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Extent of Arsenic Contamination and Its Impact on the Food Chain and Human Health in the Eastern Ganges Basin: A Review

N. Rajmohan and S. A. Prathapar

International Water Management Institute

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Contents

Acronyms and Abbreviations

BGS	British Geological Survey
CGWB	Central Ground Water Board
DOI	Department of Irrigation
DPHE	Department of Public Health Engineering, Bangladesh
DWSS	Department of Water Supply and Sewerage
EGB	Eastern Ganges Basin
ENPHO	Environment and Public Health Organization
FAO	Food and Agriculture Organization of the United Nations
FINNIDA	Finnish International Development Agency
GBM	Ganges-Brahmaputra-Meghna
NEWAH	Nepal Water for Health
NRCS	Nepal Red Cross Society
RWSSFDB	Rural Water Supply and Sanitation Fund Development Board
RWSSSP	Rural Water Supply and Sanitation Support Program
STW	Shallow Tube Well
WB	West Bengal
WHO	World Health Organization

Summary

Arsenic (As) is one of the hazardous elements found in the environment, and its exposure causes serious health issues such as cancer in the skin, lungs, bladder, liver, and the kidneys; and cardiovascular, neurological, hematological, renal, and respiratory problems. Arsenic contamination of groundwater is reported worldwide and, in the Eastern Gangetic Basin (EGB), in particular. Recent studies show that food crops are also a major route for As exposure, because of the usage of As-contaminated groundwater for irrigation. The EGB is home for 358.97 million people, where, 80% live in rural areas depending on agriculture for their livelihoods. Groundwater is a major source of water for drinking, domestic and agriculture purposes. However, in some parts of this region, the quality of groundwater is questionable due to arsenic contamination. Intention of this paper is to create an overall assessment of As pollution in the EGB based on existing literature. The main objective of this study is to demark the extent of the As-contaminated area in the EGB, and to document the As impacts on the food chain and human health. This study will help for better planning and management of groundwater in the study region.

Arsenic contamination of groundwater is encountered mostly along the course of the Ganga River, and this clearly manifested in Bihar and West Bengal. Groundwater in 15 districts in Bihar, 14 districts in West Bengal, 61 districts in Bangladesh and 20 districts in Nepal Terai are completely or partially affected by arsenic contamination. In the EGB, 75% of its total population is living in the affected region. In the affected region, application of As-contaminated groundwater for irrigation accumulates arsenic in the soil and food grains. Rice being the staple food in the EGB, it is mostly cultivated through flood irrigation that enhances arsenic prevalence and accumulation in the roots, which is subsequently transferred to the grains.

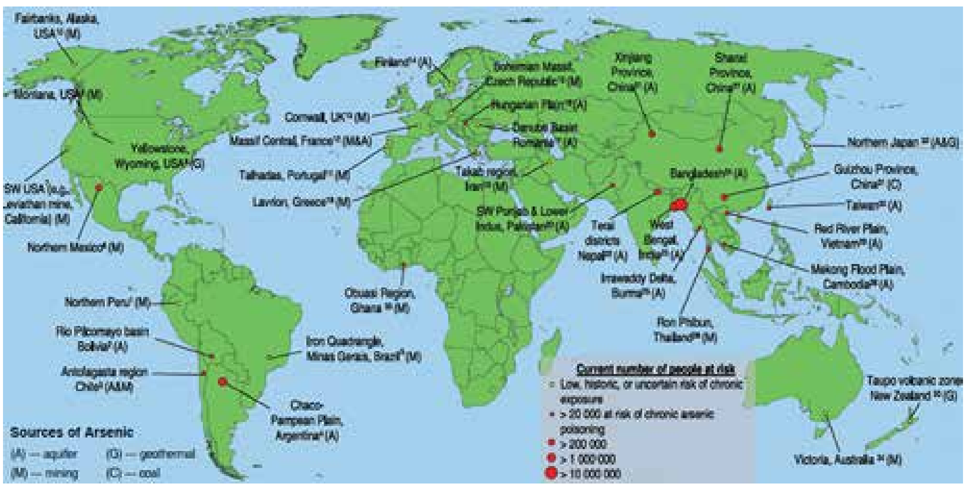
Even though several studies were carried out to understand As contamination in the EGB, nothing was concentrated on long-term monitoring of As in the affected areas. Moreover, although numerous researchers contributed to As estimation in the EGB, still there is a debate to identify the exact source and transport processes for As contamination. Hence, a comprehensive method should be developed to conduct a complete evaluation of As contamination in the soil, water, foods (grains, vegetables, fruits, etc.), and its impact on human health. Arsenic contamination in Bihar and Nepal is not evaluated systematically, especially arsenic accumulation in the food chain and human health issues. Numerous groundwater wells remain to be tested in order to determine the magnitude of the problem in the EGB. Hence, this review recommends systematic monitoring and analysis of As contamination in groundwater, soils and food across the EGB.

INTRODUCTION

Arsenic (As) is one of the hazardous elements in the environment. Arsenic contamination of groundwater is widely reported worldwide, including Argentina, Bangladesh, Bolivia, Brazil, Chile, China, Cambodia, Ghana, Greece, Hungary, India, Japan, Korea, Mexico, Mongolia, Nepal, New Zealand, Poland, Taiwan, Vietnam and the USA (Aiuppa et al. 2003; Bibi et al. 2008; Buschmann et al. 2006; Casentini et al. 2011; Ravenscroft et al. 2009; Sahoo and Kim 2013; Smedley and Kinniburgh 2002; Thakur et al. 2011; Yoshizuka et al. 2010) (Figure 1). The situation is critical in the Bengal Basin (Bangladesh and West Bengal (India)) compared to how the rest of the world is being affected by As contamination. Earlier studies reported that As- contaminated drinking water is a major source that exposes the people living in the As- contaminated region to its ill effects. Recent studies implied that food crops are also a major route for As exposure due to the usage of As-contaminated groundwater for irrigation. Arsenic exposure causes serious health issues such as cancer in the skin, lungs, bladder, liver and the kidneys; and cardiovascular, neurological, hematological, renal, and respiratory problems. A detailed discussion is given in a later section.

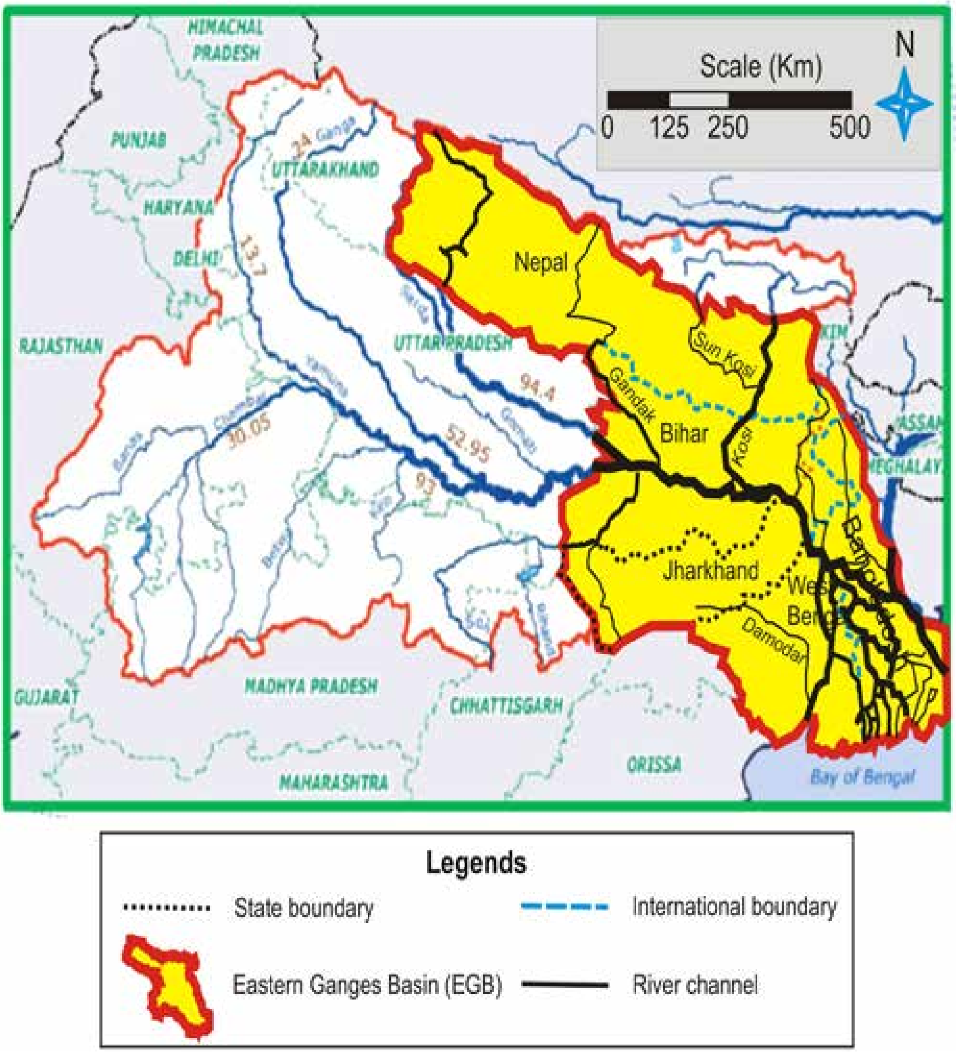
Numerous studies reported the As contamination in the Ganges Basin, especially West Bengal and Bangladesh. In the EGB (India (Bihar and West Bengal), Bangladesh and Nepal Terai (Figure 2), the total population was 358.97 million (2011 census), which is 5.14% of the world population (6,974 million). From the total population, 80% live in rural areas and depend on agriculture for their livelihoods. Poverty is acute in the EGB, where household incomes are low, food security is not assured and devastating floods (and also water shortages) occur frequently, causing severe adverse impacts on the populations, particularly the poor. Groundwater is a major source of water for drinking, domestic and agriculture usage in this region. However, the quality of groundwater in the EGB is questionable due to arsenic contamination. Intention of this paper is to create an overall scenario of As pollution in the EGB using existing literature, and to identify the gaps for future research. Furthermore, this paper also suggests some suitable mitigation options to tackle As issues. The main objective of this study is to demark the extent of As-contaminated area in the EGB and to document the As impacts on the food chain and human health. This review will help for better management and development of groundwater in the EGB region.

FIGURE 1. Map shows worldwide arsenic distribution, arsenic source, and numbers of people at risk of chronic exposure.



Source: Garelick and Jones 2008.

FIGURE 2. Ganges and Eastern Ganges basin. The stream-flow data is the annual average in cubic kilometers.



Source: Rajmohan and Prathapar 2013; Harshadeep 2011.

ARSENIC SOURCE AND TRANSPORT

Source of arsenic contamination may be broadly classified into two origins: a) natural or geogenic; and b) man-made activities or anthropogenic. Arsenic may originate from As minerals like arsenopyrite, orpiment, realgar, claudetite, arsenolite, pentoxide, scorodite and arsenopalledenite, which are commonly identified (Smedley and Kinniburgh 2002). In sedimentary formations, flood deposits cause As occurrence. However, arsenopyrite (sometimes called, As-rich pyrite) is mostly reported in the literature, and is a commonly abundant mineral (Boyle and Jonasson 1973; Smedley and Kinniburgh 2002; Welch et al. 1988). Besides, anthropogenic sources such as industrial waste, coal combustion, oil, cement, phosphate, fertilizers, mine tailing, smelting, ore processing, metal extraction, metal purification, chemicals, glass, leather, textiles, alkalis, petroleum refineries, acid mines, alloys, pigments, insecticides, herbicides, fungicides and catalysts contribute in As contamination of the groundwater, soil and air. Moreover, human activities also accelerate the release of naturally existing As (BGS 2000; Klump et al. 2006; Neidhardt et al. 2013). Bhattacharya et al.

(2011) reported that in India, As occurrences are related to numerous isolated geological sources such as Gondwana coal seams in the Rajmahal Basin in eastern India; Bihar mica belt in eastern India; pyrite-bearing shale from the Proterozoic Vindhyan range in central India; Son River Valley gold belt in eastern India; and the isolated outcrops of sulfides in the eastern Himalayas. In the EGB, the major source of As is derived from natural processes. In the Bengal Basin, the groundwater wells with high As content are mostly located on younger deltaic depositions (Mallick and Rajagopal 1996). In the Bengal Basin, most of the researchers accepted that As is migrated with fluvial sediments from the Himalayas. In Bangladesh, Hossain (2006) reported that high As concentrations are found in the fine grained sediments, e.g., gray clay. According to BGS (2000), sulfide and oxide minerals are the original sources for As in groundwater in Bangladesh. In Nepal, Gurung et al. (2007) studied the fluvio-lacustrine aquifer sediments collected from the Kathmandu Valley employing the elution test, and reported that a high amount of As was obtained from the fine sediments.

Arsenic release and transport from these sources to the soil, water and air is regulated by various factors and complex geochemical processes. Arsenic mobilization is explained by four major hypotheses: 1. Oxidation of pyrite, 2; Reductive dissolution of Iron oxyhydroxides; 3. Reduction and reoxidation; and 4. Competitive ion exchange (Bhattacharya et al. 2011; Das et al. 1995; Mandal et al. 1996; Ravenscroft et al. 2009; Rahman et al. 2001; Roy and Saha 2002).

Oxidation of Pyrite

Numerous studies documented that oxidation of arsenic-bearing pyrite present in the alluvial sediments is a major source for arsenic (Acharyya and Shah 2010; Das et al. 1995; Mandal et al. 1996; Rahman et al. 2001; Roy and Saha 2002). Mandal et al. (1996) reported the occurrence of pyrite (FeS_2) in West Bengal based on the analysis of sediments collected from 51 boreholes. Oxidation of pyrite causes acid that enhances mineral dissolution, which is followed by As enrichment in pore water and groundwater. Roy and Saha (2002) and Rahman et al. (2001) suggested that dissolution of arsenopyrite-rich sediments is triggered by increased oxygen availability in the vadose zone due to groundwater withdrawal for irrigation in West Bengal. Based on a borehole sediment samples analysis, Das et al. (1995) also reported that a high amount of As is associated with the iron pyrites in West Bengal.

Reductive Dissolution of Iron Oxyhydroxides

Reductive dissolution of Iron oxyhydroxides is commonly accepted process for As sources especially in Bengal basin since high As groundwater is in reducing condition and has elevated concentration of Fe and Mn and low nitrate (Fazal et al. 2001; Horneman et al. 2004; Nickson et al. 1998; Zheng et al. 2004). In Bihar, Mukherjee et al. (2012) reported that groundwater in the younger alluvial deposits of the Ganges has high As content, and As mobility is regulated by reductive dissolution of Fe and Mn oxyhydroxides. According to Ravenscroft et al. (2009), reductive dissolution of Fe oxyhydroxides is by far the most important mode for As release to groundwater in South and South East Asia. In this process, microbial degradation of organic matter (buried peat beds) reduces ferric iron to a soluble ferrous form (McArthur et al. 2001; Nickson et al. 2000).

Reduction and Reoxidation

Reduction and reoxidation is the combination of the above two processes. This process highlights that the water table fluctuations encourage the oxidation of sulfides and reduction of Fe oxyhydroxides in surface soils, resulting the As and S mobility to groundwater. Recent studies reported that in

the Bengal Basin, reductive dissolution of (Fe-Mn) OOH-phase releases the adsorbed As phases in the soil zone (Bhattacharya et al. 2011; Harvey et al. 2002; Mukherjee et al. 2008; Stuben et al. 2003; van Geen et al. 2004).

Competitive Ion Exchange

In competitive ion exchange process, As adsorbed onto the Fe oxyhydroxides is entered into the solution by exchanging with phosphate. Some studies documented that competitive anion exchange and microbial reduction are responsible for the release of As to aquifer in Bengal basin (Acharyya et al. 1999; Appelo et al. 2002; Islam et al. 2004; van Geen et al. 2008). Zheng et al. (2004) reported that As mobility and release is regulated by Fe and S in the system.

In Bangladesh, As mobility and transport are controlled by two major processes such as oxidation of pyrites and reductive dissolution of Fe oxyhydroxides (Fazal et al. 2001; Karim et al. 1997; Horneman et al. 2004; Nickson et al. 1998; Zheng et al. 2004). Like West Bengal, oxidation of arseno-pyrite in the vadose zone is triggered by lowering of the water table. The As released from this process is readsorbed on to the Fe hydroxide during the recharge period and again liberated to groundwater during reduction of Fe hydroxide (Karim et al. 1997; Hossain 2006). Several studies suggested the existence of organic matter with As-bearing Fe hydroxide sediments, which enhances the reduction process and the leaching of As to the groundwater (Fazal et al. 2001; Horneman et al. 2004; Nickson et al. 1998; Zheng et al. 2004). In Nepal Terai, elevated As (up to 800 µg/L) is correlated with the thickness of organic clays (Brikowski et al. 2013). Arsenic release to groundwater in Nepal Terai is not fully understood. Based on sediment-aquifer studies, Kansakar (2004) reported that Siwalik Hills and higher parts of the Himalayas are possible sources of As in the Terai region (Yadav et al. 2011). According to Williams et al. (2004), alluvium derived from the Siwalik group by erosion is a major source of As in the groundwater of Nepal Terai.

ARSENIC IN GROUNDWATER AND SOIL

Table 1 shows the As calamity in India and Bangladesh till December 2005. Arsenic generally occurs in four major oxidation states (+5, +3, 0 and -3) in the environments. In groundwater, As is identified in inorganic (arsenate ($H_2AsO_4^-$, pH < 7; $HAsO_4^{2-}$, pH > 7) and arsenite (H_3AsO_3, pH < 9.2; $H_2AsO_3^-$) and organic forms (methyl arsenic acid [$CH_3AsO(OH_2)$] and dimethyl arsenic acid [$(CH_3)_2AsO(OH)$] (Fazal et al. 2001; Fitz and Wenzel 2002). Arsenite is 60–80 times more toxic than arsenate due to a greater thermodynamic stability of the combination with the thiol (-SH) part of proteins (Fazal et al. 2001; Villaescusa and Bollinger 2008). Arsenic species and their behavior, especially chronic toxicological effects, lead the WHO to lower the regulatory limits of arsenic from 50 µg/L to 10 µg/L in the groundwater (Kapaj et al. 2006; Lubin et al. 2007; Mandal and Suzuki 2002; WHO 2008). The USA (USEPA 2002) and the European Union (EU 1998) also reduced the As permissible limit from 50 µg/L to 10 µg/L.

The arsenic burden in soil is another major concern in the world. This is due to the fact, that the arsenic uptake by crops is regulated by soil arsenic content along with irrigation water (Huang et al. 2006). In the soil, the baseline concentrations of As are in the order of 5–10 mg/kg (BGS and DPHE 2001). Likewise, the guideline value of arsenic for irrigation water is 100 µg/L (FAO 1985). Boyle and Jonasson (1973) mentioned that the average baseline concentration of As in world soils is 7.2 mg/kg. Arsenic is distributed in major soils and rocks types and its

TABLE 1. Groundwater arsenic contamination in India (Bihar and West Bengal) and Bangladesh (till December 2005).

Parameters	Bihar	West Bengal	Bangladesh
Area (sq km)	94,163	88,752	1,47,570
Population (in millions)	82.9	80.2	122
Total arsenic-affected districts (As >50 μg/L)	12	12	50
Total arsenic-affected blocks/PS (As > 50 μg/L)	32	111	189
No. of villages where groundwater arsenic >50 μg/L	201	3,417	2,000
Total hand-tube well water samples analyzed	15,000	140,150	51,001
% of samples having arsenic > 10 μg/L	33	48.1	43
% of samples having arsenic > 50 μg/L	20	23.8	31
Total number of biological samples analyzed (hair, nail and urine)	920	39,624	10,000
Total people screened by medical group of SOES-JU	4,513	96,000	18,841
People registered with arsenical skin lesions	525	9,356	3,725
People at risk of drinking arsenic-contaminated water >10 μgL-1 (in millions)	-	9.5	50.1
People at risk of drinking arsenic-contaminated water >50 μgL-1 (in millions)	-	4.6	32.1

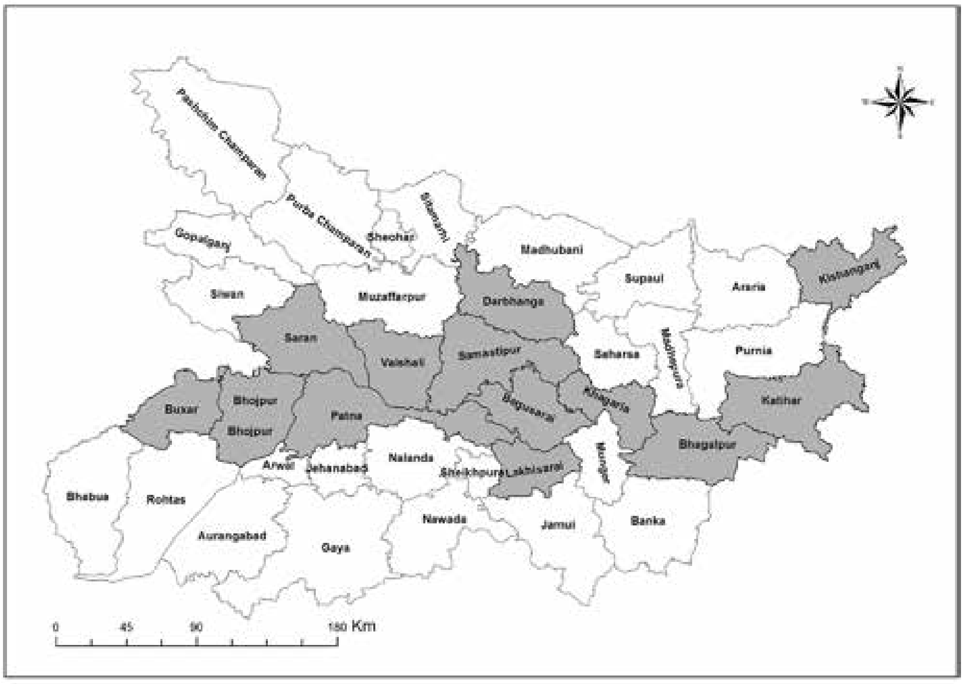
Source: Sengupta et al. 2009

concentration in rocks and in contaminated soils varies between 0.5 and 2.5 mg/kg and from 10 to 2,470 mg/kg, respectively (Hossain 2006). Arsenic in the soil mostly originates from natural sources. Besides, As-contaminated irrigation water, mining, smelting, coal burning, wastes application, animal manures, arsenic-containing pesticides and herbicides also enhance the As load in the soil (Alam et al. 2003; Baroni et al. 2004; Camm et al. 2004; Dutré et al. 1998; Flynn et al. 2002; Mandal and Suzuki 2002; Warren et al. 2003). Brammer and Ravenscroft (2009) calculated the As accumulation in soil by irrigation water assuming that annual water application is 1,000 mm. Their calculation results suggest that if a soil irrigated with 1,000 mm water containing 100 μg/L As, the soil gets 1 kg of As/ha/year. Arsenic content in irrigation water does not reach the soil in irrigated land completely, as it is reduced during the flow in the irrigation channel. Based on a study near Faridpur, Bangladesh, Hossain (2005) observed that the As content in irrigation water was decreased from 136 μg/L (well-head) to 68 μg/L (end of channel) during the flow in a 100 m distribution channel. Likewise, Roberts et al. (2007) documented the As loss from 397 to 314 μg/L during the flow in 152 m irrigation channel near Munshiganj, Bangladesh. They also observed that the As accumulation in the field also varies with the As load in the irrigation water. Based on a study about As content in a field's top soil, Dittmar et al. (2007) reported that As concentrations decreased gradually from 23 mg/kg near the field inlet to 11.3 mg/kg at the far corner of the field. The variation in As in irrigation water during flow seems to be the adsorption of arsenic on Fe hydroxides, which is formed when the groundwater is exposed to aerobic condition (Brammer and Ravenscroft 2009). Furthermore, it is well known that As-contaminated water has high iron content (DPHE 1999; Gurung et al. 2005; Postma et al. 2010).

Bihar

In Bihar, arsenic in groundwater was first discovered in 2002 in two villages (Semariya-Ojhapatti and Doodhghat) in the Bhojpur District, which exceeded 50 µg/L (Chakraborti et al. 2003). Consequently, CGWB carried out detailed survey and encountered maximum As concentration of 178 µg/l and Hand pumps with medium depth (20–35 mbgl) are mostly affected (Saha et al. 2009). However, dug wells with shallow depth (< 8 m) are free from As contamination. In addition, they reported that aquifer below 80m is free from As and maximum concentration (62 µg/l) was recorded at 19 m depth at Bariswan village. Nickson et al. (2007) studied the As contamination in groundwater of 50 blocks in 11 districts of Bihar. They found that 12,097 samples out of 66,623 samples tested had As between 10 and 50 µg/L and 7,164 samples exceeded As > 50 µg/L. Table 2 shows the As-affected blocks with maximum As concentration encountered in Bihar. Figure 3 illustrates the As-affected districts in Bihar.

FIGURE 3. Arsenic-affected districts in Bihar, India. Refer Table 2 for more details.



In Bihar, the As content in groundwater is largely varied with geological formations. The wells with high As content (mean 94.93±124.6 µg/L) are located mostly at a newer alluvium in the Bhojpur District (Saha et al. 2010). Districts and blocks that exist along the course of the Ganga River are severely affected (Figure 3). Hand pumps located at the newer alluvium (depth 15-35 m) show high As content, and it varies from BDL to 620 µg/L. Consequently, some organizations are engaged in As issues in Bihar. The UNICEF conducted a detailed survey to assess the As contamination in Bihar. In the north Bihar, ~3,100 groundwater samples were tested in 9 districts in the Nepal Border, and reported the As content below 50 µg/L (Saha et al. 2009). Along the course of the Ganga River, the PHED carried out a blanket survey and tested around 82,000 samples (CGWB and PHED 2005; Saha et al. 2009). They reported that 11% of samples exceeded 50 µg/L of As and 57 blocks in 15 districts are affected by As contamination

(Table 2). These blocks are located on the banks of the Ganga River, and the districts most affected are Bhojpur and Buxar. Chakraborti et al. (2003) analyzed 206 tube wells in the Semria Ojha Patti Village, in the Bhojpur District and reported that 56.8% of the samples have As > 50 µg/L and 19.9% of samples have As > 300 µg/L. Ghosh et al. (2007) tested 27,061 Hand pumps using field test kits in four districts (Patna, Bhojpur, Vaishali and Bhagalpur). They concluded that

TABLE 2. Arsenic-affected blocks in different districts of Bihar.

Sl. No.	District	Blocks affected	Max.As (mg/L)	Sl. No.	District	Blocks affected	Max.As (mg/L)
1	Begusarai	Bachwara	>0.05	30	Khagaria	Parbatta	>0.05
2	Begusarai	Balia	>0.05	31	Kisanganj	Bahadurgarh	0.085
3	Begusarai	Barauni	>0.05	32	Kisanganj	Kisanganj	0.058
4	Begusarai	Begusarai	>0.05	33	Lakhisarai	Lakhisarai	0.23
5	Begusarai	Matihani	>0.05	34	Lakhisarai	Piparia	0.241
6	Begusarai	Sabehpurkamal	>0.05	35	Munger	Bariarpur	>0.05
7	Bhagalpur	Jagdishpur	>0.05	36	Munger	Dharhara	>0.05
8	Bhagalpur	Nathnagar	>0.05	37	Munger	Jamalpur	>0.05
9	Bhagalpur	Sultanganj	>0.05	38	Munger	Munger	>0.05
10	Bhojpur	Ara	0.426	39	Patna	Bakhtiarpur	>0.05
11	Bhojpur	Barhara	0.42	40	Patna	Barh	0.584
12	Bhojpur	Behea	0.08	41	Patna	Danapur	>0.05
13	Bhojpur	Koilwar	0.306	42	Patna	Maner	1.81
14	Bhojpur	Shahpur	1.63	43	Purnea	Kasba	0.067
15	Bhojpur	Udawant Nagar	0.051	44	Purnea	Purnea East	0.097
16	Buxar	Brahmpur	1.22	45	Samastipur	Mohanpur	0.626
17	Buxar	Buxar	0.94	46	Samastipur	Mohinuddin Nagar	0.37
18	Buxar	Chakki	>0.05	47	Samastipur	Patori	>0.05
19	Buxar	Semary	1.4	48	Samastipur	Vidyapati Nagar	>0.05
20	Darbhanga	Biraul	>0.05	49	Saran	Chapra Sadar	0.205
21	Katihar	Amdabad	>0.05	50	Saran	Dighwara	>0.05
22	Katihar	Barari	>0.05	51	Saran	Revelganj	>0.05
23	Katihar	Kursela	>0.05	52	Saran	Sonepur	0.23
24	Katihar	Manihari	>0.05	53	Vaishali	Bidupur	>0.05
25	Katihar	Mansahi	>0.05	54	Vaishali	Desri	>0.05
26	Katihar	Sameli	>0.05	55	Vaishali	Hajipur	>0.05
27	Khagaria	Gogri	>0.05	56	Vaishali	Raghopur	>0.05
28	Khagaria	Khagaria	>0.05	57	Vaishali	Sahdei Bujurg	>0.05
29	Khagaria	Mansi	>0.05				

Sources: Kunar et al. 2009; CGWB and PHED 2005

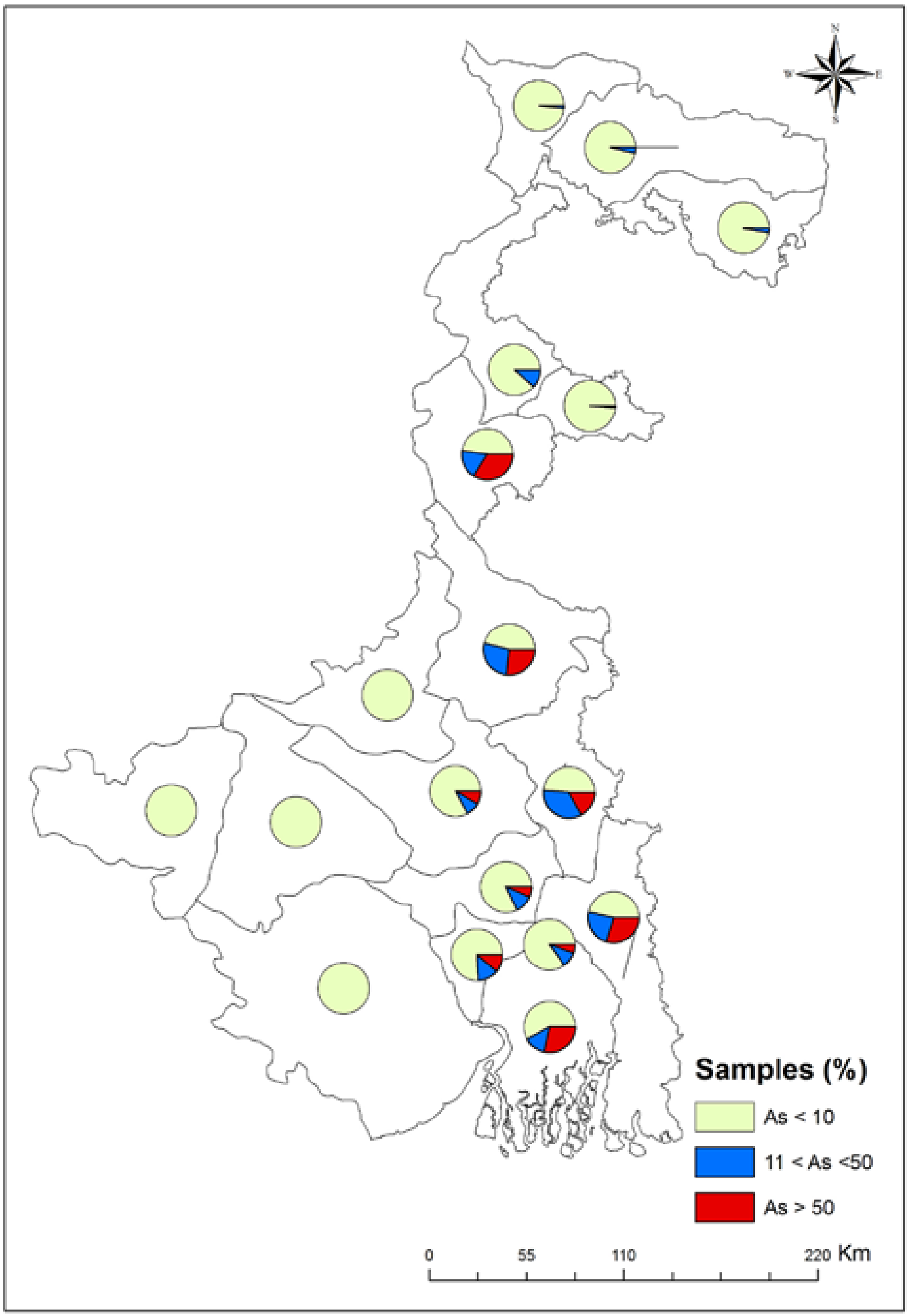
the arsenic content in 5,757 Hand pumps exceeded the WHO guidelines (As >10 μg/L), and the maximum As concentration (1,861 μg/L) was recorded in the Bhojpur District. Bhattacharya et al. (2011) reported that more than 28,000 samples were collected along the 10 km zone following the main channel of the Ganges River and tested. Results suggested that more than 1,050 samples from the Patna District were contaminated with As with Maner Block having a maximum As concentration of 724 μg/L. Likewise, 47.7% of 6,292 wells were contaminated with As in the Bhojpur District with maximum value of 4,861 μg/L (Barhara Block). In the Raghopur Block in the Vaishali District, all the wells tested were As-contaminated and the As ranged from 10 to 300 μg/L. According to this study, the worst affected is the Bhagalpur District, and Hand pumps and dug-wells were contaminated. In addition, the study revealed that the As concentration in the Nathnagar Block exceeded 500 μg/L.

With regards to soil, literature is not available or accessible to discuss the As load in irrigation soil. Future research may concentrate on this topic in Bihar.

West Bengal

Groundwater contamination by As is well pronounced in West Bengal (Figure 4). Table 3 exhibits the As content in groundwater in West Bengal. In India, arsenic contamination in groundwater was first reported in West Bengal in 1978 (Kunar et al. 2009). School of Tropical Medicine (STM) and All India Institute of Hygiene and Public Health (AIIH and PH) identified and diagnosed arsenical dermatosis in West Bengal in 1983, which was the first arsenic case reported in India. Consequently, several organizations got involved in arsenic issues such as the Central Ground Water Board (Eastern Region); Centre for Study of Man and Environment, Calcutta; Public Health Engineering Department (PHED); Government of West Bengal; SSKM – Hospital, Calcutta; Directorate of Health Services; and the Government of West Bengal (Sengupta et al. 2009). According to Kunar et al. (2009), groundwater in 79 blocks in 8 districts is contaminated by arsenic and exceeded 50 μg/L of As. Arsenic-affected districts such as Malda, Murshidabad, Nadia, North-24-Parganas, South-24-Parganas, Howrah, Hugli and Bardhman are located on the eastern and western sides of the Bhagirathi River. It is well known that the groundwater in the top aquifer (depth < 100 m) in West Bengal is arseniferous and modern recharged water (< 50 years) (Kunar et al. 2009; CGWB and BARC 2009). According to Sengupta et al. (2009), total arsenic-affected districts and blocks (As>50 μg/L) were 12 and 111, respectively, till December 2005 (Tables 1 and 3). Based on an analysis of 140,150 water samples collected from 19 districts (241 blocks out of 341 blocks), they reported that As in groundwater exceeded 10 μg/L in 14 districts and 50 μg/L in 12 districts (Figure 4). Based on groundwater As concentration, nine districts (Maldah, Murshidabad, Nadia, North-24-Parganas, South-24-Parganas, Bardhaman, Haora, Hugli and Kolkata) are severely affected (As>10 μg/L in 67,306 [49.7%] samples; As>50 μg/L in 33,470 [24.7%] samples) and five districts (Koch Bihar, Jalpaiguri, Darjiling, North Dinajpur and South Dinajpur) are mildly affected where As< 100 μg/L (10<As>4, 285 (9.8%); As>10 μg/L, 163 (5.7%); As>50 μg/L, 6 (0.2%) samples). Total population in the severely affected 9 districts and mildly affected 5 districts are 50.4 million and 11.4 million, respectively, in 2001 census and 57.08 million and 13.21 million, respectively in 2011 census. According to the 2011 census, 76.94% of the total population (91.35 million) of West Bengal is living in these 14 districts. Groundwater arsenic in other five districts (Bankura, Birbhum, Puruliya, Medinipur and West Medinipur) are low (<3 μg/L) and free from arsenic contamination. Based on the review, Bhattacharya et al. (2011) reported that the groundwater arsenic concentration is varied from <1 μg/L to 4,200 μg/L in West Bengal.

FIGURE 4. Arsenic distribution in groundwater in West Bengal. Refer Table 3 for more details.



Accumulation of arsenic in irrigation soil is very common due to the usage of arsenic-contaminated groundwater. Arsenic in irrigation water and soil in West Bengal has been reported by several researchers (Bhattacharya et al. 2010a; Norra et al. 2005; Samal 2005). Roychowdhury et al. (2002) studied the As content in arsenic-affected Domkal Block in the Murshidabad District and reported that arsenic concentrations in the agricultural land soils are 11.5 and 28 mg/kg, which are irrigated by groundwater that contains 0.082 and 0.17 mg/L of arsenic, respectively. Samal et al. (2003) tested the arsenic content in water, soil, crop and vegetables in the Uttarpara Village in the Nadia District and Doulatpur Village in 24-parganas, and documented that the soil arsenic content was 19.94±22.27 mg/kg and 21.75±5.42 mg/kg, respectively, in these villages. Roychowdhury et al.

TABLE 3. Arsenic distribution in hand-tube wells surveyed in all 19 districts of West Bengal, India.

Districts	Area (km^2)	Population	NBS (TNB)	NBS with As >50 µg/L	NBS with As >10 µg/L	n	Distribution of total samples in different arsenic concentration (µg/L) ranges						Max. As (µg/L)
							<10	11-50	51-100	101-300	301-1,000	> 1,000	
North-24-PGS	4,094	8,934,286	22 (22)	22	21	54,368	25,350	13,001	6,403	7,780	1,785	49	2,830
South-24-PGS	9,960	6,906,689	17 (29)	12	11	8,333	4,834	1,141	743	1,068	517	30	3,700
Murshidabad	5,324	5,866,569	26 (26)	25	24	29,668	13,715	8,042	3,267	3,307	1,266	71	3,003
Nadia	3,927	4,604,827	17 (17)	17	17	28,794	14,044	9,810	2,265	2,150	512	13	3,200
Maldah	3,733	3,290,468	14 (15)	13	9	4,449	2,127	810	488	742	260	22	1,904
Haora	1,467	4,273,099	12 (14)	12	7	1,471	1,115	192	87	63	13	1	1,333
Hugli	3,147	5,041,976	17 (18)	16	11	2,212	1,815	251	77	66	3		600
Kolkata	185	4,572,876	-	-	-	3,626	3,079	345	85	102	15		825
Bardhaman	7,024	6,895,514	24 (31)	12	7	2,634	2,170	244	86	116	17	1	2,230
Koch Bihar	3,387	2,479,155	5 (12)	4	1	474	460	13	1				54
Darjiling	3,149	1,609,172	4 (12)	3	0	562	552	10					19
Dinajpur (N)	3,140	2,441,794	7 (9)	6	2	990	874	112	4				68
Dinajpur (S)	2,219	1,503,178	6 (8)	2	1	452	445	6	1				51
Jalpaiguri	6,227	3,401,173	7 (13)	4	0	445	429	16	-				27
Bankura	6,882	3,192,695	17 (22)	0	0	279	279						<3
Birbhum	4,545	3,015,422	11 (19)	0	0	718	718						<3
Puruliya	6,259	2,536,516	14 (20)	0	0	314	314						<3
Medinipur (E+W)	14,081	9,610,788	18 (54)	0	0	361	361						<3
Grand Total	88,750	80,176,197	238 (341)	148	111	140,150	72,681	33,993	13,507	15,394	4,388	187	

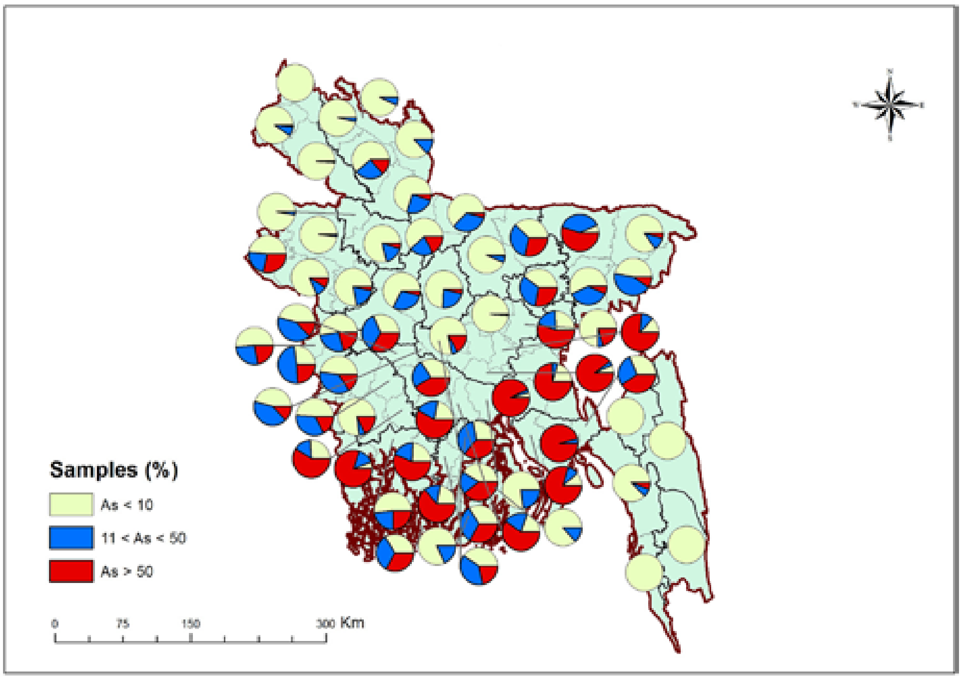
Source: Sengupta et al. 2009
Notes: TNB – total number of blocks, NBS – number of blocks surveyed, n – number of samples analyzed

(2005) documented the mean arsenic content (mean 14.2 mg/kg, range: 7.56–21 mg/kg, n = 300) in soil of the Murshidabad District in West Bengal and emphasized, that the groundwater arsenic is strongly correlated with the arsenic in agricultural soil and plants. Norra et al. (2005) carried out a detailed study to understand the impact of arsenic-rich irrigation water on soil and crops. They mentioned that As content in the top soil layers in paddy fields (38 mg/kg) irrigated with As-rich groundwater (0.5 – 0.8 mg/L) is five times higher than As content (7 mg/kg) in paddy soil irrigated with uncontaminated water. Furthermore, the arsenic in the paddy field is decreased with depth (11 mg/kg at 100-110 cmbgl). Bhattacharya et al. (2010a) reported based on a study in five blocks of the Nadia District, West Bengal, the total arsenic content in the soil varied from 5.70 to 9.71 mg/kg and that it is higher than the background value of arsenic (2.31–3.07 mg/kg) in soil collected from nonirrigated land. This enrichment of arsenic is mainly due to the extensive use of As-contaminated groundwater as the As in the irrigation water ranged between 0.318 to 0.643 mg/L.

Bangladesh

The British Geological Survey (BGS 1999) reported that the groundwater in 61 districts out of 65 districts in Bangaladesh is affected by arsenic contamination. Figure 5 and Table 4 explain the overall outline of As contamination in Bangladesh. According to the BGS (2000) report, the shallow tube wells (STW) (depths ranging from 10–70 m) with water table fluctuation between 5 and 10 mbgl are highly contaminated compared to deep aquifers. Based on the analysis of 6,000 water samples collected from 25 km^2 area, van Geen et al. (2003) reported that the arsenic content in water samples collected from STW (depth 15–30 m) exceeded the Bangladesh drinking water standard of 50 µg/L. Based on the detailed survey, SOES and DCH (2000) reported that arsenic content of tube well waters in 47 districts exceeded the Bangladesh drinking water standard (As > 50 µg/L). For this study, they collected 22,003 tube well water samples from 64 districts during the period 1995-2000, and analyzed for arsenic content. Islam (2003) reported that around 100,000 tube wells in the counties of Chandpur District are contaminated by As. Bibi et al. (2008) carried out a geochemical study to evaluate As

FIGURE 5. District-wise arsenic distribution in groundwater in Bangladesh. Refer Table 5 for more details.



concentration in groundwater of the Chandpur District (Meghna River delta) and reported that the As concentration in groundwater varies from 6 to 934 μg/L with an average of 347 μg/L. Chakraborti et al. (2010) reported that 27.2% of the 52,202 tube well water samples collected from 64 districts contained As greater than 50 μg/L, and 50 districts showed a similar trend (As > 50 μg/L) (Table 5; Figure 5). Tube wells with maximum arsenic content (As > 1 mg/L) is reported in the southern and eastern parts of Bangladesh, and more than of 60% of tube wells are severely affected (Escobar et al. 2006; Kinniburgh and Kosmus 2002; Safiuddin et al. 2011).

TABLE 4. Statistics of arsenic calamity in Bangladesh,

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

Sources: 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; Safiuddin et al. 2011

In Bangladesh, irrigation with arsenic-contaminated groundwater has resulted an increase in the As level (83 mg/kg) of the soil (Ullah 1998). Meharg and Rahman (2003) encountered the maximum concentration of As (46 mg/kg) in the soil, based on a preliminary survey of 71 soil samples throughout Bangladesh. Furthermore, they reported that a low soil arsenic content (10 mg/kg) was found in areas irrigated with water containing low levels of As. In soils, the baseline concentrations of As are in the order of 5–10 mg/kg (BGS and DPHE 2001). Spallholz et al. (2008) estimated the arsenic content in agricultural soils and reported that the arsenic content ranges from 11.7 to 51.9 mg/kg, with an average of 32.8 mg/kg (n = 70) that exceeded the world average soil concentrations of As (5–10 mg/kg). According to Uddin (1998), mean As concentration in uncontaminated agricultural soils varied from 2.6 mg/kg to 7.6 mg/kg. High As (57 mg/kg) is encountered in soils collected from different locations, which causes elevated concentration of As in the rice grain and rice straw (Alam and Sattar 2000). According Huq et al. (2006), if the rice field is irrigated with groundwater containing 0.55 mg/L As, it will accumulate 5.5 kg As/ha/year. Roberts et al. (2007) mentioned that the arsenic content in the topsoil of irrigation fields has enhanced significantly over the last 15 years, due to the usage of arsenic-rich groundwater. Duxbury and Zavala (2005) documented that topsoil As levels is greater than 10 mg/kg at 48% of 456 STW sites in irrigated areas. Likewise, based on 24-upazila study, Huq et al. (2006) mentioned that 21% of soil samples contained As levels >20 mg/kg with a maximum value of 80 mg/kg. Duxbury and Zavala (2005) evaluated that

TABLE 5. Arsenic content of groundwater in 64 districts of Bangladesh.

District	NTS (TNT)	NT >50 µg/L	n	Distribution of total samples in different As concentrations (µg/L)							Max As (µg/L)
				<10	11 - 50	51 - 99	100 -299	300 - 699	700- 1,000	> 1,000	
Bagherhat	3 (9)	3	371	90	72	34	79	84	12		958
Bandarban	2 (7)		41	41				0			
Barguna	2 (5)		43	35	8			0			15
Barisal	6 (10)	6	803	179	113	40	227	181	47	16	1,770
Bhola	3 (7)		74	57	17			0			50
Bogra	11 (11)	4	767	607	125	17	16	1		1	1,040
Brahmanbaria	2 (8)	2	47	12	9	9	17	0			210
Chandpur	7 (8)	7	1,165	50	36	30	675	348	21	5	1,318
Chittagong	14 (26)	2	366	319	26	13	8	0			275
Chuadanga	4 (4)	4	457	124	223	73	11	24	2		841
Comilla	6 (13)	6	545	113	26	29	128	198	25	26	1,769
Cox's Bazar	2 (7)		58	58				0			
Dhakaa	6 (6)	3	574	449	29	26	63	7			352
Dinajpur	13 (13)		2,641	2,612	28	1		0			77
Faridpur	5 (8)	5	707	243	171	67	142	64	12	8	1,630
Feni	2 (5)	2	186	58	53	40	28	6	1		1,000
Gaibanda	7 (7)	5	1,233	863	308	40	17	5			512
Gazipur	4 (5)	1	3,386	3,312	33	8	16	17			533
Gopalganj	5 (5)	5	384	86	74	55	146	21	2		920
Habiganj	2 (8)	2	103	59	37	6	1	0			100
Jamalpur	2 (7)	1	144	89	30	7	6	4	6	2	1,172
Jessore	6 (8)	6	5,465	4,227	248	317	457	181	32	3	1,120
Jhalakati	3 (4)	2	42	17	16	3	5	1			310
Jhenaidaha	3 (6)	3	388	185	142	24	27	10			592
Joypurhat	5 (5)		398	388	10			0			32
Khagrachari	3 (8)		39	39				0			
Khulna	12 (14)	9	1,000	518	233	55	138	45	5	6	3,143
Kishoreganj	12 (13)	11	1,328	527	429	238	133	1			365
Kurigram	7 (9)		539	467	72			0			50
Kushtia	6 (6)	5	2,065	1,082	557	154	168	75	13	16	2,190
Lakshmipur	4 (4)	4	2,662	304	235	339	852	667	177	88	2,030
Lalmanirhat	5 (5)		464	434	30			0			50
Madaripur	4 (4)	4	2,309	453	480	336	622	392	21	5	1,200
Magura	4 (4)	3	496	243	168	44	33	5		3	1,050

(Continued)

TABLE 5. Arsenic content of groundwater in 64 districts of Bangladesh (Continued).

District	NTS (TNT)	NT >50 µg/L	n	Distribution of total samples in different As concentrations (µg/L) <10	11 - 50	51 - 99	100 -299	300 - 699	700- 1,000	> 1,000	Max As (µg/L)
Manikganj	3 (7)	3	282	79	101	44	55	3			586
Meherpur	3 (3)	3	1,024	526	271	95	95	32	4	1	1,230
Moulavi Bazar	5 (6)	2	152	72	65	12	3	0			133
Munshiganj	5 (6)	5	151	10	6	12	80	43			529
Mymensingh	9 (12)	6	1,825	1,705	101	12	6	1			330
Naogaon	10 (11)		537	527	10			0			22
Narail	3 (3)	3	371	96	56	35	164	20			375
Narayanganj	3 (5)	2	412	54	42	34	147	104	26	5	1,750
Narshingdi	5 (6)	3	336	252	16	7	23	34	4		1,000
Natore	3 (6)	2	117	91	22	4		0			63
Nawabganj	5 (5)	4	1,902	920	434	173	273	80	12	10	1,600
Netrokona	10 (10)	10	533	201	180	84	49	19			580
Nilphamari	6 (6)		523	505	18			0			50
Noakhali	4 (6)	4	843	5	36	92	413	159	48	90	4,730
Pabna	9 (9)	7	5,117	1,595	1,807	807	691	176	25	16	2,108
Panchagarh	5 (5)		462	458	4			0			15
Patuakhali	1 (7)		15	13	2			0			10
Pirojpur	4 (6)	4	124	42	41	8	24	8	1		731
Rajbari	3 (4)	2	174	79	72	5	15	1	2		714
Rajshahi	10 (13)	7	2,698	2,197	266	105	121	9			524
Rangamati	2 (10)		47	47				0			
Rangpur	8 (8)	2	464	285	114	19	20	24	2		939
Satkhira	5 (7)	5	532	32	73	56	236	134	1		750
Shariatpur	3 (6)	3	152	63	29	20	26	14			580
Sherpur	5 (5)	3	303	191	100	7	5	0			275
Sirajganj	4 (9)	3	278	187	79	8	4	0			216
Sunamganj	2 (10)	2	89	6	34	29	17	3			302
Sylhet	5 (11)	1	391	331	44	14	2	0			177
Tangail	11 (11)	4	597	443	131	21	2	0			224
Thakurgaon	5 (5)	2	461	416	38	6	1	0			130
Total	338 (487)	197	52,202	29,768	8,230	3,714	6,487	3,201	501	301	
%				57	15.8	7.1	12.4	6.1	1	0.6	

Source: Chakraborti et al. 2010
Notes: NTS (TNT) – number of Thana surveyed (total number of Thana); Dhaka City (22 thana) is considered as a thana (27 = 6); NT – number of Thana; n – number of samples analyzed

ten years of irrigation using As-contaminated water would add 5–10 mg of As/kg of soil to 41% of their 456 paddy field sites in Bangladesh. The evaluation was based on available As national data in STW used for drinking water and *boro* rice production purposes. Dittmar et al. (2007) reported that arsenic concentrations remained unchanged at the start of two successive irrigation seasons, because arsenic accumulated during the first (*boro*) irrigation season was leached by floodwater during the following monsoon (*aman*) season. Most of the studies concentrated on surface soil samples (up to 15 cm depth), and some studies concentrated on the As enrichment in the soil profile. Yamazaki et al. (2003) carried out a detailed study through the collection of five soil profiles of 15 m depth at Deuli Village (Southwest Bangladesh), and reported that As concentration in the soil is dependent on the type of sediment. They mentioned that sandy sediments contained 3–7 mg/kg (median, 5 mg/kg); clay sediments contained 4–18 mg/kg (median, 9 mg/kg), while peat and peat-clay sediments contained 20–111 mg/kg. Alam and Sattar (2000) selected 25 locations in five subdistricts (Chapai Nawabganj Sadar, Kustia Sadar, Bera, Ishurdi and Saishabari) of four districts; and soil samples were collected at three depths (0–15 cm, 15–30 cm and 30–45 cm) (Heikens et al. 2007). They reported that As concentrations in soils varied from below detection limit to 56.7 mg/kg. Furthermore, they mentioned that there is a positive correlation between soil and water. Likewise, Das et al. (2004) also reported a positive correlation between As in STW and the soil. Heikens et al. (2007) reported based on a detailed review of As behavior in groundwater and soil to crops that As-rich irrigation water increases the As load in the soil. Nevertheless, as the potential risk of As in irrigation water to crop production and plant growth is not fully understood, more research needs to be focused on these areas.

Nepal

The total population in Nepal is 26.5 million, and 50.3% of the populace is in Nepal Terai (13.3 million) (2011 census). In the Terai region, 90% of people depend on groundwater for their livelihoods. In Nepal Terai, there are 20 district and the groundwater in all these districts contains As >10 µg/L (Table 6 and Figure 6; Thakur et al. 2011; Yadav et al. 2011). In 1999, the Department of Water Supply and Sewage (DWSS) initiated an investigation to assess As contamination in groundwater. In this study, 18,635 samples (20%) exceeded the WHO guideline (As>10 µg/L) (Sharma 1999; Yadav et al. 2011). Furthermore, DWSS (2007) carried out a blanket study in 24 districts of Nepal and tested 259,828 wells. The study concluded that 27,529 wells exceeded As>10 µg/L, whereas 7,232 wells contained As>50 µg/L. Consequently several national and international organizations got involved in As issues and carried out detailed studies in Nepal Teri such as the Nepal Red Cross Society (NRCS); Japanese Red Cross Society (JRCS); Rural Water Supply and Sanitation Support Program (RWSSSP); Environment and Public Health Organization (ENPHO); Nepal Water for Health (NEWAH); Finish International Development Agency (FINNIDA); Center for Affordable Water and Sanitation Technology (CAWST); and the Canada and Massachusetts Institute of Technology (MIT) (Pokhrel et al. 2009; Yadav et al. 2011). Bhattacharya et al. (2003) reported that the total As in groundwater of this region varied from 1.7 to 404 µg/L, and mostly identified as arsenite (As (III)). According to Shrestha et al. (2003), the maximum concentration is encountered in the Rupandehi District (As = 2,620 µg/L). This observation is well correlated with what Maharjan et al. (2006) mentioned, i.e., the maximum concentration of arsenic in groundwater (tube wells) in Nawalparasi, Bara, Parsa, Rautahat, Rupandehi, and Kapilvastu districts are 571, 254, 456, 324 and 2,620 µg/L, respectively. According to Smedley (2005), As content in deeper tube wells was less than 10 µg/L. Likewise, old tube wells and medium depth wells (10–30 m) have high As concentrations (Shrestha et al. 2003; World Bank 2005). In 2003, the National Arsenic

Steering Committee (NASC) and the Environment and Public Health Organization (ENPHO) jointly carried out a detailed survey to test tube wells for arsenic. They tested 18,635 tube wells, which are distributed in the 20 districts of Nepal. However, the tested wells are not uniformly distributed in the districts, e.g., the Nawalparasi District (17.2%), Kapilvastu District (13.4%), Parsa District (12.1%), Rautahat District (11.0%), Rupandehi District (11.0%) and Bara District (10.5%) and so on. The lowest number of these tube wells, (i.e., 172 or 0.9%) is distributed in the Sunsari District. Among 18,635 arsenic-tested tube wells, approximately 7.4% tube wells exceeded As>50 µg/L; 16.3% tube wells contained 11-50 µg/L of As; 23.7% tube wells were above WHO Guideline (As>10 µg/L); and majority of tube wells (76.3%) were below WHO Guideline (NASC/ENPHO 2004). The maximum concentrations of As in groundwater in each district are given in Table 6. Among the 20 districts, groundwater wells in Rautahat, Nawalparasi, Kapilvastu and Banke districts are

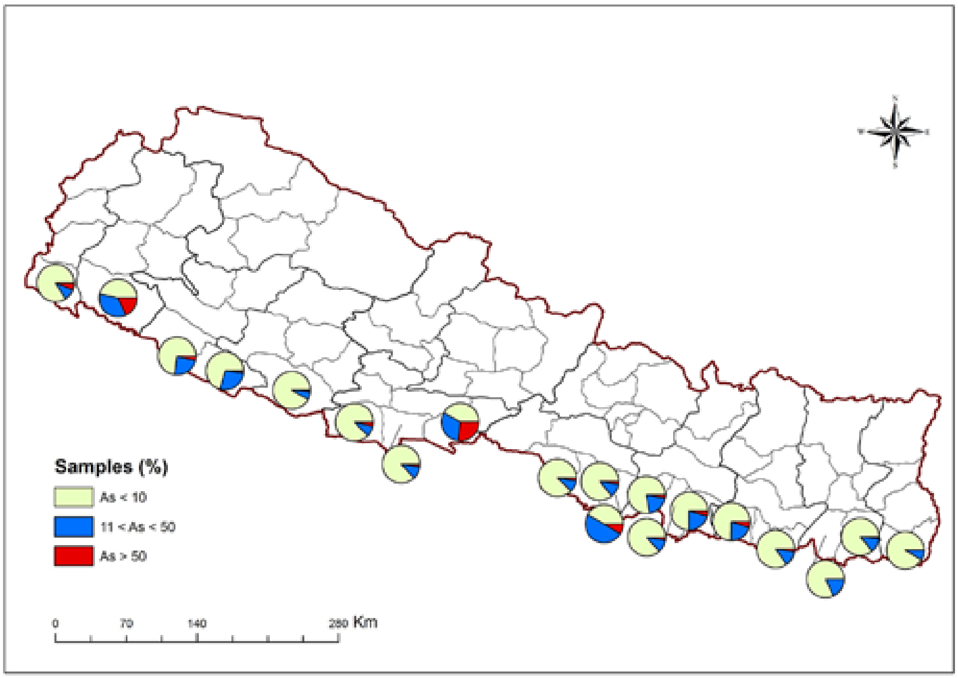
TABLE 6. Status of arsenic contamination in Terai districts of Nepal.

District	As (µg/L)			Total test	Max. As (µg/L)	% of sample above WHO guideline value	% of sample above As>50 µg/L
	0–10	10–50	>50				
Kailali	87	66	34	187	213	53	18
Kanchanpur	128	16	9	153	221	16	6
Bardiya	386	125	20	531	160	27	4
Dang	91	7	1	99	50	8	1
Banke	1,216	474	31	1,721	270	29	2
Kapilvastu	2,246	235	91	2,572	589	13	4
Rupandehi	1,807	225	46	2,078	2,620	13	2
Nawalparasi	1,492	1,135	953	3,580	829	58	27
Parsa	1,862	206	52	2,120	456	12	2
Bara	1,725	240	46	2,011	254	14	2
Rautahat	1,011	1,191	211	2,413	324	58	9
Saptari	532	82	14	628	98	15	2
Dhanusha	157	43	9	209	106	25	4
Siraha	195	54	13	262	107	26	5
Sarlahi	345	87	13	445	93	22	3
Mahotari	79	10	2	91	82	13	2
Sunsari	303	67	2	372	—	19	1
Morong	149	22	2	173	70	14	1
Jhapa	462	42	1	505	79	9	0
Chitwan	-	-	-	-	—	—	—
Total = 20	14,273	4,327	1,550	20,150	—	29	8

Sources: Yadav et al. 2011; Department of Water Supply and Sewerage (DWSS), Nepal Red Cross Society/Environment and Public Health Organization (NRCS–ENPHO), Rural Water Supply and Sanitation Support Program – Finnish Government Organization for Developing Countries (RWSSSP–FINNIDA), Plan, Nepal Water for Health (NEWAH), Rural Water Supply and Sanitation Fund Development Board (RWSSFDB), Department of Irrigation (DOI)

severely affected by the As crisis. In these districts, number of wells affected by As contamination is comparatively more (Table 6). Ahmad et al. (2004) conducted a detailed study in Goini and Thulo Kunwar villages in the Nawalparasi District, and reported that As in groundwater in Goini and Thulo Kunwar villages varied from 104 to 1,702 μg/L and between 4 to 972 μg/L, respectively.

FIGURE 6. Arsenic distribution in groundwater in Nepal Terai districts. Refer Table 6 for more details.



Limited number of studies were carried out in the Nepal Terai to evaluate the arsenic load in the soil. Spallholz et al. (2008) analyzed soil samples collected from an agriculture field in the Nawalparasi District, and reported that the average arsenic content is 6.3 mg/kg. Gurung et al. (2005) carried out a detailed study to understand the geological and geochemical examination of arsenic contamination in Nepal's Nawalparasi District, and reported an average arsenic concentration of 9 mg/kg in sediments, and stated that the distribution is not homogeneous. They observed also that the arsenic enrichment in finer sediments (black clay, As = 31 mg/kg) is far greater than in coarse sediments (silt and fine sand, As = 3 mg/kg). Dahal et al. (2008a) studied the As content in irrigation water in three villages of the Nawalparasi District and concluded that the mean arsenic content in irrigation water is 137 mg/L, and that the arsenic concentration in 65% of the wells exceeded 50 μg/L and in 36% it exceeded 100 μg/L. In addition, they concluded that continuous use of As-contaminated water for irrigation will add an average of 1.5 mg/kg/year of arsenic to agricultural soil. Furthermore, they insisted that the addition of arsenic may rise up to 10.19 mg/kg/year. Dahal et al. (2008b) reported that the arsenic content in top soil (<10 cm) and subsurface soil (10-20 cm) in a rice field in the Nawalparasi District varied from 7.4 to 12.5 mg/kg and 7.4 to 10.5 mg/kg, respectively. Likewise, the arsenic content in soil collected from a vegetable field also slightly varied with depth (top soil – 6.4 to 16.7 mg/kg; subsurface – 6.6 to 16.1 mg/kg). In addition, they concluded that there is a strong correlation between irrigation water and soil arsenic contents. In summary, a very limited number of studies have been carried out in Nepal Terai and, as such, needs to carry out more studies to understand the relation between water and soil As interaction.

IMPACT ON THE FOOD CHAIN AND HUMAN HEALTH

Studies carried out by several groups of researchers have revealed that As-contaminated foods such as rice, vegetables and fish also lead to potential As exposure to hundreds of millions of peoples in the world (Bhattacharya et al. 2010a; Lin et al. 2004; Ohno et al. 2007; Schoof et al. 1999; Signes-Pastor et al. 2008; Signes-Pastor et al. 2009). Arsenic-contaminated irrigation water and soils are major sources of As enrichment in foods (Table 7). Enhancement of As in agricultural soils from contaminated irrigation water followed by As uptake by rice, vegetables and other food crops have been the cause of the increasing number of health issues in this region (Meharg and Rahman 2003; Williams et al. 2006). According to Sun et al. (2006), about 200 million people in South and South East Asia is supposed to be exposed to As contamination through water and foods. Due to the usage of As-contaminated irrigation water, rice contains a high concentration of As compared to other agricultural products (Das et al. 2004; Schoof et al. 1999). Pal et al. (2009) found a correlation in As content in raw rice, irrigation water and soil. Moreover, paddy rice is one of the major and potential exposure sources of arsenic for humans (Meharg and Rahman 2003; Mondal and Polya 2008; Pillai et al. 2010; Rahman and Hasegawa 2011; Singh et al. 2010; Tuli et al. 2010; Williams et al. 2006; Zavala and Duxbury 2008). Abedin et al. (2002a) and Meharg and Rahman (2003) have reported that As enrichment in rice samples is higher than the WHO recommended permissible level of 1.0 mg/kg. Rice cultivation is mostly carried out in the flood irrigation method (also known as 'border irrigation'). Flooded (anaerobic) condition enhances the availability and mobility of arsenite (As [III]), which is easily absorbed by the rice plant from the soil solution (Xu et al. 2008; Zhu et al. 2008). In contrast, in aerated soil, arsenic is present as As (V) and is unavailable for the plant due to adsorption followed by precipitation with Fe hydroxides. Arsenic availability for plant uptake is regulated by several factors such as redox potential, pH, organic matter content, iron, manganese, phosphorus, calcium carbonate, plant species, soil microbes and chemical form of arsenic and its content in the soil

TABLE 7. Arsenic levels in the soil, rice, wheat and vegetables grown in India, Bangladesh and Nepal.

Country	Arsenic in soil (mg/kg)	Arsenic in crops (mg/kg)			Reference
		Rice	Wheat	Vegetables	
India (WB)	11.35	0.245	0.362	<0.0004–0.693	Roychowdhury et al. (2002)
India (WB)	7 – 38	0.30	0.70	NA	Norra et al. (2005)
India (WB)	6.87–7.74	0.156–0.194	0.872	0.084–0.330	Samal (2005)
India (WB, Nadia District)	5.70–9.71	0.334–0.451	0.010–0.190	0.030–0.654	Bhattacharya et al. (2010a)
Bangladesh	NA	0.358	NA	0.034	Chowdhury et al. (2001)
Bangladesh	NA	NA	NA	0.306–0.489	Alam et al. (2003)
Bangladesh	NA	NA	NA	0.011–0.103	Farid et al. (2003)
Bangladesh	7.31–27.28	0.04–0.27	NA	0.02–3.99	Das et al. (2004)
Bangladesh	14.5	0.5–0.8	NA	NA	Rahman et al. (2007)
Nepal	6.1–16.7	0.180	NA	<0.010–0.550	Dahal et al. (2008b)

Source: Bhattacharya et al. 2010a
Note: NA – not available

(Liebig 1966; Mahimairaja et al. 2005; Marin et al. 2003; NRC 2001). Furthermore, arsenic in rice is mostly in an inorganic form (Meharg et al. 2009; Rahman and Hasegawa 2011; Sun et al. 2008; Torres-Escribano et al. 2008).

Meharg et al. (2009) carried out an extensive analysis on the arsenic content in polished (white) rice, using 901 grain samples collected from 10 countries. They reported that the median total arsenic content in rice in India (0.07 mg/kg) is comparatively low compared to that of USA (0.25 mg/kg) and France (0.28 mg/kg). They also modeled the global distribution of total arsenic in rice and calculated the daily intake of inorganic arsenic and the internal cancer risk. The authors estimated, if 60 kg per person was considered, the median excess internal cancer rates to be 1/10,000 people in Italy, 15/1,000 in China and 22/10,000 in Bangladesh. Abedin et al. (2002a, 2002b) conducted a greenhouse study and reported that usage of As-rich irrigation water reduces plant height, rice yield, the number of filled grains, grain weight and root biomass; whereas the arsenic concentrations in root, straw, and rice husk increased significantly. Arsenic accumulates more in rice straw (up to 91.8 mg/kg) and root (up to 107.5 mg/kg), which may cause an indirect threat to human beings through cattle meat and milk. Based on a detailed review, Rahman and Hasegawa (2011) reported that arsenic content in Australian, Philippian, and Canadian rice is lowest, whereas it is high in Bangladeshi and Indian (West Bengal) rice.

Arsenic occurrences and its chemical form act as a major role of toxicity to humans. Several researches reported that trivalent inorganic arsenic compounds are more toxic to human health than pentavalent inorganic arsenic compounds. Based on toxicological study, Styblo et al. (2000) suggested that methylated trivalent arsenic is more toxic than inorganic arsenic. Arsenic is a hazardous material and act as a promoter for cancer development. Arsenic mostly affects the lungs and the skin, and also causes internal cancer in the liver, bladders, kidney, lungs and skin (Adeel 2002; Booth 2009; WHO 2011). Health implications are generally caused due to the consumption of arsenic-enriched water. Earlier studies reported various ways of arsenic exposure, for example, inhalation, ingestion and dermal contact (Mondal and Polya 2008; Pal et al. 2007; Rahman et al. 2006b). Human exposure to arsenic is mainly through drinking water compared to food and air (Kwok 2007; Villaescusa and Bollinger 2008; Yu et al. 2007). Symptoms of acute toxicity caused by arsenic are vomiting, muscle cramps, colicky abdominal pain, tingling of the hands and feet. Long exposure to arsenic provokes arsenicosis, cardiovascular diseases, skin lesions etc. (Bissen and Frimmel 2003). List of major diseases identified in arsenic-contaminated areas are hyper pigmentation, keratosis, weaknesses, anemia, burning sensation of the eyes, swelling of legs, liver fibrosis, chronic lung diseases, gangrene of toes, neuropathy, skin cancer, etc. (Government of India 2007). All these diseases are collectively referred to as arsenicosis. Some studies reported that dermatological, respiratory, gastrointestinal, cardiovascular, hepatic, neurological, hematological, renal, mutagenesis, reproductive, cancer and mental health are major diseases caused by As contamination. Arsenic toxicity to human beings varies with respect to several factors such as chemical and physical form of the arsenic compound, the dosage, duration of exposure, dietary compositions of interacting elements, age and sex of individuals, the route by which it enters the body, nutritional status of the person, immunity level of the individual etc. (DCH 1997; Khan and Ahmed 1997).

Bihar

Groundwater is the major source of water for irrigation in Bihar; and rice, wheat, maize, pulses, vegetables, etc., are the people's staple food and, as such, are cultivated widely. There is every likelihood that arsenic accumulation in these crops through As-contaminated groundwater will

cause health issues. However, very few studies focused on this issue in Bihar, as most of the studies concentrated on the As load in groundwater. Singh and Ghosh (2011) collected soil samples, rice grains (Sonam Dhan), wheat (wheat 2,338), maize (K-H-101) and lentils from the Rampur Diara Panchayat in the Maner Block located in the Patna District and analyzed. They reported that the arsenic concentration in wheat (0.024 mg/kg), maize (0.011 mg/kg), rice grain (0.019 mg/kg), husk (0.022 mg/kg), lentil (0.015 mg/kg) were within the permissible limit of the Australian food standard (1 mg/kg). This data quality is questionable because there is no information about the total number of samples collected, analysis details, etc.

In Bihar, very limited studies were carried out on health issues related to arsenic contamination. Existing literature shows that 57 blocks in 15 districts, located along the course of the Ganga River, are affected by arsenic contamination, and 10.4 million people (2001 census) are exposed to arsenic calamity (Saha et al. 2009). Chakraborti et al. (2003) carried out a medical examination for 550 people (390 adults and 160 children) in the Semria Ojha Patti Village, in Bhojpur District, and reported that 13% of the adults and 6.3% of the children had typical skin lesions. Based on a review, Bhattacharya et al. (2011) reported that the estimated numbers of people at risk from arsenic exposure in Patna District, Bhojpur District and Vaishali District were 555,339, 366,039 and 479,138, respectively. Singh and Ghosh (2012) carried out a health-risk assessment in two As-prone panchayats (Rampur Diara and Haldichapra) in the Maner Block of the Patna District. In Rampur Diara Panchayat, they surveyed 264 people and reported that 1.1%, 5.6%, 2.6% and 0.4% population had been affected by diarrhea, gastric problems, body itching and pigmentation, respectively. In Haldichapra, 0.9%, 5.8%, 4% and 2.3% of the population were suffering from diarrhea, gastric problems, body itching and pigmentation on their bodies, respectively. In summary, only three districts were surveyed for health-risk and very few studies concentrated on As accumulation in the food chain. Hence, proper planning is required to study all the arsenic-affected districts in the future.

West Bengal

Roychowdhury et al. (2002) investigated total arsenic food composites collected from Jalangi and Domkal blocks of the Murshidabad District in West Bengal, where groundwater is a major source for agriculture. In the study site, since the arsenic concentrations in the tube well water and soil using for irrigation are 0.085 mg/L (mean, n = 6) and 11.35 mg/kg (mean, n = 36), respectively, the authors expected As contamination to be in the food chain and reported the arsenic concentration in various food stuffs (Table 8). They reported that the As content is generally high in the skin of most of the vegetables. Furthermore, high As was also observed in the cooked foodstuff compared to the raw variety. Based on foodstuff arsenic content, Roychowdhury et al. (2002) estimated the daily dietary intakes of As for adults (171.20 μg) and children (91.89 μg). Samal et al. (2003) analyzed the arsenic content in crop and vegetables in the Uttarpara Village in the Nadia District and Doulatpur village in 24-parganas. They mentioned that the arsenic accumulation in arum is higher than in green gram, and it is present in a decreasing order in arum>rice>spinach>potatoes. In another study, Roychowdhury (2008) evaluated the impact of sedimentary arsenic through irrigated groundwater on soil, plants, crops and on human well-being in the Murshidabad and Nadia districts of West Bengal. He suggested that higher amounts of arsenic are accumulated in paddy plants, cooked food and vegetable skin and mean arsenic concentration in food stuff is 107 μg/kg. Moreover, he mentioned that the daily dietary intake of inorganic arsenic by an adult from rice grain itself (2.32 μg/kg body wt./day) is higher than the WHO recommended Provisional Tolerable Daily Intake (PTDI) value of inorganic arsenic (2.1).

TABLE 8. Mean arsenic content in rice, wheat, pulses, vegetables and spices from Jalangi and Domkal blocks in the Murshidabad District and five blocks in the Nadia District, West Bengal, India.

Category	Domkal Block		Jalangi Block		Nadia District (Five blocks*)	
	n	As (μg/kg)	n	As (μg/kg)	n	As (μg/kg)
Amaranth					16	372
Arum					10	407
Beans	4	17	2	66		
Beans					23	91
Bittergourd					9	21
Brinjal	3	131	–	–	16	279
Cabbage					14	209
Cauliflower					22	293
Garlic					18	126
Garlic (flesh)	3	0.8	3	0.04		
Green chilli	20	7.76	6	6.92	29	85
Lady's finger					14	301
Leafy vegetables	9	58.9	9	38.6		
Lemon					30	12
Lentil	3	41.1	5	4.39	14	96
Mustard seed					18	198
Onion (flesh)	6	60	6	60		
Onion bulb					23	162
Papaya					26	258
Pea					23	141
Potato (flesh)	5	2.32	5	2.32		
Potato tuber					23	654
Pulse item	3	152	2	3.56		
Pumpkin					11	184
Radish					21	344
Rice	23	233	11	232		
Rice grain (*aman*)					18	334
Rice grain (*boro*)					21	451
Spinach					22	257
Tomato					29	84
Turmeric					14	3
Turmeric powder	10	-	2	435		
Wheat	5	31.3	2	5.22	8	129
White cumin	4	199	4	48.7		

Sources: Roychowdhury et al. 2002; Bhattacharya et al. 2010a
Notes: * Five blocks - Haringhata, Chakdaha, Ranaghat-I, Shantipur and Krishnanagar; n – number of samples

Samal (2005) reported the arsenic concentration in rice (0.156–0.194 mg/kg) and crops (0.084–0.330 mg/kg) in the Haringhata Block of West Bengal. Roychowdhury et al. (2005) reported the mean soil arsenic concentrations in surface, plants root, top soil (0–30 cm) and all the soils, collected from four agricultural lands are 14.2 mg/kg (range: 9.5–19.4 mg/kg, n = 99), 13.7 mg/kg (range: 7.56–20.7 mg/kg, n = 99), 14.8 mg/kg (range: 8.69–21 mg/kg, n = 102) and 14.2 mg/kg (range: 7.56–21 mg/kg, n = 300), respectively. The arsenic accumulation in plant parts are also reported, and the mean arsenic content in root, stem, leaf and all parts of plants are 0.996 mg/kg (range: <0.00004–4.850 mg/kg, n = 99), 0.297 mg/kg (range: <0.00004–2.900 mg/kg, n = 99), 0.246 mg/kg (range: <0.00004–1.600 mg/kg, n = 99) and 0.513 mg/kg (range: <0.00004–4.850 mg/kg, n = 297), respectively. Bhattacharya et al. (2010a) carried out a detailed study to estimate the arsenic content in rice, wheat, pulses and vegetables in five blocks of the Nadia District, West Bengal (Table 8). They reported that the total arsenic concentrations varied between <0.0003 and 1.02 mg/kg (d.wt.) in these materials, and that potato had the highest mean arsenic concentration (0.654 mg/kg). They documented the mean arsenic content (mg/kg, d.wt.) of other materials also *boro* rice grain (0.451), arum (0.407), amaranth (0.372), radish (0.344), *aman* rice grain (0.334), lady's fingers (0.301), cauliflower (0.293), brinjals (0.279), wheat (0.129), garlic (0.126), lentil (0.096), beans (0.091), green chili (0.085), tomato (0.084), bittergourd (0.021), lemon (0.012), and turmeric (0.003)). Bhattacharya et al. (2011) reported that in West Bengal, high arsenic content in food grains (rice – 2 mg/kg, rice root – up to 178 mg/kg) is mainly caused by the usage of arsenic-contaminated water. Based on a review, Rahman and Hasegawa (2011) reported that the arsenic concentration in rice varied from 0.04 to 0.43 mg/kg, (d.wt.) in the arsenic-affected areas of some districts in West Bengal. Table 9 shows the arsenic concentration in rice in West Bengal as well as in India. Mondal and Polya (2008) tested As concentration in rice collected from some areas of the Nadia District of West Bengal, and documented that the As content in raw rice is varied from 0.02 to 0.17 mg/kg (d. wt.) with a mean value of 0.13 mg/kg (d. wt., n = 50). Pal et al. (2009) studied the arsenic load in raw and cooked rice in the populations of arsenic-affected and unaffected areas and Kolkata City, and reported that there is a significant correlation between irrigation water and rice; soil and rice for both *boro* (groundwater) and *aman* (rainwater) rice varieties. The average arsenic contents in *boro* and *aman* raw rice collected from the contaminated area are 249 μg/kg and 82 μg/kg, respectively, whereas in the uncontaminated area, they are 53 μg/kg and 36 μg/kg, respectively. Likewise, the mean arsenic content in the raw rise collected from Kolkata City is 137 μg/kg. Samal et al. (2010) studied the accumulation of arsenic in cereals, pulses and vegetables in the selected villages of Habra-II Block of North-24-Parganas, West Bengal. They reported that the arsenic content (μg/kg, d.wt.) in rice (*boro*), rice (*aman*), wheat, pea, lentil, green gram, mustard seed were 492.97±178.47 (n = 12); 161.19±23.91 (n = 6); 94.52±22.79 (n = 3); 101.47±41.93 (n = 3); 21.86±9.66 (n = 4); 31.52±4.35 (n = 3); and 88.94±10.42 (n = 3), respectively. In the case of vegetables, minimum and maximum accumulation of arsenic were found in green chili (32.85±7.41 μg kg-1) and arum (Colocasia Sp) (908.48±1,164.41 μg/kg), respectively. Arsenic accumulation is prone to vary with the type of crop. Higher arsenic accumulation is observed in arum, radish, potato, pith of the plantain tree, basella, cabbage, amaranth and spinach (more than 300 μg/kg) compared to other vegetables such as tomato, kidney bean and cauliflower (less than 100 μg/kg). Likewise, green gram, pulses and lentil show less arsenic accumulation (< 50 μg/kg). Based on a field study, Bhattacharya et al. (2010b) reported that arsenic uptake in rice varied with the season (pre-monsoon > post-monsoon), and arsenic accumulation also varied with rice varieties, e.g., white minikit (0.31±0.005 mg/kg), IR 50 (0.29±0.001 mg/kg), and Jaya rice variety (0.14±0.002 mg/kg). Besides, they found maximum arsenic accumulation in the straw (0.89±0.019 - 1.65±0.021 mg/kg) compared to the husk (0.31±0.011 - 0.85±0.016 mg/kg) and the

TABLE 9. The concentration of total, inorganic and organic arsenic fractions in raw rice from India and West Bengal.

Country	Total As mean (range)	Inorganic As mean (range)	Organic As mean (range)	% of inorganic As mean (range)	Survey range	References
India	0.07 (0.07–0.31)	0.03 (0.02–0.07)	–	43	Market basket	Meharg et al. 2009
	0.05 (0.03–0.08)	0.04 (0.02–0.05)	BDL–0.01	56 – (36–67)		Williams et al. 2005
West Bengal	0.14 (0.02–0.40)	–	–	–	Household	Pal et al. 2009
	0.25 (0.14–0.48) — *boro*	–	–	–	Household (contaminated area)	Pal et al. 2009
	0.08 (0.03–0.16) — *aman*	–	–	–		
	0.13 (0.02–0.17)	–	–	–	Field (market household)	Mondal and Polya 2008
	0.21 (0.11–0.44)	–	–	–		Roychowdhury et al. 2002
	0.33 (0.18–0.43)	–	–	–	(Contaminated area)	Roychowdhury et al. 2002

Source: Rahman and Hasegawa 2011
Notes: Concentration in mg/kg, d.wt.; BDL - below detection limit

grain (0.14±0.002 - 0.31±0.005 mg/kg). Biswas et al. (2010) also found similar results in paddy and encountered high arsenic in the straw (3.82–7.24 mg/kg) compared to the husk (0.35–1.79 mg/kg) and the grain (0.08–1.0 mg/kg). In summary, existing literature highlighted that most of these studies have been carried out only in four districts (Murshidabad, Nadia, 24-parganas (South and North)) and in Kolkata.

In West Bengal, several studies have been made to concentrate on human health issues linked to arsenic contamination. Chowdhury et al. (2001) carried out a detailed screening and diagnosis of 86,000 peoples in 306 villages belonging to 7 arsenic-affected districts in West Bengal. They reported that the mean arsenic content (µg/kg) in hair, nail, urine and skin scale were 1,480 (n = 7,135), 4,560 (n = 7,381), 180 (n = 9,795) and 6,820 (n = 165), respectively. Roychowdhury et al. (2002) calculated the daily intake of total arsenic through water and food for two locations in West Bengal. They concluded that arsenic intake of adults and children (10-year old) via foods was approximately 180 and 97 µg/d, respectively. Likewise, the intake through drinking water is 400 and 200 µg/d for adults and children, respectively. Based on a detailed survey in the Jalangi Block, West Bengal, Rahman et al. (2005) reported that 88% of biological samples (hairs, nails and urine) contained As levels above normal values, i.e., 0.08–0.25 mg/kg (hair); 0.43–1.08 mg/kg (nail); 0.005–0.04 mg/day/1.5l (urine). In addition, they mentioned that 21% of the people is affected with skin lesions. Moreover, based on the analysis of 1,916 water samples, they documented that the groundwater arsenic content was greater than 0.01 mg/L in 77.8%, As > 0.05 mg/L in 51% and As

> 0.3 mg/L in 17% of the samples. Uchino et al. (2006) evaluated the main intake source of arsenic by the villagers by eliciting information from arsenic-affected families in Jalangi and Domkol blocks in the Mushidabad District, West Bengal, India. They reported that the drinking water contributed 6.07%, 26.7% and 58.1% of the total arsenic intake of mild, moderate and high arsenic-affected families, respectively. They also mentioned that As-contaminated food composites are a major source of As intake for mild and moderate As-affected families. Mondal and Polya (2008) estimated the human cancer risk due to As contamination using field, laboratory and computational methods in the Chakdaha Block of Nadia District in West Bengal. The authors reported that the contribution of drinking water, rice and cooked rice for cancer risk is 48%, 44% and 8%, respectively. Furthermore, they suggested that rice is a major potential source of As exposure in the As-affected study areas in West Bengal, and it was the most potential exposure pathway for groups exposed to low or no arsenic in their drinking water. Similarly, Samal et al. (2011) mentioned that the total intake of As from foodstuffs by adults and children is 560 µg/day and 393 µg/day, respectively in the Nadia District. They estimated the As in urine to vary between 154 and 276 µg/L, and also highlighted the potential risk of As exposure to local inhabitants through the food chain.

Bangladesh

In Bangladesh, groundwater is a major water source for agriculture. Hence, soil and crops are vulnerable for arsenic contamination due to arsenic-contaminated groundwater usage. In many areas, high arsenic is encountered in agricultural soil due to groundwater usage (Farid et al. 2003; Huq at al. 2006; Roychowdhury et al. 2005). The arsenic is accumulated in vegetables and rice grains during cultivation from irrigation water and soil (Huq et al. 2006; Khan et al. 2010; Rahman and Hasegawa 2011; Saha and Zaman 2011). Table 10 shows the arsenic content in food and forage plants. Arsenic concentration varies from <0.01 to 5 mg/kg (d.wt.) in plants (Mandal and Suzuki 2002), and highest concentrations were recorded in old leaves and in roots (Pendias and Pendias 1992). In addition, leafy vegetables contain higher concentrations compared to fruits (Hossain 2006). Das et al. (2004) reported that the arsenic levels in vegetables like kachu sak (colocasia antiquorum), potato (solanum tuberosum) and kalmi sak (ipomea reptans) exceeded the food safety limits of 1.0 mg/kg (Abedin et al. 2002a). Furthermore, they reported higher arsenic contents (0.07– 1.36 mg/kg) in potatoes. Based on a study of 37 vegetables, pulses and spices, Williams et al. (2006) reported that a maximum arsenic content in radish leaves (0.79 mg/kg), arum stolons, spinach and cucumber; and a lowest of 0.2 mg/kg in most fruits, vegetables and spices. Farid et al. (2003) carried out a detailed study on arsenic- contaminated irrigation water and its effect on vegetables in Bangladesh, both in arsenic-contaminated and non-contaminated areas, and reported the arsenic contents of vegetables is in the order of potato 0.103 mg/kg > brinjal 0.049 mg/kg > cauliflower 0.011 mg/kg.

Arsenic in the soil also contributes to the arsenic load in rice. Table 11 shows the total arsenic content in irrigation soil and rice. High arsenic in the rice correlates with the high arsenic in the soil. Table 12 shows the arsenic content in raw rice grain in Bangladesh (Rahman and Hasegawa 2011). It explains that inorganic As is the dominant fraction in rice grains. Meharg and Rahman (2003) reported that the arsenic content in rice grain collected from arsenic-contaminated western part of Bangladesh varies from 0.03 to 1.84 mg/kg (d.wt.). Williams et al. (2006) documented that arsenic concentration in rice grains collected from southern part of Bangladesh varies with *aman* (dry season) and *boro* (monsoon season). Arsenic level in the rice grains ranged from 0.04 to 0.92 mg/kg (d.wt.) and 0.04 to 0.91 mg/kg (d.wt.) during *aman* and *boro* seasons, respectively (Table 12). Islam et al. (2004) reported that the arsenic in the *boro* rice collected

TABLE 10. Arsenic content of food and forage plants.

Plants	Tissue sample	Dry weight basis (mg/kg)
Rice	Grains	110–200
Wheat	Grains	50, 3–10
Barley	Grains	3–18
Oats	Grains	10
Corn	Grains	30–400
Beans	Pods	7–100
Cabbage	Leaves	20–50
Spinach	Leaves	200–1,500
Lettuce	Leaves	20–250
Carrot	Roots	40–80
Onion	Bulbs	50–200
Potato	Tubers	30–200
Tomato	Fruits	9–120
Apple	Fruits	50–200
Orange	Fruits	11–50
Edible Mushroom	Whole	280
Clover	Tops	20–160

Sources: Pendias and Pendias 1992; Hossain 2006

from Gopalganj, Rajbari and Faridpur districts in Bangladesh is 0.05–2.05 mg/kg (d.wt.). In the Satkhira District, the arsenic content in raw rice collected from a highly arsenic-contaminated area is 0.57–0.69 mg/kg (d.wt.) (Rahman et al. 2006a). According to Rahman et al. (2007), the arsenic concentration in rice fractions is in the order of husk>bran>whole rice>polish rice. In Bangladesh, 44 to 86% of the total arsenic found in rice is inorganic (Meharg et al. 2009; Rahman and Hasegawa 2011; Sun et al. 2008; Williams et al. 2005; Williams et al. 2006; Table 12). Based on a field study, Ohno et al. (2007) reported that the arsenic in Bangladesh rice is 100% inorganic. In Bangladesh, cooked rice poses 10 to 35% of high arsenic content compared to raw rice (Misbahuddin 2003). Williams et al. (2006) estimated the total and inorganic As content in Bangladeshi rice to determine the contribution of inorganic As to the maximum tolerable daily intake (MTDI) for a Bangladeshi adult weighing 60 kg (Table 13). They concluded that it would be 55–79% depending on the rice variety and inorganic As content.

In Bangladesh, several studies reported that about 35 million people (2,000 villages in 178 blocks) are at risk of As poisoning (Akter and Ali 2011; Biswas et al. 1998; Chowdhury et al. 1999; Dhar et al. 1997; Hossain 2006; Jakariya and Bhattacharya 2007; Khan and Ahmad 1997; Nickson et al. 1998, 2000; Uddin 1998; Ullah 1998; van Geen et al. 2003). According to Chakraborti et al. (2010), approximately 6.8 million people in Bangladesh are affected by arsenical skin lesions (arsenicosis) due to groundwater As contamination. Based on a review, Safiuddin et al. (2011) reported that about 30 million are potentially exposed to As poisoning and another 80 million people are at risk. Tables 1 and 4 explain overall statistics of As calamity in Bangladesh.

TABLE 11. Total arsenic concentrations in rice and soil from Bangladesh.

Location	Rice (mg/kg, d.wt)	Soil (mg/kg)	Remarks	References
Gazipur 2003	0.092 (0.043–0.206)	10.9; 14.6	11 cultivars*	Meharg and Rahman 2003
Bogra	0.058–0.104	4.9–15.5	4 cultivars	
Dinajapur	0.203	11.7	BR11	
Naogaon	1.835	24.3; 26.7	BR11	
Nawabgonj	1.747; 1.775	15.7; 20.9	BR11	
Mymensingh	0.078	6.0–25.4	BR8	
Rangpur	0.185	6.5–11.5	BR11	
Rajshahi	0.075–0.117	7.8	3 cultivars	
Various	0.183 (0.108–0.331)		Raw *boro* rice (n = 78); 14% water	Duxbury et al. 2003
Various	0.117 (0.072–0.170)		Raw *aman* rice (n = 72); 14% water	
Various	0.125		Processed rice (n = 21)	
Kachua, Hajiganj, Sharishabari	0.14 (0.04–0.27)	15.68 (7.31–27.28) (15–45 cm depth)	(n = 10)	Das et al. 2004
Northwest	0.173		As-affected area	Watanabe et al. 2004
Chapai	0.759	11.2 (5.8–17.7)	As-affected area	Jahiruddin et al. 2005
Market	0.13 (0.3–0.30)		Various *aman* cultivars (n = 15)	Williams et al. 2005

Source: Heikens et al. 2007
Note: *lowest concentration in BR11: 0.043 mg/kg d.wt

In 2000, the School of Environmental Studies (SOES) and the Dhaka Community Hospital (DCH) collected more than 10,000 hair, nail, urine and skin-scale samples from 210 As-affected villages in Bangladesh and analyzed. They reported that 83.2% of hair samples and 93.8 % of nail samples contained As greater than toxic (1 mg/kg) and normal level, respectively (Arnold et al. 1990; Dhar et al. 1997; Safiuddin et al. 2011). In addition, 95.1% of urine samples and 97.4% of skin-scale samples exceeded normal and toxic levels, respectively (Arnold et al. 1990; Farmer and Johnson 1990). Chowdhury et al. (2000) collected hair (3,332 samples), nail (3,321 samples), urine (1,043 samples) and skin-scale (373 samples) from As-affected villages and analyzed. They reported that 81, 94 and 95% of hair, nail and urine samples, respectively, exceeded the normal levels. In the Chandpur District, over 3,000 patients have been affected by the As crisis (Islam 2003). In Bangladesh, people are mostly suffering from melanosis, leuco-melanosis, keratosis, hyper-kerotosis and skin cancer (Karim 2000; Safiuddin et al. 2011; Yunus et al. 2011). In addition, higher rate of fetal loss and infant deaths is also reported from areas where people consume high As through groundwater (Sohel et al. 2010). The relation between diabetes and As contamination is also reported in literature. Rahman et al. (2006b) reported that males were more susceptible to developing skin lesions than females when exposed to As contamination.

TABLE 12. The concentration of total, inorganic and organic arsenic fractions in raw rice from Bangladesh.

Total As mean (range)	Inorganic As mean (range) (mg/kg, d.wt.)	Organic As mean (range) (mg/kg, d.wt.)	% of inorganic As mean (range)	Survey range	References
0.13 (0.02–0.33)	0.08 (0.01–0.21)	–	61	Market basket	Meharg et al. 2009
0.50 (0.03–1.84)	–	–	–	Field	Meharg and Rahman 2003
0.34 (0.15–0.59)				Field	Ohno et al.
0.39 (0.26–0.58)	0.39 (0.26–0.58)	0.005 (0.001–0.010)	100	Field	2007
0.08–0.36 (0.04–0.92) — *aman*	–	–	–		
0.14–0.51 (0.04–0.91) — *boro*	–	–	–	Field	
0.23 (0.18–0.31) — *aman*	0.16 (0.11–0.22)	–	65 (60–71)	Market basket	Williams et al. 2006
0.24 (0.21–0.27) — *boro*	0.20 (0.17–0.22)	–	82 (81–83)		
0.13 (0.03–0.30)	0.08 (0.01–0.21)	0.02 (<BDL–0.05)	60 (44–86)	Market basket	Williams et al. 2005
0.69 (0.41–0.98)	0.31 (0.23–0.39)	0.23 (0.05–0.43)	44 (45–59)	–	Sun et al. 2008
0.57–0.95 (0.05–2.05)	–	–	–	Field	Islam et al. 2004
0.57–0.69	–	–	–	Field	Rahman et al. 2006a

Source: Rahman and Hasegawa 2011
Note: BDL - below detection limit

Nepal

In Nepal Terai, only few studies concentrated on As contamination in the food chain and its impact on human health. Arsenic content in the food chain was estimated by Dahal et al. (2008b) in the Nawalparasi District. They carried out a detailed study to understand the As load in irrigation water, agricultural soils (rice and vegetable fields), rice and vegetables. They reported the As content in rice and vegetables (d.wt.) as: rice (0.06–22.20 mg/kg); potato (<0.01–0.79 mg/kg); cauliflower (0.09–3.45 mg/kg); onion (<0.01–1.20 mg/kg); and brinjal (<0.01–1.14 mg/kg). They documented that the As content in different parts of rice and vegetables decreases in the order of roots > shoots > leaves > grains (without husk)/fruits.

TABLE 13. Total and inorganic arsenic concentrations in rice grain, and the contribution of inorganic arsenic to the WHO's provisional maximum tolerable daily intake (MTDI) of arsenic for humans (2.1 μg/d/kg body wt) in Bangladesh.

Rice type/ variety	Total As (mg/kg, d.wt.)	Inorganic As (mg/kg, d.wt.)	Inorganic As (%)	Contribution of inorganic As to MTDI (%)	References
BRRI dhan10	0.31 ±0.02	0.22 ±0.02	71	79	Williams et al. 2006
BRRI dhan11	0.21 ±0.00	0.14 ±0.02	66	48	Williams et al. 2006
Kalizira (local variety)	0.18 ±0.03	0.11 ±0.03	60	38	Williams et al. 2006
BRRI dhan 28	0.25 ±0.00	0.21 ±0.02	83	74	Williams et al. 2006
BRRI dhan 29	0.21 ±0.01	0.17 ±0.02	82	62	Williams et al. 2006
Nayanmoni (local variety)	0.27 ±0.02	0.22 ±0.03	81	79	Williams et al. 2006
Digha	0.21 ±0.04	0.15 ±0.04	72	55	Williams et al. 2006
Mixed	0.39	0.39	100	139	Ohno et al. 2007
Mixed	0.13	0.08	61	29	Meharg et al. 2009
Mixed	0.13	0.08	60	29	Williams et al. 2006
Mixed	0.69	0.31	44	111	Sun et al. 2008

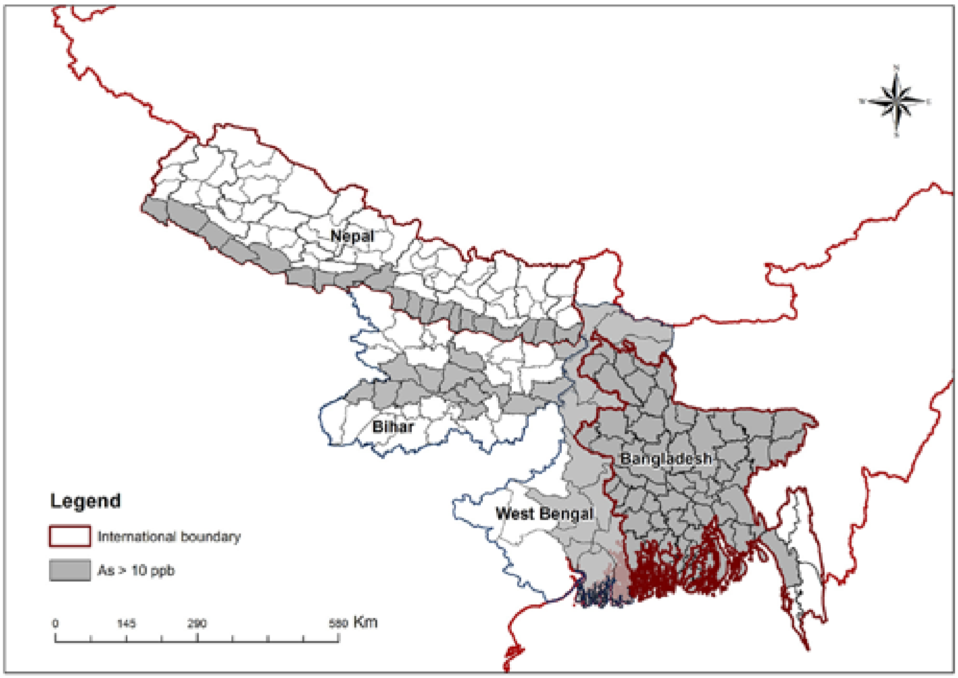
Source: Williams et al. 2006; Rahman and Hasegawa 2011
Note: The MTDI is based on total grain arsenic concentration, a body weight of 60 kg, a consumption rate of 0.5 kg rice/d, inorganic arsenic content (%), and bioavailability of inorganic arsenic in cooked rice (90%) (Laparra et al. 2005).

According to Pokhrel et al. (2009) and Neku and Tandukar (2003), 3.5 million people are expected to be exposed to As level between 10 and 50 μg/L. According to Shrestha et al. (2003), 2.53 million people (As>10 μg/L) and 0.5 million people (As>50 μg/L) are at risk of As exposure. They carried out a survey in As-affected households (5,215 individuals) of Bara, Parsa and Nawalparasi districts, exposed to an As level greater than 50 μg/L and identified arsenicosis-related dermatosis (skin disease) in 1.3 to 5.1% of the population. Most of them have symptoms of melanosis and keratosis on the palms, torso, and soles of the feet. Suspected arsenicosis patients were identified in Tilakpur and Thulokunuwar villages of the Nawalparasi District, where the groundwater As concentration is very high (271 and 473 μg/L, respectively) (Neku and Tandukar 2003; Pokhrel et al. 2009). Arsenic content in hair samples collected from As-affected areas indicated that 95% of samples exceeded the normal level (0.080-0.250 mg/kg), whereas 62% of samples exceeded the acute toxicity levels (1 mg/kg) (Shrestha et al. 2003). Ahmad et al. (2004) conducted clinical observations in Goini and Thulo Kunwar villages in the Nawalparasi District and identified melanosis (95.6% of patients), keratosis (57.8% of patients) and leucomelanosis (3.3% of patients) in these villages. Maharjan et al. (2006) carried out a detailed survey to find out the arsenicosis cases in six districts of Nepal Terai namely, Nawalparasi, Bara, Parsa, Rautahat, Rupandehi and Kapilvastu, during 2001-2004. They reported that the prevalence of arsenicosis ranged from 0.7% in the Kapilavastu District to 3.6% in the Nawalparasi District with an average of 2.2%. In addition, they mentioned that the highest prevalence (18.6%) of arsenicosis was found in the Patkhouli Village of Nawalparasi, where 95.8% of tube wells were contaminated with As. Melanosis and keratosis are common symptoms of arsenicosis in the study site. Overall, arsenic load in the food chain and its impact on human health in Nepal Terai is not understood properly due to lack of data and studies. Hence, a detailed study is recommended in this region.

ARSENIC CRISIS IN THE EGB

In the EGB, appropriate mitigation and prevention programs should be undertaken to handle the As calamity. Arsenic crisis is a major issue in Bangladesh and West Bengal compared to Bihar and Nepal in the EGB. Figure 7 illustrates overall As contamination of groundwater in the EGB. Figure 7 apparently shows that As contamination is mostly along the course of the Ganga River, especially Bihar and West Bengal. Groundwater in 15 districts in Bihar, 14 districts in West Bengal, 61 districts in Bangladesh and 20 districts in Nepal Terai are completely or partially affected by arsenic contamination (As > 10 µg/L). In the total population, 75% is living in the arsenic-affected area and there is a considerable chance of them being subject to potential exposure of As contamination through water and food.

FIGURE 7. Arsenic contamination status in groundwater in the EGB (India [Bihar and West Bengal], Bangladesh and Nepal).



RECOMMENDATIONS

Some studies recommended alternative methods or potential water sources to tackle As issues in the EGB (Adeel 2002; Safiuddin et al. 2011). The present study recommends the following acceptable and reliable options for water usage to manage As issues.

(1) Arsenic-free deep aquifer pumping.

(2) Usage of surface and rain water for irrigation, drinking and domestic usage instead of groundwater.

(3) Implementing rainwater harvesting techniques at the community level.

(4) Reducing As-contaminated groundwater pumping for all purposes, in general, and for irrigation, in particular.

(5) Crops that require less water should be recommended in the affected area. Border (flooded) irrigation should be avoided.

(6) Installation of shallow Hand pumps and dug-wells in As-free shallow aquifers.

(7) Installation of common treatment systems for the treatment of As-affected groundwater and surface water.

(8) Distribution of treated groundwater and surface water through pipe lines.

(9) Encourage community participation and awareness campaigns in the As-affected areas to manage the As crisis.

RESEARCH GAP AND FUTURE RESEARCH DIRECTIONS

Although numerous studies have been carried out to understand As contamination in groundwater, soil and crops in the EGB, nothing has been concentrated on long-term monitoring of As accumulation in As-affected areas. Long-term monitoring of data, for example, groundwater, will help to understand temporal variation in As concentrations with respect to recharge and evaporation. It will also facilitate to avoid the uncertainties associated with As estimations in the field as well as in the laboratory. Hence, periodic monitoring should be planned to estimate the As contamination in water, soil and foods. Furthermore, As testing methods should be updated (having in place field-oriented user friendly methods may be a reliable option for testing the groundwater in large areas). Moreover, even though several studies and researches have contributed in providing an As estimation in the EGB, there is still a debate to identify the exact source and transport processes linked to As contamination. Hence, a comprehensive method should be developed to conduct a complete and thorough evaluation of As contamination in soil, water, foods (grains, vegetables, fruits, etc.) and its impact on human health.

As per availability of data on arsenic is concerned, existing As data is more than one decade old, except for few other studies. For example, in Bangladesh, the BGS conducted a detailed survey during 1998 and 1999 for the whole country. Since then, no detailed As contamination survey has been conducted up to now. Few site-specific works are available in literature; however, there is no reported work available that represents the whole of Bangladesh. Likewise, a limited number of research works related to As contamination in Bihar and Nepal have been reported. There are numerous groundwater wells that remain to be tested in order to determine the magnitude of the problem in the EGB. Hence, this study recommends the following options for development and management of As-affected regions in the EGB.

1. Researchers working with As calamity may form an association or group in the EGB to share knowledge, data, methodology, recommendations, etc. This coordination will avoid the duplication of earlier work.
2. A data base should be created and all relevant information stored, for example, As concentration in groundwater, surface water, soil, foods, As-affected populations, etc.
3. Using Geological Information System (GIS), thematic maps should be created and affected areas demarked. A complete and detailed As concentration map encompassing the whole of EGB should be made available.

4. Having in place a data base and an As map will help the government body, researchers, NGOs and volunteers to identify the severity of the As crisis (in moderately or severely affected areas), and also help to implement better planning and management of As-affected areas.
5. The modeling approach will help to predict future scenarios like As enrichment, population at risk, possible remediation techniques, etc., in As-affected areas in the EGB.

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