

An Analysis of Arsenic Contamination in the Groundwater of India, Bangladesh and Nepal with a Special Focus on the Stabilisation of Arsenic-Laden Sludge from Arsenic Filters

Dr. Amartya Kumar Bhattacharya

BCE (Hons.) (Jadavpur), MTech (Civil) (IIT Kharagpur), PhD (Civil) (IIT Kharagpur), Cert.MTERM (AIT Bangkok), CEng(I), FIE, FACCE(I), FISH, FIWRS, FIPHE, FIAH, FAE, MIGS, MIGS – Kolkata Chapter, MIGS – Chennai Chapter, MISTE, MAHI, MISCA, MIAHS, MISTAM, MNSFMFP, MIIBE, MICI, MIEES, MCITP, MISRS, MISRMTT, MAGGS, MCSI, MIAENG, MMBSI, MBMSM
Chairman and Managing Director, MultiSpectra Consultants, 23, Biplabi Ambika Chakraborty Sarani, Kolkata – 700029, West Bengal, INDIA.
E-mail: dramartyakumar@gmail.com

Dr. Rajashree Lodh

BE (Civil) (TIT, Tripura), ME (Civil) (BESU, Shibpur), PhD (Civil) (IIT Kharagpur)
Assistant Professor, Heritage Institute of Technology, Kolkata, West Bengal, INDIA, and
Post-doctoral Researcher, MultiSpectra Consultants, 23, Biplabi Ambika Chakraborty Sarani, Kolkata – 700029, West Bengal, INDIA. E-mail: shree1504@gmail.com

Asoke Kumar Roy

MTech (Environmental) (VREC, Nagpur), CEng(I), FIE, FAWWA, FIPHE, FIAM, FACCE(I)
Former Executive Engineer / Deputy Superintending Engineer, West Bengal Public Health Engineering Directorate, and Consultant and Advisor, SEPL (SREI initiative).
107, Garfa Main Road, Kolkata - 700075, West Bengal, INDIA.
E-mail: asokeroy48@gmail.com

D.M.P. Karthik

Honorary Director, MultiSpectra Consultants, 23, Biplabi Ambika Chakraborty Sarani, Kolkata – 700029, West Bengal, INDIA. E-mail: dmpkarthik@gmail.com

Dr. Ajai Singh

Associate Professor and Head, Centre for Water Engineering and Management,
Central University of Jharkhand, Ranchi - 835205, Jharkhand, INDIA.
E-mail: ajai@cuja.ac.in

Sweta Kumari, Varsha Kumari, Kumar Daksh, Pankaj Kumar, Anurag

Students of Integrated MTech in Water Engineering and Management,
Central University of Jharkhand, Ranchi - 835205, Jharkhand, INDIA, and
Interns, MultiSpectra Consultants, 23, Biplabi Ambika Chakraborty Sarani,
Kolkata – 700029, West Bengal, INDIA. E-mail: swetakumari0809@gmail.com,
varsha.kumari@cuja.ac.in, kumar.daksh@cuja.ac.in, mepankajb@gmail.com,
kanurag611@gmail.com

Abhay Kumar Mishra

Undergraduate Student,
Indian Institute of Technology Kanpur, Kanpur - 208016, Uttar Pradesh, INDIA, and
Intern, MultiSpectra Consultants, 23, Biplabi Ambika Chakraborty Sarani,
Kolkata – 700029, West Bengal, INDIA. E-mail: abhaym@iitk.ac.in

ABSTRACT

The present paper starts by presenting an overview of the Arsenic contamination in the groundwater in different parts of India. The paper goes on to present standards regarding Arsenic in drinking water and then proceeds to give a state-wise status of Arsenic contamination. Adverse effects of Arsenic on the health of human beings, accumulation of Arsenic in the food chain and ill-effects of using Arsenic-laden water for irrigation are elaborated upon in the paper. The paper proceeds to explore technological options to deliver Arsenic-free water by various ways and means. Providing medical relief to affected people is also included. Methods for safe disposal of Arsenic-laden sludge from Arsenic filters and various issues related to the same are also key aspects of the paper.

INTRODUCTION

Groundwater plays a vital role in India to meet water demands of various sectoral uses. About 80% of rural domestic needs and 50% of urban and industrial needs and about 65% of irrigation water requirements are met by groundwater. Groundwater quality deterioration from the contaminants of geogenic origin, in which Arsenic is the one, in many States, mainly in the Ganga-Brahmaputra-Barak fluvial plains, has emerged as a major concern to this important resource. The groundwater potential of the Ganges and Brahmaputra Barak basin in India has been assessed 171 BCM (Billion Cubic Metre) and 26 BCM, respectively, which is about 45.7% of the total annual replenishable groundwater resources of India (CGWB, 2011). Increased number of contaminated districts and States, where the contamination is reported beyond the acceptable limit for drinking use as prescribed by the BIS (Bureau of Indian Standards) is a matter of grave concern from different viewpoints, which include: (a) risk apprehended on human and animal health due to the exposure to Arsenicosis by the uses of Arsenic-contaminated

groundwater; (b) scope and infra-structural facilities available to detect and diagnose Arsenic impacted patients; (c) alternative source and other remedial measures for supply of Arsenic safe water in the affected and vulnerable areas; (d) reliance and dependency of rural people more on groundwater for drinking and irrigation purposes; (e) risk exposed to the agricultural sector due to the uses of Arsenic-contaminated groundwater and biomagnification of Arsenic content in the agricultural products; (f) possible damage caused to the soils health by the use of Arsenic-contaminated water on agricultural lands; (g) impact on socio-cultural and socio-economic aspects and (h) technological solutions available to resolve the issues and provide Arsenic-free water. Until the year 2008, occurrence of high Arsenic content in groundwater in excess to the limit of 50 $\mu\text{g/L}$ or 50 ppb (BIS standards prevailed until 2009, later modified to 10 $\mu\text{g/L}$) was mainly reported in the Ganges-Brahmaputra fluvial plains covering pockets of seven states namely, West Bengal, Jharkhand, Bihar, Uttar Pradesh, Assam, Manipur and Chhattisgarh (NIH and CGWB, 2010, Bhattacharya et al., 2016, Bhattacharya, 2017a, Bhattacharya, 2017b). Until the year 2014, the count of number of groundwater Arsenic-exposed States has increased from 7 to 10. The reported States are: West-Bengal, Jharkhand, Bihar, Uttar Pradesh, Assam, Manipur, Chhattisgarh, Haryana, Punjab, and Karnataka. In West Bengal, Bihar, Jharkhand and Uttar Pradesh, the Arsenic-exposed areas are mostly located in the floodplain of the Ganga River; in Assam and Manipur the exposed areas are mainly in the floodplains of the Brahmaputra-Barak and Imphal rivers, respectively; in Haryana these areas are in the plains of Yamuna river and its tributaries; in Punjab the exposed areas are mainly in the floodplains of Ravi and Beas rivers; in Chhattisgarh and Karnataka the Arsenic-exposed areas are in hard-rock areas, which have different characteristics than the alluvium plains of Ganges and Brahmaputra. Ironically, except Chhattisgarh and Karnataka, all other States represent Upper Quaternary aquifers which are otherwise potential from groundwater point of view.

STANDARDS FOR ARSENIC IN DRINKING WATER

Different countries have set different standards of Arsenic content for drinking water quality. World Health Organisation's (WHO) norms for drinking water quality go back to 1958; in that year, the international Standard for drinking water was established at 200µg/L (i.e, 200 ppb; ppb : parts per billion) as an allowable concentration for Arsenic. In 1963, the standard was re-evaluated and reduced to 50µg/L(50 ppb). The WHO guidelines have been revised during the recent past and the permissible limits have been reduced from 50µg/L to 10µg/L (10 ppb) in the year 1993 due to the adverse health reports that arose from different parts of the world, where Arsenic has caused severe health problems. Until 2009, in India the acceptable limit for Arsenic in drinking water was 50 ppb. After the year 2009, Bureau of Indian Standards (BIS) has set the desirable limit of Arsenic in drinking water as 10 ppb and in the absence alternative sources, 'maximum permissible limit' in drinking water has been set to 50 ppb.

Arsenic in Groundwater of India

Isolated pockets in 86 districts in ten States have been reported affected by groundwater Arsenic content beyond BIS maximum permissible limit of 50 ppb. Occurrence of Arsenic in groundwater in those affected areas has been highly sporadic in nature and not necessarily all the sources were contaminated. As per IMIS (Integrated Management Information System) data of Ministry of Drinking Water and Sanitation, about 22.38 lakh population is affected by Arsenic in 1800 habitations.

Arsenic occurrences in groundwater in India can broadly be put into two categories: (i) occurrence in parts of West Bengal, Bihar, Jharkhand, Uttar Pradesh, Assam, Manipur, Punjab, and Haryana in the alluvial terrain, and (ii) in parts of Karnataka and Chhattisgarh in the hard-rock terrain. In general, worldwide large-scale groundwater Arsenic-contamination is reported from Late Quaternary fluvial and deltaic deposits. However, there are exceptions, such as in Chhattisgarh and Karnataka, where it is very limited in areal extent and site specific. In these two states, Arsenic is reported to be associated with sulphide mineralisation especially Arsenopyrite. In Karnataka, it is mainly restricted to the gold mineralisation areas covering parts of Raichur and Yadgir districts and in Chhattisgarh, it has been reported from the acid volcanic associated with Kotri lineament. Arsenic from Arsenic-bearing minerals like Arsenopyrite, which is common in those settings, has been released into groundwater under favourable geological conditions.

Assam

In Assam, Arsenic was first detected in 2004. Initially few samples collected from Karimganj, Dhubri and Dhemaji districts showed groundwater Arsenic concentration of more than 50 ppb. A recent report indicated 18 out of 23 districts covering 76 blocks and 603 habitations were affected by groundwater Arsenic toxicity. Subsequently, a comprehensive task of analysing groundwater samples was undertaken by the PHED, Government of Assam jointly with the UNICEF. The task was performed in a three tier system with Field Kit (FTK), UV-1 at Rural Lab and AAS at State laboratory. It was reported that 2571 habitations were severely affected by the exposure to groundwater Arsenic-contamination.

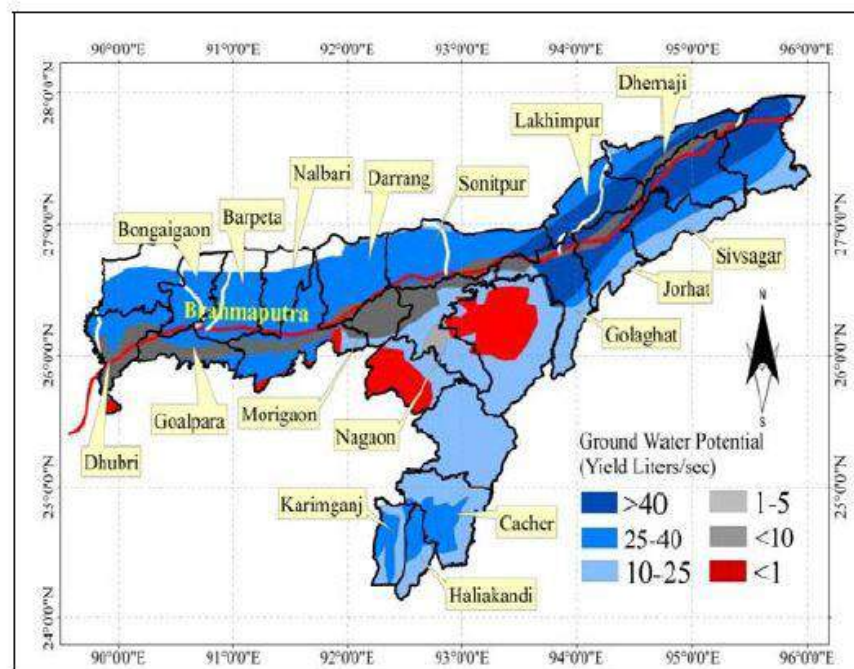


Figure 1: Map showing Arsenic exposed districts in Assam, superimposed on map of hydrogeology and river course.

Bihar

Elevated Arsenic concentration in groundwater was first detected, in 2002, from two villages, Barisban and Semaria Ojhapatti in Bhojpur district located in the Middle Ganga Plain (MGP). The area is located in the flood-prone belt of the Sone-Ganga interfluvial region. Investigations by Central Ground Water Board (CGWB) and Public Health Engineering Department, Bihar indicated Arsenic concentration as high as 178 ppb in the hand pumps with depth ranging between 20 metres and 40 metres below ground level. A total of 1590 habitations distributed over 15 districts were found affected by the Arsenic concentration of more than 50 ppb. With the mitigation measures adopted by the State, the Arsenic-affected habitations were reduced from 1590 to 95 by April 2015. The remaining 95 affected habitations are spread over 9 districts namely Begusarai, Bhagalpur, Buxar, Darbhanga, Lakhisarai, Munger, Patna, Sambalpur and Saran. At present, the total population residing in the risk zone is around 9 million. Most of these districts are located along the course of River Ganga in Bihar. The geological formations in the affected areas are Quaternary Alluvium holding multi-aquifer system. The aquifers are represented by medium to fine sands having occasional coarse-grained sand layers alternating with clay, sandy clay layers.

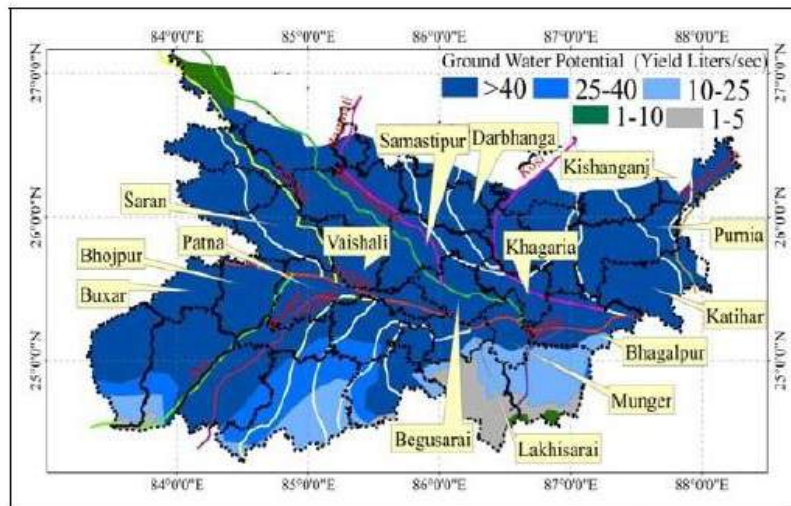


Figure 2: Map showing Arsenic exposed districts in Bihar, superimposed map of hydrogeology and river course.

Chhattisgarh

Other than the flood plain areas of Ganga-Brahmaputra-Barak rivers, contamination was also detected from hard-rock areas in Ambagarh Chowki block of Rajnandgaon district in Chhattisgarh State. A few hundred people were exposed to Arsenical skin lesions from the affected villages. One cancer patient (with Arsenical skin lesions) and many patients with keratosis were identified. Analysis of groundwater samples showed that 11 villages are affected by Arsenic-contamination.

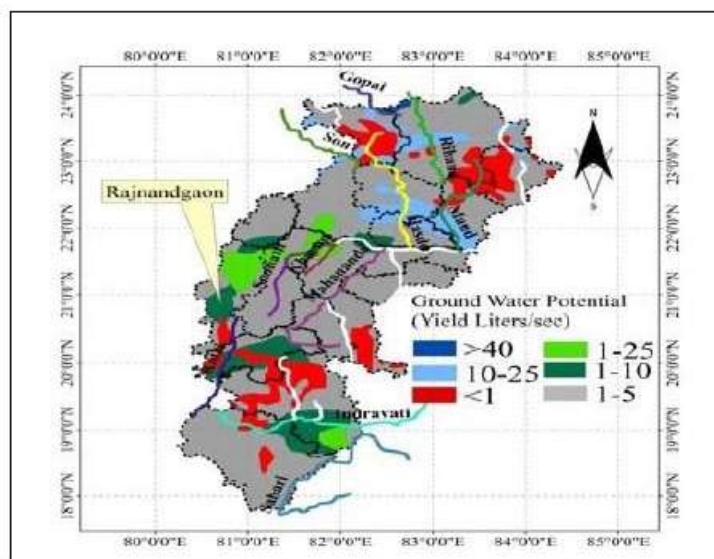


Figure 3: Map showing Arsenic exposed district in Chhattisgarh, superimposed on map of hydrogeology and river course.

Haryana

The study of CGWB-NWR, Chandigarh in the year 2003 and 2013 under the Aquifer Mapping Project showed Arsenic concentration in groundwater more than 50 ppb in sporadic areas in different districts covered by alluvial aquifers in Haryana. High concentration of Arsenic has been suspected to be due to the mobilisation of Arsenic from sediments containing Arsenic-rich minerals which dissolved under reducing conditions and mixed with the groundwater. The source of Arsenic is geogenic, present in alluvial sediments. However, no report of Arsenicosis from any part of the Haryana has been reported till date. The districts exposed to groundwater Arsenic-contamination are in the river courses of the Yamuna river and its tributaries which have routes originating from the Himalayas.

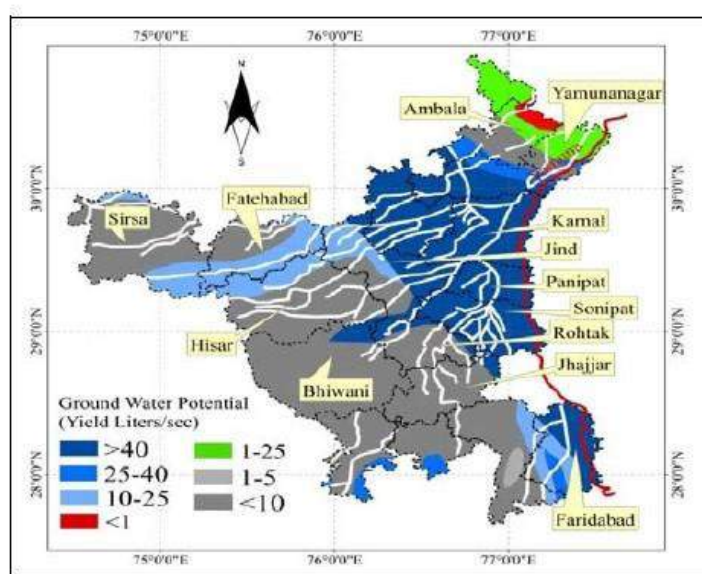


Figure 4: Map showing Arsenic exposed districts in Haryana, superimposed on map of hydrogeology and river course.

Jharkhand

Groundwater Arsenic-contamination above 50 ppb was first reported during 2003-04 from the Sahebganj district of Jharkhand located between the Middle and Lower Ganga Plains. Later during 2006-07, it was confirmed by CGWB through detailed investigation. In all 278 habitations, counting population of about 209060 were affected by Arsenic toxicity. Arsenic-contamination has been reported from the area close to the Ganga River and it is in those areas where the Ganga River has been shifted during the recent past. The hand pumps and tube-wells of depth ranges between 25 and 50 metres below ground level (mbgl) have been reported to be contaminated. The affected areas have similar geological formations as in the adjacent Bihar and West Bengal. The dug-wells have been reported free from Arsenic-contamination (CGWB, 2008).

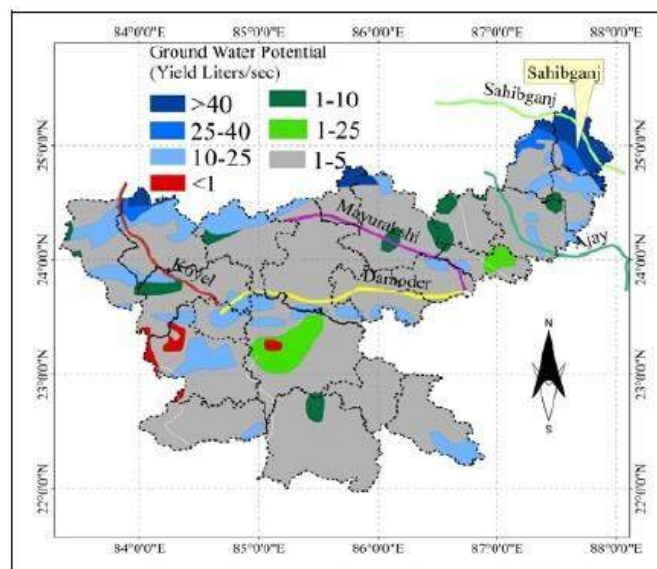


Figure 5: Map showing Arsenic exposed district in Jharkhand, superimposed on map of hydrogeology and river course.

Karnataka

In Karnataka, Arsenic in groundwater has been reported mostly from the areas influenced by gold mining and associated activities. The occurrence of Arsenic is related to arsenopyrite mineral present in the host rock. Examples are the Hutti Gold mining area in Lingasugur taluk of Raichur district and abandoned gold mining areas in Shorapur taluk of present Yadgir district, which was earlier in Gulbarga district. After extraction of the gold, the chemical waste was dumped on the ground surface in the adjoining areas of the mine. These dumped materials having arsenopyrite leached out Arsenic during rainy season and joined the groundwater regime. The leaching and enrichment of Arsenic is localised and its effect is more in the proximity of the underneath phreatic aquifer. The Arsenic in those areas has been reported as geogenic contamination which may not reflect the general groundwater condition in the area.

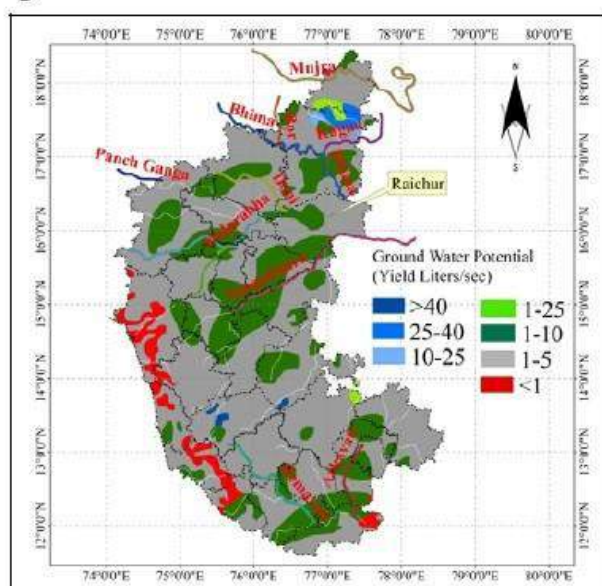


Figure 6: Map showing Arsenic exposed district in Karnataka, superimposed on map of hydrogeology and river course.

Manipur

The valley districts of Manipur namely, Kakching, Imphal East, Imphal West, and Bishnupur have Arsenic in groundwater. These districts are located along the river courses which have originated from the eastern Himalayas. These four districts cover about 10% of the total area of Manipur and about 70% of the total population of the State. In Manipur, people normally do not use hand-pump and tube-well water for drinking, cooking and agricultural purposes and no case of Arsenic-affected patients has been reported from the State.

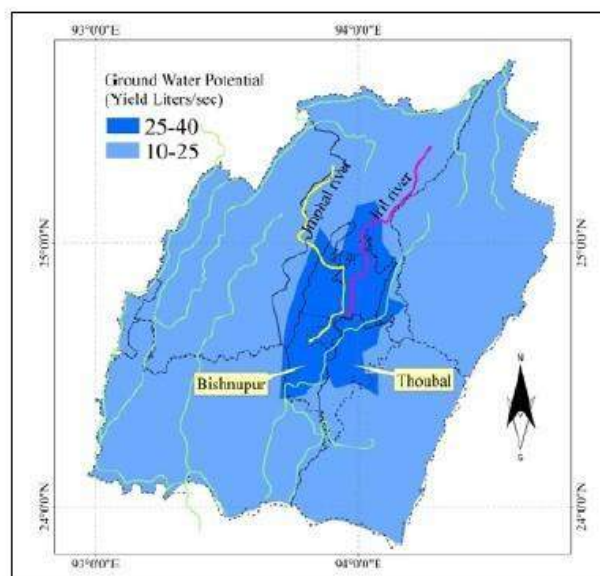


Figure 7: Map showing Arsenic exposed districts in Manipur, superimposed on map of hydrogeology and river course.

Punjab

Analysis of 261 shallow groundwater samples of Punjab State carried out by CGWB in the year 2004 showed presence of Arsenic in groundwater with wide spatial variation. Arsenic concentration exceeding value of 10 ppb was encountered at 12 locations in districts of Amritsar, Gurdaspur, Hoshiarpur, Kapurthala and Ropar. All these Arsenic-exposed districts are located along the river courses of the Ravi and Beas, which have also routes originating from the Himalayas. Analysed results of samples collected from those locations during the post-monsoon period showed substantially higher Arsenic concentration than observed from the samples of the pre-monsoon period. The analysed results of 105 samples collected from different locations and different sources viz. canal water, hand pumps and tubewells spread over all over the district of Mansa (Punjab) by CGWB-NWR in July, 2010 showed that tube-well samples at 6 locations had Arsenic concentration above 10 ppb. The depth from where those water samples were collected ranged from 13 m to 35 m.

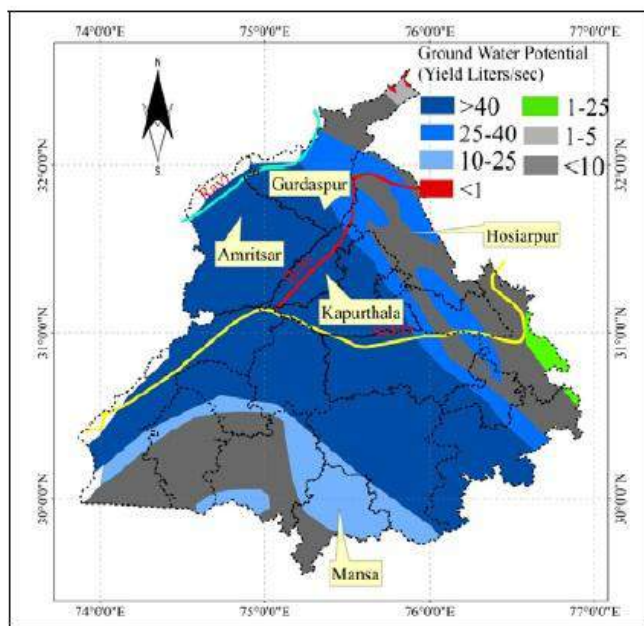


Figure 8: Map showing Arsenic exposed districts in Punjab, superimposed on map of hydrogeology and river course.

Uttar Pradesh

Arsenic-contamination of groundwater was first reported in the year 2003 from a survey of 25 villages in Ballia district. Thereafter, two more districts, Ghazipur and Varanasi were detected with Arsenic-contamination of groundwater. As on 2008, 3 districts covering 69 villages in 7 blocks were reported as affected with people suffering from Arsenical skin lesions. The Arsenic-affected villagers used to drink water generally from hand-pumps which tap groundwater from shallow aquifers of depth about 20-30 m. 20 districts have been reported to have elevated Arsenic in groundwater in scattered pockets. It is of interest to note that all the Arsenic-affected districts in Uttar Pradesh and 12 districts in Bihar are aligned along the linear track along the course of the river Ganga.

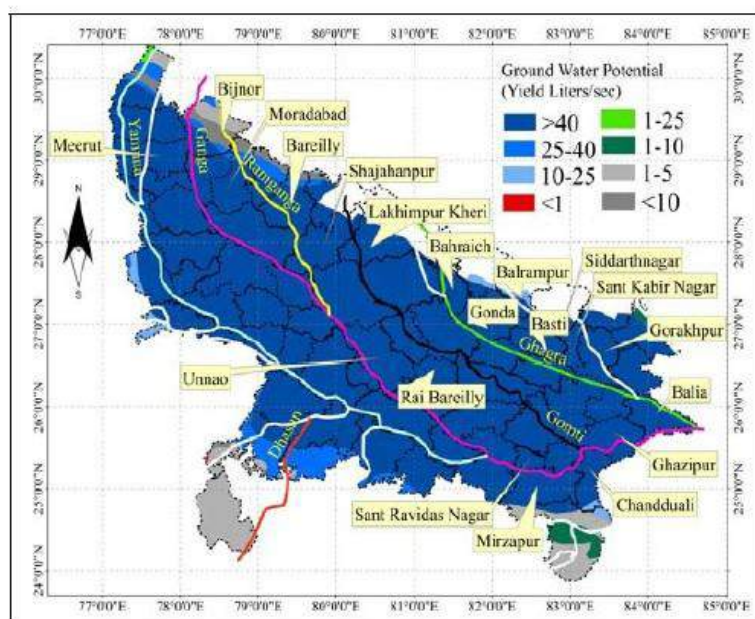


Figure 9: Map showing Arsenic exposed districts in Uttar Pradesh, superimposed on map of hydrogeology and river course.

West Bengal

Arsenic, with a concentration of more than 50 $\mu\text{g/L}$ in groundwater, first surfaced from West Bengal in the year 1983 from 33 villages in four districts, namely, South 24 Parganas, North 24 Parganas, Nadia and Murshidabad. The status as compiled by NIH (National Institute of Hydrology) and CGWB (2010) indicated that as on year 2008, 9 districts (including Kolkata) covering 3417 villages spread in 111 blocks have been reported as contaminated. The contaminated areas are in patches and encompass the districts of Murshidabad, Nadia, North 24 Parganas, South 24-Parganas and Kolkata to the east and Howrah, Hugli and Bardhaman to the west of the River Bhagirathi / Hugli and Malda to the north of the River Ganga. There can be several other lists of Arsenic-affected areas prepared by different organisations, which may differ from one another, because of a number of reasons, e.g, (i) number of samples analysed, and different sampling locations; (ii) compilation of information may be different etc. However, the fact is that with every additional survey, an increasing number of contaminated villages and more affected people have been identified. For all the 9 districts (including Kolkata) in West Bengal, the severity has been classified into three categories: severely affected (>300 ppb), mildly affected (between 10 and 50 ppb), and unaffected (< 10 ppb). Nine districts (Malda, Murshidabad, Nadia, North 24-Parganas, South 24-Parganas, Bardhaman, Howrah, Hooghly and Kolkata), where more than 300 ppb Arsenic concentration was reported in tube-wells, had been categorised as severely affected. Out of 135,555 samples analysed from these nine districts 67,306 (49.7%) samples showed Arsenic concentration above 10 ppb and 33,470 (24.7%) samples above 50 ppb. Interestingly, all the 9 severely affected districts (concentration > 50 ppb) are in a linear track along the river Bhagirathi (the stretch of the river Ganga which passes through Kolkata). Most of the affected areas lie along the left-hand-side of the river along the direction of groundwater flow. The groundwater flow direction in those areas is towards south-east direction and the affected areas also swell mostly along the same direction. The geological formations in those areas are of thick alluvial deposits of Quaternary age. Arsenic-contaminated groundwater strata lies largely in the intermediate zone having depth range between 15 m and 50 m. The demographic survey of the affected areas and analysis of water samples by many organisations carried out upto year 2008 estimated that more than 13.85 million people could be under the threat of contamination level above 10 ppb, in which more than 6.96 million

people could be above 50 ppb, against the total population of those areas, which could be of the order of 50 million.

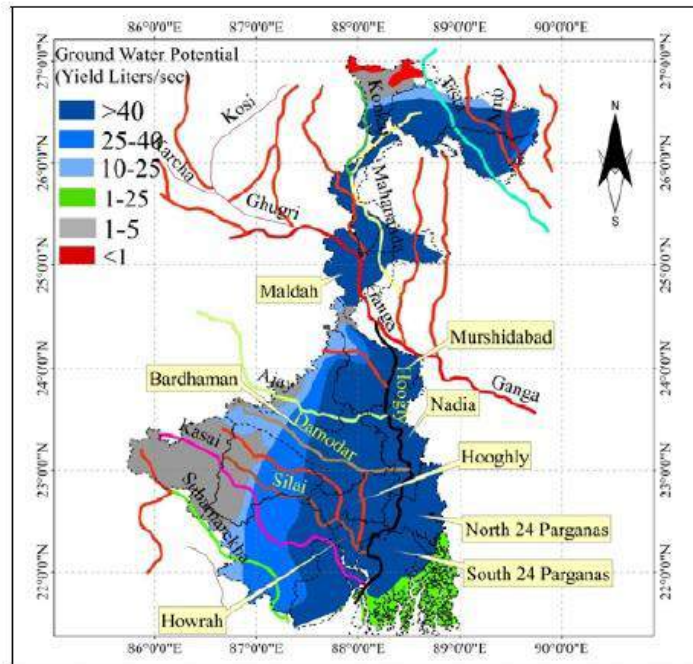


Figure 10: Map showing Arsenic exposed districts in West Bengal, superimposed on map of hydrogeology and river course.

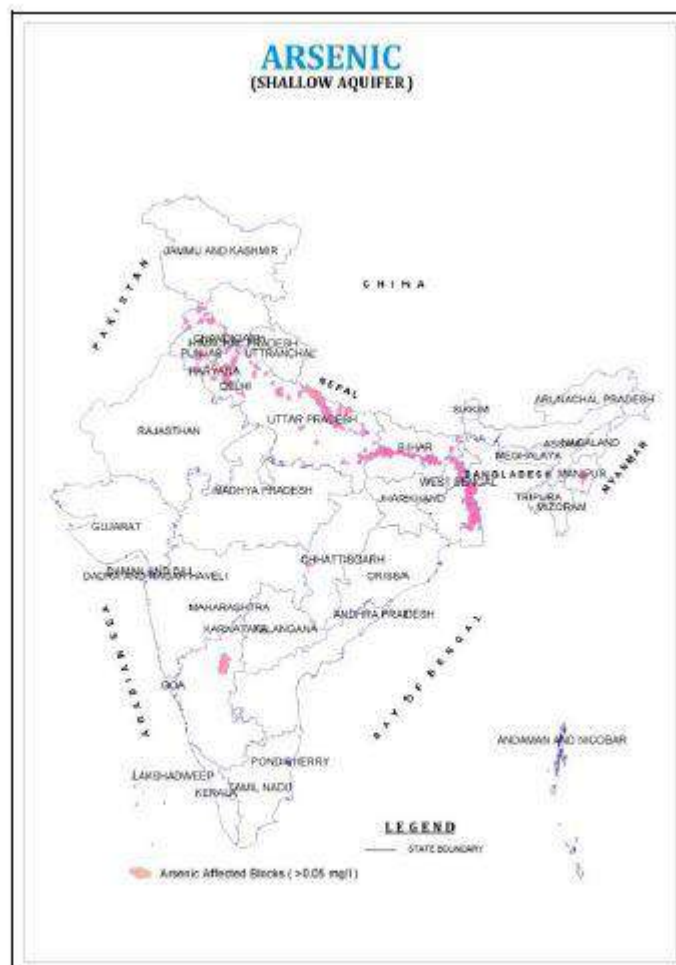


Figure 11: State-wise distribution of Arsenic contamination in ground water. The areas as depicted in the map are indicative only (source: Central Ground Water Board).

Arsenic in Groundwater of Bangladesh

According to BGS (1999), groundwater in 61 out of 65 districts are affected by arsenic contamination. Table 1 depicts the overall scenario of As contamination in Bangladesh. The shallow tubewells (STW, depth 10 – 70 m) with water table fluctuation between 5 and 10 mbgl are highly contaminated compared to deep aquifer (BGS, 2000). Van Geen et al (2003) studies also supported this observation and they suggested that arsenic contents in water samples collected from STW (depth 15 – 30mbgl) exceed the Bangladesh drinking water standard (50 $\mu\text{g/l}$) based on the analysis of 6,000 water samples collected from 25 km² area. Likewise, it was highlighted that arsenic content of tube well waters in 47 districts exceeded the Bangladesh drinking water standard (As > 50 $\mu\text{g/l}$). For this study, they collected 22,003 tube well water samples from 64 districts during 1995-2000 and analyzed for arsenic. Islam (2003) also insured that around 1,00,000 tube wells in the counties of Chandpur district are contaminated by As. Bibi et al (2008) also reported that the As concentration in groundwater varies from 6 to 934 $\mu\text{g/l}$ with an average of 347 $\mu\text{g/l}$ in the Chandpur district (Meghna river delta). Chakraborti et al (2010) suggested that 27.2% of 52,202 tube well water samples collected from 64

districts contain As greater than 50 $\mu\text{g/l}$ and 50 districts shows similar trend (As > 50 $\mu\text{g/l}$) (Table 1). Tube wells with maximum arsenic content (As > 1mg/l) are encountered 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).

In Bangladesh, Arsenic load in soil is increased due to usage of arsenic contaminated groundwater (83 mg/kg, Ullah, 1998) (Table 2). Based on a preliminary survey (71 soil samples) throughout Bangladesh, Meharg and Rahman (2003) also implied the correlation between arsenic in soil and irrigation water and estimated the maximum soil As concentration as 46 mg/kg. In the soils, the baseline concentrations of As are of the order of 5–10 mg/kg (BGS and DPHE, 2001). Spallholz et al (2008) noted that the arsenic content ranges from 11.7 to 51.9 mg/kg with an average of 32.8 mg/kg (n=70) in the agricultural soils which exceeded 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. Likewise, based on 24-upazila study, Huq et al. (2006) mentioned that 21% of soil samples contain As levels >20 mg/kg with a maximum value of 80 mg/kg. They also calculated that the irrigation water with 0.55 mg/l As will accumulate 5.5 kg As/ha/year in the irrigation soil. Duxbury and Zavala (2005) evaluated that ten year of irrigation using As-contaminated water would add 5–10 mg/kg soil to 41% of their 456 paddy field sites in Bangladesh.

Few studies explain the effect of irrigation on soil arsenic content. Dittmar et al (2007) suggested that arsenic accumulated in the soil during the first (Boro) irrigation season was leached by floodwater during the following monsoon (aman) season. Roberts et al. (2007) mentioned that arsenic contents in topsoil of irrigation field have 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. Most of the studies concentrate on surface soil samples (upto 15 cm depth) and some studies concentrated the As enrichment in soil profile. Yamazaki et al. (2003) carried out detailed study through the collection five soil profiles of 15 m depth at Deuli village (Southwest Bangladesh) and concluded that As concentrations in soil rely on the type of sediment. They mentioned that sandy sediments contained 3–7 mg/kg (median, 5mg/kg), clay sediments contained 4–18 mg/kg (median, 9mg/kg) while peat and peat-clay sediments contained 20–111mg/kg. Alam and Sattar (2000) selected 25 locations in five sub-districts (Chapai Nawabganj Sadar, Kustia Sadar, Bera, Ishurdi, and Saishabari) of four districts and soil samples were collected at three depths (0–15cm, 15–30cm, 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 and also suggested that there is a positive correlation between soil and water. Likewise, Das et al. (2004) also identified a positive correlation between As in STW and soil. Heikens et al., (2007) explained based on detailed review on As behaviour that soil As load increases by As rich irrigation water; however, potential risk of As in irrigation water to crop production and plant growth is not fully understand and need more research in these areas.



Figure 11.a. Presence of arsenic in the Ganga-Meghna-Brahmaputra (GMB) plain in India (Source: Schaepman, 2012)

Arsenic in Groundwater of Nepal

In Nepal Terai, groundwater in all these districts contains As $>10 \text{ } \square\text{g/l}$ (Figure 2) as per different investigators. Department of Water Supply and Sewage (DWSS) initiated the investigations to assess As contamination in groundwater in 1999. In this study, it was found that the As content in 18,635 samples (20%) exceeded WHO guideline (As $>10 \text{ } \square\text{g/l}$). Further, DWSS (2007) carried out blanket study in 24 districts of Nepal and tested 2,59,828 wells. That study concluded that 27,529 wells and 7,232 wells exceeded As $>10 \text{ } \square\text{g/l}$ and As $>50 \text{ } \square\text{g/l}$, respectively. Consequently several national and international organizations involved in the total As in groundwater of this region varied from 1.7 to 404 $\square\text{g/l}$ and mostly identified as Arsenite (As (III)). The maximum As concentration is encountered in Rupandehi district (As = 2,620 $\square\text{g/l}$). This observation is well correlated with another study and they mentioned that 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 $\mu\text{g/L}$, respectively. It was also investigated that As content in deeper tube wells was less than 10 $\square\text{g/l}$. Likewise, old tube wells and medium depth wells (10–30m) have high As concentrations. They tested 18,635 tube wells which are distributed in the 20 districts of Nepal. However, the wells are not uniformly distributed in the districts like Nawalparasi district (17.2%), Kapilvastu district (13.4%), Parsa district (12.1%), Rautahat district (11.0%), Rupandehi district (11.0%), Bara district (10.5%) and so on. The lowest number of these tube wells (i.e., 172 or 0.9%) is distributed in Sunsari district. Among 18,635 arsenic tested tube wells, about 7.4% tube wells exceeded As $>50 \text{ } \square\text{g/l}$, 16.3% tube wells contain 1–50 $\square\text{g/l}$ of As, 23.7% tube wells are above WHO Guideline (As $>10 \text{ } \square\text{g/l}$) and majority of tube wells (76.3%) are below WHO Guideline. Among the 20 districts, groundwater wells in Rautahat, Nawalparasi, Kapilvastu and Banke districts are severely affected by As crisis (Figure 2). In these districts, number of wells affected by As contamination are comparatively more. A detailed study was conducted in Goini and Thulo Kunwar villages in Nawalparasi district and reported that As in groundwater in Goini and Thulo Kunwar villages varied from 104 to 1,702 $\mu\text{g/l}$ and between 4 to 972 $\mu\text{g/l}$, respectively. Limited studies were carried out in Nepal Terai to evaluate soil arsenic load. Analysis of soil samples collected from agriculture field at Nawalparasi district was done and was reported that the average arsenic content is 6.3 mg/kg. A detailed study to understand the geological and

geochemical examination of arsenic contamination in Nawalparasi district, Nepal was done and an average arsenic concentration of 9 mg/kg in sediments in this district was reported and observed that the distribution is not homogeneous. Arsenic enrichment in finer sediments (Black clay, As = 31 mg/kg) are greater than coarse sediments (Silt and fine sand, As = 3 mg/kg). Study of the As content in irrigation water in three villages at Nawalparasi district was conducted which revealed that the mean arsenic content in irrigation water is 137 mg/l and arsenic concentration in 65% and 36% of the wells exceeded 50 $\mu\text{g/l}$ and 100 $\mu\text{g/l}$, respectively. 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. Further, they insisted that the addition of arsenic may reach up to 10.19 mg/kg/year. Moreover the arsenic content in top soil (<10 cm) and sub-surface soil (10-20 cm) in rice field varied from 7.4 to 12.5 mg/kg and 7.4 to 10.5 mg/kg in Nawalparasi district, respectively was also found. Likewise, the arsenic content in soil collected from 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 strong correlation between irrigation water and soil arsenic contents. In summary, very limited studied carried out in Nepal Terai. Need more studies to understand relation between soil and water As interaction.

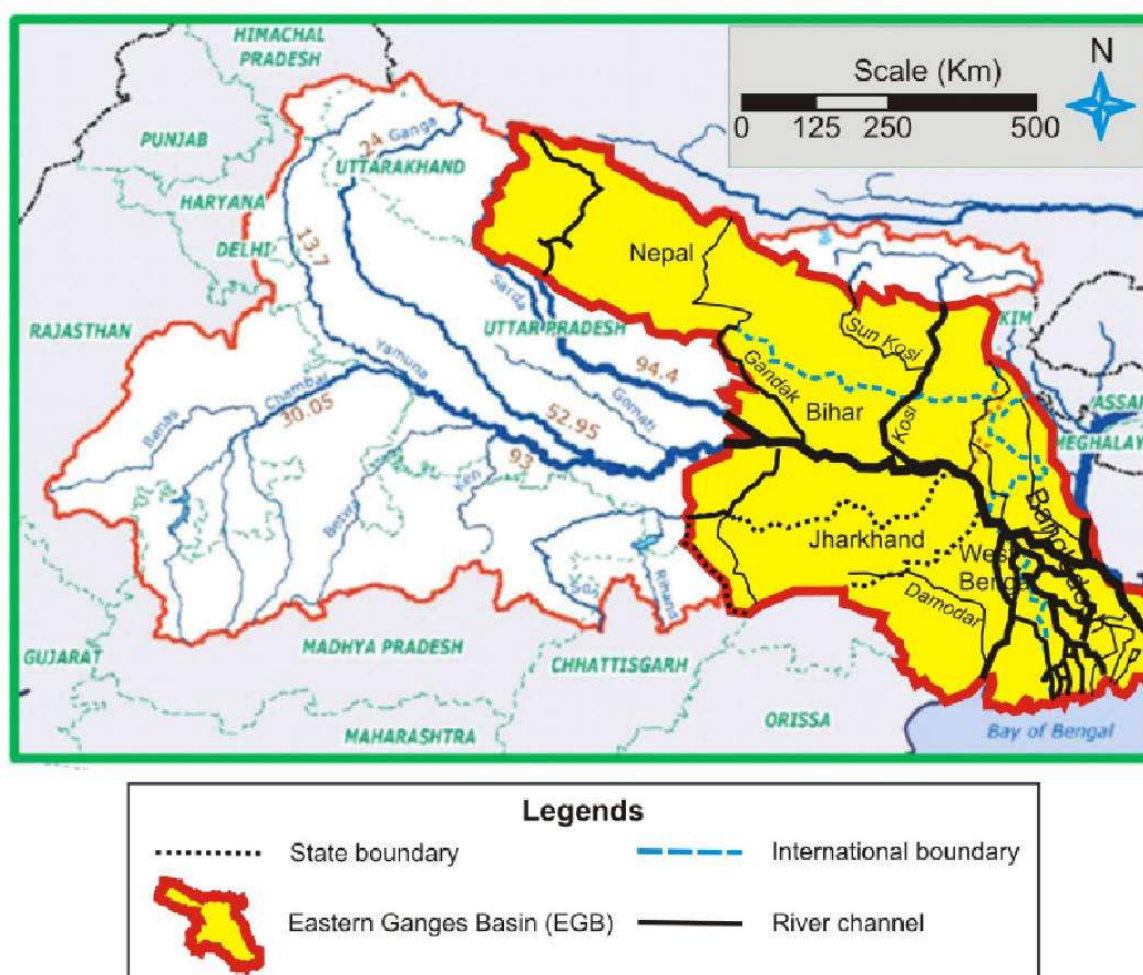


Figure 11.b. Ganges and Eastern Ganges basin. The streamflow data is the annual average in cubic kilometers. (After Rajmohan and Prathapar, 2013, 2014; Harshadeep 2011).

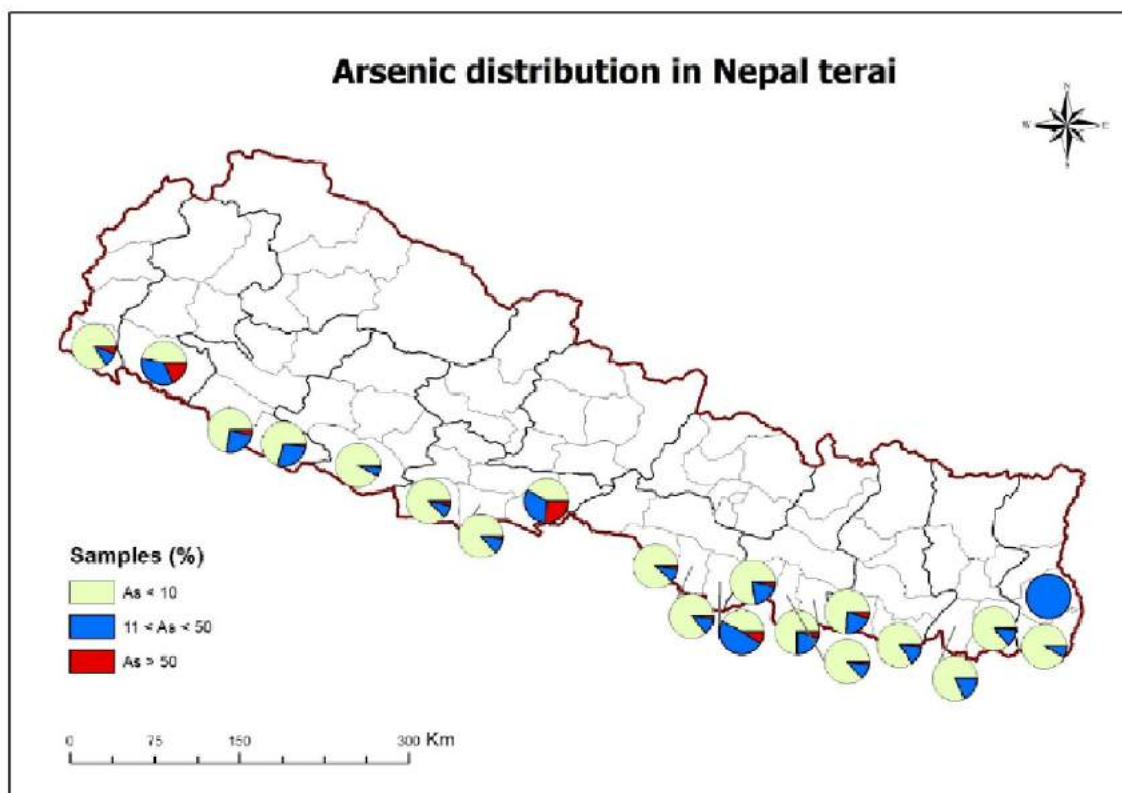


Figure 11.c. Figure 2. Arsenic distribution in groundwater in Nepal Terai districts (after Rajmohan and Prathapar, 2014)

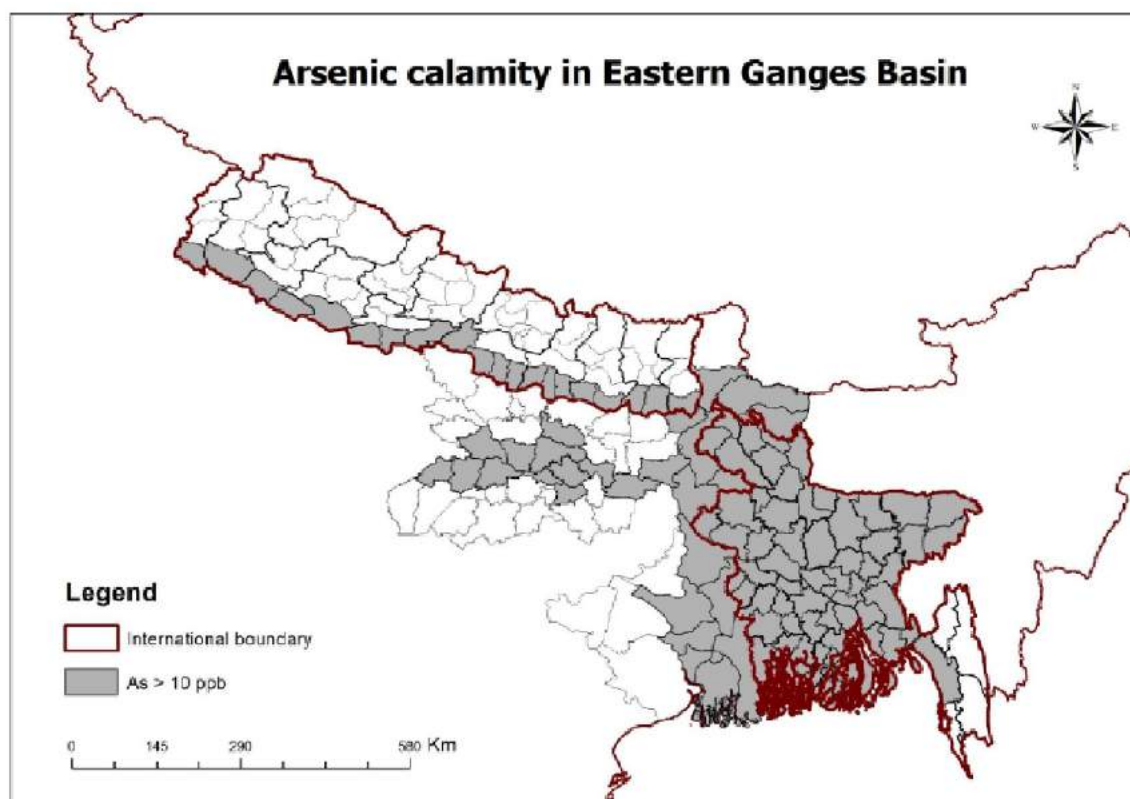


Figure 11.d. Arsenic contamination status in groundwater in EGB (India (Bihar and West Bengal), Bangladesh and Nepal terai) (after Rajmohan and Prathapar, 2014)

Impacts of Arsenic on Human Health in Chronically Exposed Population

Arsenic can exert its toxic effects through impairment of cellular respiration by inhibition of various mitochondrial enzymes and uncoupling of oxidative phosphorylation. The As(III) species can react with -SH group of protein and enzymes, thereby make them inactive and increase reactive oxygen species in the cells causing cell damage. Research studies revealed that Arsenic could inhibit 200 enzymes in the body. It has been regarded that multi-systemic non-cancer effect could be due to deactivation of essential enzymatic functions by trivalent Arsenic compounds and subsequent oxidative stress to cell. More recent studies have detected all the 4 species [As(III), As(V), MMA(V), DMA(V)] and also the presence of MMA(III) and DMA(III) in urine. It is also considered that inorganic As(III) and the reduced forms of MMA(III) and DMA(III) formed during methylation are highly reactive and contribute to the observed toxicity of inorganic Arsenic. So far, no evidence has been found that inorganic Arsenic directly causes genetic mutations affecting cancerous cells. Inorganic Arsenic indirectly enhances susceptibility to cancer-inducing chromosomal alterations, inhibition of DNA repair process, oxidative stress and cell proliferation. Arsenate (AsO_4^{3-}) has similar structure as phosphate (PO_4^{3-}) and thus can substitute for PO_4^{3-} in adenosine diphosphate (ADP). This substitution prevents conversion of ADP to ATP (adenosine triphosphate) which produces energy to cell. The available health effect reports, after ingestion of Arsenic-contaminated groundwater, are mainly from the epidemiological study of chronic Arsenic exposure. Number of incidents and studies related to acute Arsenic toxicity are meagre compared to chronic Arsenic exposure. During the last decade plenty of chronic Arsenic exposure incidents have been reported from Asian countries due to use of Arsenic-contaminated groundwater and associated health effects. More and more studies have been carried out to know various health effects due to chronic exposure. During the last decade, 4 monographs (IARC, 2004; IPCS, 2001; and NRS, 1999; 2001) along with large number of reports and special

issues have been published to include the research activities of chronic Arsenic exposure and various carcinogenic and noncarcinogenic health effects. Inorganic Arsenic exposure deactivates the function of enzymes, some important anions, cations, transcriptional events in cells and causes other direct or indirect effects. Such activities of inorganic Arsenic result in numerous illnesses that have been also confirmed by repeated epidemiological investigations. Examples of the same are: (i) Dermatological effects, (ii) Cardiovascular effects, (iii) Respiratory effects, (iv) Gastrointestinal effects, (v) Endocrinological effects (diabetes mellitus), (vi) Neurological effects, (vii) Reproductive and developmental effects, (viii) Cancer effects and (ix) other effects. Symptoms of Arsenicosis are primarily manifested in the form of different types of skin disorders such as skin lesions, hyper keratosis and melanosis.

Other Multisystemic Common Features in Arsenic-Affected Areas

The following common features were reported mainly from the Arsenic-endemic areas of India and Bangladesh :

- a. Most of the population suffered from Arsenic skin lesions were from a poor socio-economic background,
- b. Skin itching to sun rays, burning and watering of eyes, weight loss, loss of appetite, weakness, lethargy and fatigue limited the physical activities and working capacities,
- c. Chronic respiratory complaints. Chronic cough with or without expectoration was evident in more than 50%. As reported by the villagers, the unique sound of 'Cough of Arsenicosis'. The cough may be painful and sputum may contain blood to be misdiagnosed as pulmonary tuberculosis. In later stages, shortness of breath might predominate,
- d. Gastrointestinal symptoms of anorexia, nausea, dyspepsia, altered taste, pain in abdomen, enlarged liver and spleen, and ascites (collection of fluid in abdomen) observed in many patients,
- e. Moderate to severe anaemia was evident in some cases,
- f. Conjunctival congestion. Most of the population suffering from Arsenic skin lesions are from poor socio-economic background and Leg-edema was less common.



Figure 12: Photographs showing different kinds of skin ailments resulting from prolonged exposure to drinking water having high Arsenic content. (Source: SOES, Jadavpur University, adopted from the vision document by NIH and CGWB, 2010)

Arsenic in Food Chain

It has been reported by experts that there has been no relation between concentration of Arsenic in drinking water and disease load among the affected population. A number of studies reported that vegetables and crops grown by using Arsenic-contaminated groundwater can add manifold daily Arsenic intake through food consume apart from drinking water. The economy of the Arsenic-affected areas, particularly those in the alluvial plains mainly depends on agriculture; therefore, the practice of using Arsenic-contaminated groundwater for irrigation purposes is continuing. It has also been reported that tuberous vegetables accumulate higher amount of Arsenic than leafy vegetables which in turn accumulate higher amount of Arsenic than followed by fruity vegetables. Higher Arsenic accumulation has been reported in potato, brinjal, arum, amaranth, radish, lady's finger and cauliflower and relatively low level of Arsenic accumulation has been reported in beans, green chilli, tomato, bitter gourd, lemon and turmeric. The major oilseeds and pulses have also been reported to contain high levels of Arsenic. Arsenic accumulation was reported to be more in Boro rice season than in Aman season. The high yielding rice varieties have more Arsenic accumulation than the local varieties. The people having poor nutrition have been reported to be affected more from Arsenic toxicity than the people having adequate nutrition.

Transmission of Arsenic in Agricultural Soil through Irrigation

The immediate and long-term impact of using Arsenic-contaminated water on irrigating paddy soils are another important concern, as Arsenic can transfer from water to soil. This phenomenon has been reported in

several studies. Boro (dry season) rice requires approximately 1000 mm depth of irrigation water per season. Mehar and Rahman (2003) predicted that soil Arsenic levels could be raised by 1 $\mu\text{g/g}$ per annum due to irrigation using Arsenic-contaminated water. A number of studies have reported that Arsenic contamination in soils has positive correlation with Arsenic content in water and Arsenic-rich irrigation water can enrich the Arsenic level in agricultural soil upto five times than the normal soil.

Social Implications of Arsenic-Contamination and Vulnerable Groups

Arsenic-contamination in groundwater has other far-reaching consequences not only as health and environmental hazards but also as social problem. About 30% of the affected population constitutes illiterate inhabitants living below poverty line. Women, children and infants are more vulnerable to Arsenic toxicity than male and adults. There has been little or no social education concerning the treatment of persons affected by Arsenic toxicity and about ill effects of using Arsenic-contaminated water. Because of illiteracy and lack of information, many confuse the skin lesions with leprosy, which among village people is considered a contagious killer. As a result, those who have early symptoms of Arsenicosis do not disclose their condition to avoid certain ostracism. When family members come to know of a sufferer's warts and black spots, they tend to avoid direct contact with the affected person. Sufferers in rural areas are not allowed to appear in public. Affected school-age children are prevented from attending schools. Adults are barred from attending cultural/religious functions. Often, when employers discover their affliction, the affected workers immediately lose their jobs. Arsenicosis also affects the productivity of victims, who are often so incapacitated that they are unable to work and become liabilities for their families. These can be regarded as the social disorderliness and problems causing by the use of Arsenic-contaminated water.

Technological Options

Technological options to combat Arsenic menace in groundwater to ensure supply of Arsenic-free water in the affected areas can be one of the followings or a combination of more than one options :

- In-situ remediation of Arsenic from aquifer system.
- Ex-situ remediation of Arsenic from tapped groundwater by Arsenic removal technologies.
- Use of surface water source as an alternative to the contaminated groundwater source.
- Tapping alternative safe aquifers for supply of Arsenic-free groundwater.
- Biological Arsenic removal.

Since the major source of Arsenic in groundwater is of geogenic origin and is intricately linked to the aquifer geometry and groundwater flow regime, its effective remediation warrants understanding of physicochemical processes in groundwater and aquifer framework, lithology and groundwater flow regime of the area. The remedial measures includes variety of options, ranging from removing Arsenic from groundwater after it is extracted, searching alternative aquifers, reducing Arsenic level within the aquifer itself, dilution of the contaminants by artificial recharge, blending with potable water, etc.

Ex-situ Arsenic Treatment

This method primarily targets to lower the concentration of Arsenic after the water is extracted from aquifers. A variety of treatment technologies, based on oxidation, co-precipitation, adsorption, ion-exchange and membrane process, have been developed and are available for removal of Arsenic from contaminated water

(DST, 2015, Bhattacharya et al., 2016, Bhattacharya, 2017a, Bhattacharya, 2017b). However, question, regarding the efficiency and applicability/appropriateness of the technologies, remains, particularly because of low influent Arsenic concentration and differences in source water composition. Some of these methods are quite simple, but the disadvantage, associated with them, is that they produce large amounts of toxic sludge. This needs further treatment before disposal into the environment, besides the sustainability of these methods in terms of economic viability and social acceptability. Many of these technologies can be adopted in household and community scale for the removal of Arsenic from groundwater. During the last couple of decades, many small scale Arsenic removal technologies have been developed, field tested and used in various countries including India. There is a need of prioritising available technological solutions based on their effectiveness, cost, operation and maintenance, and acceptability. Various technologies available for removal of Arsenic from contaminated water are based mainly on five principles:

i) **Oxidation and filtration**

ii) **Co-precipitation:** Oxidation of As (III) to As (V) by adding suitable oxidising agent followed by coagulation, sedimentation and filtration (co-precipitation).

iii) **Adsorption:** Activated Alumina, Iron filings (zero valent iron) and hydrated iron oxide.

iv) **Ion exchange** through suitable action and anion exchange resins.

v) **Membrane technology:** Reverse osmosis, nanofiltration and electrodialysis.

The details about the processes of these techniques are available in many literatures (NIH and CGWB, 2010; DST 2015). Arsenic is normally present in groundwater in As (III) and As (V) states in different proportions. Most treatment methods are effective in removing Arsenic in pentavalent state and hence, include an oxidation step as pretreatment to convert As (III) to As (V).

Arsenic-Safe Alternative Aquifers

This technique advocates tapping safe alternative aquifers right within the affected areas. In the vast affected areas in the Gangetic Plains covering Bihar and Uttar Pradesh as well as Deltaic Plains in West Bengal is characterised by multi-aquifer system (CGWB, 1999; Acharya, 2005; Saha, 2009; Shah, 2007, Bhattacharya et al., 2016, Bhattacharya, 2017a, Bhattacharya, 2017b). The sedimentary sequence is made up of Quaternary deposits, where the aquifers have unconsolidated sands, which are separated by clay/sandy clay, making the deeper aquifer/aquifers semi-confined to confined in nature. The Arsenic-contamination is mainly in the upper slice of the sediments, particularly in the shallow aquifer system within 80 metre below ground level (CGWB, 1999, Saha et al, 2009, Bhattacharya et al., 2016, Bhattacharya, 2017a, Bhattacharya, 2017b). However at places, like Maldah district in West Bengal, single aquifer exists till the bedrock is encountered at 70-120 mbgl. The lithologic, groundwater flow, isotope and hydrochemical modeling carried out by CGWB along with other agencies like BARC has indicated that the deep aquifers (>120 mbgl) underneath the contaminated shallow aquifer have been reported Arsenic-free. Long duration pumping tests and isotopic studies carried out in West Bengal and Bihar indicated that limited hydraulic connection between the contaminated shallow and contamination free deep aquifers, and the groundwater belong to different age groups having different recharge mechanisms (CGWB, 1999, Saha et al, 2011, CGWB and BARC, 2009, Bhattacharya et al., 2016, Bhattacharya, 2017a, Bhattacharya, 2017b). Deep aquifers in West Bengal, Bihar and Uttar Pradesh have the potential to develop for community-based water supply. For single aquifer system, as reported in Malda district of West Bengal, this technique may not be useful. These eventually advocate that there is an immediate need of preparing Arsenic risk map of affected States indicating Arsenic risk and vulnerable zones, Arsenic-safe aquifers, etc.

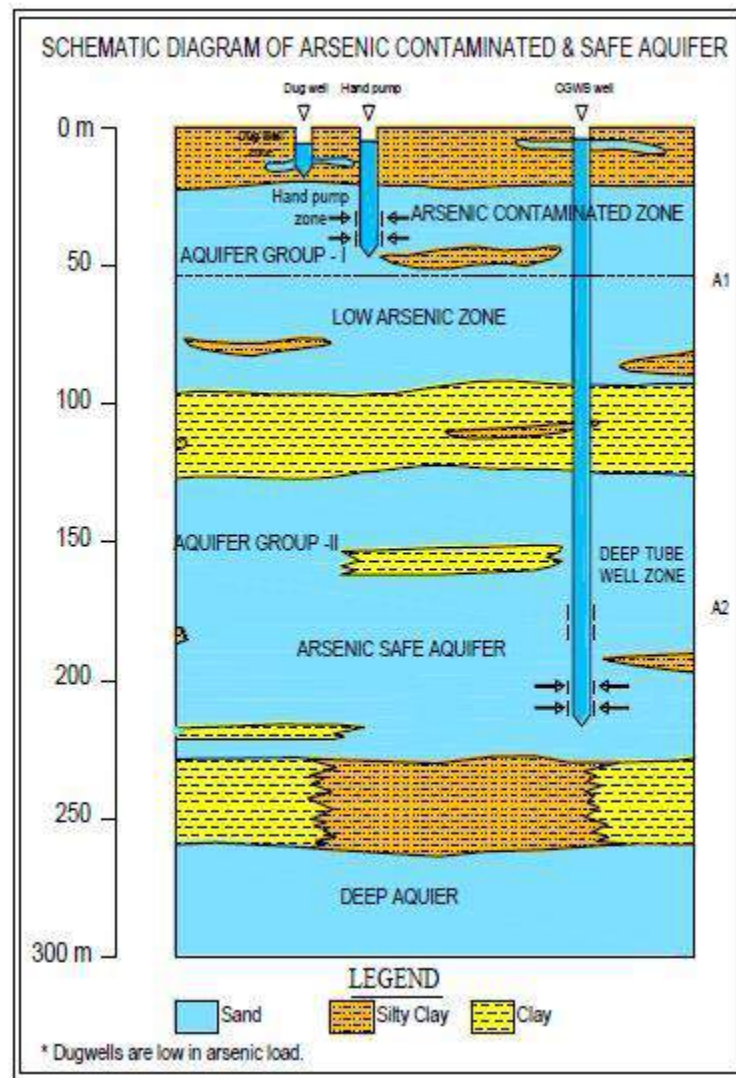


Figure13: Schematic diagram showing distribution of Arsenic in multi-layered alluvial aquifer in parts of Middle Ganga Plain.

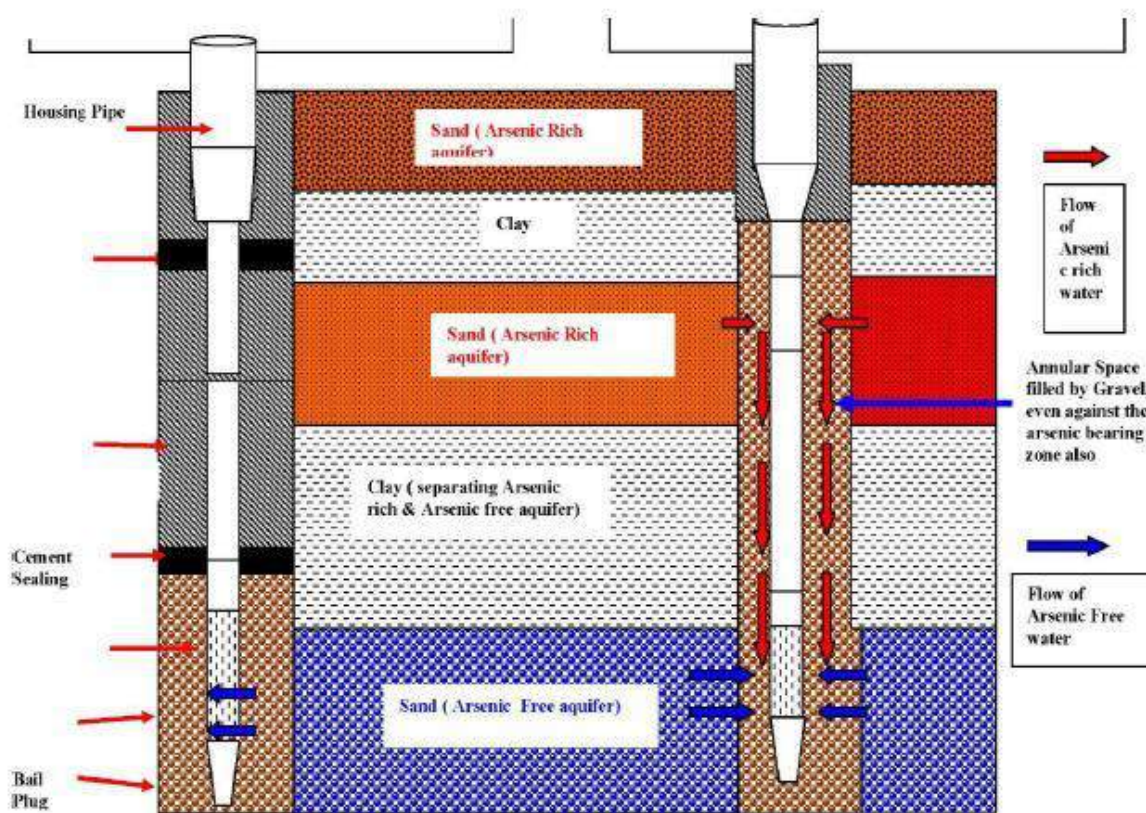


Figure 14 : Tube-well design of a deeptube well tapping Arsenic safe deeper aquifer (the well on the left shows a properly designed tube well tapping deeper aquifer while the one on the right shows an improperly designed well).

In-situ (Subsurface) Arsenic Treatment

In-situ remediation refers to all such techniques that make Arsenic immobilisation possible within the aquifer itself. As Arsenic is mobilised in groundwater under reducing conditions, it may also be possible to immobilise the Arsenic by creating oxidized conditions in the sub-surface. However, further investigations on geochemistry of Arsenic and its speciation would be necessary. Some of the in-situ treatments applied successfully elsewhere for Arsenic treatment are mentioned here :

- (a) Use of atmospheric O_2 for iron and Arsenic-rich water,
- (b) Use of atmospheric O_2 and ferrous chloride for low Iron and Arsenic-rich water,
- (c) Permeable Reactive Barriers (PRB),
- (d) Electro-kinetic treatment.

Biological Arsenic Removal

Arsenic in water can be removed by microbiological processes (Rahman and Ravenscroft, 2003). Two main types of metal-microbe interactions which can potentially be used for the removal of Arsenic from groundwater are: (a) microbial oxidation of Arsenic (III) to Arsenic (V) to facilitate its removal by conventional Arsenic removal processes, and (b) bioaccumulation of Arsenic by microbial biomass. In addition to the

techniques mentioned above, Phytoremediation, which is an in-situ technology applicable to contaminated soil and groundwater, uses aquatic plants to accumulate Arsenic and thus remove Arsenic from groundwater. Azolla and Spirodela (duckweed) species have the highest efficiency to remove Arsenic. A study on duckweed was carried out in Bangladesh (Rahman and Ravenscroft, 2003) and found to be efficient. The results indicated that a complete cover of plant could accumulate about 175 g of Arsenic from a pond of one hectare area per day. In-situ remediation of Arsenic from aquifer system or decontamination of aquifer is the best technological option. However, in-situ remediation of Arsenic-contaminated aquifer would be very expensive and may be a difficult task because of the size of the plan and absence of complete understanding of the physico-chemical and geochemical processes and behavior of aquifer system. Although the use of surface water sources, as an alternative to the supply of treated contaminated groundwater, seems to be a logical proposition, it would require availability and supply of surface water flow and organized water supply system for ensuring supply of both drinking and irrigation water. To meet requirement of potable water in Arsenic-affected areas, this approach can prove to be a potential alternative in areas having thick population. Based on this approach, Governments of West Bengal and Bihar have developed some schemes to supply drinking water to some of the Arsenic-affected areas. Tapping alternative safe aquifers, for supply of Arsenic-free groundwater, could also prove to be a logical proposition. This has also been explored in many areas on a local scale. However, this approach would require extensive studies and analyses for mapping of groundwater availability, freshwater reserves and to examine mobilisation of Arsenic in the aquifer, both on spatial and temporal scale.

MITIGATION AND REMEDY OF ARSENIC-CONTAMINATION IN GROUNDWATER OF INDIA

State-wise Initiatives

Since the report of groundwater Arsenic-contamination from West Bengal in the year 1983, thereafter eventually from other States, various Central Government and State Government Departments have taken up a number of initiatives for mitigation and remedy of Arsenic-contamination viz. Identification of contaminated sources, establishment of treatment plants, alternative freshwater supply etc. State-wise action taken, as reported by the State Government departments, for remediation of Arsenic-contamination are as follows:

Assam : Out of 2571 Arsenic toxicity affected habitations, the State has taken some mitigation measures in 2212 habitations. Piped water supply schemes (PWSS) have been provided in 115 habitations and new dug-wells tapping shallow aquifer (free of Arsenic-contamination) have been constructed in 2097 habitations with a total project cost of Rs. 390.09 crore. For the remaining 359 habitations, the State has a plan to take mitigation measures by providing PWSS to 50 habitations and dug-wells to 18 habitations with an estimated cost of Rs. 151 crore.

Bihar : The State adopted some short and long term remedial measures. The short term measures include: conversion of dug-wells into sanitary wells, replacement of tube-wells by India Mark-II hand pumps with more than 100 m depth, construction of new sanitary wells fitted with solar pumps and construction of hand pumps with Arsenic removal units. The long term measures include: construction of deeper hand pumps with proper sealing; surface water based multi village piped water supply schemes; rainwater harvesting and mini water supply schemes attached with Arsenic treatment units earmarked to the specialized technical agencies for operation and maintenance. Presently, 7 projects are under implementation at a cost of Rs.986.26 crore covering 1296 villages in Patna(E), Sambalpur, Begusarai, Vaishali, Bhagalpur(E), Bhagalpur(W) and Buxur divisions.

Chhattisgarh : To mitigate the Arsenic problem, a grouped water supply scheme in 18 villages are under implementation stage. The grouped water supply scheme has to cover Hathikanhar, Sonsaytorla, Mangatola, Pangari, Bhansula, Atargaon, Biharkhurd and Biharkala, Kaurikasa, Bhagwantola, Arajkund, Ambagarh

Chowki, Sanghali, Telitola, Dhadutola, Kotara, Joratara, Thelitola and Jadutola, villages. PHED, Government of Chhattisgarh has the responsibility to put in place the project within 3 years. The Operation and Maintenance after OHT's would be on the respective Gram Panchayat of grouped villages.

Haryana : No habitation has been reported affected by Arsenic-contamination.

Jharkhand : The State Government has constituted a 'State Water Quality Task Force' to deal with the issues pertaining to Arsenic-contamination. The groundwater sources having excess Arsenic concentration have been identified and all those locations are being monitored regularly as per 'Uniform Rural Drinking Water Quality Monitoring Protocol'. The planning and implementation of mitigation measures have been done on the basis of Arsenic concentration limit as 10 ppb. Sahebganj mega water supply scheme, based on surface water source, is under implementation and reported to be completed by 2016. This scheme having cost of Rs. 134 crore has plan to cover 100000 villagers dwelling in Sahebganj, Udhua and Rajmahal blocks of Sahebganj district. Village-wise security and safety plan is under execution through public participation by involving Gram Panchayat and 'Village Water and Sanitation Committee'. Mobile water quality testing facility has been provided to test Arsenic at door step. Non-governmental organisations have identified and marked the hand pumps infected by Arsenic. Mass awareness campaign, folks and media coverage programme have been organized. Jal Sahiyas have been trained and community level detection using 'Field Test Kit' is in progress.

Karnataka : In Karnataka, 24 habitations have been detected to be Arsenic-affected. Out of 24 habitations, 23 have been provided by surface water based multi village water supply scheme. The multi village water supply scheme has its source from rivers, lakes and canals. Remaining one habitation has been provided water by purification plant.

Manipur : People do not use hand pump or tube-well water for drinking purpose and therefore, no action has been initiated for groundwater Arsenic mitigation.

Punjab : Department of Water Supply and Sanitation, Government of Punjab, has prepared an action plan, which aimed at installation of 1884 units of AMRIT (Arsenic and Metals Removal Indian Technology developed by IIT Madras) in 1512 Arsenic-affected villages. The initial capital cost of 1884 units has been worked out to be Rs. 57.17 crore with an annual recurring cost of Rs. 6.41 crore.

West Bengal : The problem of Arsenic-contamination in West Bengal was detected in 1980s. Immediately after the detection of the problem, short term measures like installation of handpumps in deeper aquifers, were adopted. The short term measures were followed by the medium term measures like installation of community water purification plants. The community purification plants were based on the technologies like chemical precipitation, adsorption, sedimentation, ion exchange method and in-situ treatment. Under different programs of Government of India, viz., MSDP/BaDP etc., the Panchayat Raj Institutions have also implemented some community purification plants all over the affected areas. In view of the magnitude of the problem, the Government of West Bengal conceived the idea of long term plans/solutions and constituted a Task Force. The Task Force, based on the results of 132267 groundwater samples, recommended preparing a Master Plan in 2005-06. In the Master Plan, it was proposed to implement 338 nos. of groundwater based Piped Water Supply schemes (PWSS), 12 nos. of surface water based PWSS and installation of 165 nos. of Arsenic Removal Plants on the existing groundwater based schemes. On implementation of the Master Plan, the Public Health Engineering Department, Government of West Bengal, during the last decade, has covered most of the Arsenic-affected habitations.

Areas of Concern

A critical analysis of the issues reported by the concerned States and different Central Ministries has been carried out to ascertain the areas of concern and identify gaps in the approach of “Arsenic Mitigation”. The major areas of concern and the gaps are listed below, followed by a brief discussion on the challenges.

- Identification of areas affected by Arsenic-contamination and contaminated sources indicating vulnerable areas,
- Human and animal health risk and socio-economy and socio-cultural impact assessment,
- Arsenic testing facilities, sampling protocols, etc.
- Providing medical relief to affected people,
- Supply of Arsenic safe water to the Arsenic-affected and vulnerable areas,
- Arsenic removal technologies,
- Assessment of Arsenic in food chain and soil,
- Increasing awareness about Arsenic-contamination.

Identification of Areas Affected by Arsenic-Contamination and Contaminated Sources Indicating Vulnerable Areas

Though there are many organisations involved in monitoring and identification of Arsenic content in groundwater, however, there is no unified database or map of Arsenic-contamination in the country. Proper coordination and liaison among the stakeholder ministries and departments/organisations both in the Central and State level is required for mapping of Arsenic-affected areas and vulnerable areas. A proper geo-referenced databases on Arsenic concentration in source water and Arsenic-contaminated aquifers is prerequisite for developing comprehensive mitigation plan.

Human and Animal Health Risk and Socio-Economical and Socio-Cultural Impact Assessment

Though about 30 million people are living in the hydro-geologically risk zones (79 affected rural blocks and 12 urban communities) in West Bengal and substantial population in Jharkhand, Bihar, Chhattisgarh, Uttar Pradesh and Assam, the exact number of people exposed to Arsenic-contamination, suffering from Arsenicosis and consequential effects is yet to be established scientifically and epidemiologically. Considerable confusion and contradiction persist on these matters. The official statistics of the Department of Health, Government of West Bengal, reported, Arsenic related disease burden to be <15000, while the unofficial sources put the figure between 200,000 and 300,000. The impact and symptoms of Arsenic-contamination differ in severity between individuals, population groups and geographical areas. The severity and manifestation of symptoms also depend upon the concentration of Arsenic in water, the daily average intake, overall health and nutritional level of the person and many other factors. These make assessment of burden of Arsenic consumption, on an individual's health, a complex exercise. A scientific epidemiological assessment of the extent and magnitude of the problem is therefore necessary. High concentration of Arsenic in community water sources do not always correlate with high levels of Arsenicosis symptoms in the community. Usually the affected people are those who are economically backward. Women are affected more compared to men. Further, infants and children are adversely affected than the adults. An Arsenic patient loses its strength and cannot work outdoors. Many of them borrow money from the local moneylender who charges them a high rate of interest. The Arsenic problem, thus, has a major effect on the socioeconomic structure. People often mistake symptoms of Arsenic poisoning for leprosy or other contagious skin diseases, and thus marriage, employment, and even the simplest social interaction become impossible for the victim. A detailed database of affected persons, assessment of health risks, and assessment of socio-economic problems is a necessity and a challenge.

Arsenic Testing Facilities, Sampling Protocols, etc.

In West Bengal, all public tube wells have been tested through a network of rural laboratories. Near about 150,000 water samples have been analysed in the block level laboratories and GIS Database has been created at the district, block and habitation level. However, the most challenging task, which is yet to be accomplished, is the testing of near about 500,000 private sources. In comparison to West Bengal, the identification of contaminated public tube wells has remained incomplete in other states like Bihar, Uttar Pradesh, Jharkhand,

Chhattisgarh, Assam, etc. The basic task of identifying all Arsenic-contaminated sources, public as well as private, has remained largely incomplete. If one considers the tube wells used for irrigation in the Arsenic-affected districts, the task becomes gigantic and complex. With regard to the magnitude of the tasks involved in raising the use of field kits vis-à-vis creation of network of block/village level laboratories; in West Bengal, considering the risk of false positive and false negative data, by the use of field test kits, the Arsenic Task Force opted for creation of a network of rural laboratories, at the rate of one laboratory for every three blocks, through Public-Private Partnership. It must, however, be noted that though the above system has been successful in monitoring public sources, the big question remains on the monitoring of water quality of the private sources. In Bangladesh, a community-based approach, using field kits, has created a very large database covering both public and private sources. However, the precision and dependability of the same is always open to question. The challenge is to produce field test kits, which are robust, reliable, cheap and simple enough to be used by relatively unskilled users in the villages. In addition to Arsenic contamination in water, testing facilities for health impacts is also a major gap. There are two types of testing possible. One is testing of blood samples; however which the experts do not agree among themselves regarding the conclusiveness of blood tests. The second is testing nail and hair which conclusively establishes Arsenic content. Unfortunately, that test is only available at forensic science laboratories at present and such facilities are not available at district levels.

Providing Medical Relief to Affected People

Acute consumption of Arsenic for short term may cause gastrointestinal symptoms including nausea, vomiting and diarrhea, cardiopulmonary toxicity and neurological effects like headache, seizures and neuropathy. Specific medication with supportive therapy is the mainstays of treatment of acute cases. Chronic consumption of drinking water with Arsenic concentrations more than permissible limits may produce symptoms involving skin, risk of development of diabetes and cancer. Management of chronic poisoning consists of termination of exposure and symptomatic supportive care. Providing proper medical treatment to the affected populace remained a challenge largely due to the following four reasons –

- Lack of proper database of affected/vulnerable persons,
- Most of the affected persons live in rural areas with inadequate infrastructure,
- Majority of such persons are poor and cannot bear the cost of treatment,
- Lack of proper awareness among people/ local health workers as regards Arsenic related health hazards.

Supply of Arsenic-Safe Water to the Arsenic-Affected and Vulnerable Areas

Supply of Arsenic-safe water to the Arsenic-affected areas has been the task that remained as a great challenge. Though the water supply agencies have been trying to provide Arsenic-safe drinking waters, as per IMIS data of MoDWs, however, about 1490 habitations having total population of 23.98 lakh with Arsenic limit as 50 ppb are yet to get Arsenic safe drinking water. If the limit is considered as 10 ppb, the affected habitations would increase to 15,108 with total population of more than 120 lakh. There is an immediate need to ensure Arsenic safe drinking water to those habitations.

Arsenic-Removal Technologies

The major issues which need to be factored-in while adopting Arsenic-removal technologies are given below:

- a. Development of cost effective and efficient materials for Arsenic-removal based on locally available resources,
- b. Cost effective detection techniques with technical performance better or comparable to currently available alternatives,
- c. Development of household and community Arsenic-removal systems based on indigenously developed materials,
- d. Field demonstration of developed systems to assess their suitability in specific social context,
- e. Popularisation of cost-effective techniques,
- f. Capacity-building at appropriate levels for installation, operation and maintenance of Arsenic-removal plants.
- g. Safe disposal of sludge.

Assessment of Arsenic in Food Chain and Soil

Efforts are being aimed at ensuring safe drinking-water, either through mitigation techniques or through finding alternative sources of water. Even if supply of Arsenic-free drinking-water is ensured, Arsenic-contaminated groundwater will continue to be used for irrigation purposes, posing a significant risk of this toxic element accumulation in the soil and, consequently, entering into the food-chain through plant uptake and consumption by animals and humans. The risk of Arsenic-contaminated water, being used, in such case would also be high. During the past 10 years, researchers have mainly focused on ingestion of Arsenic through contaminated drinking-water, but the incidence of Arsenicosis in the population is not consistent with the concentration of Arsenic in drinking-water, obtained from groundwater. Based on available studies, it is difficult to adequately assess the impact of use of Arsenic-contaminated groundwater and the dietary impact of the same on human health. More elaborate studies are required to adequately assess the situation and formulate policies and practices for agricultural methods and selection of crops in Arsenic-affected areas.

Increasing Awareness about Arsenic-Contamination

The eventual sufferer of any natural calamity and eventual beneficiaries of any initiatives is the society exposed to the problem. Experts opined that by awareness and precaution, a substantial protection against the harmful effect of this toxic content can be attained. A widespread social awareness program together with institutional capacity building can help reduce the Arsenic hazard on human and animal health.

Safe Utilisation of Arsenic-Laden Sludge from Arsenic Filters

There are a number of Arsenic filters available and still more are being developed. One issue that arises when using Arsenic filters is the issue of safe disposal of Arsenic-laden sludge. Obviously, this sludge cannot be dumped into the ground as it will then leach into the groundwater making the groundwater unsuitable for drinking. Also, plants may take in the Arsenic through their roots and thus the Arsenic will make its way into the food chain irrespective of whether the plants are directly eaten by human beings or indirectly by means of human beings eating herbivorous animals.

Incineration of Arsenic-laden sludge is rendered out of the question because the Arsenic will pollute the air. Nor are geosynthetic-bounded landfills the solution because such landfills will get filled-up sooner or later and, furthermore, any breakage of the geosynthetic will result in the Arsenic contaminating the soil and groundwater.

It has been mooted that earthworms can devour Arsenic and the Arsenic can continue to be stabilised in the bodies of earthworms generation after generation. However, this does not appear to be a very practical solution as the earthworms will dispose all the Arsenic in their tissues in case of accidental death. The floaters of this idea purported to show that the excreta of earthworms do not contain any Arsenic and the Arsenic ingested by the earthworms simply continues in the bodies of the earthworms for generation after generation by means of earthworms cannibalising the bodies of dead earthworms.

Used rubber tyres have been safely disposed of by mixing them in the bitumen used for road construction. Kilometres after kilometres of roads have been constructed using used rubber tyres as an admixture to the bitumen. However, this method cannot be used for disposal of Arsenic for two reasons. Firstly, when the bitumen is heated prior to its being used in roads, Arsenic will vapourise and pollute the air. Secondly, roads, by their very nature, are always subject to intense wear and tear and Arsenic will escape and partly pollute the air and partly pollute the soil and groundwater.

Therefore, the preferred option of the authors is to dispose of the Arsenic-laden sludge by using this sludge as an admixture to concrete. Since concrete is an artificial rock, Arsenic is stabilised and does not leach out to the outside environment from the concrete. To start with, the Arsenic-laden sludge can be used for that concrete which is not intended to be used for structural purposes, that is, for that concrete that is intended to be used for architectural finishing only. Even then, concrete containing Arsenic should be used only in the core portion of the total concreting with the exterior being cast in ordinary Arsenic-free concrete so as to eliminate the

possibility of Arsenic getting in contact with the exterior. Only after intense research has been conducted on load-bearing and deformation characteristics of concrete having Arsenic-laden sludge as a part of the admixture and it has been conclusively proved that Arsenic-bearing concrete is not inferior to ordinary concrete in terms of strength and stiffness, can such concrete can be used for structural purposes. Arsenic-laden sludge can also be stabilised by using it in bricks. These two methods are elaborated below.

Mixing with Concrete as an Admixture in a Controlled Ratio

Cement is used to treat a large amount of harmful wastes by improving the physical characteristics of the contaminants and by decreasing the toxicity and transmissivity of contaminants. This process involves mixing the waste, either in form of a sludge, a liquid or a solid, into a cementitious binder system. However, the effectiveness of Arsenic-laden sludge treatment through cement-based solidification and stabilisation is strongly influenced by the type of Arsenic compound present. Arsenate has the lowest mobility. It is found that Ca of cement influences the leaching and immobilisation of Arsenic. With higher Ca:As molar ratio, lower Arsenic leaching generally results. Solidification and stabilisation with lime and Ordinary Portland cement (OPC) is an effective means of stabilisation of Arsenic-contaminated sludge.

Mixing with Clay for Brick Manufacturing

When Arsenic-laden sludge is stabilised using clay, it is observed using Arsenic-laden sludge is safe when used upto 10% of clay by volume. In the case of ornamental bricks and tiles, Arsenic-laden sludge can be used safely only upto 4% of ornamental bricks and tiles by volume. It must be remembered that the compressive strength of the bricks decreases at all firing temperatures with increase in percentage of sludge.

Issues relating to Disposal of Arsenic Sludge from Arsenic Filters

However, there are certain issues that need to be considered when considering the disposal of Arsenic sludge from Arsenic filters. Arsenic is well known to be a poisonous element and the construction industry is unlikely to risk using Arsenic in construction, even in non-structural concrete, because if word gets out that a certain builder is using Arsenic sludge in his construction, then his product, be it apartments or any other products that the builder may be building, will not be sold due to public fear of Arsenic and the builder will be left with huge losses. Also, the owners of neighbouring buildings may go to court against this particular builder on the ground that the builder is polluting the atmosphere by using Arsenic in his construction and secure an injunction halting the construction from the court and the builder will have to fight a legal case, which may go on for a few years, in his attempt to vacate the injunction. All this combined, would bring endless trouble, problem wastage of time and money and mental worry and distress to the builder.

Because rumours spread fast among the public, even if one builder uses Arsenic in construction, the entire construction industry will suffer because the public will suspect that the other builders are also using Arsenic in their construction.

Therefore, a public awareness campaign needs to be carried out for a period of years to build awareness among the public that civil engineers are going to use Arsenic sludge safely in construction and there will be no danger to occupants of the buildings that are going to be constructed with Arsenic mixed with non-structural concrete. This public awareness campaign must be carried through all possible channels like radio, television, newspaper, banner advertisements on roads and other public places, social media and so on. Because the construction industry carries out its business for a profit and there is very intense competition within the construction industry with builders trying their level best to lower costs of construction so as to get projects, this short of advertisement for public awareness would add an extra cost which builders would be loath to take. Therefore, the government must bear a large portion of the cost of this public awareness campaign. The medical professional, media, social welfare organisations and the general public all have a very vital role to play in building up this public awareness.

After the construction industry is of the opinion that sufficient public awareness has been generated, the construction industry can join hands to build a single pilot project with Arsenic mixed in non-structural concrete and carefully observe the public response to their construction. If it is found that the public reaction is negative, then the public awareness needs to be carried on for some more time and another pilot project constructed later. In the meantime, the entire construction industry bears the losses for the failed pilot project and in this way the loss is shared by several builders and the situation of any one single builder facing huge losses is avoided.

Even with the above steps, there is a tough problem remaining. This pertains to casting concrete in two stages with the Arsenic-laden concrete in the core part and the Arsenic-free concrete in the exterior. This sort of two-stage construction will necessarily increase construction time. That means that the builder will have to pay more wages to the workers and more rental costs for construction equipment will also occur. If other builders save time and cost by constructing with Arsenic-free concrete, no builder is going to willingly incur greater cost by two-stage construction with Arsenic-laden concrete knowing fully well that this step is going to make him uncompetitive in a highly competitive market. Also, owners of residential apartments and other types of structures typically pay a large booking amount to the builder and go on paying various sums of money at periodic intervals to the builder until such time as they physically occupy the construction. Therefore, the money of the owners gets blocked up without giving any benefit to the owners until such time as the owners physically occupy the construction for which they are paying. Naturally then, owners, that is the general public, will want the pace of construction to be fast so that their money is blocked up for a shorter period. Hence, any modification in the construction method which results in a longer period of construction will be unpopular with the general public.

There is no easy solution to the above problem. The only solution is for the government to make laws making it mandatory for all builders to use Arsenic-laden concrete so that all builders have a level-playing field. But this is again going to add another layer to the government bureaucracy because the government is going to need a set of government inspectors to visit each and every construction site for ensuring that every builder is complying with government laws. Moreover, such a government law is going to increase the cost of construction for the construction industry as a whole and, therefore, the already-high housing costs are going to rise even higher. This would put a greater financial strain on the buyers of residential apartments and other types of construction and, thus on, society as a whole. Any law which is going to increase purchase costs is going to make the government extremely unpopular with the public and opposition political parties are going to seize the opportunity in the next election. Hence, the government would also not like to risk by making such a law.

In view of all these, there appear to be severe problems in using Arsenic for construction.

What is the solution then? That is indeed a very difficult question to answer and no satisfactory solution has yet been found. Arsenic is not the raw material of any industry and therefore, unlike Chromium which is widely used in the leather industry and also in some other industries, it cannot be input as the raw material in any industry. The current practice of dumping Arsenic waste in landfills is also not a satisfactory solution because landfills filled up and new landfills have to be built. Also, if geosynthetics are used to construct the landfills, even if the geosynthetics are designed to withstand normal load, they may break during earthquakes leaching the entire Arsenic to the soil thus resulting in an environmental catastrophe. However, it seems that, considering all factors connected with all possible disposal methods, landfills are not going away anywhere in a hurry.

Arsenic can be used in concrete structures built and owned by the government along with an intensive campaign to generate public awareness about the safety of such structures to the public from a public health point of view. Arsenic can also be used as an alloy with Aluminium for Aluminium products that are fully manufactured in the factory and are only sold outside. For Aluminium products which need cutting at site, it is not desirable to use Arsenic-blended Aluminium as Arsenic will pollute the atmosphere when the Aluminium alloy is being cut at site.

It must be kept in mind that the issue of safe disposal of Arsenic waste, including the generation of public awareness, must be tackled unitedly by various professionals like environmental engineers, structural engineers, architects, doctors, lawyers, journalists, etc.

CONCLUSIONS

It may be concluded that plenty of work has been done in the areas of diagnosis of Arsenic-affected areas, the harmful effects of Arsenic and in sensitising the scientific community and the people at large about the baneful effects of Arsenic. However, it may be mentioned that much more needs to be accomplished before it may be said that the problem of Arsenic in groundwater has been arrested, let alone solved. Some methods of disposal of Arsenic-laden waste from Arsenic filters have also been examined in this paper and the most effective methods considered in detail.

REFERENCES

Acharya S K, (2005). Arsenic Trends in groundwater from Quaternary Alluvium in the Ganga Plain and the Bengal Basin, Indian Sub-continent : Insights into Influences of Stratigraphy. *Gondwana Res.*, 8(1): 55-66.

Alam, M.B.; Sattar, M.A. 2000. Assessment of As contamination in soils and waters in some areas of Bangladesh. *Water Sci. Technol.* 42:185– 193.

BGS (British Geological Survey) 1999. Groundwater Studies for Arsenic Contamination in Bangladesh. Main Report and Supplemental Volumes 1-3, Government of the Peoples Republic of Bangladesh, Ministry of Local Government, Rural Development and Cooperatives, Department of Public Health Engineering, Dhaka, Bangladesh and Mott MacDonald International Ltd., UK. Available at <http://www.bgs.ac.uk/research/groundwater/health/arsenic/Bangladesh/reports.html> (accessed in February 2014)

BGS (British Geological Survey) 2000. Executive Summary of the Main Report of Phase I, Groundwater Studies of As Contamination in Bangladesh. British Geological Survey and Mott MacDonald (UK) for the Government of Bangladesh, Ministry of Local Government, Rural Development and Cooperatives DPHE and DFID (UK). Available at <http://www.engconsult.com/arsenic/article/DFID-sum.html> (accessed in February 2014)

BGS and DPHE. 2001. Arsenic contamination of groundwater in Bangladesh. Kinniburgh, D G and Smedley, P L (Editors). British Geological Survey Technical Report WC/00/19. British Geological Survey. Available at <http://www.bgs.ac.uk/research/groundwater/health/arsenic/Bangladesh/reports.html> (accessed in February 2014)

Bhattacharya A.K., Karthik D.M.P., Gautam A., Sharma A., Srinivas K., Singh P.K., (2016). Arsenic Contamination in the Groundwater of India. *Green and Sustainable Development*, 3, 17, 36-60.

Bhattacharya A.K., (2017). Arsenic Contamination in Indian Groundwater. *Journal of the Institution of Public Health Engineers, India*, XXXV, 2, 18-36.

Bhattacharya A.K., (2017). Arsenic Contamination in Indian Groundwater. *Indian Journal of Power and River Valley Development*, 67, 11&12, 169-182.

BIS, (2009). Drinking Water-Specification (IS-10500:2009), 24.p.

BIS, (2012). Drinking Water- Specification (second revision). IS-10500:2012. 11p.

CGWB, (1999). High Incidence of Arsenic in groundwater in West Bengal. Central Ground Water Board, MoWR, GoI.

CGWB, (2011). Dynamic groundwater Resources of India (As on 31st March, 2009). 225p.

CGWB and BARC, (2009). Studies on Arsenic Pollution of groundwater Using Isotopic and Geochemical Methods in Arsenic Bhojpur District of Bihar, India, CGWB-Mid Eastern Region, Patna, 49p.

Das, H.K.; Mitra, A.K.; Sengupta, P.K.; Hossain, A.; Islam, F.; Rabbani, G.H. 2004. Arsenic concentrations in rice, vegetables, a fish in Bangladesh: a preliminary study. *Environ Int* 30: 383–387.

- Dittmar, J.; Voegelin, A.; Roberts, L.C.; Hug, S.J.; Saha, G.C.; Ali, M.A., et al. 2007. Spatial distribution and temporal variability of arsenic in irrigated rice fields in Bangladesh. 2. Paddy soil. *Environ Sci Technol* 41:5967–5972.
- Duxbury, J.M.; Zavala, Y.J. 2005. What are safe levels of arsenic in food and soils. CIMMYT/USGS. 2005.
- Escobar, M.E.O.; Hue, N.V.; Cutler, W.G. 2006. Recent developments on arsenic: contamination and remediation. *Recent Res. Dev. Bioenerg.* 4: 1-32.
- Heikens, A.; Panaullah, G.M.; Meharg, A.A. 2007. Arsenic behaviour from groundwater and soil to crops: Impacts on agriculture and food safety. *Rev Environ Contam Toxicol* 189:43–87.
- Huq, S.M.I.; Joardar, J.C.; Parvin, S.; Correll, R.; Naidu, R. 2006. Arsenic contamination in food-chain: transfer of arsenic into food materials through groundwater irrigation. *J. Health Popul. Nutr.* 24(3): 305-316.
- IARC (International Agency for Research on Cancer), (2004). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Vol. 83, France. 1396 p.
- Kinniburgh, D. G.; Kosmus, W. 2002. Arsenic contamination in groundwater: some analytical considerations. *Talanta*, 58:165–180.
- Meharg, A.A.; Rahman, M. 2003. Arsenic contamination of Bangladesh paddy field soils: implications for rice contribution to arsenic consumption. *Environ Sci Technol* 37:229–34.
- NIH and CGWB, (2010). Mitigation and Remedy of groundwater Arsenic Menace in India : A Vision Document. MoWR, GoI. 184p.
- Rajmohan N., Prathapar S.A. (2016). Arsenic Distribution in Groundwater and Soil in the Eastern Ganges Basin A Review, Proceedings, Sixth International Groundwater Conference, 11-13 February, 2016, Chennai. Paper ID TS4 – 05, Pages TSIV – 78-93.
- Rahman A A, and Ravenscroft P, (2003). Groundwater Resources and Development in Bangladesh, Chapter-23, Options for Arsenic Removal from groundwater. Firoz Mallick, A.S.M. and Hirendra Kumar Das, The University Press Ltd., 2003.
- Roberts, L.C.; Hug, S.I.; Dittmar, J.; Voegelin, A.; Saha, G.C.; Ali, M.A.; et al 2007. Spatial distribution and temporal variability of arsenic in irrigated rice fields in Bangladesh. 1. Irrigation water. *Environ Sci Technol* 41(17):5960–5966.
- Safiuddin, M.D.; Shirazi, S.M.; Yusoff, S. 2011. Arsenic contamination of groundwater in Bangladesh: A review. *International Journal of the Physical Sciences* 6(30):6791 – 6800.
- Saha Dipankar, Dhar Y R, Vittala S S, (2009). Delineation of groundwater Development Potential Zones in Parts of Marginal Ganga Alluvial Plain in South Bihar, Eastern India. *Environmental Monitoring Assessment*, 165:179-191.
- Saha Dipankar, Sahu S, Chandra P C, (2011). Arsenic-Safe Alternate Aquifers and their Hydraulic Characteristics in Contaminated Areas of Middle Ganga Plain, Eastern India. *Environmental Monitoring Assessment*. 175, 1-4, 331-348.
- Shah B A, (2007). Role of Quaternary Stratigraphy on Arsenic Contained groundwater from parts of Middle Ganga Plain, UP-Bihar. *Indian Environmental Geology*. Doi : 10.1007/s00254-007-0766-y
- Schaepman. G., (2012), “Control of Fluvial Architecture on the Spatial Distribution of Arsenic Ground Water, Bihar, India” Ph.D thesis, Department of Civil Engineering, Section for Applied Geology, Department of Applied Earth Sciences, Delft University of Technology, P.O. Box 5028, The Netherlands, Jan., pp. 1-117.
- Spallholz, J.E.; Boylan, L.M.; Robertson, J.D.; Smith, L.; Rahman, M.M.; Hook, J.; Rigdon, R. 2008. Selenium and arsenic content of agricultural soils from Bangladesh and Nepal. *Toxicological & Environmental Chemistry* 90(2):203-210.

Thakur, A.K. and Ojha, C.S.P. (2005). "A preliminary assessment of water quality at selected riverbank filtration sites at Patna, India" In: Ray, C. and Ojha, C.S.P.(eds.) Riverbank Filtration – Theory, Practice and Potential for India. Proc. Two-Day Intl. Workshop Riverbank Filtration, 1-2 March 2004, IIT Roorkee, India. Publ. Wat. Res. Res. Center, Univ. of Hawaii, Manoa, USA (Cooperative Report CR-2005-01), 113-130.

Thakur, A. K., Ojha, C.S.P., Singh, Vijay P., Chaudhur, B.B. (2016). Potential of river bank filtration in Arsenic affected regions, Proceedings, Sixth International Groundwater Conference, 11-13 February, 2016, Chennai. Paper ID TS4 – 60, Pages TSIV – 385-394.

Uddin, M.K. 1998. Arsenic contamination of irrigated soils, groundwater and its transfer into crops in some areas of Bangladesh. M.Sc. Thesis. Department of Soil, Water and Environment, University of Dhaka, Dhaka 1000, Bangladesh.

Ullah, S.M., 1998. Arsenic contamination of groundwater and irrigated soil of Bangladesh. In: International

Van Geen, A.; Zheng, Y.; Versteeg, R.; Stute, M.; Horneman, A.; Dhar, R.; Steckler, M.; Gelman, A.; Small, C.; Ahsan, H.; Graziano, J.H.; Hussain, I.; Ahmed, K.M. 2003. Spatial variability of arsenic in 6000 tube wells in a 25 km² area of Bangladesh. Water Resour. Res. 39 (5):1140.

Yamazaki, C.; Ishiga, H.; Ahmed, F.; Itoh, K.; Suyama, K.; Yamamoto, H. 2003. Vertical distribution of arsenic in Ganges delta sediments in Deuli Village, Bangladesh. Soil Sci Plant Nutr 49:567–574.



© 2019 ejge

Editor's note.

This paper may be referred to, in other articles, as:

Dr. Amartya Kumar Bhattacharya *et al.*: "An Analysis of Arsenic Contamination in the Groundwater of India, Bangladesh and Nepal with a Special Focus on the Stabilisation of Arsenic-Laden Sludge from Arsenic Filters" *Electronic Journal of Geotechnical Engineering*, 2019 (24.01), pp. 1-34. Available at ejge.com.