,430 arsenicosis patients were identified. Figure 4 shows the distribution of arsenicosis patients in the survey area. While the results from this survey are currently being analyzed, results from previous surveys show poor correlation between the extent of contamination in a particular area and the distribution density of patients (BGS and DPHE 2001). Although the BAMWSP survey shows relatively low prevalence of arsenicosis, many fear it to be the “tip of the iceberg,” considering the usual delayed effect of arsenic on an exposed population.

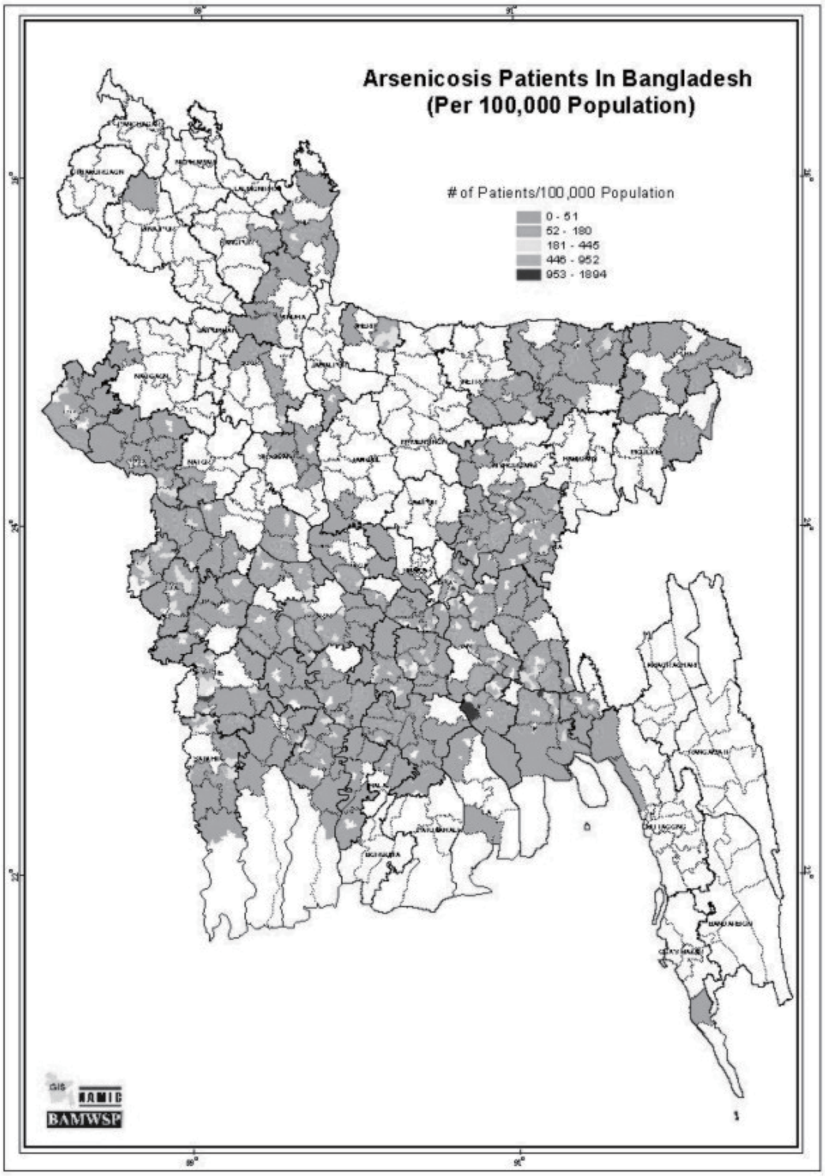

Figure 4. Distribution of arsenicosis patients in Bangladesh

Source: BAMWSP 2005.

3. Mobilization of arsenic in the subsurface

Available information suggests that the source of arsenic in groundwater is geologic, and it is believed that arsenic is released to groundwater as a result of a number of mechanisms that are not yet clearly understood. In Bangladesh, arsenic rich iron oxyhydroxides appear to be a major source of arsenic, from which arsenic is released by dissolution and desorption. The original source of arsenic can most likely be traced to the oxidation of sulfide minerals, principally pyrite, derived from the granitic and metamorphic source regions of the Himalayas. It has been suggested that pyrite oxidation occurred during weathering at the source in the Himalayas and that arsenic was transported and deposited in the Ganges Delta in association with the resulting iron oxides (McArthur et al. 2004).

Several research works (e.g., BGS and DPHE 2001; Harvey et al. 2002; McArthur et al. 2004; van Geen et al. 2003) describe the following two distinct types of aquifer sediment: (1) brown (or orange to yellow) sediment, presumably containing iron oxyhydroxides, where dissolved arsenic concentrations are low; and (2) gray sediments, where dissolved arsenic concentrations may be high. Brown sediments are found at depths in the older Pleistocene-era aquifers such as the Dupi Tila formation, where water with a low level of arsenic is found, as well as near the surface. Dissolved arsenic is presumably low in these sediments because of the capacity of iron oxyhydroxides to adsorb it. The reducing condition of almost all groundwater in Bangladesh (demonstrated by high levels of dissolved ferrous iron and methane and low values of Eh),[2] as well as the weak but statistically significant positive correlation of dissolved arsenic to iron and bicarbonate, suggest that most arsenic is liberated by the dissolution of iron oxyhydroxides or perhaps by desorption of arsenic after reduction from arsenate to arsenite (BGS and DPHE 2001; Harvey et al. 2002). The low concentration of sulfate and the generally reducing conditions indicate that arsenic has not been mobilized from sulfide minerals (Harvey et al. 2002).

Microbial processes drive geochemical transformations in Bangladesh’s groundwater. Harvey et al. (2002) reported, based on the results of a study carried out at a field site in Munshiganj near Dhaka, a high concentration of radiocarbon-young methane, which indicates that young carbon has driven the more recent biogeochemical processes. This study also suggests that irrigation pumping is sufficient to have drawn water to the depth where dissolved arsenic concentration peaks (30–40 m in depth) and thus could promote biogeochemical transformation (reductive dissolution and desorption) leading to arsenic mobilization. Field injection experiments carried out at the Munshiganj site (Harvey et al. 2002; Swartz et al. 2004) showed that introduction of organic carbon in the aquifer (in the form of molasses) quickly mobilizes arsenic. On the other hand, introduction of nitrate in the aquifer (which acts as an oxidant) lowered arsenic concentration.

Harvey et al. (2005a, forthcoming), however, argue that the role the iron oxyhydroxides may have played in controlling the current concentration of dissolved arsenic is difficult to determine. Iron oxyhydroxides must exist, or have existed very recently, according to the theory that arsenic is released from iron oxyhydroxides in local sediments by organic carbon oxidation. These iron oxyhydroxides have not been definitively demonstrated in the gray sediment, however, and high concentrations of methane and hydrogen in strongly reducing water indicate that geochemical conditions are not conducive to the stability of iron oxyhydroxides (Harvey et al. 2002). Given that dissimilatory iron reduction, the primary means of iron reduction, precedes methane generation in sediment diagenesis, active iron reduction would most likely have occurred at an earlier stage in diagenesis as opposed to the present time (Harvey et al. forthcoming). Further complicating the puzzle over the role of iron

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[2] Eh is a parameter which indicates redox potential.

oxyhydroxides, Swartz et al. (2004) showed that only very small quantities would be required to explain the current ratio of sorbed to dissolved arsenic. Thus, it is conceivable that slow reductive dissolution within aquifer sediments could be responsible for high dissolved arsenic concentrations, but only if the geochemical system happens to be in a state where iron oxyhydroxides have released almost all of their sorbed arsenic (Harvey et al. 2005a).

Some recent works suggest that arsenic-bearing pyrite grains have reached the Ganges Delta and are incorporated in the aquifers (Harvey et al. forthcoming). These works argue that minerals are cyclically weathered near the land surface, where the water table rises and falls each year. In the presence of oxygen, sulfide minerals are oxidized, iron oxides are formed, and arsenic is transferred from pyrite to iron oxides. During anoxic conditions, which may coincide with periods of recharge as return flow from irrigated rice fields, iron oxides dissolve and arsenic is released into the water column where it is transported to depth with the recharge water. Thus it is conceivable that dissolved arsenic originates from near-surface sediments above the aquifer that may have a much larger composition of iron oxyhydroxides (Harvey et al. forthcoming).

4. National policy and plan for arsenic mitigation

4.1. Bangladesh National Policy for Arsenic Mitigation

In the backdrop of widespread arsenic contamination of groundwater, the government of Bangladesh adopted a national policy in 2004 (GoB 2004), intended to serve as a guideline for arsenic mitigation programs in the arsenic-affected areas of the country. The policy focuses on ensuring access for all to safe water for drinking and cooking, diagnosis of arsenicosis patients and their treatment and management, and the possible impact of arsenic on the agricultural environment. The specific issues addressed in the policy include the following: (1) identification of the nature and extent of the problem; (2) arsenic mitigation activities; (3) institutional arrangement; (4) research and development; (5) information, applied research, and reference laboratory; (6) collaboration and cooperation; and (7) policy implementation issues.

For identification of the nature and extent of the arsenic problem, the policy emphasizes the following: (1) screening and regular monitoring of all tube wells, including irrigation wells; (2) survey of the population for identification of arsenicosis patients; and (3) assessment of arsenic levels in soil and agricultural products.

Arsenic mitigation activities included in the national arsenic policy focus on the following four major aspects: (1) raising public awareness about the arsenic problem, (2) alternative arsenic-safe water supply options, (3) diagnosis and management of arsenicosis patients, and (4) capacity building. The policy document emphasizes awareness development regarding the impact of arsenic ingestion, alternative safe water sources, and the fact that arsenicosis is not contagious. With regard to alternative safe water supply options, the national policy gives preference to surface water over groundwater as a source of water supply. It also promotes the use of piped water supply systems wherever feasible. For proper diagnosis and management of patients, it emphasizes the development of protocols for diagnosis and management of arsenicosis patients, training of health service providers, and rehabilitation of arsenicosis patients. With regard to capacity building, it puts emphasis on capacity building at all levels (government, local/community, private sector) for proper management of the arsenic problem. It also emphasizes the establishment of a network of well-equipped laboratories with measurement capacities at an appropriate level.

Institutionally, the policy emphasizes effective coordination of activities of government ministries and agencies, a greater role of local government institutes and local communities in planning and service delivery, and involvement of non-governmental organizations (NGOs) and the private sector in service delivery. It also promotes research and development works for better understanding of the impact of arsenic on water supply, health, food, and agriculture. It places emphasis on better cooperation and coordination among the different organizations and institutes (including donor organizations) involved in arsenic mitigation.

The policy also suggests that an implementation plan should be prepared for arsenic mitigation within the framework of the policy, and that the policy should be reviewed and updated depending on the feedback from implementation programs.

4.2. Implementation plan for arsenic mitigation in Bangladesh

The implementation plan for arsenic mitigation in Bangladesh has the following four major components: (1) water supply, (2) health issues, (3) agricultural issues, and (4) cross-cutting issues (GoB 2004). The following section briefly describes the implementation plan for each component.

a. Water supply

The major issues addressed in the water supply component of the implementation plan include screening and monitoring, technology options, provision of alternate water supply, urban water supply, research and development, and institutional arrangement. As noted earlier, the BAMWSP has already completed a comprehensive survey of tube wells and the population in 270 arsenic-affected upazilas of the country. The implementation plan puts emphasis on the development of field test kits as well as appropriate laboratory facilities for measurement of arsenic and other water quality parameters. While the plan promotes a range of options for safe water supply, it gives priority to surface water over groundwater. A number of technology options are promoted in the implementation plan, recognizing that no single technology will be applicable in all arsenic-affected areas. The technology options include the following: (1) improved dug well design and construction, (2) surface water treatment using pond/river sand filters (PSF/RSF) or large treatment plants, (3) deep hand tube wells, and (4) rainwater harvesting. Many of these technology options are currently being implemented in different arsenic-affected areas. (These technologies and their field performances are briefly discussed in the next section of the paper.)

The implementation plan recognizes that many local as well as foreign organizations are involved in testing and marketing of different arsenic removal technologies and that there is no regulation for assessing their performance. In order to ensure public safety, the government decided that marketing of any arsenic removal technology is not allowed without prior testing and validation by the Bangladesh

Council for Scientific and Industrial Research (BCSIR). A protocol has already been developed for validation of different arsenic removal technologies under the Environmental Technology Verification-Arsenic Mitigation (ETV-AM) Program, and the first phase of the verification process has already been completed. Results from this process are summarized in the next section of the paper.

Supplying safe water through provision of alternative water supply options is the first priority of the arsenic mitigation plan. The wide variation of arsenic contamination from one village to another makes a phased approach to arsenic mitigation imperative. The implementation plan has devised three different response levels, depending on the severity of arsenic contamination in a particular area. Villages with more than 80 percent of tube wells contaminated with arsenic (i.e., arsenic concentration exceeding 50 μg/L) come under "emergency response," those with 40–80 percent of tube wells contaminated with arsenic come under "medium-term response," and the "long-term response" covers the whole country—the aim being to provide sustainable water supply options to all. The implementation plan has developed criteria for the emergency, medium- and long-term responses (e.g., selection of intervention area, mitigation approach, service delivery, cost sharing, institutional arrangement). As part of the emergency response plan, the villages with more than 80 percent of tube wells contaminated with arsenic have already been identified based on the BAMSWP nationwide survey. Four alternative water supply technologies were considered for the emergency response plan, which included dug well, pond/river sand filter, deep hand tube well, and rainwater harvesting. Arsenic removal technologies were not considered at this stage. The applicability of these technologies in the different arsenic-affected areas has been analyzed and a detailed report with maps of union-wise (administrative unit comprising several villages) feasible water supply technology is being prepared (Mahmud 2005).

b. Health issues

Arsenic in tube well water is a serious public health concern. Although the nationwide survey carried out by the BAMWSP shows relatively low prevalence of arsenicosis, many fear it to be the tip of the iceberg. Similar to the provisions of alternative water supply options, health issues are to be addressed depending on the severity of arsenic contamination at the village level under emergency response, short-term response, and long-term response. Activities under emergency response include identifying intervention areas, training health workers, screening total population for case identification of arsenicosis according to approved protocol, treatment and management of arsenicosis patients according to approved protocol, and a social mobilization and awareness campaign. It should be noted that case identification and case management protocols for identification and management of arsenicosis patients, respectively, have already been developed and are currently being field-tested (GoB 2004). The implementation plan also elaborates on the criteria for medium- and long-term responses, institutional arrangement, and research and development related to the health aspects of the arsenic problem.

c. Agricultural issues

The principal concern in the agricultural sector related to the arsenic problem stems from the fact that huge quantities of groundwater are used in irrigation during the dry season in Bangladesh. The national implementation plan for arsenic mitigation focuses on improving understanding of the effects of arsenic on the agricultural environment and the food chain. The plan has identified a number of activities to be carried out in this regard, including the following: (1) research on arsenic in the food chain, (2) research on the impact of arsenic and agro-chemicals on soil fertility, (3) research on the effect of arsenic-contaminated irrigation water on agricultural products, and (4) establishment of a national standard for arsenic in groundwater used for irrigation and in agricultural products. The Bangladesh Agricultural Research Council has been entrusted with the task of preparing a prioritized list of studies and research to be carried out on this issue. The Bangladesh Agricultural Development Corporation (BADC) has initiated a number of studies focusing on the effects of arsenic-bearing irrigation water on soil quality and the food chain (Alam 2005). Section 6 of this paper summarizes the present understanding of the effect of arsenic-bearing irrigation water on soil quality and the food chain.

d. Cross-cutting issues

The implementation plan for arsenic mitigation has identified a number of cross-cutting issues related to the arsenic problem that should form integral parts of projects in the relevant sectors. These include public awareness of the problem, gender equality, rights of the poor, linkage with sanitation, groundwater management, and coordination of all stakeholders, including civil society.

5. Alternative water supply options

One of the major focuses of the national policy and implementation plan for arsenic mitigation is to ensure access to safe water for drinking and cooking in all arsenic-affected areas through implementation of alternative water supply options (GoB 2004). The options commonly suggested as possible alternatives to arsenic-affected groundwater can be broadly categorized as follows: (1) alternate groundwater sources (e.g., deep tube well, dug well), (2) surface water sources (e.g., using pond sand filters), (3) rainwater harvesting, and (4) groundwater treatment for arsenic removal. The following section provides a brief overview of the different options.

5.1. Alternative groundwater sources

Alternative groundwater sources include arsenic-free deep tube well, arsenic-free shallow shrouded tube well (SST), very shallow shrouded tube well in the coastal areas, and dug well. Deep tube wells and dug wells have been identified as potential alternative water supply sources in the national policy and implementation plan for arsenic mitigation, and have been installed in many arsenic-affected areas to supply safe water.

a. Arsenic-free deep tube well

Arsenic-free water is available in the deep aquifers in many regions of the country, which could be a very suitable option for obtaining arsenic-free water. The important issues in this regard are as follows: (1) the presence and identification of aquifers, (2) cost, and (3) possible cross-aquifer contamination.

It is important to first delineate the areas where such deep aquifers are available and are separated from shallow, contaminated aquifers by relatively impermeable layers. The annular space of the borehole of a deep tube well is required to be sealed at the level of impermeable strata to avoid percolation of arsenic-contaminated water from the aquifer above.

The BAMWSP has already installed 1,851 deep tube wells in the arsenic-affected areas of Barisal, Chandpur, Gopalgonj, Jahalakhati, Jhenaidah, Khulna, Laksmipur, Pirojpur, and Satkhira—mostly in the south and southeastern regions of the country. It plans to install 8,981 more in other arsenic-affected areas (BAMWSP 2005). DPHE-Danida and World Vision have also installed deep tube wells in other arsenic-affected areas (APSU 2004).[3] Of the 111 deep tube wells installed by the BAMWSP in the Haziganj upazila of Chandpur District, water samples from 86 wells were tested for arsenic and a range of other water quality parameters. Results show that none of the deep tube wells contain arsenic above the Bangladesh standard and all were free from fecal contamination, although 76 wells contained high iron content (BAMWSP 2005). Recently, the Bangladesh government's Arsenic Policy Support Unit (APSU) carried out risk assessments of different arsenic mitigation options, including deep tube well, dug well, pond sand filter, and rainwater harvesting. As part of the assessment, water samples from deep tube wells, mostly from south and southeast Bangladesh, were analyzed for arsenic and a wide range of water quality parameters (APSU 2004). Results show that none of the deep tube well water exceeded the Bangladesh standard or WHO guideline value for arsenic. Thermotolerant coliforms were detected in 8 percent of the wells, however, and high iron and manganese concentrations, exceeding the Bangladesh standard, were detected in 58 percent and 19 percent of the samples, respectively. Also, high ammonia and color, in excess of the Bangladesh standard, were detected in about half of the water samples.

b. Dug well

The dug well is probably the oldest method of groundwater withdrawal, in which a hole is dug in the ground to a depth below the groundwater table. The flow of water in the dug well is actuated by the lowering of the water table in the well due to withdrawal of water. It is widely used in many countries for domestic water supply (Ahmed and Rahman 2000). A large number of dug wells were found operating in Chittagong, Sylhet, and northern parts of Bangladesh, where constructing a hand-pump tube well is not always possible due to adverse hydrogeological conditions. Dug wells are not successful in many areas of the country that have a thick clayey soil layer, because they do not produce enough water to meet requirements. In areas with a very low water table and those with loose sand and silt, there may be difficulty in well construction as well as withdrawal of water. Although tube wells have replaced traditional dug wells in most areas, about 1.3 million people in both urban and rural areas still use dug wells for drinking water (GoB 2002). It is very difficult to protect the water of a dug well from bacterial contamination.

Conventional open dug wells are easily contaminated. In covered dug wells, the top of the well is closed for better sanitary protection. A pipe (or opening) is provided on the top of the cover slab for aeration. The well water is drawn through a hand pump fixed either on the top of the slab or by the side of the well. Bad smell in some dug well water is sometimes attributed to lack of aeration of the water. The government's national policy and implementation plan for arsenic mitigation both recommend an "improved dug well" as an option for arsenic mitigation (GoB 2004). As shown in figure 5, an improved dug well has facilities for the entry of air and sunlight into the well. Such dug wells have a cover or roof supported on a frame above the well.

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[3] Danida is Denmark's international development agency.

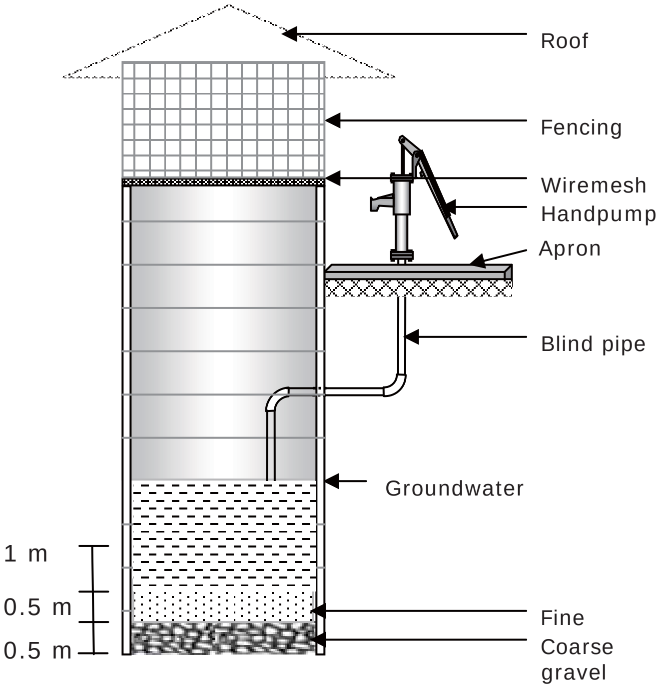

Figure 5. Schematic view of an improved dug well design

Many organizations have started installing dug wells in different arsenic-affected areas. A recent survey shows that the BAMWSP, Dhaka Community Hospital (DCH), NGO Forum, Asian Arsenic Network (AAN), World Vision, International Development Enterprises (IDE), DPHE-Danida, Bangladesh Rural Development Board (BRDB), and the DPHE-Government of Bangladesh (GoB)-IV project had constructed a total of 5,626 dug wells as an option for arsenic mitigation by the end of December 2004 (APSU 2005a). Water quality studies conducted so far show that using dug wells have reduced arsenic ingestion, but they have also exposed the population to high health risks from microbial contamination. Thermotolerant coliform organisms have been detected in 94 percent of dug wells by the APSU (2004), 74 percent by the DCH (2003), 40 percent by the Development Association for Self-reliance, Communication and Health (DASCOH 2004), 90 percent by the National Institute of Preventive and Social Medicine (NIPSOM 2003), and in most of the dug wells tested by the Japan International Cooperation Agency (JICA)-AAN (JICA and AAN 2004). It has been observed that bacterial contamination is most prevalent during the rainy season, probably due to the inflow of contaminated water to wells (APSU 2005b). Microbial contamination has also been reported in West Bengal, India (Smith et al. 2003). On the other hand, arsenic concentration exceeding the Bangladesh standard of 50 μg/L has been detected in 3 percent of dug wells studied by the APSU (2004), 2 percent by DASCOH (2003), 3 percent by the DCH (2003), 15 percent by NIPSOM (2003), and 43 percent by JICA and AAN (2004). Apart from arsenic and microbial contamination, high levels of color, turbidity, ammonia, iron, and manganese were also detected in dug well water samples. Thus, disinfection of dug well water appears to be essential to make it microbiologically safer. Some recent data, however, suggest that in situ disinfection may not be very effective in decontaminating dug well water (Majed 2005).

5.2. Alternative surface water sources

Since surface water sources (e.g., ponds, rivers) are usually microbiologically unsafe, some form of treatment is required to make them potable. A number of systems and processes are available for this purpose, including, among others, use of a pond sand filter/river sand filter (PSF/RSF), infiltration gallery, household filters, and solar disinfection.

The National Policy for Arsenic Mitigation 2004 put emphasis on giving preference to surface water over groundwater for water supply. The implementation plan for arsenic mitigation recommended using a PSF (or RSF) as an alternate water supply option in arsenic-affected areas. The following section provides a brief overview of the different aspects of PSFs.

The pond sand filter is a package-type slow sand filter unit developed to treat surface water, usually low-saline pond water, for domestic water supply. A PSF is usually installed on or near the bank of a pond that does not dry up in the dry season. The pond water is pumped by a manually operated hand tube well to feed the filter bed, and the treated water is collected through a tap. The operating period of a PSF between cleaning of the filter bed is usually two months.

The problems encountered with PSFs include low discharge and difficulties in washing the filter bed. Pretreatment is usually needed to reduce the turbidity of raw water to get trouble-free operation of the filter chamber. Roughing filtration is often used as a pretreatment unit. Community involvement in operation and maintenance is essential to keep a PSF operational. Although the PSF has high bacterial removal efficiency, it may not remove 100 percent of pathogens from heavily contaminated surface water. The depth of the sand bed must be adequate for complete removal of bacteria. In many cases, the treated water may require chlorination for disinfection. Proper pond development and management is essential for successful operation of a PSF. The pond should be well protected from external pollution loads for efficient filter operation, and culture fishing, bathing, or washing in the pond should not be allowed. Re-excavation may be required in case of deposited clay or a shallow pond loaded with organic material. Occasional use of algaecide may be necessary to control algae growth. Involvement of the user groups for regular operation, monitoring, maintenance, and repair is needed for proper functioning of a PSF.

According to available information, five different organizations (BAMWSP, DPHE-Unicef, DPHE-Danida, DPHE-GoB-IV, and AAN) have already installed 458 PSFs in different arsenic-affected areas (APSU 2005a). In a recent study, thermotolerant coliforms were detected in almost all water samples collected from 42 PSFs, mostly in southern Bangladesh (APSU 2005b). Arsenic concentration in the PSF water samples was found to be low, and a few samples showed higher concentrations of total solids and ammonia. High levels of contamination in pond water, inadequate filter depth, and poor maintenance have been identified as the main reasons for bacterial contamination of PSF water (APSU 2005b).

5.3. Rainwater harvesting

The use of rainwater for potable water dates back thousands of years (e.g., the early civilizations of the Middle East and Asia, the Mediterranean region, and North Africa). In recent times, it has been widely used in many parts of the world, particularly in the water-scarce regions of Africa, Australia, and Asia. In the coastal belt and hilly areas of Bangladesh, rainwater harvesting (RWH) has been practiced as an alternate water supply option, even before the detection of widespread arsenic contamination in groundwater. Rainwater harvesting is a potential alternate water supply option in many arsenic-affected areas and has already been used in some areas with considerable success. A rainwater harvesting system (figure 6) includes the following: (1) a catchment surface where the rainwater run-off is collected, (2) a storage reservoir where the rainwater is stored for use, and (3) a delivery system for transport of the water from the catchment to a reservoir (e.g., gutters). Rainwater harvesting may be used as a supplementary, partial, or backup supply system. Where rainwater is the main or only source of potable water, reliability of the system becomes critical. Supply and demand analysis is therefore an important consideration in the design of the system.

Figure 6. A rainwater harvesting system in a rural area of Bangladesh

Source: Courtesy of Professor Mujibur Rahman, Department of Civil Engineering, BUET, Dhaka, Bangladesh.

The quality of rainwater is generally good, but it lacks minerals (e.g., fluoride and calcium), which are considered essential to human health, although it is not clear if this would have any adverse health effects, since the majority of such nutrients are derived from food. The lack of dissolved minerals, however, affects the acceptability of rainwater for drinking. In a study carried out by the BAMWSP in 2002, it was found that 34 percent of the respondents did not like drinking rainwater because of its lack of taste (APSU 2005b).

According to available information, two organizations (DPHE-Unicef and DPHE-Danida) have installed 2,606 rainwater-harvesting units in different arsenic-affected areas (APSU 2005b). In a recent study, thermotolerant coliforms were detected in 42 percent of the samples collected from RWH units during the monsoon season and in 62.5 percent of the samples collected during the dry season (APSU 2005b). In an earlier study, Rahman et al. (2003) found the water to be essentially free from fecal pollution in RWH systems in two arsenic-affected upazilas of Rajshahi. Contamination of rainwater usually occurs on the rooftop catchment, in unsanitary surroundings, and with poor handling of water. The chemical quality of water samples collected from RWH units was found to be generally good, with arsenic levels mostly below the detection limit of 1 μg/L. Zinc and lead were detected in some water samples, but their concentrations were below the Bangladesh drinking water standard.

5.4. Arsenic removal technologies

Various technologies have been used for removing arsenic from groundwater. The most commonly used ones include co-precipitation with alum or iron, adsorptive filtration (e.g., using activated alumina), ion exchange, and membrane processes such as reverse osmosis.

In coagulation with ferric chloride, freshly precipitated amorphous ferric hydroxide ($Fe[OH]_3[am]$) is formed upon addition of the coagulant. Arsenic removal is primarily achieved by adsorption onto the surface of ferric hydroxide flocs and subsequent co-precipitation. In case of alum, removal is achieved by adsorption onto aluminum hydroxide flocs and subsequent co-precipitation. Pre-oxidation of arsenic(III) to arsenic(V) with locally available bleaching powder significantly improved arsenic removal efficiency.

The coagulation-based household arsenic removal units are commonly referred to as “bucket treatment units” (BTUs). The most common BTUs used include the following: (1) the DPHE-Danida bucket treatment unit (using alum), (2) the BUET-UNU bucket treatment unit (using ferric chloride),[4] and (3) the Stevens Technology for Arsenic Removal (STAR) bucket treatment unit (using iron salt). A coagulation-based community arsenic removal unit, known as the “fill-and-draw” unit, has been developed and installed in some areas under the DPHE-Danida Arsenic Mitigation Pilot Project. Besides this, a number of conventional iron removal plants (IRPs) have been modified for arsenic-iron removal, where arsenic removal is effected by co-precipitation and adsorption onto iron hydroxide flocs.

In adsorptive filtration, removal of arsenic is primarily achieved by adsorption onto the filter media surface. Presence of high concentrations of iron in many regions of Bangladesh appears to be a potential threat to adsorptive devices, as iron flocs may quickly clog the filter media. Arsenic removal efficiency of adsorptive filtration devices may be improved if the raw water can be pretreated for partial removal of naturally occurring iron.

The common adsorptive filtration-based systems include the following: (1) the SIDKO filter (using granular ferric hydroxide); (2) Shapla filter (using iron-coated brick chips); (3) activated alumina-based arsenic removal units (e.g., BUET activated alumina unit, MAGC Technologies-Alcan activated

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[4] UNU = United Nations University.

alumina unit, Apyron arsenic treatment unit);[5] (4) READ-F arsenic removal unit (using hydrous cerium oxide); (5) BUET unit based on iron-coated sand; (6) SONO filter; and (7) the Safi filter.

Technologies based on ion exchange and membrane techniques are relatively limited in number. Ion exchange-based removal units include the Tetratreat system of Tetrahedron (USA); membrane technique-based systems include the Techno Food water technology system, MRT-1000 system, etc. (Ahmed 2003).

a. Validation of arsenic removal technologies: The ETV-AM Program

As noted earlier, the government of Bangladesh decided that marketing of arsenic removal technology would not be allowed without prior testing and validation by the BCSIR. A protocol has already been developed for validation of different arsenic removal technologies under the Environmental Technology Verification-Arsenic Mitigation (ETV-AM) Program. Broadly, the protocol consists of a technology screening process and a technology verification process. The screening protocol provides a set of criteria (technical, social, and cost-related) for ranking technologies according to how well they meet Bangladesh's requirements. The technology verification protocol considers only technical criteria. During phase I of the ETV-AM Program, 18 technologies went through the screening process and the following five were selected for technology verification: (1) MAGC/Alcan (enhanced activated alumina), (2) READ-F (hydrous cerium oxide), (3) SONO 45-25 (iron filings/zero valent iron), (4) Tetratreat (ion exchange resin), and (5) SIDKO (granulated ferric hydroxide) (figure 7). Among these, SIDKO is a community-scale technology, while the other four are household-scale technologies. No coagulation-based removal unit was tested in the first phase of the verification process.

Since none of the technology proponents had a body of scientific data that would allow the verification of these technologies, technology-specific field-testing plans were developed and field performances were evaluated accordingly. The field tests were conducted in five hydrogeologically different regions of Bangladesh (Bera, Hajigonj, Manikgonj, Nawabgonj, and Faridpur) in order to test the technologies in stratified concentrations of arsenic, iron, and phosphate. Seven units of each of the four household technologies and five SIDKO community units were deployed in each of the five testing areas. The arsenic removal technologies were operated until (a) there was a media breakthrough, that is, when the effluent's arsenic concentration is consistently greater than 50 μg/L in successive effluent samples; or (b) the water volume was reached that the technology proponent claims can be treated before the effluent reaches 50 μg/L of arsenic.

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[5] The BUET filter was developed at the Bangladesh University of Engineering and Technology, hence the name.

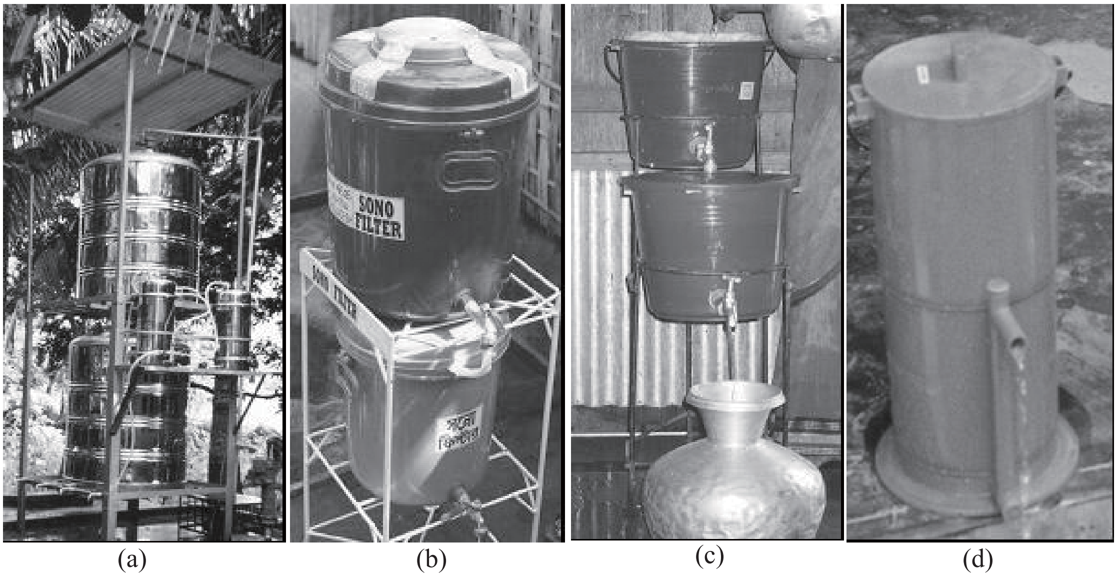

Figure 7. Four arsenic removal systems included in phase I of the ETV-AM Program

Source: Courtesy of Professor Feroze Ahmed, Department of Civil Engineering, BUET, Dhaka, Bangladesh.
Note: (a) SIDKO community unit, (b) SONO 45-25 unit, (c) MAGC/Alcan unit, and (d) READ-F unit.

Based on the results of the verification process, provisional verification certificates (along with stipulated conditions for deployment) were issued by the BCSIR to four technologies—the MAGC/Alcan unit, Read-F unit, SONO 45-25 unit, and the SIDKO community unit; the Tetratreat unit was rejected. The provisional certificate is valid for marketing the technologies in Bangladesh for a period of two years from the date of issuance. During the two-year period, the technologies will be monitored, and a final verification certificate may be issued by the BCSIR depending on the results.

Although detailed results of the verification process have not yet been made public, summary results and general observations from this process have been gathered from a number of sources (e.g., Ahmed 2005; Morsheda 2005). Most of the technologies did not meet their stated performance claims with respect to media life—a key measure of a technology's performance. The Read-F units, however, performed well with respect to media life, except for the units installed in Hajigonj. It was observed that the composition of groundwater in the wells tested had a significant effect on the media life of a given technology. For example, the performance of removal units was found to be consistently poor in the Hajigonj area, which is characterized by high levels of phosphate, pH, and silica in the groundwater. Based on the results, it was recommended that none of the five technologies should be deployed in areas with a phosphate level greater than 10 mg/L and a pH greater than 7.5. It has been suggested that during phase II of the verification process, one or more coagulation-based arsenic removal systems may be tested in the field to see if they perform better than the adsorption-based systems in groundwater conditions characterized by high levels of phosphate, pH, silicate, etc.

b. Disposal of arsenic-rich wastes from arsenic removal systems

Along with the effectiveness of arsenic removal technologies, the disposal of arsenic-rich waste materials generated from different removal units is becoming a matter of concern. The arsenic-rich waste materials can be classified into (1) wastes generated from coagulation-based systems, and (2) wastes generated from systems based on absorptive filtration and other techniques (e.g., ion exchange). The waste from the first category is primarily slurry containing coagulated flocs of alum or iron salt that are rich in arsenic. Currently, disposal of such wastes in cow-dung beds is widely practiced. It has been suggested that the biochemical processes in a cow-dung bed transform inorganic arsenic and release it into the air, but only limited data are available supporting such processes (Rahman 2004). The wastes belonging to the second category are primarily spent adsorption/ion-exchange media that are rich in arsenic. With increasing use of arsenic removal units, concerns have been raised regarding safe disposal of these wastes and possible contamination of the environment from the arsenic present in the wastes. Ali et al. (2003c) and Badruzzaman (2003) carried out tests using the Toxicity Characteristics Leaching Procedure (TCLP), U.S. EPA Method 1311, on a wide range of arsenic-rich treatment wastes (both from coagulation-based and sorptive filtration-based arsenic removal units) and reported that none of the waste samples are “hazardous” as defined by the U.S. EPA. As part of the technology verification process of the five technologies described above, tests using the TCLP and the Dutch Total Available Leaching Procedure Modified Version (TALP) were carried out on spent media from the MAGC-Alcan, READ-F, SONO 45-25, and SIDKO units. These test results also showed that none of the spent filter media could be classified as “hazardous.” A metal-scan of the TCLP and TALP extracts showed that each of the regulatory metal tested had a concentration below the U.S. EPA guideline value (Morsheda 2005). A number of methods have been proposed for safe disposal of such wastes. For instance, Rouf and Hossain (2003) used arsenic-rich sludge in bricks, and Hossain et al. (2004) used such sludge in concrete mix. A national waste management protocol is presently being developed for safe disposal of wastes generated from arsenic removal technologies.

6. Arsenic in the food chain

Besides domestic use, groundwater is also widely used in Bangladesh for irrigation during the dry season, particularly for growing the dry-season rice called boro, which requires irrigation of about 1 m deep. A total of 925,152 shallow tube wells and 24,718 deep tube wells were used for irrigation during the 2004 dry season (BADC 2005), and groundwater irrigation covered about 75 percent of the total irrigated area. Boro cultivation and irrigation have both increased since 1970, and from 1980 up to the present, the area irrigated with groundwater increased by almost an order of magnitude (Harvey et al. 2005a). During the 2003 dry season, about 87 percent of the total irrigated area of about four million hectares (about 28 percent of the total area of the country) was under boro cultivation, and boro accounted for about 49 percent of total rice production (MoA 2004). Thus, groundwater irrigation has greatly increased agricultural production in Bangladesh and the country’s food security is heavily dependent on it.

Ali et al. (2003a) estimated that over 900 tonnes of arsenic is cycled each year with irrigation water. Thus, the accumulation of arsenic in rice field soil and its introduction into the food chain through uptake by rice plants are major concerns. Rice production is reported to decrease by 10 percent at 25 milligrams per kilogram (mg/kg) arsenic concentration in soil (Xiong et al. 1987). Pot studies (Jahiruddin et al. 2004) showed that higher levels of arsenic in irrigation water and soil resulted in lower yield of a local rice variety (BR-29). In a greenhouse study, Abedin et al. (2002) also observed reduced yield of a local variety of rice (BR-11) irrigated with high arsenic-bearing water. Possible impact of arsenic-bearing irrigation water on crop yield is another area of concern.

Due to its affinity for metal oxides/hydroxides in soil, higher accumulation of arsenic in irrigated surface soils is expected, and a number of studies have reported relatively higher levels of arsenic in rice field soils irrigated with arsenic-bearing groundwater (e.g., Ullah 1998; Alam and Sattar 2000; Huq et al. 2001a; Meharg and Rahman 2003; Z. Ahmed 2005; Farid et al. 2005; Islam et al. 2005; Jahiruddin et al. 2005). A number of recent studies, however, showed that arsenic concentration in rice field soils irrigated with high arsenic-bearing groundwater varied significantly with both depth and time (e.g., Ali et al. 2003b; Saha and Ali 2004, forthcoming).

Saha and Ali (forthcoming) monitored arsenic concentrations in the top soil layers (~450 millimeters [mm]) of 12 rice (boro) fields located in four arsenic-affected areas and two unaffected areas of the country during 2003. In the unaffected areas, where irrigation water contained little arsenic (< 1 parts per billion [ppb]), arsenic concentrations of rice field soils were relatively low, ranging from about 1.5–3.0 mg/kg, and did not vary significantly with either depth or sampling time. In the arsenic-affected areas where irrigation water contained higher arsenic levels (79–436 ppb), arsenic concentrations in rice field soils were much higher compared to those in the unaffected areas and varied significantly with both depth and sampling time (figure 8). For the top 0–150 mm segment of soil layer, arsenic concentration increased significantly at the end of the irrigation season (May–June 2003). It has been estimated that about 71 percent of arsenic that comes to the rice field with irrigation water is accumulated in the top 0–75 mm segment of soil layer at the end of the irrigation season. After the rainy season, however, during which the rice fields were inundated with flood/rain water, the arsenic level in the top 0–150 mm segment of soil layer decreased significantly and came down to levels comparable to those found in soil samples collected at the beginning of the irrigation season in March 2003. The majority of arsenic in the top soil layers has been found to be associated with iron oxyhydroxides. Since a reducing condition prevails in the top soil layers during inundation, this phenomenon is most likely due to partitioning of arsenic from soil into the aqueous phase during inundation through reductive dissolution of iron oxyhydroxides and desorption and its subsequent transport away from the top soil layer.

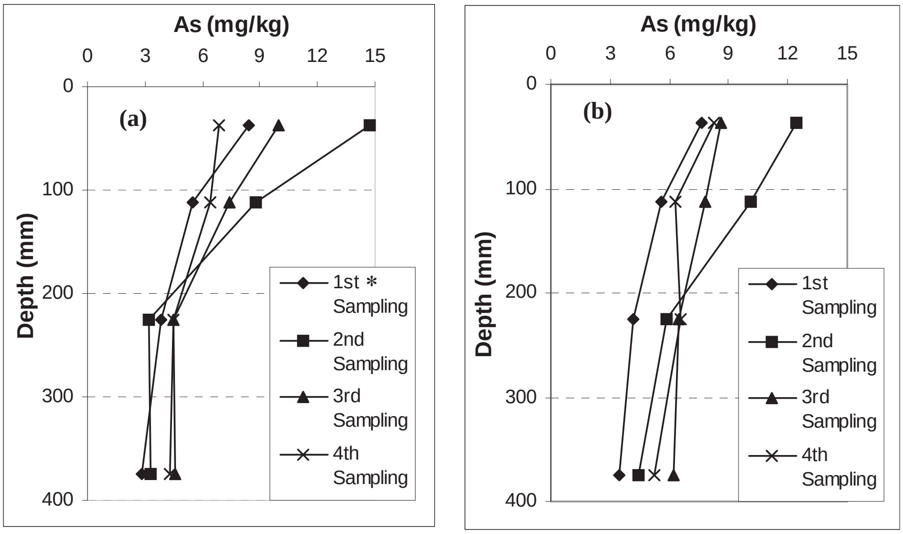

Figure 8. Arsenic profile of soil cores collected from irrigated rice fields in Munshiganj

*Sampling times: 1st: March 2003; 2nd: May–June 2003; 3rd: June–July 2003; 4th: November 2003–January 2004.
Note: (a) Field 1, arsenic in irrigation water: 320 μg/L; (b) Field 2, arsenic in irrigation water: 436 μg/L.

A number of studies have been carried out to assess the effect of arsenic-bearing irrigation water on the accumulation of arsenic in rice (e.g., Shah et al. 2004; USAID 2003; Duxbury et al. 2003; Hironaka and Ahmad 2003; Meharg and Rahman 2003; Ali et al. 2003b; Masud 2003). Uptake of arsenic by paddy rice as well as other crops may depend on a wide range of factors, including the chemical properties of irrigation water and soil and the plant species in question. In general, higher levels of arsenic in irrigation water has been found to result in higher arsenic in the roots, stems, and leaves of rice plants; accumulation of arsenic in rice grains has been found to be relatively low. Ali et al. (2003b) found the highest accumulation of arsenic in the roots of rice plants, followed by the leaves and stems; arsenic in rice grains has been found to be relatively low and comparable to those found in rice cultivated with arsenic-free irrigation water. For a paddy field in Munshiganj, Saha and Ali (forthcoming) estimated that arsenic taken up by paddy plants accounted for about 4.5 percent of total arsenic added to the paddy field with irrigation water. Of the total uptake by paddy plants, the root accounted for about 47.3 percent; stem, 29.4 percent; leaf, 16.7 percent; husk, 2.7 percent; and grain, 3.9 percent. Table 1 shows a comparison of arsenic concentrations in different parts of rice plants collected from two arsenic-affected areas (Munshiganj and Sonargaon districts) and one unaffected area (Dinajpur). Figure 9 shows arsenic concentrations in different parts of rice plant samples collected from the Munshiganj site.

Table 1. Comparison of arsenic concentrations in different parts of rice plants collected from two arsenic-affected areas and one unaffected area

Site (Arsenic in irrigation water), sample no.	Mean and range of arsenic concentrations in different parts of rice plant samples				
	Root (mg/L)	Stem (mg/L)	Leaf (mg/L)	Husk (mg/L)	Grain (mg/L)
Srinagar (220–537 ppb), n = 9	8.9 (2.8–16.8)	1.9 (0.5–8.1)	2.6 (0.9–7.2	0.9 (< 0.05–1.9)	0.48 (< 0.05–1.5)
Sonargaon (83–354 ppb), n = 12	11.9 (2.9–26.1)	1.76 (0.3–5.7)	2.3 (0.6–6.8)	0.66 (< 0.05–2.4)	0.45 (< 0.05–1.2)
Dinajpur (< 1 ppb), n = 9	6.8 (3.3–10.0)	0.9 (0.3–1.2)	1.3 (0.9–1.6)	0.66 (0.2–1.3)	0.54 (0.2–0.9)

Source: Data from Ali et al. 2003b.

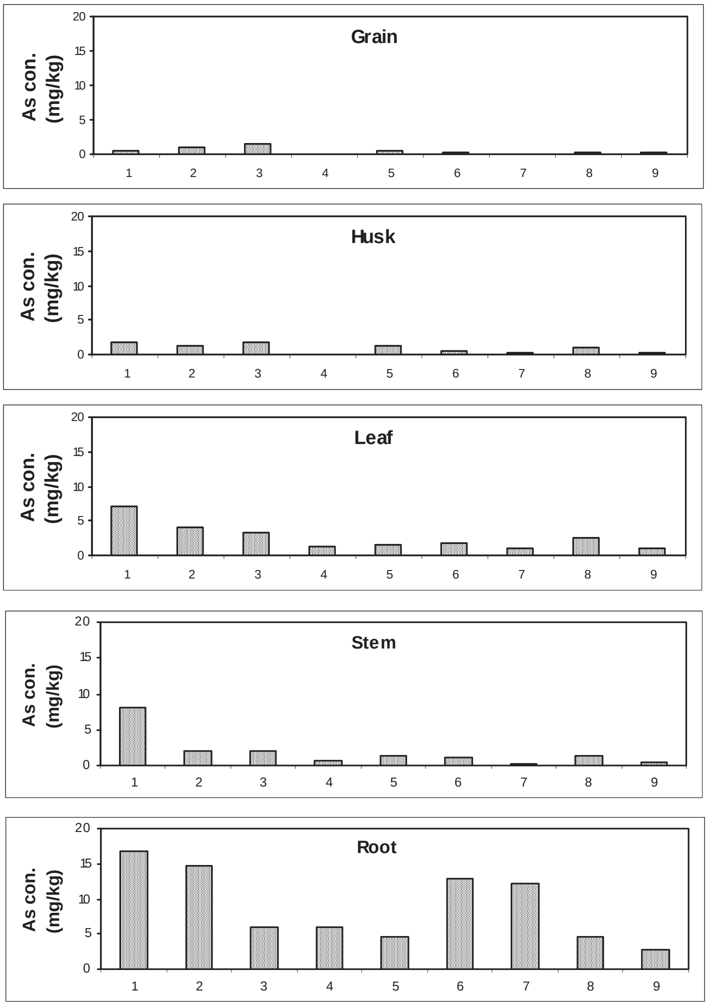

Figure 9. Arsenic concentrations in the grains, husks, stems, leaves, and roots of rice plants collected from a boro rice field in Munshiganj during 2002

Source: Ali et al. 2003b.

Note: Arsenic (As) in irrigation water: 220–537 µg/L.

Available data suggest that arsenic concentrations in different parts of certain common vegetables grown with arsenic-bearing irrigation water are relatively high (Farid et al. 2003; Ali et al. 2003b; Huq et al. 2001b; Das et al. 2004). Saha and Ali (forthcoming) evaluated the effect of arsenic-bearing irrigation water on the accumulation of arsenic in soil and six commonly grown vegetables—potato, tomato, lal shak, data shak, cabbage, and cauliflower—and showed that higher arsenic concentration in irrigation water resulted in higher arsenic concentration in both vegetable field soil and the vegetables. Table 2 shows the source and arsenic concentration in irrigation water and in the root and edible part of potato samples collected from the three different areas during 2004. It clearly shows that arsenic content in the edible part as well as the root of potato samples increases with increasing arsenic concentration in the irrigation water. In Bogra, where all irrigation water contained very little arsenic (< 1 ppb), mean arsenic content in the edible part of the potato samples was very low (up to 0.035 mg/kg). In both Chandpur and Narayangonj, arsenic content of the edible part was found to be much higher (by a factor of over two) for potatoes grown with irrigation water having high arsenic content compared to potatoes grown with surface water irrigation that had relatively low arsenic. Similar results were also observed for the other vegetables tested (Saha and Ali forthcoming). It should be noted that vegetable fields do not require much irrigation, and surface water (e.g., from ponds, canals, rivers) is commonly used for irrigating vegetable fields.

Table 2. Source and arsenic concentration of irrigation water and mean arsenic in root-soil, roots, and edible parts of potato

Sampling location	Groundwater irrigation				Surface water irrigation			
	Arsenic (As) in water (ppb)	Mean As in root soil (mg/kg)	Mean As in root (mg/kg)	Mean As in edible part (mg/kg)	As in water (ppb)	Mean As in root soil (mg/kg)	Mean As in root (mg/kg)	Mean As in edible part (mg/kg)
Bogra	< 1.0	2.55 (n = 6)	0.16 (n = 6)	0.021 (n = 6)	< 1.0	2.59 (n = 3)	0.35 (n = 3)	0.035 (n = 3)
Chandpur	95–132	4.09 (n = 6)	1.78 (n = 6)	0.234 (n = 6)	1.6	3.12 (n = 3)	0.45 (n = 3)	0.098 (n = 3)
Narayangonj	214–243	5.82 (n = 6)	2.62 (n = 6)	1.150 (n = 6)	25.3	4.90 (n = 3)	1.58 (n = 3)	0.510 (n = 3)

Note: n = number of samples.

7. Conclusions

Arsenic contamination of groundwater is particularly challenging in Bangladesh, since tube well water extracted from shallow aquifers is the primary source of drinking and cooking water for most of its population of over 140 million. Besides domestic use, huge quantities of groundwater are also used for irrigation during the dry season, mainly for the cultivation of dry-season rice (boro) and wheat. Arsenic in groundwater was first tested and detected in Bangladesh in groundwater samples from the district of Chapai Nawabgonj bordering India's state of West Bengal. A number of nationwide surveys, especially those carried out by the BGS in association with the DPHE and BAMWSP, provide a good picture of the distribution of arsenic contamination across Bangladesh. There is a distinct regional pattern of arsenic contamination in groundwater, with the greatest contamination in the south and southeast region (except in Chittagong and Chittagong Hill Tracts) and the least in the northwest and in the uplifted areas of the north-central region. On a local scale, however, arsenic concentrations have been found to be extremely patchy; neighboring wells within a village were found to contain quite different concentrations of arsenic, and high concentrations were detected within tens of meters of low concentrations in the vertical dimension. Many studies reported a bell-shaped depth profile for average arsenic concentration, with the maximum found in the 15–40 m interval.

In a nationwide survey carried out recently by the BAMWSP covering over 66 million people in 270 arsenic-affected upazilas, 38,430 arsenicosis patients were identified. While the results from this survey are currently being analyzed, results from previous surveys show poor correlation between the percentage of contaminated groundwater in a particular area and the density of patients. Although the BAMWSP survey shows relatively low prevalence of arsenicosis, many fear that the situation could become aggravated in the future, especially considering the delayed effect of arsenic on an exposed population.

Arsenic present in groundwater is of natural origin and is believed to be mobilized in the subsurface by a number of mechanisms, which are not yet clearly understood and are the subjects of many ongoing studies. Apart from the advancement of scientific knowledge, a better understanding of the biogeochemical and hydrogeological processes governing the mobilization of arsenic in the subsurface is also needed in order to address a number of important policy issues. For example, it is important to know whether arsenic concentration in contaminated areas is likely to change (increase or decrease) with time, or whether the arsenic-free deeper aquifer could provide a long-term solution to the arsenic problem. Studies conducted so far have yielded intriguing results, and ongoing studies are likely to provide more insights into the sources of arsenic and the mechanisms governing its mobilization in the subsurface.

In the backdrop of widespread arsenic contamination of groundwater, the government of Bangladesh adopted a national policy in 2004, intended to serve as a guideline for arsenic mitigation programs in the arsenic-affected areas of the country. The policy focuses on ensuring access for all to safe water for drinking and cooking; diagnosis of arsenicosis patients, their treatment, and management; and the possible impact of arsenic on the agricultural environment. The government has also developed an implementation plan for arsenic mitigation that addresses the following four major issues: water supply, health issues, agricultural issues, and cross-cutting issues. Providing safe water to the population in the arsenic-affected areas on a priority basis is a major focus of the implementation plan, which calls for an emergency response plan for areas where more than 80 percent tube wells have arsenic concentration exceeding the Bangladesh standard. The implementation plan places emphasis on giving priority to surface water over groundwater as a source of water supply and has recommended a number of technology options for alternative water supply in arsenic-affected areas, which include the following: (1) improved dug wells (DW), (2) surface water treatment using pond or river sand filters (PSF/RSF) or in a large treatment plant, (3) deep hand tube wells (DTW), and (4) rainwater harvesting (RWH).

No particular technology is suitable for all parts of the country. As part of the emergency response plan, areas have been identified for emergency response and water supply technologies suitable in different critical areas have been identified. Many of these technology options are currently being implemented by different organizations in different arsenic-affected areas. Available results suggest that water from dug wells and pond sand filters often suffer from poor water quality, including high fecal contamination. Proper operation and maintenance is also an important issue for ensuring sustainable use of these technology options. Though rainwater harvesting has been implemented in some areas with success, detection of fecal contamination in many RWH systems is a cause of concern. More research and development are needed for improving the design of these technology options (i.e., DW, PSF, RWH) and for coming up with new alternative technologies; public awareness and mobilization are also essential for proper operation and maintenance and social acceptance of the alternative water supply technologies. Deep tube wells have been installed as an alternative water supply option in many areas, mostly in southern Bangladesh, and they seem to provide good quality arsenic-free water. This option, though costly, enjoys wide public acceptance in terms of water quality and operation and maintenance. But deep tube well is not a feasible option in all areas of the country. Identification of suitable deep aquifers and proper installation of deep tube wells to avoid cross-contamination of aquifers are important issues with regard to this technology option.

The government decided that it would not allow marketing of any arsenic removal technology without prior testing and validation by the BCSIR. A protocol has been developed for validation of different arsenic removal technologies under the Environmental Technology Verification-Arsenic Mitigation (ETV-AM) Program, and the first phase of the verification process has been completed, through which five technologies have been verified. Based on the results of the process, the BCSIR issued a provisional verification certificate to four technologies—the MAGC-Alcan unit, READ-F unit, SONO 45-25 unit, and SIDKO community unit; one technology was rejected. During the two-year validation period of the certificate, the technologies will be monitored, on the basis of which a final verification certificate may be issued by the BCSIR. Although a verification certificate was issued to four technologies, it was observed during the verification process that most did not meet their stated performance claims with respect to media life—a key measure of a technology's performance. It was also observed that the composition of groundwater had a significant effect on the media life of a given technology. These observations are causes of concern. More research and development activities are needed to develop robust and user-friendly arsenic removal units for both household and community use.

Besides domestic use, groundwater is also widely used in Bangladesh for irrigation during the dry season, particularly for growing the dry-season rice called boro, which requires about 1 m of irrigation. Shallow aquifers contaminated with high levels of arsenic in many regions of the country are the primary source of irrigation water, and it has been estimated that over 900 tonnes of arsenic is cycled each year with irrigation water. Thus, the accumulation of arsenic in rice field soil and its introduction into the food chain through uptake by rice plants are major concerns.

In the arsenic-affected areas where irrigation water contained higher arsenic levels, the concentration of arsenic in rice field soils has been found to be much higher compared to that in unaffected areas, and it varied significantly with both depth and sampling time. For the top segment of soil layer (up to ~150 mm), arsenic concentration increased significantly at the end of the irrigation season (May–June 2003). After the rainy season, however, during which most rice fields are inundated with flood/rain water, arsenic levels in the top segment of soil layer were found to decrease significantly, reaching levels comparable to those at the beginning of the irrigation season. Since a reducing condition prevails in the top soil layers during inundation, this phenomenon is most likely to be due to partitioning of arsenic from soil into the aqueous phase during inundation through reductive dissolution of iron oxyhydroxides and desorption, and its subsequent transport away from the top soil layer. Thus, accumulation of arsenic on agricultural soil appears to be counteracted by biogeochemical processes leading to arsenic removal from soil. In general, higher arsenic concentration in irrigation water has been found to result in higher arsenic in the roots, stems, and leaves of rice plants, while the accumulation of arsenic in rice grains was found to be relatively low. Available data also suggest that arsenic concentrations in different parts of certain common vegetables grown with arsenic-bearing irrigation water are relatively high. Arsenic in agricultural products may therefore constitute an important human exposure pathway of arsenic. More research is needed to assess the bioaccumulation of arsenic in different agricultural products and its possible effect on population and the environment.

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