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Current Status of Ground Water Arsenic Contamination in India and Recent Advancements in Removal Techniques from Drinking Water

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Abstract

India is consisting of 29 states and 7 union territories, including a national capital, Delhi. Elevated concentrations (>10 µg l^{-1}) of arsenic (As) in ground water (GW) of many states of India have become a major concern in recent years. Up to now about 0.2 million GW samples have been analyzed for As contamination from all over India by various researchers and Government agencies. About 90% of these cover only the Eastern part of India while several states and UTs are still unexplored. However, from the available data, GW of eighteen Indian states and three union territories has been found to be As contaminated to different extents through natural or anthropogenic origin. Among these, As >300 µg l^{-1} has been reported from at least one locality from fourteen states. The maximum level of As (7350 µg l^{-1}) in GW has been reported from a highly industrialized area, Patancheru in Medak district of Andhra Pradesh. However, the gravity of problem is more in West Bengal followed by Bihar and Uttar Pradesh. Five out of eight North-Eastern states are also affected by As contamination. Manipur is ranked firstand Assam as second followed by Arunachal Pradesh, Tripura and Nagaland. The GW in these regions is naturally As enriched, and therefore wide spatial distribution of As has been found in these areas. In North India, Punjab and Haryana and in South India, Andhra Pradesh and Karnataka are suffering with GW As contamination. Low level of As (up to 17 µg l^{-1}) has also been reported in Tamil Nadu from South India. Many of the states like Jammu and Kashmir, Uttarakhand, Odisha, Gujrat, Kerala, Telengana, Goa etc. are still unexplored for GW As contamination. Thus, according to current reports out of 640 districts in India, 141 are As affected (As >10 µg l^{-1}), among them 120 are above 50 µg l^{-1}. Considering its severity, the issue of As contamination in drinking water has been taken up by the Government of India and mitigation efforts are being initiated. In order to provide safe drinking water, different agencies/ organizations have developed eco-friendly, cost effective devices/ filtration techniques having higher As removal capacity. Here we elucidated the current status of GWAs contamination in different states of India and the new developments of mitigation options.

1. Introduction

Arsenic (As) contamination in ground water (GW) is a global issue, because GW As has caused many As related health problems in various parts of the world like Argentina, Pakistan, Mexico, Thailand, Chile, Nepal, Vietnam and Myanmar (Dhar *et al*., 1997; Chakraborti *et al*., 2002; Mandal and Suzuki, 2002; Smedley and Kinniburgh, 2002; Pfeifer *et al*., 2004; Hossain, 2006; Mondal *et al*., 2006). The global scenario of GW As contamination is changing with addition of newer area with each survey. In the last decade several new incidents of As contamination, particularly in Asian countries have been reported. Before 2000, there were three major incidents of GW As from Asian countries came into the notice, which were from Bangladesh, West Bengal, India, and some sites in China and Taiwan. In between 2000 and 2005, GW of various Asian countries like, Mongolia, Nepal, Cambodia, Myanmar, Afghanistan, Korea, Pakistan and several new sites in China were reported to be As contaminated (Mukherjee *et al*., 2006). Ground water of Japan, New Zealand and France has also been reported to have As contamination associated with geothermal activities (Smedley and Kinniburgh, 2002). Ground water As problem exist in some other European countries as well (Pfeifer *et al*., 2004). The magnitude of As toxicity is yet highest in five Asian countries, which are Bangladesh, India, Mongolia, China and Taiwan (Chakraborti *et al*., 2004; Mukherjee *et al.,* 2006).

In India, the initial reports of GW As problem came from Northern India in mid-seventies. The people from Chandigarh and different villages of Punjab, Haryana and Himanchal Pradesh were diagnosed with high As in liver through As contaminated drinking water (Datta and Kaul, 1976). Later in 1983, patients from a village of 24 Parganas, West Bengal were identified with arsenical skin lesions where people were drinking As contaminated tube well water (Chakraborti *et al.*, 2002). The severity of problem in India was primarily brought into attention by Prof. Dipankar Chakraborti who identified several As contaminated areas and made people aware of the health consequences of the elevated As. The Indian standard for permissible limit of As in drinking water is 50 µg l^{-1} while it is 10 µg l^{-1} according to World Health Organization (WHO, 1993). Exceeding level of As, in comparison to national (50 µg l^{-1}) and international (World Health Organization: WHO 10 µg l^{-1}) guidelines for drinking water, were discovered in several other states situated in flood plains of Ganga river. Thus, arsenic-rich GW was mostly found in the alluvial aquifers of the Ganges delta. A number of studies concluded that the As enriched Himalayan rocks are the source of As and the rivers originating from the Himalayas or Tibet Plateau have carried it to plains of South and South-East Asia (Nickson *et al.*, 1998, 2000; Smedley and Kinniburgh, 2002; Chakraborti *et al.*, 2004). Assam and Manipur in flood plain of the Brahmaputra and Imphal rivers and the other North-Eastern Hill states situated in Eastern Himalayan foot hills were reported to have high level of As in GW (Chakraborti *et al.*, 2004, 2008; Singh, 2004). Though most of the As affected areas are located along the main channel and tributaries of Indus, Ganges and Brahmaputra rivers, occurrence of As in the Damodar fan-delta and Son river in Eastern and Central India, however, demonstrate that an Himalayan origin is not essential. Therefore, considering the extent of As contamination and in its toxicity to human, As has been included along with and other toxic elements/ chemical in GW quality monitoring parameters by government and non government agencies. Additionally, in recent years various workers have monitored As in other states of Central, Western and Southern India as well (Ahamed *et al.,* 2006; Shukla *et al.*, 2010; Bhagure and Mirgane, 2011; Nathan *et al.*, 2012; Yano *et al.,* 2012; Pandey *et al.*, 2013; Chakraborty *et al.*, 2014; Singh *et al.,* 2014). These recent surveys have added several new As affected areas, not only through geogenic origin but also from industrial and mining activities, hence, changing the scenario of GW As contamination in India. Thus, it seems worthwhile to know the real picture of As contamination in India and mitigation efforts being taken to tackle the problem. This review provides an updated state wise view of GW As contamination including from natural geogenic and industrial sources in India and the emerging treatment techniques for removal of As from drinking water.

2. Present Scenario of Arsenic Contamination in India

From the first report of As contamination in India during seventies till the recent surveys, most of the geographical regions of India has been reported to have As contamination in the GW. The distribution of As, collating all the available information, has been presented in Fig. 1. Though, depending on age, depth and geographical condition of wells and the sources of As, the level of contamination vary strongly. In some of the regions spatial distribution of As contamination is prominent, i.e., As contamination exists in larger area while in some regions it is more localized (Table 1). The state wise severity of As contamination is discussed in following section.

2.1. Arsenic contamination in North and Central India

North India officially refers to the states of Jammu & Kashmir, Himachal Pradesh, Haryana, Punjab, Rajasthan, Uttar Pradesh, Uttarakhand and the Union Territories of Delhi and Chandigarh, while Central India consists of Madhya Pradesh and Chhattisgarh. The As contamination in North Indian region was already reported around 4 decades ago by Datta and Kaul (1976). Water of dug wells, hand-pumps, and spring-water collected from different localities of Chandigarh and surrounding areas of Punjab, Haryana and Himachal Pradesh were found to contain high level of As (30-150 µg l^{-1}) with a hand pump water containing 545 µg l^{-1} As. They also reported high As in the liver of patients suffering from non-cirrhotic portal hypertension from these areas. Since then no survey was performed in Himanchal Pradesh and Haryana. Only recently a few surveys, including government agencies, were performed in Punjab and Haryana. Although no further information about As poisoning from North India has been reported, As >50 µg l^{-1} has been reported from 14 districts of Haryana and 10 districts of Punjab (Tables 1-2).

A wide spatial variation has been found in the occurrence and distribution of As in GW of the Punjab. Punjab fall into three physiographic regions. The concentration of As in GW varied from 3.5-42 µg l^{-1} in submountainous aquatic part, while 9.8 to 42.5 µg l^{-1} in ustic moisture areas of the central plain. The concentration of As in aridic South-Western part of Punjab contains high As contamination ranging between 11.4-688 µg l^{-1}, in this region no single water sample was found safe for drinking (Hundal *et al.*, 2007).

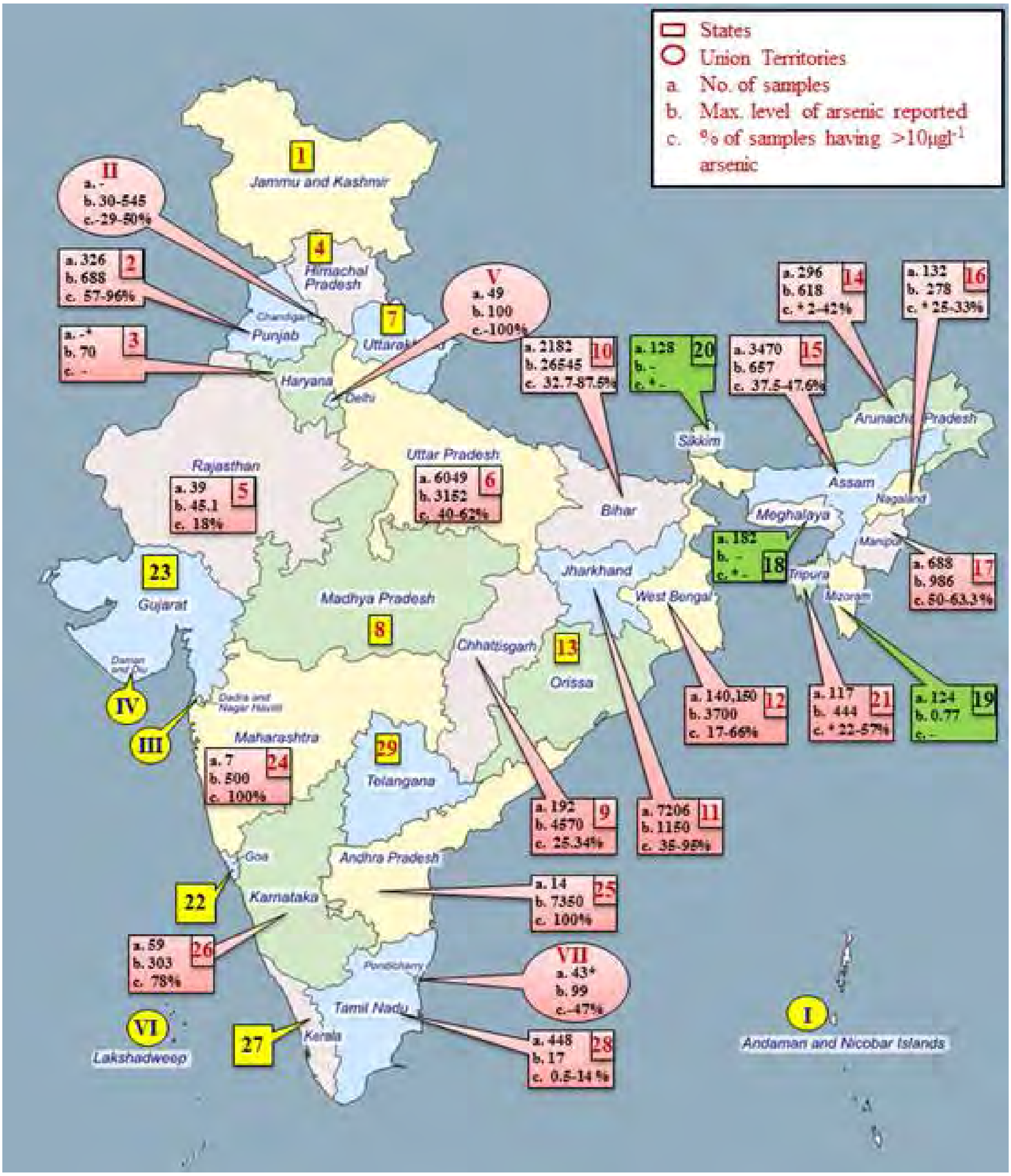

Fig. 1: Current scenario of ground water As contamination in India. Red color denotes As contaminated, yellow unexplored and green As free states/UTs as per the available reports. 24 & 25 are the ground water samples from highly industrialized localities, 26 is the samples from a gold mining area. For details of number and names of districts in particular state/UT and range of As in ground water, refer to Tables 1-2.

*% of samples >50 µg l^{-1} as the report for >10 µg l^{-1} was not available.

Table 1. Number of districts affected and range of ground water As contamination in different states of India

Sl. No.	Name of State/ Union Territories	No. of As affected districts (As>10 $\mu g\ l^{-1}$)	Range of GW As ($\mu g\ l^{-1}$)	References
i. STATES				
			A. North India	
1	Jammu & Kashmir	-	Not surveyed yet	-
2	Punjab	17	2-688	Hundal *et al.,* 2007; CGWB, 2014; Sidhu *et al.,* 2014; Kaur *et al.,* 2015
3	Haryana	14	50-70	CGWB, 2015; http://cgwb.gov.in/gw_profiles/st_haryana.html
4	Himachal Pradesh	-	Not surveyed yet	-
5	Rajasthan	3	1.48-45.10	Duggal *et al.,* 2012
6	Uttar Pradesh	25	<3-3192	Ahamed *et al.,* 2006; Chakraborti *et al.,* 2009; Shah, 2010; Yano *et al.,* 2012; Katiyar and Singh, 2014
7	Uttarakhand	-	Not surveyed yet	-
			B. Central India	
8	Madhya Pradesh	-	Not surveyed yet	
9	Chhattisgarh	2	1-4570	Chakraborti *et al.,* 1999, Pandey *et al.,* 2006, Pandey *et al.,* 2013
			C. East India	
10	Bihar	14	<3-2182	Chakrabarti *et al.*, 2008, 2016; Nath *et al.*, 2013; Singh *et al.,* 2014
11	Jharkhand	1	<3-1150	Nayaka *et al.,* 2007; Alam *et al.,* 2016
12	West Bengal	14	<3-3700	Chakraborti *et al.,* 2004, 2013a,b; SOES, 2012
13	Odisha	-	Not surveyed yet	-
			D. North-Eastern India	
14	Arunachal Pradesh	6	58-618	Singh, 2004
15	Assam	23	<3-657	Singh, 2004; Hazarika and Bhuyan, 2013; Kumar *et al.,* 2013; Goswami *et al.,* 2014; Puzari *et al.,* 2015
16	Nagaland	3	50-278	Singh, 2004; Puzari *et al.,* 2015
17	Manipur	4	<3-986	Singh, 2004; Chakraborti *et al.,* 2008
18	Meghalaya	0	As free state	Singh, 2004
19	Mizoram	1	<3	Singh, 2004; Kumar *et al.,* 2013
20	Sikkim	0	As free state	Singh, 2004
21	Tripura	4	65-444	Singh, 2004; Banerjee *et al.,* 2011
			E. Western India	
22	Goa	-	Not surveyed yet	-
23	Gujrat	-	Not surveyed yet	-
24	Maharashtra	1	12.1-500.1	Bhagure and Mirgane, 2011
			F. South India	
25	Andhra Pradesh	1	140-7350	Chandra Sekhar *et al.,* 2003
26	Karnataka	3	<3-303	Chakraborty*et al.,* 2014
27	Kerala	-	Not surveyed yet	-
28	Tamil Nadu	2	1.0-17	Manimaran and Manimaran, 2013; State Ground Water Report, Tamil Nadu, 2014
29	Telangana	-	Not surveyed yet	-
ii. UNION TERRITORIES				
I	Andaman and Nicobar Islands	-	Not surveyed yet	-
II	Chandigarh	1	30-545	Datta and Kaul, 1976
III	Dadra and Nagar Haveli	-	Not surveyed yet	-
IV	Daman and Diu	-	Not surveyed yet	-
V	Delhi	1	17-100	Lalwani *et al.,* 2004
VI	Lakshadweep	-	Not surveyed yet	-
VII	Pondicherry	1	3-99	Nathan *et al.,* 2012

For the name of As affected districts refer to Table 2

In Punjab seventeen districts have As contaminated GW and areas like Gandiwind (Amritsar), Patti (Tarn Taran), Jhunir (Mansa), Dhilwan (Kapurthala), Ropar and Fazilka have more than >50 μg l^{-1}. In fact, 30 blocks in 13 districts of Punjab have As contamination ranging between >10 and 99 μg l^{-1} (CGWB, 2015; Kaur *et al*., 2015). Sidhu *et al*. (2014) reported As level above maximum permissible limit (>10 μg l^{-1}) in Mansa, Hoshiarpur, Kapurthala, Ropar, Bathinda, Moga and Faridkot. In Amritsar the level of As was reported upto 99 μg l^{-1} fallowed by Roopnagar (91 μg l^{-1}), Taran Taran (83 μg l^{-1}) and Gurdaspur (58 μg l^{-1}) (Kaur *et al*., 2015).

Duggal *et al*. (2012) monitored GW As in four districts (Hanumangarh, Sri Ganganagar, Churu and Sikar) of Northern Rajasthan. The results indicated that As concentration ranges between 1.48 to 45.10 μg l^{-1} in these districts. One or more localities in these districts have As>10 μg l^{-1} except Sikar district where all the localities had <10 μg l^{-1} As. Rajgarh and Chimnpura area of Churu district had higher level of As (45.10 and 41.5 μg l^{-1} respectively). In Central India, Rajnandgaon district of Madhya Pradesh (now in Chhattisgarh) was reported to have GW As contamination (Chakraborti *et al*., 1999). In 146 GW samples collected from 22 villages of Chowki block, As exceeded >10 μg l^{-1} in eight villages and >50 μg l^{-1} in four villages, with the highest concentration being 880 μg l^{-1}. Interestingly, in Rajnandgaon district the dugwells were also reported to contain As up to 520 μg l^{-1} while at other places it was mostly tube well which contain As. The adjoining district, Kanker is also contaminated by As (Pandey *et al*., 2006). Shukla *et al*. (2010) reported that in this area all the wells in the granitic terrain with pegmatite intrusions contain high level of As contamination up to 250 μg l^{-1}.

The Union Territory Delhi has not been thoroughly surveyed with respect to GW As contamination, though, the possibility of contamination has already been warned a decade ago when several GW samples were reported to have >50 μg As l^{-1} (Lalwani *et al.,* 2004). They analyzed 49 GW samples collected from different areas of Delhi and found that As ranges between 17 to 100 μg l^{-1} with the mean of 43 μg l^{-1}. The minimum concentration was found at Raney Well while maximum at Kotla Mubarakpur. The areas where the As level in GW was >50 μg l^{-1} were Masjid Moth, Gulmohar Park, Raney Well, Lajpat Nagar, Saket and Kotla Mubarakpur.

Among the states situated in Indo-Gangetic plains, the severity of As contamination is highest in Uttar Pradesh after West Bengal. In recent years extensive survey has been done in Uttar Pradesh which show that GW As contamination has now spread across 25 districts of the state (Ahamed *et al*., 2006; Yano *et al*., 2012; CGWB, 2014). Collating all the information, over 6100 samples have been analyzed, of which 40-62% of the samples contained >10 μg l^{-1} As. Nine districts are highly As contaminated viz. Ballia, Lakhimpur, Ambedkar Nagar, Baghpat, Badaun, Pilibhit, Unnao, Ghazipur and Bahraich. Four districts where As level ranged between 10-<50 μg l^{-1} were Kaushambi, Saharanpur, Sultanpur and Raebareli.

The first report of GW As contamination in Uttar Pradesh came in 2003 from Ballia district (Chakraborti *et al*., 2003). Afterward, several other surveys were performed in Eastern Uttar Pradesh. Ahamed *et al.* (2006) carried out a survey in three districts viz., Ballia, Varanasi and Ghazipur and analyzed 4780 tube well water samples. They revealed that in 46.5% samples the concentrations of As exceeded 10 μg l^{-1}, in 26.7%, 50 μg l^{-1} and in 10%, 300 μg l^{-1}, thus none of the tube wells water was safe according to WHO guideline. Chayan Chapra village in Ballia district was highly As contaminated where 81.8% samples contained As more than 300 μg l^{-1}. The As concentrations up to 3192 μg l^{-1} were found in this village. The study also concluded that older tube wells had a greater chance of As contamination. Shah (2010) surveyed tube well waters from Ghazipur, Varanasi and Mirzapur districts and found 60% of the samples had ≥10 μg l^{-1} and 20% ≥50 μg l^{-1}. According to a survey by Uttar Pradesh Government under the assistance of UNICEF, the tube well water of 20 districts in Uttar Pradesh contained As >10 g l^{-1} and the ratio of contaminated over total number of tube wells were highest in Bahraich followed by Ballia and Kheri District, though the study included only Government tube wells (Yano *et al*., 2012). Government tube wells (depth: 30 m) were contaminated with As while the private tube wells (depth: 10 m) were not affected. In Tejwapur block of Bahraich district, 9 out of 80 villages had As >50 μg l^{-1}. The GW of Gorakhpur district is also contaminated with As. Piprauli, Barhalganj, Brahmpur, Campeirgunj, Khorabar and Jungle Kauria blocks had As contamination >50 μg l^{-1}, being maximum (91 μg l^{-1}) in Khorabar, while in Gorakhpur city mean As concentration is 47 μg l^{-1} (Kumar *et al*., 2014). According to Shah (2010) Varanasi town is virtually As-safe due to its position in older alluvial upland surfaces, whereas villages located in Holocene newer alluvium sediments in entrenched channels and floodplains of Ganga river, have GW As contamination. All these studies showed that As contamination of GW in Eastern Uttar Pradesh is a cause of big concern.

The GW of villages and towns along Allahabad-Kanpur track are also contaminated with As. On this track, in the Lilapur-Kalan village, Allahabad, 66% of hand tube wells contained As above >10 µg l^{-1} and 53% contain >50 µg l^{-1} while 4.5% samples contain As above 300 µg l^{-1} with maximum up to 707 µg l^{-1} and in Shuklagunj, Unnao, 39% of hand tube wells contain As above >10 µg l^{-1} and 18% contain >50 µg l^{-1} while 2% samples contain As above 300 µg l^{-1} with maximum As up to 333 µg l^{-1} (Chakrabotri *et al*., 2009). Kumar *et al*. (2014) surveyed 47 localities in and around Shuklaganj, Unnao and found 17 locations had >50 µg l^{-1} As, among them 10 localities had >200 µg l^{-1}. Katiyar and Singh (2014) found significant positive co-relation between degree of As contamination with depth and age of tube wells. Their study showed that 21-30 years old tube wells having maximum As concentration with mean value of 52.57 µg l^{-1}, while 30-40 years old wells having lowest mean As value (4.44 µg l^{-1}). Several other district of Western Uttar Pradesh viz., Aligarh, Bareilliy, Shahjanpur, Lakhimpur, Moradabad, Bijnaur etc. are also having GW As >50 µg l^{-1} (CGWB, 2014).

2.2. Arsenic contamination in East India

East India consists of four Indian states, West Bengal, Bihar, Jharkhand and Odisha and one union territory, Andaman and Nicobar Islands. Since the first report of As toxicity through GW As contamination, published by a local daily newspaper in December 1983 mentioned in Chakraborti *et al*., (2002), West Bengal has been copiously studied primarily by the School of Environmental Studies (SOES), Jadavpur University. After the report of As above the WHO limit for drinking water in Bengal Delta, West Bengal was considered as the hot spot of As contamination in India (Acharyya *et al*., 1999; Chakraborti *et al*., 2003, 2004, 2009; Rahman *et al*., 2003, 2005).

In over 25 years, SOES has surveyed all 19 districts of West Bengal and have analyzed 140150 GW samples covering 7823 villages, of which 3417 villages have As >50 µg l^{-1} (Chakraborti *et al*., 2004, 2013a). Fourteen out of 19 district are As contaminated, with 48.1% of the samples having As >10 µg l^{-1}, 23.8% >50 µg l^{-1} and 3.3% >300 µg l^{-1} As. Thus, based on the intensity of As concentrations in GW they classified West Bengal into three zones: highly affected (9 districts mainly in eastern side of Bhagirathi river), mildly affected (5 districts in northern part) and unaffected (5 districts in western part). The estimated population from 9 highly affected districts, drinking As contaminated water above >10 and >50 µg l^{-1} were 9.5 and 4.6 million, respectively. Interestingly, GW As concentration decreased with increasing depth of the tube wells. According to Chakraborti *et al.* (2009) a total of 187 (0.13%) hand tube wells were found highly contaminated (>1000 µg l^{-1}). The maximum As concentration (3700 µg l^{-1}) was found in Ramnagar village of Ramnagar II Gram Panchayat, Baruipur block, in South 24 Parganas district. Similarly the GW of all 17 blocks of Nadia district contained As >50 µg l^{-1} with maximum observed level of 3200 µg l^{-1} (Rahman *et al.,* 2014). The temporal variation in GW As contamination of WB is also observed by Rahman *et al.* (2014). The studies demonstrated that in a span of 3-7 years, tube wells that had initially been safe (As <10 µg l^{-1}) were found to be contaminated (As >50 µg l^{-1}) in many villages and As concentration in many tube wells had increased by as much as 5–20-folds (Rahman *et al*., 2003; Sengupta *et al*., 2004). Over all, at present severe As problem exist in 9 districts and 111 blocks of West Bengal. The worst-affected districts of West Bengal are Maldah, Murshidabad, Nadia, North and South 24 Parganas and less affected in the adjoining areas of Howrah, Hooghly, Burdwan and Kolkata.

In Bihar eighteen districts are As affected (Tables 1-2), and its range have been found very high is most of the areas (Ghosh *et al.,* 2007, 2009; Saha *et al.*, 2009; SOES, 2012). Singh and Ghosh (2012) reported high As-contamination in Maner block of the Patna district. In this area, an average of 142 µg l^{-1} of As was detected with the highest value of 498 µg l^{-1} from Haldichapra Panchayat of Maner Block, Patna, >50 µg l^{-1} As was found in GW samples of 15 blocks while >100 µg l^{-1} of As was reported from Danapur and Naubatpur block. In Bihar, the highest level of As, 2182 µg l^{-1}, was reported from Buxar district (Chakraborti *et al*., 2008; SOES, 2012). Other severely As affected districts of Bihar, where the level of As exceeded 1000 µg l^{-1} in GW are Bhojpur, Patna, Samastipur and Bhagalpur. More than 50 µg l^{-1} of As were detected in Vaishali, Saran, Begusarai, Khagaria, Munger, Katihar, Vaishali and Bhagalpur districts (Table 2) (SOES, 2012; Singh *et al*., 2014). However, from Siwan and Supaul, As contamination were below 50 and >10 µg l^{-1}, respectively (SOES, 2012). The GW As ranged 3-143 µg l^{-1} in Bhagalpur (Singh *et al*., 2014). According to a study, 19.9% residents of Semria Ojha Patti village in the Bhojpur district are using GW containing ≥300 µg As l^{-1}, 56.8% with ≥50 µg As l^{-1} and 24.7% with 10-50 µg As l^{-1}. Only 18.4% residents used safe water (<10 µg l^{-1} As) (Chakraborti *et al.,* 2003, 2016).

Jharkhand state consists of 24 districts, of which only one, Sahibganj district, situated in the flood plain area, is reported to be highly As contaminated with As affected patients. Out of 9 blocks of Sahibganj district, 3 blocks viz., Sahibganj city, Rajmahal and Udhawa were As contaminated and the level of As were up to >1000 µg l^{-1} (Bhattacharjee *et al*., 2005; Nayaka *et al.,* 2007). No study showing GW As status in Odisha was available.

2.3. Arsenic contamination in North-Eastern India

The monitoring of GW As contamination in North-Eastern (NE) region was done for the first time in 2003 (Singh, 2004). He surveyed all the eight NE states viz., Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura. He reported higher level of As (>50 µg l^{-1}) in GW of NE states except Meghalaya, Mizoram and Sikkim. Later, Kumar *et al.* (2013) also declared Mizoram as non As contaminated state. In recent years extensive GW monitoring was carried out by Prof. Dipankar Chakraborti and his group in Assam and Manipur (Chakraborti *et al.,* 2008; Goswami *et al.,* 2014). However, further monitoring of GW of other NE states is urgently needed considering the WHO permissible limit of 10 µg l^{-1}.

In Assam, the concentration of As in GW has been found >50 µg l^{-1} in most of the districts (24 out of 27 districts). The range of As in different districts of the Assam has been found in between 50-657 µg l^{-1}. Jorhat, Laksmipur, Nalbari, and Nagaon districts are the most affected. In Jorhat district, the contamination of As was highest in the range of 194-657 µg l^{-1} while in Lakhimpur district, it was in between 50-550 µg l^{-1}. In Nalbari district, 19 percent samples (72 samples) contained As level between 100 to 422 µg l^{-1} (Singh*,* 2004). The level of As ranged 100-200 µg l^{-1} in the flood plain area of Assam (Barpeta, Dhemaji, Dhubari, Darrang, and Golaghat districts). In the remaining fourteen districts As ranged between 50-100 µg l^{-1}. Three districts namely, Karbi Anglong, NC Hills and Morigaon were free from As contamination. Arsenic level up to 128 µg l^{-1} has been reported in Golaghat district, an adjoining region of the West Bengal and Bangladesh borders in Assam (Chetia *et al*., 2011). Majuli Island, a subdivision of Jorhat and located in the middle of the Brahmaputra river is also As contaminated. Mazuli is the largest inhabited riverine island of the world. The level of As in GW of Majuli ranged from <3 to 468 µg l^{-1} (n=380) with 37.6% and 16% of the samples having As above 10 and 50 µg l^{-1}, respectively (Goswami *et al.,* 2014).

In Arunachal Pradesh, out of 13 in 2004, 6 districts namely Papum Pare, West Kameng, East Kameng, Lower Subansiri, Dibang Valley and Tirap are reported to have As contamination (Table 1). All these six districts are situated near the border area of Assam. The concentration of As ranged from 58 to 618 µg l^{-1} with maximum As was found in part of Midland block of Dibang Valley district (Singh, 2004). Similarly the border area of Nagaland, adjacent to Jorhat district of Assam is As affected. In Nagaland, out of eight, two districts Mokok Chong (50-278 µg l^{-1}) and Mon (67-159 µg l^{-1}) were having elevated level of As. The traces of As (<10 µg l^{-1}) were also found in Wokha and Zunheboto district of Nagaland (Singh, 2004). Most part of Tripura is also As affected. The level of GW As ranged between 65-444 µg l^{-1} in West Tripura (Jriania block), Dhalai (Salema block) and North Tripura (Dharmanagar block) districts of Tripura. The order of magnitude of As contamination was two-fold higher in Dhalai district in comparison to West and North Tripura (Singh, 2004).

Ground water As contamination has been reported in Manipur as well. Out of 9 district, four district situated in Manipur valley inhabiting 59% of the total population of Manipur, are monitored for GW As contamination (Chakraborti *et al*., 2008). Chakraborti *et al.* (2008) analyzed 628 of the estimated 2,014 hand tube wells in the Manipur Valley, and found that 63.3% had As ≥10 µg l^{-1}, 23.2% between 11 and 50 µg l^{-1} and 40% <50 µg l^{-1}. The most severely arsenic-affected district was Thoubal, where 77.6% of tube wells contained above 10 µg l^{-1} and 44.4% above 50 µg l^{-1} with highest As concentration (798-986 µg l^{-1}) in Kakching block of Thoubal district. In an earlier study, Singh (2004) also reported that 50% samples of Thoubal district contained >50 µg l^{-1} of As. The least affected district was Bishnupur, where 21.4% of wells contained above 10 µg l^{-1} and 7.1% above 50 µg l^{-1} (Chakraborti *et al*., 2008). The percentages of contaminated wells are higher in Manipur than in other As affected states. Interestingly, in Manipur there is no co-relation between As concentration and the depth of tube wells.

2.4. Arsenic contamination in Western India

Western India consists of the states of Maharashtra, Gujarat and Goa, along with the Union territory of Daman and Diu, Dadra and Nagar Haveli. Most part of this region is highly industrialized, with a large urban population. In Western India there is severe scarcity of monitoring studies for GW As contamination. In a study, the GW of Thane Region (Maharashtra) has been found to contain high concentrations of As (12-500 µg l^{-1}) along with other toxic elements such as Cd, Hg, Pb, Cr etc., through industrial sources (Bhagure and Mirgane, 2011). Arsenic enrichment in quaternary sediments from the industrial area of Western Indian state of Gujarat has been reported by Shirke and Pawar (2015). The study showed probability of GW contamination in the area due to downward migration of As. However, no report is available showing the level of As in water from this region.

Table 2: Name of districts affected by As contamination in GW in India

Sl. No.	Name of State/ Union Territories	Districts affected by As in ground water (i.e. $>50\ \mu g\ l^{-1}$ As) Ministry of Water Resource (2014-15, 2015-16)
i. STATE		
		A. North India
1	Jammu & Kashmir	Not surveyed yet
2	Punjab	Amritsar, Bathinda, Faridkot, Taran Taran, Firozpur, Gurdaspur, Fazilka, Barnala, Nawa Shahar, Roparnagar, Moga*, Hoshiarpur*, Ludhiyana*, Mansa*, Kapurthala*, Pathancoat*, Patiyala*
3	Haryana	Ambala, Bhiwani, Faridabad, Fatehabad, Hissar, Jhajjar, Jind, Karnal, Panipat, Rohtak, Sirsa, Sonepat, Yamunanagar, Mewat (http://cgwb.gov.in/gw_profiles/st_haryana.html)
4	Himachal Pradesh	Not surveyed yet
5	Rajasthan	Hanumangarh*, Sri Ganganagar*, Churu*
6	Uttar Pradesh	Agra, Aligarh, Bahraich, Ballia, Ghazipur, Balrampur, Bareilly, Basti, Bijnor, Chandauli, Gonda, Gorakhapur, Lakhimpur Kheri, Raibareli, Mathura, Moradabad, Sant Ravidas Nagar, Santkabir Nagar, Shajahanpur, Siddharthnagar, Unnao, Varanashi, Kaushambi*, Saharanpur*, Sultanpur*
7	Uttarakhand	Not surveyed yet
		B. Central India
8	Madhya Pradesh	Rajnandgaon#
9	Chhattisgarh	Kanker, Rajnandgaon
		C. East India
10	Bihar	Begusarai, Bhagalpur, Bhojpur, Buxar, Darbhanga, Katihar, Khagaria , Kisanganj, Lakhisarai, Patna, Purnea, Samastipur, Saran, Vaishali
11	Jharkhand	Sahibganj
12	West Bengal	Murshidabad, Malda, Nadia, North 24 Parganas, South 24 Parganas, Bardhaman, Howrah, Hooghly, Kolkota, Darjiling*, Jalpaiguri*, Kochbihar*, Uttar Dinajpur*, Dakhin Dinajpur*
13	Odisha	Not surveyed yet
		D. North-Eastern India
14	Arunachal Pradesh	Papum Pare, West Kameng, East Kameng, Lower Subansiri, Dibang Valley, Tirap
15	Assam	Nagaon, Jorhat, Lakhimpur, Nalbari, Golghat, Dhubri, Darrang, Barpeta, Dhemaji, Baksa, Bongaigaon, Cachar, Chirang, Dibrugarh, Goalpara, Hailakandi, Karimganj, Kokrajhar, Sivasagar, Sonitpur, Tinsukia, Kamrup Metropolitan, Kamrup Udalguri
16	Nagaland	Mokok Chong, Mon, Dimapur
17	Manipur	Imphal East, Imphal West, Thoubal, Bishnupur
18	Meghalaya	As free state (According to As $>50\ \mu g\ l^{-1}$)
19	Mizoram	Aizawl
20	Sikkim	As free state (According to As $>50\ \mu g\ l^{-1}$)
21	Tripura	West Tripura, Dhalai, North Tripura, South Tripura*
		E. Western India
22	Goa	Not surveyed yet
23	Gujarat	Not surveyed yet
24	Maharashtra	Thane
		F. South India
25	Andhra Pradesh	Medak
26	Karnataka	Yadgir, Gulbarga, Raichur
27	Kerala	Not surveyed yet
28	Tamil Nadu	Perambalur*, Virudhunagar*
29	Telangana	Not surveyed yet
ii. UNION TERRITORIES		
I	Andaman and Nicobar Islands	Not surveyed yet
II	Chandigarh	Chandigarh
III	Dadra and Nagar Haveli	Not surveyed yet
IV	Daman and Diu	Not surveyed yet
V	Delhi	Delhi
VI	Lakshadweep	Not surveyed yet
VII	Pondicherry	Pondicherry

*>10 to <50 $\mu g\ l^{-1}$, #Now in Chhattisgarh State

2.5. Arsenic contamination in South India

South India consists of Andhra Pradesh, Karnataka, Kerala, Tamil Nadu and Telangana and the union territories Lakshadweep and Pondicherry. Among them, high GW As contamination has been reported from Karnataka, Andhra Pradesh and Pondicherry. In the industrial estate of Patancheru in Medak District of Andhra Pradesh near Hyderabad, high concentrations of As in many soil and water (ground and surface) samples have been reported by various workers (Govil *et al.*, 2001; Gurunadha Rao *et al.,* 2001; Kishan, 2001). Chandra Sekhar *et al.* (2003) reported 140-7350 µg l^{-1} As in GW while up to 80-8960 µg l^{-1}As in surface water in the industrial region of Patancheru, one of the world's industrially most polluted areas. Water samples from gold mining areas of Mangalur greenstone belt of Karnataka, have been found to contain high As (Chakraborti *et al.* 2013b). Ground water samples collected form Gulbarga, Yadgir, and Raichur districts by Government of Karnataka and Chakraborti's group contained >10 µg As l^{-1} with up to >300 µg As l^{-1} in a few samples. Patients suffering from arsenicosis are also identified from this area. In a report by the state ground and surface water resources data centre (State Ground Water Report, Tamil Nadu, 2014), out of 29 districts of Tamil Nadu the GW of 2 districts (Perambalur and Virudhunagar) contained >10 µg As l^{-1} (16.67 and 11.5 µg l^{-1}, respectively). The level of As in GW ranged between 3-17 µg l^{-1} in Tuticorin and Tirunelveli districts of Tamil Nadu (Manimaran and Manimaran, 2013). Thus in general the level of As in GW sample of Tamil Nadu was within the limit of WHO for safe drinking water (CGWB, 2014).

Nathan *et al.* (2012) collected forty three GW samples from various aquifers of Pondicherry region covering urban, rural and industrial areas and analyzed for trace elements concentration including As. Almost 47% of the samples contained As level >10 µg l^{-1}, ranging from 3 to 99 µg $l^{-1}$with a mean value of 20.5 µg l^{-1} in this region.

3. Emerging Treatment Technologies for Arsenic Removal

The conventional techniques for As removal involves chemical precipitation, oxidation and coagulation which often show lower efficiency, consumption of chemicals, produces toxic sludge and thus, having many disadvantage (Table 3). In recent years, various organizations have developed a number of As removal devices/ units showing good As removal efficiency from GW. These techniques are novel, eco-friendly, sorbent material based and have higher sorption capacity of As. These devices/ units vary in size, filtering mechanisms, and mechanisms of operation, therefore based on the size, the devices are of two type's: (1) Arsenic Removal Unit (ARU) and (2) Arsenic Removal Plant (ARP).

Arsenic Removal Units are those, whose inlet are directly connected to a hand pump or tube well. It is normally a small domestic assembly which can filter up to 500 l of water per day and can meet requirement of water for a smaller section of people. On the other hand, As Removal Plants (ARPs) has the capability to treat a large quantity of water and can cover a large section of general public. Some cost effective As removal technologies developed by different Indian Institutes are as under:

3.1. Ceramic micro-filtration membrane unit

Central Glass and Ceramic Research Institute (CSIR-CGCRI), Kolkata has developed Ceramic Micro-Filtration Membrane based unit for simultaneous removal of As and Fe from contaminated GW. The technique is based on the principle of aerial oxidation of As^{III} and Fe^{II}, adsorption on nano-colloidal media and filtration of water through solid-liquid separation technique using ceramic micro-filtration membrane modules. In this device the As contaminated GW is directly pumped to a tank, containing the adsorbent media and allowed to come in contact with the suspended media for a pre-determined time depending on the concentration of As. The contaminated water along with the colloidal media is then passed through tubular ceramic membrane module under pressure in a cross-flow filtration mode for separation of the media particles in the retentive stream and production of safe drinking water as the permeate. The simultaneous removal of Fe and As up to WHO recommended limits for drinking water (<10 and <30 µg l^{-1}, respectively) from the water containing As (up to 2.7 mg l^{-1}) and iron (up to 13 mg l^{-1}) and low sludge generation are the advantages of the device. Initial field demonstration showed the capacity of 500 l day^{-1} connected to a hand pump tube well containing up to 1.5 ppm As and 15 ppm iron in North 24 Parganas District of West Bengal. The community level pilot plants, however, have shown up to 2500 l day^{-1} capacity.

3.2. AMRIT

Amrit is a nano-technology based water purifier developed by Indian Institute of Technology, Madras. It is a storage type filtration device requires only gravity for function. It uses nano-scale iron oxyhydroxide, prepared with a particle size less than 3 nm and can reduce As from contaminated water (up to 1 mg l^{-1}) to below 1 µg l^{-1} at a very low cost. Apart from the As the filter can also effectively remove microbes, turbidity

Table 3: Disadvantage of some conventional As removal techniques

Sl. No.	Techniques	Applicable for		As removal efficiency (%)		Disadvantage
		Household	**Community**	**As^{III}**	**As^{V}**	
A.	**Oxidation/ precipitation**					
	Air oxidation	Yes	Yes	<30	<30	Partial removal of As, slow process
	Chemical oxidation	Yes	Yes	<30	30-60	
B.	**Coagulation/ co-precipitation**			<30	>90	Operations require training, Forme toxic sludge.
	Alum coagulation	Yes	Yes	<30	>90	Pre-oxidation must, Generate toxic waste
	Iron coagulation	Yes	Yes	60-90	>90	Pre-oxidation required
	Lime softening	Yes	Yes	30-60	>90	Readjustment of pH required, Generate large amount of waste
	Enhanced coagulation	Yes	Yes	60-90	>90	Not proven enough on practical sc
C.	**Sedimentation**	Yes	Yes	<30	<30	Low removal efficiency of As
D.	**Oxidation/ filtration**	Yes	Yes	<30	60-90	Low removal efficiency of As^{III}
E.	**Adsorption**	Yes	Yes	<30	>90	Requires monitoring and periodica regeneration
	Active alumina	Yes	Yes	60-90	>90	Re-adjustment of pH required, toxi solid waste generated, monitoring difficult
	Iron based sorbents	Yes	Yes	30-60	>90	Requires pH adjustment, requires replacement of media after exhausting, and requires regular testing for safe operation
F.	**Ion exchange**					
	Anion resin	Yes	Yes	<30	>90	High operating skill, monitoring difficult, interference from sulphat nitrate and TDS.
G.	**Membrane/ reverse osmosis**	Yes	Yes	<90	60-90	High running cost, high tech operation and maintenance, re-adjustment of water quality requir
	Electrodialysis		Yes	<90	< 90	High cost, interference by oxidizin agents, toxic waste water.
	Nano-filtration			<90	60-90	Very high capital running cost
	Coagulation assisted membrane process (CAMP)		Yes	<90	>90	Pre-treatment required, high runni cost

and iron from water. The purification process takes place in two stages. First the microbial impurities are removed by killing them with a very small concentration of silver ions released from silver nano-particles. After that, the As and other metals are removed with the help of different nano-materials. There are two variants of the purifier. The larger unit that can provide 18,000 l of pure water per hour, and the smaller unit, domestic version can filter 6 l of water per hour. The filters have been installed in several As affected villages of West Bengal.

3.3. IITB arsenic filter

The Indian Institute of Technology, Bombay has developed a zero valent iron based As removal filter. It is cost-effective and robust, does not require extensive monitoring. This filter provides drinking water to meet the daily needs of 200-300 families and is able to achieve As level of <10 µg l^{-1} from the water containing upto 500 µg As l^{-1} at a flow rate of 600-1000 l h^{-1}. The techniques involved in the filter is co-oxidation of Fe^{II} and As^{III} in the presence of dissolved oxygen and subsequent As removal by hydrous ferric oxide, which is formed from oxidation of Fe^{II} naturally present in GW. The filter take advantage of natural enrichment of Fe^{II} in As contaminated GW and additional Fe^{II} produced by corrosion of zero valent iron and oxidation achieved without addition of any chemicals. Around 50 units are installed in several villages of Assam, Bihar, Uttar Pradesh, and West Bengal states.

3.4. DRDO arsenic removal filter

A household As removal unit was developed by Defence Research and Development Organisation (DRDO). It is also based on the principle of co-precipitation and adsorption. It can be operated successfully without electricity, having filtration rate 1.2 l h^{-1}. It is made up of plastic materials and consists of aeration pump and two cylindrical chambers. First chamber consists of ceramic candles and second chamber consists of main filtration unit with different layers of filter media. It lowers down the As from 200 to <10 µg l^{-1}. Several units are working in the villages namely Arbandi and Lalmath district Nadia, West Bengal, Tiwaritolla, Ramgarh district Ballia, Uttar Pradesh and Ranuchak, Nathnagar district Bhagalpur, Bihar.

3.5. Low cost laterite based arsenic filter

The Indian Institute of Technology, Kharagpur has developed an ultra-low cost eco-friendly laterite based filter for providing As safe water. It is made from naturally occurring red laterite soil. This material has undergone chemical treatment to enhance its capabilities to adsorb As. It can filter water without power requirement and lower down the As <10 µg l^{-1}. The filter has long life of about five years, upon exhaustion of the filter; the medium can be safely dumped without any risk of leaking and further contamination.

3.6. ARI ground water arsenic treatment plant

ARI As treatment plant is developed by Agharkar Research Institute (ARI), Pune, which comprises of three steps. In the first step As is oxidized using a bacterial culture (*Microbacterium lacticum*) immobilized on brick pieces in a polypropylene column. In the second stage, the oxidized As is adsorbed on activated alumina. In the third stage bacteria from the water are removed by charcoal filtration and ultraviolet treatment. The treatment method has worked with very high and consistent efficiency at the scale of 1000 liters per day in the laboratory conditions for two years. As in case of other adsorption technologies, the As adsorbed on activated alumina needs to be removed periodically and disposed off safely. This technology has been field tested in 11 villages in Rajnandgaon district of Chhattisgarh state.

Though these novel technologies are efficient in As removal in laboratory and have also performed well in field conditions in As contamination regions. They are also comparatively cheaper. There long term performance, however, depends on maintenance and community participation. The previous As removal plants installed by Government had largely failed due to lack of awareness for handling and maintenance and community participation (Hossain *et al.*, 2006). In this regard, All India Institute of Hygiene and Public Health (AIIH&PH), Kolkata, in collaboration of some NGOs and with the financial support of the India-Canada Environment Facility (ICEF), New Delhi, took a project to evaluate As removal plants known as the Technology Park Project (TPP), where 19 ARPs from 11 different national and international manufacturers were installed in 2001. Results indicated that 10 of 13 ARPs failed to remove As below the WHO provisional guideline value (10 µg l^{-1}), while six plants could not achieve the Indian Standard value (50 µg l^{-1}). The highest concentration of As in filtered water was observed to be 364 µg l^{-1}. The 2-year study showed that none of the ARPs could maintain As in filtered water below the WHO provisional guideline value and only two could meet the Indian Standard value (50 µg l^{-1}) throughout (Hossain *et al.*, 2005).

4. The Ultimate Solution: Use of Surface and Rain Water

Previously surface water in the form of river, pond and lakes were the main source of water for household activities and drinking. Due to outbreak of water borne diseases and chemical contamination after green revolution these sources became considered unsafe. During 1980s most of the regions in India started to use GW for household and irrigation purposes after the recommendation of WHO and UNISEF. However, still the proper use of surface waters is one of the best options to get rid of toxicants like As and fluoride. After proper treatment for bacterial contamination, the surface and rain water can be safely use for drinking. The river, ponds and lakes should be restored and must be used for irrigation purposes to prevent food chain contamination by As. Various governments worldwide are now emphasizing on the implementation of rainwater harvesting, either voluntarily or mandatory, but harvesting of the rainwater is still uncommon practice in many parts of India.

5. Conclusion

The present review concluded that in the recent years the instances of As contamination have come from several states which were previously not affected. Also with each survey many new As affected areas are identified from Uttar Pradesh, Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu (South India). In North, North-East and Central India the source of As contamination in GW is primarily geogenic while the Western and Southern Indian states are mostly contaminated through the Industrial or mining waste percolation. The current review also emphasizes the high heterogeneity in the water monitoring. There is drastic lack of data from Western and Southern Indian states and some Northern and Central Indian states like Jammu & Kashmir, Uttarakhand and Madhya Pradesh. The reports of As in GW from Chhattisgarh warns that apart from Indo-Gangetic plains, As from natural geogenic sources may occur in other states as well. The heterogeneity apparent in the level of As, particularly from naturally contaminated regions may due to the difference in water table and depth of wells. Considering the fact that the previously uncontaminated tube well showed increased As level after 7-10 years of use, the periodic monitoring is essential for taking precautionary actions. In the recent years several cost effective, ecofriendly, As removal devices has been developed by National research organizations. These technologies have demonstrated good efficiency to remove As below WHO permissible limits for drinking water (10 µg l^{-1}) under field conditions in As affected areas. Yet awareness of people about the As hazards and proper use of the filters including disposal of As loaded sludge/ material is needed. Further, the problem of food chain contamination, another major As exposure route, through As loaded irrigation water is still unresolved. Considering the continuous lowering of water table in several states of India and presence of toxic elements in GW, the management, restoration and awareness about the use of surface water for various purposes must be at first place in government policies. Rainwater harvesting should be emphasized not only as a source of water but toxin free water.

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References

Acharyya, S.K., Chakraborty, P., Lahiri, S., Raymahashay, B.C., Guha, S. and Bhowmik, A. 1999. Arsenic poisoning in the Ganges Delta. *Nature* **401**:545-546.

Ahamed, S., Sengupta, M.K., Mukherjee, A., Hossain, M.A., Das, B., Nayak, B., Pal, A., Mukherjee, S.C., Pati, S., Dutta, R.N., Chatterjee, G., Mukherjee, A., Srivastava, R. and Chakraborti, D. 2006. Arsenic groundwater contamination and its health effects in the state of Uttar Pradesh in Upper and Middle Ganga Plain, India: A severe danger. *Science of the Total Environment* **370**:310-322.

Alam, M.O., Shaikh, W.A., Chakraborty, S., Avishek, K. and Bhattacharya, T. 2016. Groundwater arsenic contamination and potential health risk assessment of Gangetic Plains of Jharkhand, India. *Exposure and Health* **8**(1):125-142.

Banerjee, S., Das, B., Umlong, I.M., Devi, R.R., Kalita, H., Saikia, L.B., Borah, K., Raul, P.K. and Singh, L. 2011. Heavy metal contaminants of underground water in Indo Bangla Border Districts of Tripura, India. *International Journal of ChemTech Research* **3**(1):516-522.

Bhagure, G.R. and Mirgane, S.R. 2011. Heavy metal concentrations in ground waters and soils of Thane Region of Maharashtra, India. *Environmental Monitoring and Assessment* **173**:643-652.

Bhattacharjee, S., Chakravarty, S., Maity, S., Dureja, V. and Gupta, K.K. 2005. Metal contents in the ground water of

Sahebgunj district, Jharkhand, India, with special reference to arsenic. *Chemosphere* **58**:1203-1217.

Central Ground Water Board, Ministry of Water Resource 2014-15. Occurrence of High Arsenic Content In Ground Water, Annual Report of Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India, New Delhi.

Central Ground Water Board, Ministry of Water Resource 2015-16. Standing Committee Report on Water Resources, 16th Lok Sabha, Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India, New Delhi.

Chakraborti, D., Biswas, B.K., Roy Chowdhury, T., Basu, G.K., Mandal, B.K., Chowdhury, U.K., Mukherjee, S.C., Gupta, J.P., Chowdhury, S.R. and Rathore, K.C. 1999. Arsenic groundwater contamination and sufferings of people in Rajnandgaon district, Madhya Pradesh, India. *Current Science* **77**:502-504.

Chakraborti, D., Rahman, M.M., Paul, K., Chowdhury, U.K., Sengupta, M.K., Lodh, D., Chanda, C.R., Saha, K.C. and Mukherjee, S.C. 2002. Arsenic calamity in the Indian sub-continent-what lesions have been learned? *Talanta* **58**:3-22.

Chakraborti, D., Mukherjee, S.C., Pati, S., Sengupta, M.K., Rahman, M.M., Chowdhury, U.K., Lodh, D., Chanda, C.R., Chakraborti, A.K. and Basu, G.K. 2003. Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: A future danger? *Environmental Health Perspectives* **111:**1194-1201.

Chakraborti, D., Sengupta, M.K., Rahman, M.M., Ahamed, S., Chowdhury, U.K. and Hossain, M.A. 2004. Groundwater arsenic contamination and its health effects in the Ganga-Meghna-Brahmaputra Plain. *Journal of Environmental Monitoring* **6**:74-83.

Chakraborti, D., Singh, E.J., Das, B., Shah, B.A., Hossain, M.A., Nayak, B., Ahamed, S. and Singh, N.R. 2008. Groundwater arsenic contamination in Manipur, one of the seven North-Eastern Hill states of India: A future danger. *Environmental Geology* **56**(2):381-390.

Chakraborti, D., Ghorai, S.K., Das, B., Pal, A., Nayak, B. and Shah, B.A. 2009. Arsenic exposure through groundwater to the rural and urban population in the Allahabad-Kanpur track in the Upper Ganga Plain. *Journal of Environmental Monitoring* **11**:1455-1459.

Chakraborti, D., Rahman, M.M., Mitra. S., Chaterjee, A., Das, D., Das, B., Nayak, B., Pal, A., Chowdhury, U.K., Chowdhury, T.R., Ahmed, S., Biswas, B.K., Sengupta, M., Load, D., Das, A., Chakraborty, S., Chakraborty, R., Dutta, R.N., Saha, K.C., Mukherjee, S.C., Pati, S. and Kar, P.B. 2013a. Ground water arsenic contamination in India: A review of its magnitude, health, social, socio-economic effect and approaches for arsenic mitigation. *Journal of the Indian Society of Agricultural Statistics* **67**(2):235-266.

Chakraborti, D., Rahman, M.M., Murrill, M., Das, R., Siddayya, Patil, S.G., Sarkar, A., Dadapeer, H.J., Yendigeri, S., Ahmed, R. and Das, K.K. 2013b. Environmental arsenic contamination and its health effects in a historic gold mining area of the Mangalur greenstone belt of North-Eastern Karnataka, India. *Journal of Hazardous Materials* **262**:1048-1055.

Chakraborti, D., Rahman, M.M., Ahamed, S., Dutta, R.N., Pati, S. and Mukherjee, S.C. 2016. Arsenic contamination of groundwater and its induced health effects in Shahpur block, Bhojpur district, Bihar state, India: Risk evaluation. *Environmental Science and Pollution Research* **23**(10):9492-9504.

Chakraborty, S., Alam, M.O., Bhattacharya, T. and Singh, Y.N. 2014. Arsenic accumulation in food crops: A potential threat in Bengal Delta Plain. *Water Quality, Exposure and Health* **6**:233-246.

Chandra Sekhar, K., Chary, N.S., Kamala, C.T., Venkateswara, Rao, J., Balaram, V. and Anjaneyulu, Y. 2003. Risk assessment and pathway study of arsenic in industrially contaminated sites of Hyderabad: A case study. *Environment International* **29**:601-611.

Chetia, M. Chatterjee, S. Banerjee, S. Nath, M.J., Singh, L., Srivastava, R.B. and Sarma, H.P. 2011. Groundwater arsenic contamination in Brahmaputra river basin: a water quality assessment in Golaghat (Assam), India. *Environmental Monitoring and Assessment* **173**:371-385.

Datta, D.V. and Kaul, M.K. 1976. Arsenic content of drinking water in villages in Northern India: A concept of arsenicosis. *Journal of the Association of Physicians of India* **24**:599-604.

Dhar, R.K., Biswas, B.K., Samanta, G., Mandal, B.K., Chakraborti, D., Roy, S., Jafar, A., Islam, A., Ara, G., Kabir, S., Khan, A.W., Ahmed, S.A. and Hadi, S.A. 1997. Groundwater arsenic calamity in Bangladesh. *Current Science* **73**:48-59.

Duggal, V., Rani, A. and Mehra R. 2012. Assessment of arsenic content in groundwater samples collected from four districts of Northern Rajasthan, India. *Der ChemicaSinica* **3**(6):1500-1504.

Ghosh, A.K., Singh, S.K., Bose, N. and Chaudhary, S. 2007. Arsenic contaminated aquifers: A study of the Ganga levee zones in Bihar, India. Annual Conference 2007. Royal Geographical Society, London. Session key: BSG-Session 3, August, 29-31.

Ghosh, A., Singh, S.K., Bose, N., Roy, N.P., Singh, S.K., Upadhyaya, A.K., Kumar, S. and Singh, A. 2009. Arsenic hotspots detected in Patna District, Bihar (India): A serious health hazard for estimated population of 5.5 lakhs, *Assessment of Ground Water Resources and Management,* International Publishing House, New Delhi, pp. 62-70 IK.

Goswami, R., Rahman, M.M., Murrill, M., Sarma, K.P., Ritu, T. and Chakraborti, D. 2014. Arsenic in the groundwater of Majuli-The largest river island of the Brahmaputra: Magnitude of occurrence and human exposure. *Journal of Hydrology* **518**:354-362.

Govil, P.K., Reddy, G.L.N. and Krishna, A.K. 2001. Contamination of soil due to heavy metals in the Patancheru industrial development area, Andhra Pradesh, India. *Environmental Geology* **41**:461-469.

Gurunadha Rao, V.V.S., Dhar, R.L. and Subramanyam, K. 2001. Assessment of contaminant migration in ground water from an industrial development area, Medak district Andhra Pradesh, India. *Water, Air and Soil Pollution* **12**:369-389.

Hazarika, S. and Bhuyan, B. 2013. Assessment of groundwater quality with reference to fluoride, arsenic and iron in tea garden belt of Lakhimpur district, Assam, India. *Pelagia Research Library Advances in Applied Science Research* **4**(2):93-97.

Hossain, M.A., Sengupta, M.K., Ahamed, S., Rahman, M.M., Mondal, D., Lodh, D., Das, B., Nayak, B., Roy, B.K., Mukherjee, A. and Chakraborti, D. 2005. Ineffectiveness and poor reliability of arsenic removal plants in West Bengal, India. *Environmental Science Technology* **39**(11):4300-4306.

Hossain, M.A., Mukherjee, A., Sengupta, M.K., Ahamed, S., Das, B., Nayak, B., Pal, A., Rahman, M.M. and Chakraborti, D. 2006. Million dollar arsenic removal plants in West Bengal, India: Useful or not? *Water Quality Research Journal of Canada* **41**(2):216-225.

Hossain, M.F. 2006. Arsenic contamination in Bangladesh: An overview. *Agriculture, Ecosystems and Environment* **113**:1-16.

Hundal, H.S., Kumar, R., Singh, K. and Singh, D. 2007. Occurrence and geochemistry of arsenic in groundwater of Punjab, North-West India. *Communications in Soil Science and Plant Analysis* **38**:2257-2277.

Katiyar, S. and Singh, D. 2014. Prevalence of arsenic exposure in population of Ballia district from drinking water and its correlation with blood arsenic level. *Journal of Environmental Biology* **35**:589-594.

Kaur, P., Singh, I. and Kaur, P. 2015. Arsenic contamination in groundwater of Punjab: An overview. *Journal of Applied Science* **1**(1):1-6.

Kishan, R.A. 2001. Patancheru: A hell on earth. Patancheru: AVRR Memorial Charitable Trust, pp. 26.

Kumar, S., Baier, K., Jha, R. and Azzam, R. 2013. Status of arsenic contamination in potable water of Northern areas of Mizoram state and its adjoining areas of Southern Assam, India. *Arabian Journal of Geosciences* **6**:383-393.

Kumar, S., Pandey, G. and Sharma, A. 2014. Assessment of arsenic in groundwater of Gorakhpur district in Uttar Pradesh (India). *International Journal of Engineering Research and Technology* **3**(12):766-770.

Lalwani, S., Dogra, T.D., Bhardwaj, D.N., Sharma, R.K., Murty, O.P. and Vij, A. 2004. Study on arsenic level in ground water of Delhi using hydride generator accessory coupled with atomic absorption spectrophotometer. *Indian Journal of Clinical Biochemistry* **19**(2):135-140.

Mandal, B.K. and Suzuki, K.T. 2002. Arsenic round the world: A review. *Talanta* **58**:201-235.

Manimaran, D. and Manimaran, G. 2013. Arsenic contamination of groundwater in Vallanadu region of Tuticorin district, Tamil Nadu, India. *Online International Interdisciplinary Research Journal* **3**(4):230-242.

Mondal, P., Majumdar, C.B. and Mohanty, B. 2006. Laboratory based approaches for arsenic remediation from contaminated water: Recent developments. *Journal of Hazardous Materials* **137**:464-479.

Mukherjee, A., Sengupta, M.K., Hossain, M.A., Ahamed, S., Das, B., Nayak, B., Lodh, D., Rahman, M.M. and Chakraborti, D. 2006. Arsenic contamination in groundwater: A global perspective with emphasis on the Asian scenario. *Journal of Health, Population and Nutrition* **24**(2):142-163.

Nath, A., Vendan, P.S.E., Kumar, S., Kumar, A. and Singh, J.K. 2013. Toxicity due to arsenic in Gangetic zone of Patna, India and its linkage with cancer. *Journal of Environmental and Analytical Toxicology* **3**:6.

Nathan, S.D., Manil, K.R., Sivamurthy Reddy, S., Sivasankaran, M.A. and Ramesh, R. 2012. Trace elements in groundwater of coastal aquifers of Pondicherry region, India. *Journal of Environment* **1**(4):111-118.

Nayaka, B., Bhaskar, D., Mukherjee, S.C., Pal, A., Ahamed, S., Hossain, M.A., Maity, P., Dutta, R.N., Dutta, S. and Chakraborti, D. 2007. Ground water arsenic contamination in the Sahibganj district of Jharkhand state, India in the middle Ganga plain and adverse health effects. *Toxicological and Environmental Chemistry* **90**(4):673-694.

Nickson, R.T., McArthur, J.M., Burgess, W.G., Ahmed, K.M., Ravenscroft, P. and Rahman, M., 1998. Arsenic poisoning of Bangladesh groundwater. *Nature* **395**:338.

Nickson, R.T., McArthur, J.M., Ravenscroft, P., Burgess, W.G. and Ahmed, K.M. 2000. Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. *Applied Geochemistry* **15**:403-413.

Pandey, P.K., Sharma, R., Roy, M., Roy, S. and Pandey M. 2006. Arsenic contamination in the Kanker district of Central-East India: Geology and health effects. *Environmental Geochemistry and Health* **28**:409-420.

Pandey, P.K., Deshmukh, R., Zankyani, H. and Pandey, M. 2013. Arsenic contamination and its causative factors in parts of Chhattisgarh, Central East India. *International Journal of Water* **7**(4):347-362.

Pfeifer, H.R., Girardet, A.G., Reymond, D., Schlegel, C., Temgona, E., Hesterberg, D.L. and Chou, J.W. 2004. Dispersion of natural arsenic in the Malcantone Watershed South Switzerland: Field evidence for repeated sorption-desorption and oxidation-reduction processes. *Geoderma* **122**:205-234.

Puzari, A., Khan, P., Thakur, D., Kumar, M., Shanu, K., Chutia, P. and Ahmed, Z. 2015. Quality assessment of drinking water from Dimapur district of Nagaland and Karbi-Anglong district of Assam for possible related health hazards. *Current World Environment* **10**(2):634-640.

Rahman, M.M., Mandal, B.K., Roy Chowdhury, T., Sengupta, M.K., Chowdhury, U.K., Lodh, D., Chanda, C.R., Basu, G.K., Mukherjee, S.C., Saha, K.C. and Chakraborti, D. 2003. Arsenic groundwater contamination and sufferings of people in North 24 Parganas, one of the nine arsenic affected districts of West Bengal, India: The seven years study report. *Journal of Environmental Science and Health, Part A* **38**:25-59.

Rahman, M.M., Sengupta, M.K., Ahamed, S., Chowdhury, U.K., Lodh, D., Hossain, M.A., Das, B., Saha, K.C., Kaies, I., Barua, A.K. and Chakraborti, D. 2005. Status of groundwater arsenic contamination and human suffering in a Gram Panchayet (cluster of villages) in Murshidabad, one of the nine arsenic affected districts in West Bengal, India. *Journal of Water and Health* **3**(3):283-296.

Rahman, M.M., Mondal, D., Das, B., Sengupta, M.K., Ahamed, S., Hossain, M.A., Samal, A.C., Saha, K.C., Mukherjee, S.C., Dutta, R.N. and Chakraborti, D. 2014. Status of groundwater arsenic contamination in all 17 blocks of Nadia district in the state of West Bengal, India: A 23-year study report. *Journal of Hydrology* **518**:363-372.

Saha, D., Dwivedi, S.N. and Sahu, S. 2009. Arsenic in ground water in parts of Middle Ganga Plain in Bihar: An appraisal. Central Ground Water Board, North Central Chhattisgarh region, Raipur. *Bhujal New* (Special Issue) **24**(2-3):87-99.

Sengupta, M.K., Ahamed, S., Hossain, M.A., Rahman, M.M., Lodh, D. and Das, B. 2004. Increasing trend in hand tube-wells and arsenic concentration in affected areas of West Bengal, India: A future danger. *5th International Conference on Arsenic: Developing Country's Perspective on Health, Water and Environmental Issues*, Dhaka, Bangladesh, February 14-16.

Shah, B.A. 2010. Arsenic-contaminated groundwater in Holocene sediments from parts of Middle Ganga Plain, Uttar Pradesh, India. *Current Science* **98**(10):1359-1365.

Shirke, K.D. and Pawar, N.J. 2015. Enrichment of arsenic in the quaternary sediments from Ankaleshwar industrial area, Gujarat, India: An anthropogenic influence. *Environmental Monitoring and Assessment* **187**(9):593.

Shukla, D.P., Dubey, C.S., Singh, N.P., Tajbakhsh, M. and Chaudhry, M. 2010. Sources and controls of arsenic contamination in groundwater of Rajnandgaon and Kanker District, Chhattisgarh, Central India. *Journal of Hydrology* **395**:49-66.

Sidhu, M., Mahajan, P. and Bhatt, S.M. 2014. Highly sensitive and low cost colorimetric method for quantifying arsenic metal in drinking water of Malwa, Punjab and comparison with ICAP-AES. *Annals of Biological Research* **5**(3):105-109.

Singh, A.K. 2004. Arsenic contamination in groundwater of North-Eastern India. *Proceedings of National seminar on Hydrology with focal theme on "Water Quality"* held at National Institute of Hydrology, Roorkee, pp. 1-8.

Singh, S.K. and Ghosh, A.K. 2012. Health risk assessment due to groundwater arsenic contamination: Children are at high risk. *Human and Ecological Risk Assessment: An International Journal* **18**(4):751-766.

Singh, S.K., Ghosh, A.K., Kumar, A., Kislay, K., Kumar, C., Tiwari, R.R., Parwez, R., Kumar, N. and Imam, M.D. 2014. Groundwater arsenic contamination and associated health risks in Bihar, India. *International Journal of Environmental Research* **8**(1):49-60.

Smedley, P.L. and Kinniburgh, D.G. 2002. A review of the source, behaviour and distribution of arsenic in natural waters. *Applied Geochemistry* **17**:517-568.

SOES 2012. School of environmental studies, groundwater arsenic contamination in Middle Ganga Plain, Bihar, India: A future danger? School of Environmental Science, Jadavpur University, Kolkata, India.

State Ground Water Report, Tamil Nadu 2014. An Overview of Arsenic in Groundwater, Tamil Nadu, Government of Tamil Nadu. Water Resources Department (www.groundwatertnpwd.org.in).

WHO 1993. World Health Organization. Guidelines for drinking-water quality. 2nd Ed., Geneva.

Yano, Y., Kenichi, I., Akihiko, K., Koichiro, S., Shigeki, T., Mitsuhiro, S. and Hiroshi, Y. 2012. Arsenic polluted groundwater and its countermeasures in the middle basin of the Ganges, Uttar Pradesh State, India. *Journal of Environmental Protection* **3**:856-862.