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Review

Arsenic contamination of groundwater in Bangladesh: A review

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The groundwater arsenic contamination in Bangladesh is known as the largest natural calamity in the world in terms of the affected population. The millions of tube-wells that had been sunk for drinking water supply are now dispensing poisonous arsenic. Consequently, about 80 million people are at risk and another 30 million are potentially exposed to arsenic poisoning. Most of the recognized stages of arsenic poisoning such as melanosis, keratosis, and hyper-keratosis have been identified in Bangladesh. In addition to the health crisis, the arsenic poisoning is affecting the agricultural crops and causing many social problems. The present study is an overview of the groundwater arsenic contamination in Bangladesh. The severity, sources, and causes of arsenic contamination are discussed in this paper. The health, agricultural, and social effects of the arsenic poisoning are highlighted. In addition, a number of urgent needs are given for combating the arsenic disaster.

Key words: Agriculture, arsenic mobilization, arsenic poisoning, drinking water, health crisis, social implications, tube-wells

INTRODUCTION

Bangladesh is situated in the northeastern part of South Asia. It is recognized as a land of natural disasters. Almost every year flood and drought strikes the country. The groundwater arsenic contamination has emerged in recent years as a further burden for this country. The magnitude of arsenic contamination in Bangladesh surpasses the aggregate pollution of all the twenty countries of the world where groundwater arsenic contamination has been detected. Until today, the arsenic contamination of groundwater in Bangladesh is described as one of the largest known natural disaster in human history.

The arsenic contamination of groundwater in Bangladesh and its sources and toxic effects on humans have been reported in many technical journals, books, and conference proceedings (Dhar et al., 1997; Escobar et al., 2006; Fendorf et al., 2010; Nickson et al., 1998; Safiuddin and Karim, 2001, 2003; SOES and DCH, 2000). It occurred and spread during the last one and half decades. The Department of Public Health Engineering (DPHE) first detected arsenic in the groundwater of Bangladesh in 1993 and the issue came in limelight in 1995 (Fazal et al., 2001; Smith, 1997). The millions of deep and shallow tube-wells that had been sunk in various parts of the country for drinking water supply are now dispensing poisonous arsenic (Chakraborti et al., 2010). As a result, thousands of people in Bangladesh, particularly the rural inhabitants are suffering from the toxic effects of arsenic-contaminated drinking water. Numerous arsenic-affected patients have already been identified. Many people are losing their health and dying, as they are continuing to use the arsenic-contaminated water due to the unawareness of its hazardous effects.

Many educational institutes, and government and non-government organizations (NGOs) such as Bangladesh University of Engineering and Technology (BUET), School of Environmental Studies (SOES) of Jadavpur University (located in Kolkata, India), Dhaka Community Hospital (DCH), DPHE, Bangladesh Rural Advance Committee (BRAC), Danish Aid Agency (DANIDA), and

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Table 1. Statistics of Arsenic Calamity in Bangladesh (Gathered and adapted from Chakraborti et al., 2010; Daily Star, 2008; Escobar et al., 2006; Faruque and Alam, 2002; Fazal et al., 2001; ITNC, 2008; Safiuddin and Karim, 2003).

Parameter	Value
Total number of districts in Bangladesh	64
Total area of Bangladesh	147,570 km^2
Total population of Bangladesh	153 million
WHO standard for arsenic in drinking water	0.01 mg/L
WHO-recommended maximum permissible limit for arsenic in drinking water	0.05 mg/L
Bangladesh standard for arsenic in drinking water	0.05 mg/L
Total number of tube-wells in Bangladesh	5 million
Total number of affected tube-wells	3 million
Number of districts surveyed for arsenic contamination of groundwater	64
Number of districts having arsenic above 0.05 mg/L	61
Population at risk	> 80 million
Population potentially exposed	> 30 million
Number of patients suffering from arsenicosis	> 38,000

British Geological Survey (BGS) investigated the groundwater arsenic contamination problem of Bangladesh. They primarily identified the arsenic-contaminated shallow and deep tube-wells in different parts of the country. Their studies revealed that the groundwater in Bangladesh is significantly contaminated with an arsenic concentration above the WHO (World Health Organization)-recommended maximum allowable limit (0.05 mg/L) for drinking water.

The present paper describes the severity, sources, and causes of groundwater arsenic contamination in Bangladesh. In addition, this paper highlights the health, agricultural, and social effects of arsenic poisoning. The urgent needs are also given in order to minimize the overall crisis caused by the arsenic contamination of groundwater in Bangladesh.

SEVERITY OF CONTAMINATION

A number of studies reported that the groundwater of Bangladesh is severely contaminated with lethal arsenic above the WHO's maximum permissible limit for drinking water. Altogether 400 measurements were carried out in Bangladesh in 1996 (Smith et al., 2000). Arsenic concentrations in about half of the measurements were above the maximum permissible limit of 0.05 mg/L (safe limit for drinking water in Bangladesh).

BGS tested 2,022 tube-well water samples collected from 41 arsenic-affected districts in 1998. Laboratory test results revealed that 35% of these water samples were found to have an arsenic concentration above 0.05 mg/L (Smith et al., 2000). The subsequent study of BGS showed that the groundwater in 61 out of 64 districts, covering about 85% of the total area of Bangladesh, is affected by arsenic contamination (BGS, 1999). DPHE collected and analyzed 31,651 tube-well water samples with the assistance of WHO, United Nations International Children Emergency Fund (UNICEF) and Department for International Development (DFID, UK) (Daily Star, 1999). The laboratory reports confirmed the severe arsenic contamination of groundwater. SOES and DCH jointly analyzed 22,003 tube-well water samples collected from 64 districts of Bangladesh between August 1995 and February 2000 (SOES and DCH, 2000). Five years sampling results indicated that 47 districts contain the groundwater arsenic concentration above 0.05 mg/L.

The contemporary study of Chakraborti et al. (2010) showed that 27.2% of 52,202 tube-well water samples collected from 64 districts of Bangladesh during the past 14 years have arsenic above 0.05 mg/L; they also reported that the groundwater of 50 districts is arsenic-contaminated with a concentration greater than this safe limit. Furthermore, Shirazi et al. (2011) collected 30 water samples from shallow aquifer through tube-wells and analyzed for arsenic; 26 samples showed the presence of arsenic beyond the safe limit (0.05 mg/L) of Bangladesh.

The greatest arsenic concentration in tube-wells has been found in the south and east parts of Bangladesh; more than 60% of the tube-wells in severely affected districts of these regions contain arsenic over 1 mg/L (Escobar et al., 2006; Kinniburgh and Kosmus, 2002). Consequently, the arsenic contamination of groundwater has affected millions of people and cost many lives across the country (Daily Star, 2001). Approximately 6.8 million people have arsenicosis (arsenical skin lesions) due to groundwater arsenic contamination (Chakraborti et al., 2010). As the people are also getting arsenic from foods such as rice and vegetables, the problem is growing more severe. The statistics given in Table 1 briefly present the severity of groundwater arsenic contamination in Bangladesh.

Table 2. Major Arsenic Compounds in Soils (Adapted from Smedley and Kinniburgh, 2002).

Compound	Composition	Occurrence
Niciolite	NiAs	Vein deposits and norites
Realgar	AsS	Vein deposits, clays and limestones, and hot springs deposits
Orpiment	As_2S_3	Hydrothermal veins and volcanic sublimation products
Cobaltite	CoAsS	High-temperature deposits and metamorphic rocks
Arseno-pyrite	FeAsS	Mineral veins
Enargite	Cu_3AsS_4	Hydrothermal veins
Arsenolite	As_2O_3	Obtained from oxidation of arseno-pyrite, native arsenic, and other arsenic compounds
Claudetite	As_2O_3	Obtained from oxidation of realgar, arseno-pyrite, and other arsenic compounds

SOURCES OF ARSENIC

The origin of groundwater arsenic in Bangladesh is directly related to the arsenic compounds present in soils. Arsenic can be present in soils as a metalloid or as organic and inorganic chemical compounds (Escobar et al., 2006; Fendorf et al., 2010). Some of the common arsenic compounds are listed in Table 2. Amongst these, arseno-pyrite, realgar, and orpiment are the most important compounds of arsenic. They contain a high amount of arsenic (Hossain, 2006). In the context of Bangladesh, arseno-pyrite has been primarily identified as the major source of arsenic in groundwater.

The major regions of Bangladesh lying in the Ganges delta are composed of a vast thickness of alluvial and deltaic sediments. The investigators found that there is a sediment layer containing arsenic compounds at a depth of 20 to 80 m (Independent, 1998). This layer is very rich in arseno-pyrite, which was originally derived from the granitic and metamorphic source regions of the Himalayas (Polizzotto et al., 2006). It was transported to the Ganges delta and was incorporated in the aquifers. Furthermore, arsenic can occur geologically in the sediments of Bangladesh as an adsorbed coating with ferric oxy-hydroxide (Uddin et al., 2011). It is suggested that both arsenic and ferric oxy-hydroxide derived from the oxidation of arseno-pyrite were transported and deposited in the Ganges delta along with abundant organic matters (Harvey et al., 2006; McArthur et al., 2004).

The adsorbed arsenic can be freed and mobilized to groundwater under reducing condition, which is likely to dominate when the organic matters consume the oxygen (Escobar et al., 2006; Singh, 2006; Uddin et al., 2011).

CAUSES OF CONTAMINATION

Arsenic can liberate from their compounds through geologic processes and human activities. Since the arsenic in soils is highly mobile, once liberated, it can enter the water-bearing aquifers leading to groundwater contamination (Acharyya and Shah, 2010). However, the exact causes for the arsenic mobilization are not known yet. The researchers and scientists have proposed two hypotheses on the mechanism of arsenic mobilization into groundwater in Bangladesh. These are pyrite oxidation and hydroxide reduction hypotheses.

Pyrite oxidation hypothesis

The pyrite oxidation hypothesis states that the arsenic is released into groundwater due to the oxidation of arseno-pyrite (Acharyya and Shah, 2010; Mallick and Rajagopal, 1996; Mandal et al., 1998; Singh, 2006). Arseno-pyrite remains stable unless exposed to oxygen or nitrate. When arseno-pyrite becomes under aerobic environment, it is oxidized in the presence of water resulting in elemental arsenic. Such condition prevails in Bangladesh during dry season due to the excessive extraction of groundwater for irrigation and drinking water supply. The large-scale withdrawal of groundwater creates a zone of aeration (vadoze zone) in clayey and peaty sediments containing arseno-pyrite. The vadoze zone is formed due to rapid diffusion of oxygen within the pore spaces of sediments and because of increased dissolved oxygen in the upper portion of groundwater. Under aerobic condition, the arseno-pyrite present in vadoze zone breaks down and releases arsenic, which is primarily adsorbed on ferric oxy-hydroxide. Later this arsenic dissolutes and mobilizes into the groundwater during subsequent water recharge.

The geochemical processes involved in arsenic release according to the oxidation hypothesis have been illustrated in Figure 1. This hypothesis states that the arsenic release is caused by human activities. The extent of free arsenic depends on the amount of arseno-pyrite present in sediments as well as on the rate of groundwater abstraction or the decline of water table.

The pyrite oxidation hypothesis has been accepted by several researchers as the main mechanism for arsenic

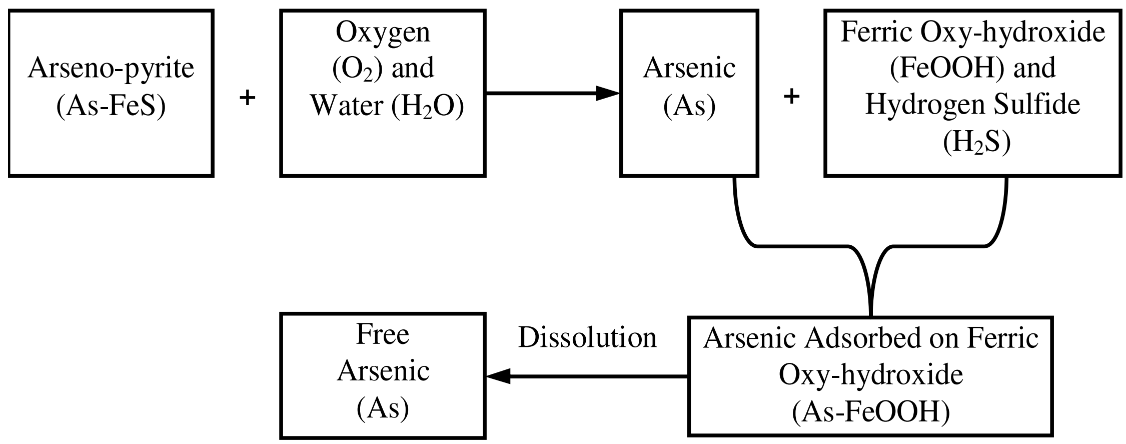

Figure 1. Arsenic release according to pyrite oxidation hypothesis (Adapted from Safiuddin and Karim, 2001).

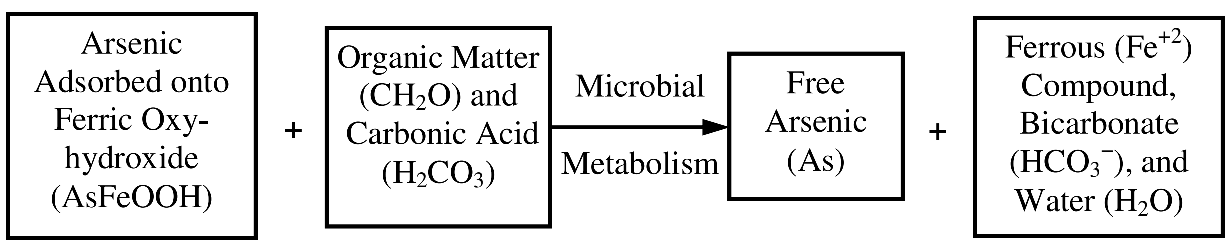

Figure 2. Arsenic release according to hydroxide reduction hypothesis (Adapted from Safiuddin and Karim, 2001).

mobilization into the groundwater of Bangladesh (Acharyya, 1997; Acharrya and Shah, 2010; Fazal et al., 2001). The intensive irrigation development of the country and the lack of arsenic patients before this development support the above hypothesis. However, there are not enough hydrological and geochemical data to validate the hypothesis completely.

Hydroxide reduction hypothesis

The hydroxide reduction hypothesis was first proposed by Nickson et al. (1998). This hypothesis assumes that the arsenic is present in alluvial sediments as an adsorbed coating onto amorphous ferric oxy-hydroxide (FeOOH). The adsorbed arsenic is released into groundwater by the reductive dissolution of arsenic-rich ferric oxy-hydroxide (Acharyya and Shah, 2010; Fendorf et al., 2010; Reza et al., 2010; Singh, 2006). The reductive dissolution is driven by the microbial metabolism of sedimentary organic matters in anaerobic environment.

The geochemical processes involved in the arsenic release have been illustrated in Figure 2. According to this hypothesis, the arsenic release occurs in the course of a geologic process. The extent of arsenic release depends on the amounts of arsenic-bearing ferric oxy-hydroxide and organic matter present in sediments.

The hydroxide reduction hypothesis has been accepted by some scientists and researchers as the main process for arsenic mobilization into the groundwater of Bangladesh (Acharyya and Shah, 2010; BGS, 1999; Harvey et al., 2002; McArthur et al., 2001; Uddin et al., 2011). The reducing condition of the vast groundwater in Bangladesh supports this hypothesis. Yet, the validity of the reduction hypothesis is questionable due to the lack of comprehensive sampling and systematic analysis of ferric oxy-hydroxide in the affected areas.

HEALTH EFFECTS

The arsenic contamination of groundwater in Bangladesh has caused manifold adverse effects on human health (both physical and mental health). The mass people in rural Bangladesh are becoming affected by the arsenic-contaminated groundwater, which they collect from the tube-wells and use for drinking and cooking (Daily Star, 2008; Islam and Islam, 2010; Safiuddin and Karim, 2001). In addition, the rural people are getting affected due to the consumption of arsenic-contaminated foods, which

Table 3. Arsenic Content in Hair, Nail, Skin-Scale, and Urine (Adapted from SOES and DCH, 2000).

Parameter	Value
Total hair samples collected from 210 arsenic-affected villages	4,386
Samples having arsenic > toxic level (1 mg/kg)	83.2%
Total nail samples collected from 210 arsenic-affected villages	4,321
Samples containing arsenic > normal level (0.43–1.08 mg/kg)	93.8%
Total urine samples collected from 20 arsenic-affected villages	1,084
Samples having arsenic > normal level (0.005–0.04 mg/day)	95.1%
Total skin-scale samples	705
Samples containing arsenic > toxic level (1 mg/kg)	97.4%

Figure 3. Melanosis on palms (Adapted from Islam and Islam, 2010).

they produce by using groundwater containing toxic arsenic (Huq et al., 2006; Khan et al., 2010). Recent research showed that about 50% of the daily arsenic intake through water and rice can come from rice grains (ITNC, 2008).

SOES and DCH analyzed more than 10,000 hair, nail, urine and skin-scale samples collected during a survey of arsenic-affected villages in Bangladesh (SOES and DCH, 2000). The results of those analyses are given in Table 3. It can be seen from Table 3 that the arsenic content in 93.8% of nail and 95.1% of urine samples was much higher than the normal level. The normal arsenic content in nail and urine is 0.43–1.08 mg/kg (Dhar et al., 1997) and 0.005–0.04 mg/day (Farmer and Johnson, 1990), respectively. In addition, the arsenic content in 83.2% of hair and 97.4% of skin-scale samples was significantly greater than the toxic level. The toxic level of arsenic in hair and skin-scale is 1 mg/kg (Arnold et al., 1990). Therefore, the findings of SOES-DCH study indicate a disastrous situation of arsenic-driven health hazards in Bangladesh.

Skin diseases such as melanosis (hyper pigmentation), leuco-melanosis, keratosis and hyperkeratosis, etc., are the most common effects of arsenic poisoning in drinking water (Dastgiri et al., 2010; Lazaroff, 2001; Smith, 1997). Melanosis is the first symptom of arsenicosis. It generally occurs throughout the body. Figure 3 shows the incidence of melanosis on palms. Melanosis can also occur in tongue and buccal mucus membrane (DCH, 1998). Keratosis appears when the spots arising from melanosis become hardened. Moreover, hyperkeratosis of the palms and soles are generally encountered due to the long-term exposure to arsenic compounds. Figures 4 and 5 show the occurrences of keratosis on palm and soles, respectively. The other effects of arsenic ingestion are liver enlargement and cirrhosis, peripheral neuropathy, hypertension (high blood pressure), chromosomal abnormality, myocardial degeneration and cardiac

Figure 4. Spotted Keratosis on palm (Adapted from Mandal et al., 1998).

Figure 5. Keratosis on soles (Adapted from Smith et al., 2000).

failure, diabetes mellitus and goiter, skin cancers, and gangrene (Dastgiri et al., 2010; Fazal et al., 2001; Yunus et al., 2011).

The data collected by the governmental bodies, NGOs, educational institutes, and private organizations reveal that many people in Bangladesh are suffering from melanosis, leuco-melanosis, keratosis, hyper-keratosis, and skin cancer due to the intake of arsenic with drinking water (Karim, 2000; Yunus et al., 2011). Melanosis and keratosis are the most commonly found skin lesions among the affected people. Patients of leuco-melanosis and hyper-keratosis have been found in many cases. Few cases of skin cancer have been identified among the patients seriously affected by the arsenic-contaminated drinking water. Furthermore, the prolonged drinking of arsenic-contaminated water has shown implications on children's cognitive and psychological development, thus affecting their learning outcome (Asadullah and Chaudhury, 2011). Higher fetal loss and infant deaths have also been observed in the areas where groundwater is highly contaminated with arsenic (Sohel et al., 2010).

AGRICULTURAL EFFECTS

The water used for the agricultural sectors in Bangladesh is mostly extracted from the groundwater sources. Since the groundwater contains arsenic, the agricultural soils as well as the agricultural crops, particularly different varieties of rice and vegetables are vulnerable to arsenic contamination (Bhattacharya et al., 2010; Khan et al., 2010; Martin et al., 2010). In fact, recent research reported that the agricultural soils in many areas of Bangladesh contain a high level of arsenic, which is directly linked with the arsenic-contaminated groundwater used for irrigation (Huq et al., 2006; ITNC, 2008).

The arsenic from both soils and irrigation water is accumulating in vegetables and rice grains during cultivation (Ahmed et al., 2003; Huq et al., 2006; Khan et al., 2010; Rahman and Hasegawa, 2011; Saha and Zaman, 2011; Williams et al., 2004), as illustrated in Figure 6. As a result, the crop yields can be reduced significantly due to the phytotoxic effects of arsenic (ITNC, 2008).

SOCIAL EFFECTS

The arsenic poisoning has panicked the rural people of Bangladesh and triggered manifold social implications (Ahmed et al., 2011; Islam and Islam, 2010; Mahmood and Halder, 2011; Safiuddin and Karim, 2001). The native people consider the arsenic diseases contagious. In many instances, the arsenic-affected people have been ostracized by relatives, friends, and neighbors. The affected people are either avoided or discouraged to appear in public places. The affected children are often

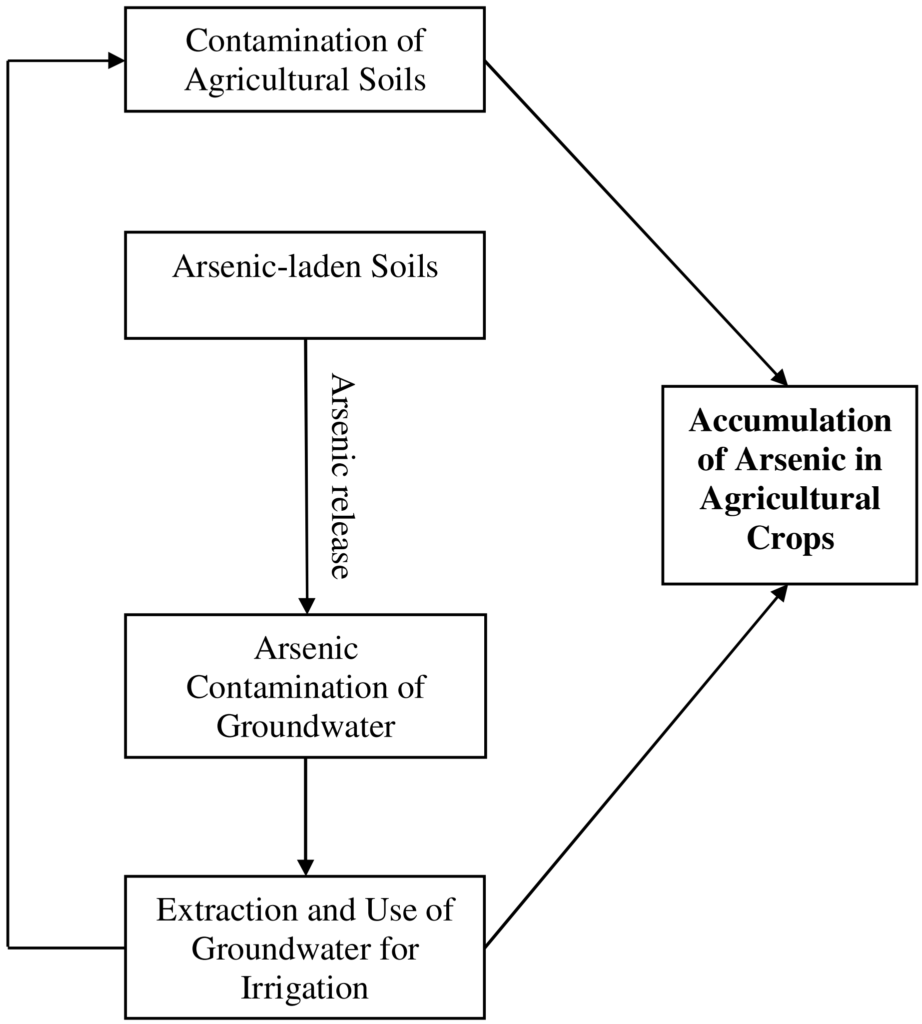

Figure 6. Arsenic accumulation in agricultural crops.

barred from attending schools and the adults are discouraged for attending offices and public meetings. Also, the qualified persons suffering from arsenicosis are often refused to get jobs. Those affected with a high level of contamination are considered incapable of working and thus thrown to be victimized by the growing poverty.

The social implications due to arsenic poisoning are much worse for women. The women suffering from arsenic diseases are increasingly facing ostracization and discrimination. The young women suffering from arsenicosis are often compelled to stay unmarried. The married women affected by arsenic diseases are no longer considered acceptable as wives due to skin lesions and sent back to their parents with children. Thus, the arsenic-affected males, females, and children are losing their normal social relation with the neighbors and relatives. The social implications caused by the arsenic contamination of groundwater in Bangladesh have been clarified in Figure 7.

URGENT NEEDS

Appropriate mitigation and prevention programs must be taken to handle the severe situation of groundwater arsenic contamination in Bangladesh. In addition, effective measures should be ensured immediately to lessen the sufferings of arsenic patients. The urgent needs for combating the nationwide arsenic poisoning problems are listed below:

1. Accurate detection of arsenic-polluted shallow and deep tube-wells existing in the country.
2. Identification of the exact sources and causes of groundwater arsenic contamination before taking any remedial actions.
3. Establishment of reliable and cost-effective arsenic detection and removal techniques.
4. Reduction in groundwater extraction for the countrywide irrigation.

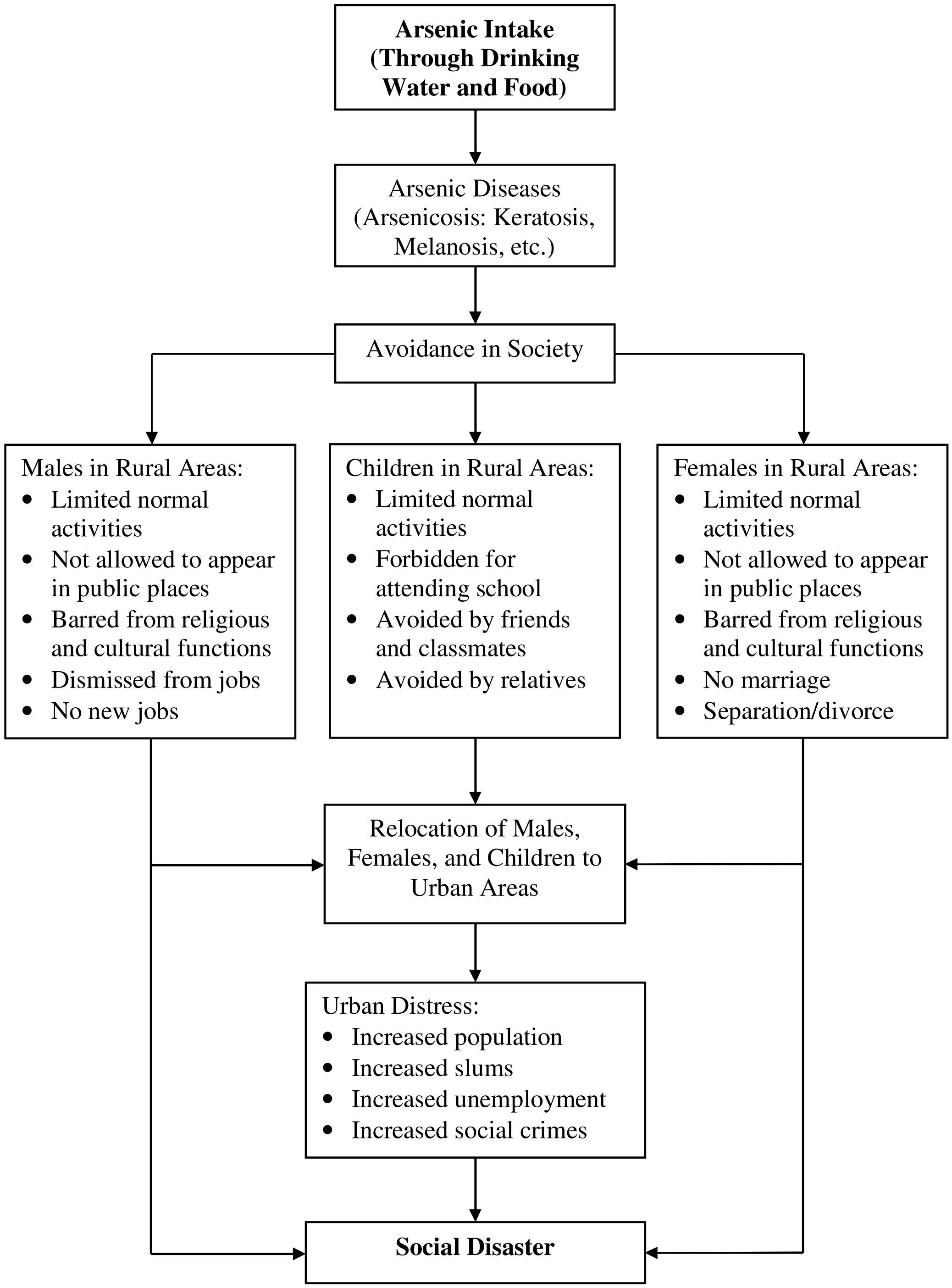

Figure 7. Social implications of arsenic intake.

5. Abstraction of groundwater from arsenic-free deeper aquifers.
6. Use of alternative sources such as surface and rain waters for irrigation and drinking water supply.
7. Installation of low-cost water purification plant for surface water treatment.
8. Establishment and implementation of a national water resources management policy.
9. Development of a comprehensive and sustainable water distribution system with efficient monitoring technique.
10. Assurance of arsenic-free drinking water supply and proper medical treatment for the arsenic patients.
11. Involvement of international community for funds,

environmental experts, and mitigation technologies.
12. Awareness campaigns and community participation for mitigating the crisis caused by arsenic poisoning.

CONCLUDING REMARKS

The groundwater of Bangladesh is severely contaminated with toxic arsenic. In 61 out of 64 districts of Bangladesh, the groundwater contains an arsenic concentration above the WHO-recommended maximum permissible limit of 0.05 mg/L. As a consequence, about 80 million people are at risk and another 30 million people are potentially exposed to arsenic poisoning.

Pyrite oxidation and hydroxide reduction hypotheses have been proposed to describe the causes of groundwater arsenic contamination in Bangladesh. However, the accuracy of these hypotheses has not been validated using proper field data.

The arsenic contamination of groundwater in Bangladesh has resulted in manifold health and social problems. Thousands of people are suffering from arsenic-driven diseases such as melanosis, leucomelanosis, keratosis, hyperkeratosis, and skin cancers. The arsenic-affected people, particularly the women are suffering from ostracization and discrimination, and losing their social relation with the neighbors and relatives.

The agriculture of Bangladesh has been affected by the arsenic contamination of groundwater. The agricultural soils in many areas are getting a high level of arsenic from arsenic-contaminated irrigation water. The arsenic from both soils and water is accumulating in different types of rice and vegetable leading to a reduction in crop yield.

Urgent alleviative and preventive measures must be taken to resolve the arsenic poisoning problems. Adequate supply of arsenic-free drinking water and proper medical treatment should also be ensured to minimize the sufferings of arsenic-affected people. Moreover, the use of arsenic-contaminated groundwater for irrigation should be minimized to reduce arsenic accumulation in agricultural crops.

Abbreviations: BGS, British Geological Survey; **BRAC,** Bangladesh Rural Advance Committee; **BUET,** Bangladesh University of Engineering and Technology; **DANIDA,** Danish Aid Agency; **DCH,** Dhaka Community Hospital; **DPHE,** Department of Public Health Engineering; **NGOs,** non-government organizations; **SOES,** School of Environmental Studies; **WHO,** World Health Organization.

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