Groundwater Arsenic Contamination in India: Vulnerability and Scope for Remedy

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Abstract

Arsenic contamination in groundwater in the Ganga- Brahmaputra fluvial plains in India and Padma-Meghna fluvial plains in Bangladesh and its consequences to the human health have been reported as one of the world's biggest natural groundwater calamities to the mankind. In India, seven states namely- West Bengal, Jharkhand, Bihar, Uttar Pradesh in the flood plain of the Ganga River; Assam and Manipur in the flood plain of the Brahamaputra and Imphal rivers and Rajnandgaon village in Chhattisgarh state have so far been reported affected by Arsenic contamination in groundwater above the permissible limit of 10 μg/L. People in these affected states have chronically been exposed to drinking Arsenic contaminated hand tube-wells water. With every new survey, more Arsenic affected villages and people suffering from Arsenic related diseases are being reported, and the issues are getting complicated by a number of unknown factors. These fluvial plains represent Holocene aquifers of recent alluvial sediments and have the routes originated from the Himalayan region. Arsenic groundwater contamination has far-reaching consequences including its ingestion through food chain which are in the form of social disorders, health hazards and socio-economic dissolution besides its sprawling with movement, and exploitation of groundwater. Arsenic contamination is understood to be of geogenic origin released from soil under conditions conducive to dissolution of Arsenic from solid phase on soil grains to liquid phase in water, and percolation of fertilizer residues might have played a modifying role in its further exaggeration. There are a number of hypotheses about the source of Arsenic and probable reasons of occurrence in groundwater. Over the last 25 years since the groundwater Arsenic contamination was first surfaced in the year 1983, a number of restorative and precautionary measures coupled with action plans focusing mainly on detailed investigations to understand the physiochemical process and mechanism, alternate arrangement to supply Arsenic free water to the affected populace and development of devices for Arsenic removal and their implementation at the field, etc. have been initiated mainly in West Bengal while in other States, they are meager. Despite a number of corrective and precautionary measures, the spread of Arsenic contamination in groundwater continued to grow and more new areas were added to the list of contaminated area. The problem resolving issues, thus, seemed to be partial and inadequate, which need to be strengthened by strategic scientific backing. Numerous investigators have come out with a number of findings, and alternatives propositions, which varied from identification of shortfalls to success stories. The present state of affairs of the Arsenic menace in India demand a systematic translation of success stories of one place/region to another, and overcoming the shortfalls by conceiving R&D studies in areas wherever deemed fit. Advancement in understanding of geochemical and mobilization processes, devising satisfactory Arsenic removal filters, identification of shortfalls in operation and maintenance of Arsenic removal techniques, delineation of risk free deeper aquifers as an alternate source of groundwater, developing surface water based water supply schemes in many Arsenic affected areas, success stories of community participation in running Arsenic removal plants, etc. are some of the important achievements, which could help derive a comprehensive framework of activities leading to mitigation and remediation of the issues emerging out of Arsenic menace. The paper is thus aimed at highlighting the state-of-affairs of Arsenic groundwater contamination in India along with narration of various corrective and precautionary measures taken up so far

by different states and success achieved and failure experienced. The paper would also discuss the gaps and areas in which further actions are to be taken up and their scope.

1. Introduction

Arsenic **(As)** is introduced into soil and groundwater during weathering of rocks and minerals followed by subsequent leaching and runoff. It can also be introduced into soil and groundwater from anthropogenic sources. Many factors control arsenic concentration and transport in groundwater, which include: Red-ox potential (Eh), adsorption/ desorption, precipitation/dissolution, Arsenic speciation, pH, presence and concentration of competing ions, biological transformation, etc. The adsorption and desorption reactions, arsenic species, Eh, pH and solid-phase dissolutions and precipitations may vary from aquifer to aquifer that depend upon the geological settings, geo-chemistry and geo-environmental conditions of an aquifer. Therefore, rigorous geochemical investigation for adequate understanding of arsenic geochemistry under different hydrogeological and geo-environmental conditions of aquifers is essentially required for evolving sustainable solutions.

In India, since the groundwater arsenic contamination was first surfaced from West-Bengal in 1983, a number of other States, namely; Jharkhand, Bihar, Uttar Pradesh in flood plain of the Ganga River; Assam and Manipur in flood plain of the Brahamaputra and Imphal rivers, and Rajnandgaon village in Chhattisgarh state have chronically been exposed to drinking arsenic contaminated hand tube-wells water above permissible limit of 50 μg/L. Many more North-Eastern Hill States in the flood plains are also suspected to have the possibility of arsenic in groundwater. Even with every additional survey, new arsenic affected villages and people suffering from arsenic related diseases are being reported. All the arsenic affected river plains have the river routes originated from the Himalayan region. Whether or not the source material has any bearing on the outcrops is a matter of research, however, over the years, the problem of groundwater arsenic contamination has been complicated, to a large variability at both the local and regional scale, by a number of unknown factors.

Arsenic groundwater contamination has far-reaching consequences including its ingestion through food chain, which are in the form of social disorders, health hazards and socioeconomic dissolution besides its sprawling with movement, and exploitation of groundwater. The food crops grown using arsenic contaminated water are sold off to other places, including uncontaminated regions where the inhabitants may consume arsenic from the contaminated food. This may give rise to a new danger.

In order to combat arsenic menace, a number of counteractive measures, steps and research studies have been initiated and put into practice mainly in West Bengal, while in other States, they are meager. The measures and steps have mainly been focused towards providing arsenic free drinking water to the entire population in the arsenic infested areas by arrangement of alternate freshwater sources and by treating contaminated groundwater using arsenic removal techniques. During the last three decades, substantial amount of R & D work has been done to enrich knowledge in respect of the following:

- *The source and cause of Arsenic contamination in groundwater.*
- *Extent and magnitude of the contamination in groundwater.*
- *Mechanism of dissolution of Arsenic from soil to groundwater.*
- *Impact on Community Health: Diagnosis of sickness and symptoms.*

- *Development of technologies for removal of arsenic from groundwater.*
- *Analytical techniques for detecting arsenic from groundwater.*

How far the counteractive measures and steps, initiated by the Government, are effective in terms of restoring, resolving and remediation of the problem, attaining sustainability to combat the menace, understanding the physical processes, etc. needs a critical appraisal to ensure its effective implementation in other arsenic contaminated areas. Needless to state that a comprehensive understanding of the above aspects would go a long way in developing immediate, interim and long term strategy and to address the problem. However, the concerns are: (i) whether available knowledge, understanding and technologies are adequate to achieve sustainable solution of the arsenic remedy for different hydro geological setups? (ii) as to how to proceed for envisaging alternate feasible solutions? (iii) whether ex-situ removal techniques are feasible solution, and how it can be made more cost effective, eco-friendly and socially acceptable? (iv) what are the feasible solutions for in-situ remedy of arsenic from contaminated aquifers? etc. After all, arsenic safe groundwater is to be made available to meet demands for both domestic and agricultural requirement in arsenic affected and arsenic vulnerable areas.

The present paper thus deals mainly with: (i) up to date status of arsenic menace in India, (ii) state-of-the-art of scientific knowledgebase, understanding and technologies available from both national & international perspectives, (iii) technologies in place, (v) preventive and corrective measures taken so far and results thereof, (v) shortcomings, and possibility of employing success stories of one place to another region, (iv) further work to be undertaken.

2. Arsenic Menace in India

Since groundwater arsenic contamination was first reported in year 1983 from 33 affected villages in four districts in West-Bengal, the number of villages has increased to 3417 in 111 blocks in nine districts till 2008 in West Bengal alone. In 1999, the arsenic groundwater contamination and its health effects in Rajnandgaon district of Chattisgarh state were also detected. In 2002, two villages, Barisban and Semaria Ojhapatti, in Bhojpur district, located in the western part of the Bihar state, were reported having contamination exceeding 50μg/L. As of 2008, out of 38 districts of Bihar, 57 blocks from 15 districts having total population nearly 10 million have been reported affected by arsenic groundwater contamination above 50μg/L. During 2003, 25 arsenic affected villages of Ballia district in Uttar Pradesh and people suffering from skin lesions came into limelight. During 2003-2004, the groundwater arsenic contamination and consequent suffering of hundreds of people were reported from 17 villages of the Sahibgunj district of Jharkhand state, in the middle Ganga plain. In 2004, arsenic concentration was also reported from Assam in pockets of 2 districts. In 2007, Manipur state, one of the seven North-Eastern Hill States, had also come into limelight of arsenic contamination in groundwater. Many more North-Eastern Hill States in the flood plains are also suspected to have the possibility of arsenic in groundwater.

As of 2008, West Bengal, Jharkhand, Bihar, Uttar Pradesh in flood plain of Ganga River; Assam and Manipur in flood plain of Brahamaputra and Imphal rivers, and Rajnandgaon village in Chhattisgarh state have so far been exposed to drinking arsenic contaminated hand tube-wells water. The area and population of these states are 529674 km^2 & approx. 360 million respectively, in which 88688 km^2 and approximately 50 million people have been projected vulnerable to groundwater arsenic contamination. Almost all the identified arsenic affected areas in the Gangetic plains except areas in Chhattisgarh and 3 districts in Bihar namely, Darbhanga, Purnea and Kishanganj, are in a linear tract on either side of the River Ganga in UP, Bihar, and

Jharkhand, and the River Bhaghirathi in West Bengal; while the areas in Assam and Manipur are in the flood plains of the Brahmaputra and Barack, respectively (Fig. 1). Analysis of 1,69,698 hand tube-well water samples from all these 7 states for arsenic detection by School of Environmental Studies, Jadavpur University (SOES, JU) reported presence of arsenic in 45.96% and 22.94% of the water samples more than 10 µg/L (WHO guideline value of arsenic in drinking water) and 50µg/L (Indian standard of arsenic in drinking water), respectively. Importantly, 3.3% of the analyzed tube-wells had been found arsenic concentrations above 300µg/L, the concentration predicting overt arsenical skin lesions. CGWB, State PHED, WB and Bihar, and other organizations also analyzed quite a large number of water samples.

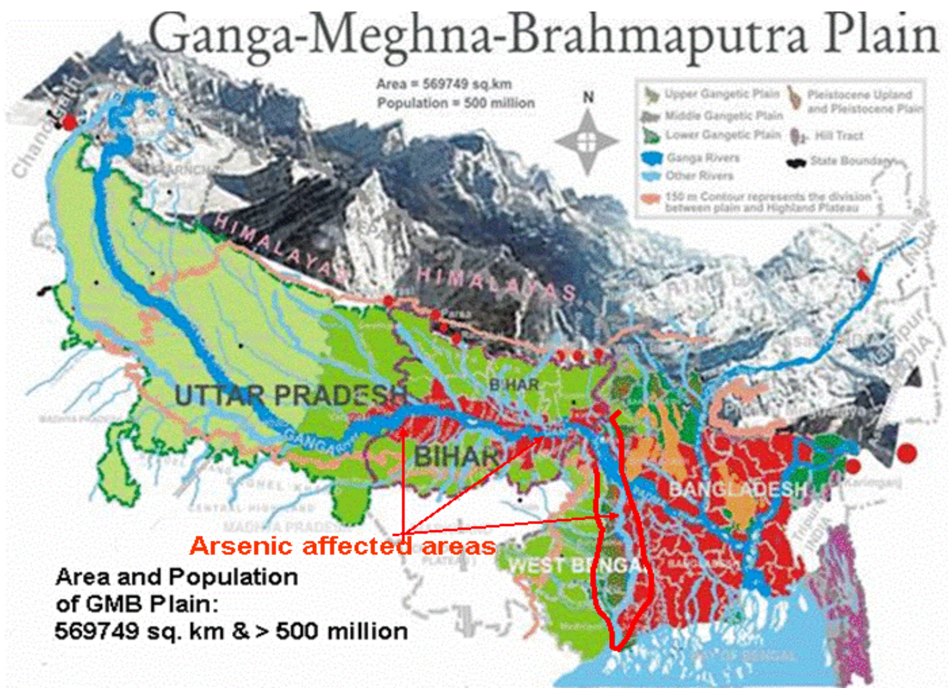

Figure 1: Arsenic affected stretches in Ganga Plains in India with reference to Ganga-Meghna-Brahmaputra Plains.

Agricultural water requirements in most of the rural areas are met from groundwater source. In arsenic affected areas often arsenic contaminated groundwater is used for agricultural irrigation resulting in excessive amount of available arsenic in the crops in those areas. Many researchers reported that food is the second largest contributor to arsenic intake by people after direct ingestion of arsenic contaminated water. In food, rice is the maximum sensitive to arsenic followed by vegetables. Most of the arsenic affected states use rice as its staple food. Recently, possibility of arsenic exposure through food chain is also considered not only in contaminated areas but also in uncontaminated areas due to open market. This eventually indicates that the effects of this occurrence have far-reaching consequences; sooner we search sustainable solutions to resolve the problem, lesser be its future environmental, health, socioeconomic and socio-cultural hazards.

Various types of skin manifestations and other arsenic toxicity were observed from melanosis, keratosis, hyperkeratosis, dorsal keratosis, and non pitting edema to gangrene and cancer. Overall prevalence of clinical neuropathy was noted in various studies in populations of 24- Pargana-North, 24- Pargana-South, Murshidabad, Nadia, and Bardhaman districts of West Bengal and in the states of Bihar, Uttar Pradesh, Jharkhand and Chhattisgarh. The children in the arsenic contaminated areas are often more affected than the adults. Most of the population suffering from arsenic skin lesions is from a poor socio-economic background. The following features were commonly noted (1983-2006) from the arsenic endemic areas of India:

(i) *Skin itching to sun rays, burning and watering of eyes, weight loss, loss of appetite, weakness, lethargy and easily fatigued limited the physical activities and working capacities,*

(ii) *Chronic respiratory complaints were also common. Chronic cough with or without expectoration was evident in more than 50%,*

(iii) *Gastrointestinal symptoms of anorexia, nausea, dyspepsia, altered taste, pain in abdomen, enlarged liver and spleen, and ascites (collection of fluid in abdomen),*

(iv) *Moderate to severe anemia was evident in some cases,*
(v) *Conjunctival congestion, Leg edema was less common.*

If we focus on the dimension of the emerged problem, the points arising before us are: (i) a large number of people have been exposed to arsenic groundwater contamination and its consumptions in various forms of usages, (ii) with persistence usages of groundwater from vulnerable aquifers, having deposit of source material, number of arsenic detected areas has increased with continuing survey of new areas, (iii) what are the sources, causes and mechanisms of groundwater arsenic contamination ?, (iv) how the problem has been triggered? (v) how could people, livestock and groundwater dependant usages be safeguarded from hazards of arsenic contamination? (vi) what alternate planning and management of water resources in those affected and vulnerable areas are to be adopted? (vii) what remediation/corrective measures are necessary to restore the affected aquifers? (viii) what short-term and long-term planning and management strategies are to be put in place? etc.

3. Sources of Arsenic in Ganga–Brahmaputra Aquifers

There is no proof regarding the natural emission of **As** in the Ganga–Brahmaputra plains so far. However, the release of **As,** by the natural processes in groundwater, has been recognized, from the Holocene sediments comprising sand, silt and clay (Bhattacharya et al., 1997; McArthur et al., 2004) in parts of the Bengal Delta Plains (BDP), West Bengal and in the Gangetic plains of Bihar. Several isolated geological sources of **As** have been recognized, viz. Gondwana coal seams in Rajmahal basin (200 mg/kg of As), Bihar mica-belt (0.08–0.12% of As), pyrite-bearing shale from the Proterozoic Vindhyan range (0.26% of As), Son valley gold belt (2.8% of **As**) and Darjeeling Himalayas belt (0.8% of As) (Bhattacharya et al., 2002; Acharyya et al., 1993; Acharyya et al., 1999; BGS/MML, 1999). The contaminated aquifers are of Quaternary age and comprise micaceous sand, silt and clay derived from the Himalayas and basement complexes of eastern India. These are sharply bound by the River Bhagirathi-Hooghly (distributary of the River Ganges) (Bhattacharyya et al., 2005) in the west, the rivers, Ganges and Padma in the north, the flood plain of the River Meghna (tributary of the River Padma), and the River Yamuna in the northeast (Acharyya et al., 2000).

The actual source of groundwater arsenic contamination, in the Ganga–Brahmaputra basin, is yet to be established. The sources of arsenic are natural or may partly stem from anthropogenic activities like intense exploitation of groundwater, application of fertilizers, burning of coal and leaching of metals from coal-ash tailings. The hypotheses about the sources of arsenic in the BDP are as follows:

(i) *Arsenic, transported by the River Ganges and its tributaries from the Gondwana coal, seams in the Rajmahal trap area located at the west of the basin can be of the order of 200 ppm. (Saha, 1991).*
(ii) *Arsenic is transported by the north Bengal tributaries of Bhagirathi and Padma from near the Gorubathan base-metal deposits in the eastern Himalayas (Ray, 1999).*
(iii) *Arsenic is transported with the fluvial sediments from the Himalayas (e.g., McArthur et al., 2004). This is the most accepted hypothesis at present.*

4. Occurrences of Arsenic in Groundwater

Several studies suggested that the groundwater arsenic contamination is mostly restricted to the alluvial aquifers of the Ganges delta comprising sediments carried from the sulphide-rich mineralized areas of Bihar and elsewhere surrounding the basin of deposition (Bhattacharya *et al*., 1997; Das *et al.*, 1995). However, recent studies indicated that the vast tract of Indo-Gangetic alluvium extending further to the west and the Brahmaputra alluvium have elevated concentrations of arsenic in wells placed in the late Quaternary and Holocene aquifers. Arsenic released during the weathering of sulphide minerals is generally adsorbed onto the surface of iron oxy-hydroxides that precipitated under oxidizing conditions normally prevailing during the deposition of the Holocene sediments. However, redox processes in the sediments triggered the reductive dissolution of iron oxides that transferred substantial amounts of arsenic in aqueous phases through biogeochemical interactions (Amaya, 2002; Smedley and Kinniburgh, 2002). Arsenic-containing groundwater in Ganga–Brahmaputra River basin is hosted by the sediments deposited by the rivers during the late Quaternary or Holocene age (< 12 thousand years). Lithology of those late Quaternary sediments includes sands, silt and clay. Mineralogical composition of those sediments consists of quartz, feldspars, illite and kaolinite and the fine-grained over bank facies are rich in organic matter (Nickson et al., 1998; Ahmed, 1999; Datta and Subramanian, 1998; Sikdar and Banerjee 2003). There is a thick layer of newer alluvium containing sand, silt and clay, which spread out by numerous rivers that originate from the Himalayas both in the north and northeast. Most environmental arsenic problems, recognized so far, are the result of mobilization under natural conditions. Thus, the occurrence of arsenic in groundwater in the BDP and Gangetic plains has been recognized as of geological origin with spread out resulting from the mobilization under natural hydro-geologic conditions.

5. Mobilization Mechanisms of As

In most studied areas it was seen that high-arsenic groundwater was not related to areas of high arsenic concentration in the source rock. Two key factors were identified: first, there should be very specific biogeochemical triggers to mobilize arsenic from the solid/sorbed phase to groundwater, and second, the mobilized arsenic should have sufficient time to accumulate and not be flushed away, that is, it should be retained in the aquifer (Smedley and Kinniburgh, 2002). In other words, arsenic released from the source should be quick, relative to the rate of groundwater flushing. There are number of processes for mobilization of arsenic in groundwater namely, (i) mineral dissolution, (ii) desorption of arsenic under alkaline and oxidizing conditions, (iii) desorption and dissolution of arsenic under reducing conditions, (iv) reduction of oxide mineral surface area, and (v) reduction in bond strength between arsenic and holt mineral surface (Smedley and Kinniburgh, 2002).

Oxidation of sulphide minerals (pyrite-FeS_2) was advocated strongly by many investigators in West Bengal as the cause of groundwater arsenic contamination (Das et al., 1994). According to this hypothesis, arsenic is released from the sulfide minerals (arseno-pyrite) in the shallow aquifer due to oxidation (Mandal et al., 1998). The lowering of water table owing to over exploitation of groundwater for irrigation is the cause of release of arsenic. A recent research study explained that desorption or dissolution of arsenic from iron oxides could be the process on regional distributions of arsenic in water (Smedley, 2004). Broadly, it can be stated that some critical reactions to transform to reducing conditions and subsequent arsenic release are likely to take place to reduce arsenic from its oxidized (As(V)) form to its reduced (As(III)) form. Under many conditions, As (III) is less strongly adsorbed to iron oxides than As (V). Dissolution of the iron oxides themselves under reducing conditions is another potentially important process. Some investigators explained that excessive use of water for irrigation and use of fertilizers have caused mobilization of phosphate from fertilizers down below the shallow aquifers, which have resulted in the mobilization of **As** due to anion exchange onto the reactive mineral surfaces. Sikdar and Chakraborty (2008) attributed that the combined processes of recharge of groundwater from rainfall, sediment water interaction, groundwater flow, infiltration of irrigation return water (which is arsenic rich due to the use of arsenic-bearing pesticides, wood preservatives, etc. and the pumping of arsenic-rich groundwater for agriculture purpose), oxidation of natural or anthropogenic organic matter and the reductive dissolution of ferric iron and manganese oxides, played a key role in the evolution of groundwater arsenic contamination in the area. Recently, a new hypothesis based on displacement of arsenic by dissolved bicarbonate as an alternative mechanism for the genesis of high-arsenic groundwater has been proposed (Smedley and Kinniburgh, 2002). It seems that there are number of hypotheses, which have their own discrepancies and limitations to explain the physical processes.

A number groundwater arsenic modeling studies was carried out (NIH and CGWB, 2001; Majumdar et al., 2002; Michael and Voss,2008; Paul and Sikdar,2008) to understand chemistry of arsenic with regard to its occurrence, release, dissolution, sorption, mechanism, etc. in soil-water phases at local scale. However, the findings of numerical modeling have remained mere exercises with number of 'ifs and buts' owing to lack of proper understanding of chemistry of arsenic in the geo-environmental and geochemical processes. The points primarily advocated in most of the modeling studies are: (i) sources of arsenic in groundwater system are in-situ and in localized patches, and their mobilization is governed by exploitation of the groundwater regime, (ii) by adopting judicious aquifer management, arsenic free groundwater can be tapped for a long period with no risk of perturbing arsenic contaminated zones, and (iii) tapping of deep uncontaminated aquifer and freshwater zones in conjunction with surface water source may ensure supply of arsenic free water both for drinking and agricultural requirement.

Although there are number of hypotheses explaining chemical processes of groundwater arsenic contamination, however, the most commonly believed chemical processes are dissolution. Among few hypotheses proposed to explain the possible mechanism of arsenic groundwater contamination, most scientists have settled down to two hypotheses: (i) oxidation of arsenopyrite or arsenic rich pyrite in soil strata, and (ii) reductive dissolution of arsenic from soils. However, based on arsenic geochemistry, three hypotheses describing probable mechanisms of As mobilization in groundwater specially, with reference to Holocene aquifers like in West Bengal and Bangladesh, have been suggested (Bose and Sharma, 2002). These are:

(i) Mobilization of arsenic due to the oxidation of **As**-bearing pyrite minerals: Insoluble **As**-bearing minerals, such as Arsenopyrite (FeAsS), are rapidly oxidized when exposed to atmosphere, realizing soluble As(III), sulfate (SO_4^{2-}), and ferrous iron (Fe^{2+}). The dissolution of these **As**-containing minerals is highly dependent on the availability of oxygen and the rate of oxidation of sulfide. The released As(III) is partially oxidized to As(V) by microbially mediated reactions. The chemical reaction is given by:

$$\mathbf{FeAsS + 13\,Fe^{3+} + 8\,H_2O \longrightarrow 14\,Fe^{2+} + SO_4^{2-} + 13\,H^+ + H_3AsO_4\,(aq.)}$$

(ii) Dissolution of **As**-rich iron oxyhydroxides (FeOOH) due to onset of reducing conditions in the subsurface: Under oxidizing conditions, and in the presence of **Fe**, inorganic species of **As** are predominantly retained in the solid phase through interaction with FeOOH coatings on soil particles. The onset of reducing conditions in such environments can lead to the dissolution of FeOOH coatings. Fermentation of peat in the subsurface releases organic molecules (e.g., acetate) to drive reducing dissolution of FeOOH, resulting in release of Fe^{2+}, As^{+3}, and As^{+5} present on such coatings. The chemical reaction is given by:

$$\mathbf{8FeOOH - As_{(s)} + CH_3COOH + 14\,H_2CO_3 \longrightarrow 8\,Fe^{2+} + As_{(d)} + 16\,HCO_3^- + 12\,H_2O}$$

where $As_{(s)}$ is sorbed As, and $As_{(d)}$ is dissolved As**.**

(iii) Release of **As** sorbed to aquifer minerals by competitive exchange with phosphate ($H_2PO_4^-$) ions that migrate into aquifers from the application of fertilizers to subsurface soil.

The second mechanism involving dissolution of FeOOH under reducing conditions is considered to be the most probable reason for excessive accumulation of **As** in groundwater.

6. Technological Options and Arsenic Removal Technologies

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 all:

i) *In-situ remediation of arsenic from aquifer system,*
ii) *Ex-situ remediation of arsenic from tapped groundwater by arsenic removal technologies,*
iii) *Use of surface water source as an alternative to the contaminated groundwater source,*
iv) *Tapping alternate safe aquifers for supply of arsenic free groundwater.*

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 not only be an exercise of throwing stone in the dark but would also be very expensive and a difficult task because of the size of the plan and the absence of complete understanding of the physico-chemical and geochemical processes and behavior of aquifer system,.

Ex-situ remediation of arsenic from tapped groundwater, by suitable removal technologies, seems to be a short-term option to provide potable arsenic free groundwater for domestic use only. But this would prove expensive and unsustainable for supply of irrigation water. Nevertheless, ex-situ technologies can only remove the arsenic from tapped groundwater but not from the aquifer system. The advantage of this approach is that it can be located on site.

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 populace.

Tapping alternate 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 mobilization of arsenic in the aquifer, both on spatial and temporal scale, due to forcing perturbation.

Out of the above options, arsenic removal technologies and ex-situ treatment technique are being practiced widely both in India and Bangladesh, to provide potable water to the people in the arsenic affected areas after treatment of contaminated groundwater. Their large scale use in West Bengal, based on different operating principles, with various degrees of success and failure, has been reported.

Conventional Arsenic Removal Technologies

A variety of treatment technologies, based on oxidation, co-precipitation, adsorption, ion exchange and membrane process, has been developed and are available for removal of arsenic from contaminated water. 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.

The arsenic removal devices developed by different agencies, and applied to treat for removing arsenic from arsenic contaminated groundwater with some degree of success are given in Table 1 .

Table 1: Arsenic removal devices applied for removal of arsenic from contaminated groundwater

Name of the device	**Operation principle**	**Filter media**	**System**	**Performance**
RPM/ Alcan AAFS -50 media by RPM Marketing Pvt. Ltd., Kolkata	Adsorption	Activated Alumina + AAFS-50.	The purification system consists of two containers; one to remove mud and suspended particles and other one consists of AAFS-50 media to remove arsenic and heavy metal.	Although the design and model are user friendly but has mixed feelings on performance. Media replacement had showed lesser efficiency than the original.
Bucket of Resins (BOR) of Water Systems International , USA by Harmonite Impex (Pvt.) Ltd., Kolkata.	Ion Exchange	Bucket of Resins	The unit 'BOR' is a rectangular container of 40 inches long, 26 inches wide, and 40 inches height attached to a tube well hand pump. The container consists of 3 cylinders to process various phases of oxidation and absorption. The system has provision of backwashing depending on content of arsenic and iron.	Field performance of the system was below satisfactory level and inconsistent.
Granular Ferric Hydroxide (GFH) of Pal Trockner (P) Ltd., Kolkata – a German Technology	Adsorption	Granular Ferric Hydroxide (GFH)	The system is based on GFH and user friendly. It does not require complicated dosing of chemicals and claimed to be non-toxic and non-hazardous.	Satisfactory performance, and less cost on operation and maintenance.

Arsenic Removal Plant by Oxide India (Catalysts) Pvt. Ltd, Durgapur	Adsorption	Activated Alumina , AS-37	The system is made of stainless steel, AISI-304. It has a back wash system and removal process is based on adsorption with special grade of Activated Alumina. It also removes heavy metal, Fluoride, Nitrate, Grease and Oils.	Satisfactory performance in all installed places. Company guarantees 2 years O & M, training including performance.
ADHIACON : AFDWS 2000 – Arsenic Removal Plant	Catalytic precipitation / Electron Exchange	AFDWS - 2000	The unit is fitted with lifted head of hand pump. It has basically three chambers - primary, secondary and Micro-filtration chambers. The water is pumped through 3 way valve to primary chamber where raw water first passes through a coarse stainless steel strainer and then comes in contact with filter media in which catalytic precipitation takes place. The purified water from the primary chamber goes to secondary chamber for downward filtration. From secondary chambers water passes through micro-filtration chamber and then purified water goes through three way valve at the outlet.	Field performance of the system was below satisfactory level.
Hand pump Attached Arsenic Removal Plant by AIIH&PH, Kolkata	Oxidation + Coagulation + Flocculation / Precipitation and filtration	Chlorinating agent (BP) + Ferric Alum	The system is comprised of a non-mechanical clari-flocculator and up-flow gravel filter and it has three chambers. Bleaching powder and alum are the two chemicals used for removal of arsenic. In the first chamber bleaching powder solution is added in appropriate dosage with pumped water where they are thoroughly mixed in presence of baffles. The chemical mixed water is thereafter passed through second chamber for precipitation of the flocs. The clean water is collected in the launder chamber. From launder water is taken to the filter (third) chamber, from where water is allowed to flow in upward direction through graded gravel media. The arsenic safe filtered water is finally collected through a tap provided in the filtered chamber.	Periodic daily dosing of chemical reagents are necessary. The system requires constant vigilance and close monitoring and chemical dosing.
IONOCHEM, Kolkata	Ion exchange	Ferric Hydroxide	The system is comprised of one Iron Removal Filter and one Arsenic Filter and the system is fitted with Hand Pump The principal media is bonded compound of $Fe(OH)_3$ and βFeOOH. When Hand Pump is operated, the pressurized raw water	Regular backwashing of iron filter is essential, which caused problem of operation and maintenance. Otherwise, the performance remained satisfactory.

			is passed initially through iron removal filter filled with catalytic filtering media and reacts with sodium arsenates and $Fe(OH)_2$. Due to chemisorption AS is bonded with the material and Arsenic is removed.	
Apyron Arsenic Treatment Units by Apyron Technologies (P) Ltd. Representing of Apyron Technologies Inc., USA	Adsorption	Aqua Bind (Activated Alumina +)	The system is comprised of an assembly of Handpump with its outlet connected to the filtering media. When the Hand Pump is operated, the raw water passes through the filter media where arsenic is removed and finally treated water is collected through an outlet pipe from the filter media. The filter media is comprised of manganese oxide and activated alumina. Manganese oxide converts As^{3+} to As^{5+}, which is adsorbed on the alumina media. The unit also removes iron.	Showed satisfactory performance, treating arsenic levels as high as 3500 ppb to a safe level of less than 50 ppb. After use, filter media can be disposed safely as ordinary sanitary waste.
Public Health Engineering Department, Govt. of West Bengal	Adsorption	Red Hematite (Fe_2O_3) lumps + quartz + sand activated alumina	Removal of arsenic is accomplished in 4 chambers. Groundwater is abstracted by Hand Pump and spray into droplets over a bed containing packed hematite lumps (Fe_2O_3) before sending to first chamber for sedimentation. Sediment free water is conveyed through chambers placed in series containing red hematite lumps, quartz and dual media (Sand-Activated Alumina), respectively.	Reported as one of the finest performing devises and capable to remove arsenic from very high level of contamination. However, the weakness is its inability to produce sufficient quantity of filtered water. Towards O & M, it had poor performance.
Simple Arsenic and Iron Removal System by School of Fundamental Research (SFR), Kolkata	Adsorption	Aluminum Silicate + Ferric Hydroxide	The system is fitted to Hand Pump, which connected through the check valve with a vertical PVC cylinder filled with silicate matrix with additional oxidizing element for removal of iron before water enters into As-removal system.	Performance of the system is yet to be established through field testing.

Despite having numerous arsenic removal devices, which have been developed, based on different working principles, very few plants could show satisfactory performance at the field level, both in terms of arsenic removal efficiency and in sustainable running. The major setbacks, with most of the devices, remain with the operation, maintenance, replacement and removal of used filters. The systems in O & M have been linked to the responsibility of suppliers, and they have shown satisfactory performance. In addition to the above devices, a number of other devices can be seen to be developed and applied in other countries. However, all the technologies are primarily based on five principles of arsenic removal: oxidation, co-precipitation, adsorption, ion-exchange and membrane process. It is to be mentioned that the efficiency, effectiveness and sustainability of arsenic removal technologies depend on: (i) how simple the devise is in use, and operation & maintenance? (ii) what is its removal efficiency? (iii) how much is the outflow rate and cost? (iv) how eco-friendly the device is? and (v) what mechanism in operation and maintenance is devised ?

Innovative Technologies

Innovative technologies, such as permeable reactive barriers, phytoremediation, biological treatment and electrokinetic treatment, are also being used to treat arsenic-contaminated water, waste water and soil. However, only a few applications of these technologies at full scale are available in the literature and additional treatment data are needed to determine their applicability and effectiveness in field condition. These technologies may be developed at full scale to treat arsenic contaminated aquifers.

Waste Disposal and Sludge Management

Waste disposal is an important consideration in the treatment selection process. Arsenic removal technologies produce several different types of waste, including sludge, brine streams, backwash slurries and spent media. These wastes have the potential for being classified as hazardous and can pose disposal problems.

Treatment of the slurry, obtained from arsenic removal process (from groundwater), is essential to make the slurry arsenic free so that it can be disposed without any hazard of the arsenic re-entering the aquifer system. The slurry may be transferred to plastic tanks and clear water from top drained off, further slurry added and top clear water drained off. The arsenic-rich sludge should be disposed in a controlled manner. The slurry can be dissolved in hydrochloric and/or sulphuric acid. Then it can be treated with metal scraps and/or other suitable reducing agents to convert arsenic of the slurry solution into arsine gas, which can be allowed to escape in the atmosphere (as a primary tentative measure). As a future research, depending on the total amount of arsenic to be treated and availability of fund, the arsenic generated may be absorbed in oxidative alkaline medium to produce sodium arsenate or calcium arsenate. The compounds may be consumed by glass industries. According to the study conducted by AIIH&PH, arsenic rich sludge may be disposed by the following method:

- *Disposal in on-site sanitation pits,*
- *Mixing with concrete in a controlled ratio,*
- *Mixing with clay for burning for brick manufacturing.*

Apparently sludge disposal, management and detoxification have not received due priority in the plan of actions, initiated along with the device installation by the ARP manufacturers. Even no discernible programme is seen for the backwash which contains high level of As in media-washed water. It needs high priority in the installation programmes. Both the raw water, pumped out for ordinary use, and back washed water; require to be passing through a soak pit type of arrangement, to avoid surface contamination.

7. Mitigation and Remediation Initiatives from West Bengal and Bihar

(a) West Bengal

The initiative to combat the menace of arsenic hazards, in true sense, came into existence in the year 1992. From 1992 onwards, Government of West Bengal and Central Government, along with several academic Institutions and Non-Governmental Organizations, have initiated a number of restorative and substituting measures coupled with action plan. Their main focus was on the detailed investigations to understand the physiochemical process and mechanism, alternate arrangement to supply arsenic free water to the affected populace and the development of devices for arsenic removal and their implementation at the field, etc. As of year 2005, the State Government of West Bengal has operationalized number of schemes spending a sum of nearly Rs. 2100 Crore. The research studies have been focused towards identifying: (i) extent and nature of arsenic contamination in groundwater, (ii) causes and mobilization, (iii) mitigation strategies, and (iv) for devising cost effective remediation techniques and developing sustainable groundwater resources management strategies. The counteractive steps and measures to combat the natural calamity of groundwater arsenic menace were mainly towards public awareness programs, devising and demonstrating some of the results acquired from scientific analysis. Some of the important steps taken from the West Bengal are as follows:

(i) *Most of the infected hand pumps and tube wells, which were being used for domestic usages in the arsenic affected areas, have been largely identified and put into hold for further usages;*

(ii) *The problem of groundwater arsenic contamination has been prioritized in the state and an 'Arsenic Task Force', comprising technical experts from different disciplines working in the state, has been constituted to prepare an arsenic mitigation action plan report for the aquifers in the arsenic infested districts;*

(iii) *A 'Master Plan' has been prepared for the entire state under the guidance of the 'Arsenic Task Force'; to provide arsenic free water to the arsenic affected villages using surface water and groundwater based schemes with the provision of Arsenic Treatment Unit.*

(iv) *Public Health Engineering Department, Government of West Bengal has established district level chemical laboratories for detecting arsenic content in groundwater. Those chemical laboratories have been equipped with equipments to trace elements other than arsenic;*

(v) *A number of surface water based schemes have been put into operation in places, wherever they are feasible, with provision of chemical treatment;*

(vi) *Arsenic removal plants, based on various treatment technologies to treat arsenic contaminated groundwater, have been installed in many places and put into operation to provide potable water to the affected populace where there were no access of other sources of potable water supply;*

(vii) *Arsenic free deeper aquifers and wells explored and constructed by CGWB have been put to use by the state agencies for public water supply;*

(viii) *Arsenic content in food chains and their effect on ingestion have been analyzed. However, what forms of arsenic, organic or inorganic, are present in groundwater and the degree of consequential impact of arsenic containing food chains on human health is yet to be established;*

(ix) *Many R & D studies focusing towards understanding source and causes, geochemical processes, extent of mobilization, social and health hazards, impact on food chains, etc. have been initiated.*

In addition to the above steps taken by the Government, a number of non-governmental organizations, academic and R & D organizations have come forward to rescue the affected populace, in supply of potable water through installation of a number of arsenic-free hand pumps and treatment devices under the community participation. Despite such considerable steps and measures, the task of ensuring potable water supply in many areas has remained a big question because of: (i) lack of proper coordination, (ii) poor operation and maintenance of arsenic removal devices, and (iii) unsatisfactory performance of the arsenic removal filters used in the devices.

A number of research studies have been pursued to investigate extent, mobilization process, geochemistry, hydro-geological properties and processes by different organizations. Findings are as follows:

(i) *Arseniferous aquifers are mainly observed within the shallow depth (within 100 m below ground level), while the deeper aquifer (>100 m bgl) in the same area is found free from arsenic. The shallow and the deeper aquifers are separated by a thick impervious clay layer and the thickness is above 10 m. The deeper aquifer is capable to yield 5 to 20 lps of water. It was further observed that when the deeper aquifer was pumped creating a drawdown of 6 m, there was not much impact on the overlain arsenic contaminated zone.*

(ii) *Groundwater in the arsenic affected area is characterized by high iron, calcium, magnesium, bicarbonate with low chloride, sulphate, fluoride and sodium.*

(iii) *Geologically, the arsenic affected areas are the parts of the Ganga-Bhagirathi delta comprising succession of thick Quaternary sediments. The arseniferous tract is restricted in the upper delta plain within shallow depth, which is mainly built up of sediments deposited by meandering streams and levees composed of sands of various grades, silt, clay and their admixtures.*

(iv) *The groundwater mostly occurs in thick zone of saturation within the unconsolidated alluvial sediments in the affected areas; and the aquifers are made up of sands of various grades. Groundwater occurs generally under unconfined hydro-geologic conditions.*

(v) *The arsenic groundwater contamination is attributed to the geogenic origin, and the source of arsenic in localized patches is due to presence of Arsenopyrite in clay and sand. Arsenic concentration is more in clay than in sand.*

(vi) *In arsenic affected areas, all tube wells harnessing shallow aquifers do not yield arsenic contaminated water. Some are arsenic affected and some others are free from such contamination.*

(vii) *All shallow dug well aquifer zones are not free from arsenic contamination rather it is the mode of abstraction that makes the difference. The very shallow tube well tapping the dug well zone aquifer has also been found to yield arsenic contaminated water.*

(viii) *There are places where the number of arsenic yielding tube wells are more in number but the degree of arsenic concentration is comparatively less and vice versa.*

(ix) *Physical manifestation of the arsenic diseases among the affected population does not always reflect the degree of concentration of arsenic in the affected area. Arsenic affected persons may be less in number in places where the degree of concentration is greater and the number of arsenic yielding tube wells are more in number and vice versa. The reason of the disease may be the quality of food consumed by the people residing in the area and/or the presence of ionic in groundwater in which arsenic occurs.*

(x) *The effect of dilution, created by artificial recharge of arsenic free surface water & rainwater onto the shallow arsenic contaminated aquifer, is found to reduce the concentration of arsenic in the groundwater.*

(xi) *The artificially injected dissolved oxygen in contaminated aquifer, as a measure of in-situ remediation of arsenic, is found to reduce arsenic and iron concentration in the aqueous phase. The arsenic concentration in the vadose zone is observed below detection limit* ($<1\mu g/L$)*.*

(xiii) *The detection of origin and age of groundwater in few arsenic affected areas showed that the shallow aquifer water is of recent recharge (< 50 years); whereas deep groundwater is of old recharge (5000 to 13000 years).*

(xiv) *The analysis of arsenic content in food items (cereals, vegetables & fruits), produced in arsenic affected areas using arsenic contaminated water, revealed possibility of arsenic intake through food items. This may affect not only the people residing in the arsenic affected areas but also the other areas where these food items are marketed.*

(xv) *The efficacy of arsenic removal units in arsenic affected areas indicated that community based arsenic removal treatment plants and domestic filters could be a promising alternative. However, the extent to which the arsenic removal devices could be effective requires a thorough evaluation.*

(xvi) *The study of mobilization mechanism carried out by CGWB in association with UCL, London, revealed that arsenic is released from solid phase to aqueous phase by reductive dissolution of FeOOH and corresponding oxidation of organic matter. This process is mainly driven by reduction of natural organic matter buried in sediment or buried peat deposits.*

The schemes adopted as remedial options can broadly be grouped as under:

(i) *Uses of surface water sources,*
(ii) *Exploring and harnessing alternate arsenic free aquifer,*
(iii) *Removal of arsenic from groundwater using arsenic treatment plants/filters,*
(iv) *Adopting rainwater harvesting/ watershed management practices*.

Supply of surface water from ponds, rivers etc. for drinking purposes through pipe network system after suitable purification by conventional method of treatment viz. coagulation, flocculation, rapid sand filtration and disinfections, as an alternate option, have been put into practice in some places by the State Govt. Horizontal roughing filter with slow sand filter have been adopted, in case of supply of pond water. Eight such surface water based schemes in the state have been operationalized by the State Government in different places, covering population of 3.85 million in 1266 mouzas. Needless to mention that all surface water based schemes are successfully running to provide potable water supply to masses covered under the schemes. Large scale implementations of surface water based schemes are constrained by number of factors, namely; (i) technical feasibility, (ii) water availability, (iii) cost factors, etc.

The arsenic contaminated zones mostly lie within the shallow aquifer (<100m bgl). But in many places the shallow aquifer is free from arsenic contamination because of hydrogeological set ups and is also free from the probable threat of contamination. Such risk free potential zones in the shallow aquifer provide scope for tapping. The deep aquifers (>100 m bgl) underneath the contaminated shallow aquifer, in many places of Bengal Delta Plains, are normally seen arsenic free. It is observed that properly designed tube wells are capable to harness deeper arsenic free aquifer without posing any future threat of arsenic mobilization from the overlain contaminated zone. Taking into consideration the above scientific propositions, the Public Health Engineering Department (PHED), Govt. of West Bengal, has put into operation few direct aquifer tapping schemes for supply of arsenic free water to the affected habitations. These schemes are: (i) 166 ring wells, each covering 500-600 population; (ii) 8037 tube wells fitted with hand pump, tapping deeper aquifers each covering 1000-1200 population; (iii) 244 piped water supply scheme with large diameter tube well for harnessing arsenic free aquifers benefiting 10000 population by each scheme. These schemes could stand alone to provide potable water to reasonable sections of population in the arsenic affected areas, and are running with a satisfactory level.

Surface water sources and deep aquifers are practiced in places wherever they are found feasible in terms of technical and financial aspects, and as such schemes are few in numbers. However, usages of arsenic contaminated groundwater, by removing arsenic with the help of arsenic removal filters, have been extended in a large scale in the West Bengal. A number of arsenic removal devices, developed by various organizations, based on different scientific propositions have been put in practice under a number of schemes. Central government, state government, academic institutions and few private organizations have implemented number of arsenic removal devices hem in many places to provide treated arsenic free water to the populace in the affected areas. Govt. of West Bengal alone has spent more than Rs.832.46 Crore on arsenic removal schemes. Different types of arsenic removal schemes have been devised. These devices vary in size, filtering mechanisms, and mechanisms of operation. Based on the size, the schemes can be categorized as ‘Arsenic Removal Unit (ARU)’ and ‘Arsenic Removal Plant (ARP)’. ARUs are those, whose inlet are directly connected to a hand pump or tube well. They are complete units. Arsenic Removal Unit is normally a small assembly which can meet requirement of water for a smaller section of people. ARPs, on the other hand, are those units, which have the capacity to treat a large quantity of water and can cover a large section of populace. Nearly, 77 ARUs, each having coverage of 15000 populations, have been installed with the existing piped water supply scheme. And 2396 ARUs, each having coverage of 600-800 population, have been fitted with the existing hand pumps. Nearly 1900 ARPs have been put in operation in many places. However, most of the arsenic removal devices particularly, ARUs, failed to produce satisfactory results mainly due to the shortcomings in operation and maintenance. The arsenic removal devices, whose O & M aspects are managed by community participation, could produce a satisfactory performance. In addition to the ARU and ARP, a large number of domestic filters have been developed by various academic and R & D institutions, which have been successful in reducing arsenic to a safe level. They have been marketed to affected habitats at a marginal cost.

(b) Bihar

Groundwater arsenic contamination in Bihar first surfaced in the year 2002 from two villages, Barisbhan and Semaria Ojhapatti in the Bhojpur district located in the flood-prone belt of Sone-Ganga. A number of scientific studies, focusing mainly on physicochemical analyses of arsenic contaminated groundwater, assessment of extent, mobilization pathways, and possibility of tapping deeper aquifers, arsenic in food chains and its effect on health, were initiated by state and Central government organizations and by different academic institutions working in the State. In addition to R & D studies and exhaustive investigations, Govt. of Bihar, has started a number of schemes, as the precautionary measures to ensure supply of risk-free potable groundwater particularly, in community based localities, and as counteractive steps to combat probable arsenic related threats. As an outcome of scientific investigations and surveys, by 2008, out of 38 districts in the state, 15 districts covering 57 blocks, have been identified as groundwater arsenic contamination above 50 μg/L. No studies, so far, have been initiated, exclusively on arsenic mitigation, except deriving insight of tapping alternative arsenic-safe aquifers and understanding of physicochemical and hydrogeological behaviors of arsenic contaminated groundwater.

In short, the outcomes of the studies carried out so far from Bihar are as follows:

(i) *Groundwater arsenic contamination is confined to Newer alluvial belt along the river Ganga,*
(ii) *Arsenic contamination is mostly in shallow aquifer (<50 m bgl) of young groundwater (< 40 years old), and is in localized pockets,*
(iii) *Dug wells are free from arsenic contamination,*

(iv) *Arsenic concentration, in the aquifer, reduces during monsoon season possibly due to recharge from monsoon rainfall,*

(v) *Deeper aquifers, which occurs under semi-confined to confined conditions, are arsenic free and hold groundwater of about ~3000 yrs,*

(vi) *The deeper arsenic-safe aquifer has potential to yield about 150-200 m^3 /hr, which can be taped through heavy duty deep tube wells.*

As counteractive and precautionary measures, against the probable threats emerged out from the groundwater arsenic menace, the Public Health Engineering Department (PHED), Govt. of Bihar, has implemented the following schemes:

(i) *Open dug wells, located in the arsenic affected areas, had been cleaned and put into operation for the villagers. The dug well water is free from arsenic contamination and acceptable to the people as those are the age old abstraction structure. Nearly, 186 new wells have been constructed and fitted with India Mark III hand pumps. In addition to that, construction of sanitary wells in 133 schools is in progress.*

(ii) *Twenty rain water harvesting structures have been constructed in different schools in the arsenic affected areas.*

(iii) *PHED has planned to install arsenic removal plants in 700 schools with two filters in each school to supply arsenic free groundwater after treatment,*

(iv) *PHED has taken up the task to construct hand pumps to tap arsenic-free deep aquifer, with provision of 5 hand pumps, in each of the arsenic affected areas.*

(v) *Deep tube wells, tapping arsenic free deeper aquifer for community based piped water supply scheme, has been installed in the Semaria Ojhapatti village, Bhojpur district.*

(vi) *A number of surface water based pipe water supply schemes are under construction. These schemes will have their intake from the Ganga River with multi-village supply. The schemes are at:*

- *Mauzanpur, Bhojpur district, covering 39 villages, One in Bidupur in Vaishali district; and*
- *one in Simri block in Buxar district for which work is about to start,*
- *One each in Mohiuddinnagar and Mohanpur blocks in Samastipur district; one each in Kahalgaon and Pirpainti blocks in Bhagalpur district; and one each in Sultanagalganj and Nathnagar blocks in Bhagalpur district; one each in Matihani, Begusarai and Barauni blocks in Begusarai district, are in final stage of implementation.*

In Bihar, the general awareness of populace about groundwater arsenic contamination and its effects is very less. And people are unaware that the skin skeletal and other health related diseases, experienced by them, are of water origin. Rural people have some phobia of not switching over from habitual use of groundwater to alternate surface sources of water. Therefore, there is a need of breaking such orthodox approach by mass awareness programmes. The corrective and precautionary measures, initiated by the Govt. of Bihar, are too less to the scale up of the problem. and to understand the problem resolving issues, counteractive measures, etc., in comparison to the State of West Bengal. While characteristics and features of the problem, geological formations and causes of the problem are largely similar and represent the hydro-geological setups of the same river basin, except the difference in socio-economic, socio-cultural and social composite structure.

(c) Other States

Although a number of other States namely, U.P., Jharkhan, Chhatisgarh, Assam and Manipur has been exposed to arsenic groundwater contamination, however, the initiative towards problem resolving issues from all those states are virtually meager. People residing in those exposed areas either have no alternate scope and continuing with the exposed risk or there has not been any major drive to rescue from potential arsenic threats.

The source of irrigation in most of the arsenic affected areas is groundwater from shallow aquifer within 100 m bgl. In the absence of alternate source of arsenic free irrigation water, rural people continue to tap arseniferous aquifer resulting in further aggravation of the problem in different forms, such as, mobilization of arseniferous groundwater to freshwater zones, spreading of the sources by the cycling process of water and use of fertilizers and pesticides, transport through food chains, etc. The crux in the management of the whole problem has boiled down to single point as to how to ensure arsenic free irrigation water into the arsenic affected areas. Wherein the use and reuse of contaminated groundwater, on one hand, have the threat of arsenic contamination through food chains; on the other hand, infiltration of arsenic contaminated water, together with residual of fertilizers and pesticides, may provoke contamination of vadose zone, and mobilization of arsenic in the freshwater zones. Ensuring supply of potable water alone, thus, seems to be inadequate to attain sustainability in terms of resolving the arsenic menace. Despite number of corrective and precautionary measures, the spread over of arsenic contamination in groundwater continues to grow and more new areas are added to the list of contaminated areas. The problem resolving issues, thus, have appeared to be partial and inadequate. It is, therefore, necessary to consider a framework of problem-solving curriculum linking one issue to another, one's favoring and posing condition to another, and resolve those systematically in a judicious manner to achieve the target of human-land-water resources management in the arsenic affected areas.

8. A Critical Appraisal: Vulnerability and Scope of Remediation

There exist a number of opinions about causes of arsenic induced groundwater contamination, in the Gangetic and Brahmaputra plains, in Indian sub-continent. However, it is now generally accepted that the source is of geological origin and percolation of fertilizer residues may have played a modifying role in its further exaggeration. Identification of parental rocks or outcrops is yet to be recognized, including their sources, routes, transport, speciation and occurrence in Holocene aquifers along fluvial tracks of the Ganga-Brahmaputra-Barrak valley and in scattered places, adjoining to it, in their basins. The speculation of sources in the Gangetic plains ranged from the sulphide belts of Bihar, Uttar Pradesh, and North Bengal to the coal seams of the neighboring Gondwana Basins, the basic rocks of the Rajmahal Traps, the metamorphic schists of the Lesser Himalaya. The question of the possible role of excessive withdrawal of groundwater for its triggering, however, has continued to have divided opinions. The chemical processes such as, Redox potential, sorption, precipitation-dissolution, pH, influence of other competing ions, biological transformation, etc under different soil-water environmental condition; influence the perturbation of arsenic in a system, having presence of source material and/or conditions of enrichment. Whether the processes of physicochemical transformation were only influenced by excessive groundwater exploitation or there were other coupled actions of a number of hydro-geological and geo-environmental disturbances, over the periods, are yet to be recognized. Surfacing new arsenic affected areas, in every additional survey, is a matter of concern. It was reported that the contaminated waters are enriched in Fe, Mn, Ca, Mg, bicarbonates, and depleted in sulphate, fluoride, chloride; pH ranged from 6.5 to 8; redox condition usually in reducing; high on organic matter content; lodged mostly in sand coatings, or sorbed on clays, HFOs, and organic matters; As-concentration diminishing down-depth, which brings out a generalized geochemical perception that could help develop *in-situ* remediation of arsenic.

. It has been proved that arsenic has affinity with iron in groundwater both positively and negatively, depending upon the condition. There is wide-scale report of the presence of dissolved iron, in arsenic contaminated groundwater, and of co-precipitation of iron and arsenic under oxidizing condition. The relationship between **As-Fe** can be interpreted as signifying that in these instances iron played the scavenger role, adsorbing arsenic from water as it precipitated out, again desorbing arsenic into water as it re-dissolved in response to appropriate change of Eh-pH conditions. This gives a positive hope of a plausible way of *in situ* remediation of the problem of **As** contamination by removal of Fe from groundwater before withdrawal.

It is also to be understood that the arsenic contamination of groundwater in the Bengal Delta Plains (BDP) is the result of interaction of the aquifer lithology and aquifer waters in flux in a complex evolutionary sequence in the mid-Holocene to the present times. Studying the morphologic and lithologic makeup of the area, its water drawal level pattern, aquifer water chemistry, mineral phases, and arsenic-and-iron concentration variation pattern, have provided basic insights into the problem.

Towards the mechanism of mobilization of **As**, the oxidation model is considered relevant only locally, while the reductive dissolution model of **As** from soils is largely acknowledged as the dominant processes of **As** mobilization in the Gangetic plains.

Removal of **As** from arsenic-contaminated water by suitable filtration techniques, to ensure supply of arsenic-free water, appears to be a viable practical solution for potable water if the related problems, such as sludge disposal and operation & maintenance, are resolved effectively. But the agricultural requirement is much more than potable water. Supply of treated groundwater to meet agricultural requirement by *ex-situ* arsenic removal technologies would not be a sustainable option or approach.

Varieties of arsenic removal devices have been developed, based on different working principles, and have been extended to fields. Many of those could not produce satisfactory performance or failed due to lacks in O & M or due to sludge disposal problems. Among the various removal technologies, lime softening and iron co-precipitation have been reported to be the most effective removal technologies, and observed running satisfactorily, where operation and maintenance problems were taken care of by public-private partnership. Majority of the operation and maintenance is linked to tube wells and day-today care, which has nothing to do with the ARP or its chemical media. Without adequate in built maintenance arrangements apparently the performance of all the devices would suffer. Proper training and mobilization of the user community in the operation and maintenance aspect would be an essential task before any future installation of ARP programme can be envisaged. Thus, future emphasis should be oriented around in-situ remediation at the source-aquifer level and also chemical fixation of the contaminant at the source should be properly explored through proper calibrated and configured studies and experimentations.

The technological opportunities, to resolve water scarcity in arsenic affected areas and, to get rid of groundwater arsenic menace, can thus be thought to be as under:

- *In-situ remedy of aquifers by decontaminating arsenic from infested aquifers,*
- *Use of groundwater after ex-situ treatment by arsenic removal devices,*
- *Use of surface water source as an alternate to the contaminated groundwater source,*

- *Exploring possibilities of tapping risk free deeper aquifers for supply of arsenic free groundwater.*

Out of these four technological options, the most fascinating one is the in-situ removal of arsenic from aquifers and restoring the aquifers from arsenic vulnerability. Till date, except the state of West Bengal, no other states in India have developed a comprehensive plan of action to deal with the situation. Even in West Bengal, where a master plan for an ambitious programme of supplying arsenic-free water to all the affected villages through a system of piped water supply after appropriate treatment is in place, implementation of the same is taking inordinately long time. As a result, a large portion of the affected population continues to be at risk. Ensuring supply of drinking water to the populace in the arsenic affected areas is the primary requirement while the irrigation water requirement in the arsenic affected areas can't be overlooked. Agriculture is the life line of rural people and groundwater is the primary source for agricultural water requirement. Exploitation and usages of arsenic contaminated groundwater for agricultural purposes will not only spread the health hazards through the agricultural products but also help to widen the arsenic contaminated area. Thus, one has to look for a comprehensive solution to ensure supply of arsenic free water to meet demands of both drinking and irrigation requirement.

As such, no specific technique except an approach claimed by 'Queen's University researchers in Belfast' has been found stating withdrawal of arsenic free groundwater or in-situ treatment of arsenic contaminated aquifer. The technology is based on recharging a part of the groundwater, after aeration, into a subterranean aquifer (permeable rock) able to hold water. Increased levels of oxygen in the groundwater slow down the arsenic release from the soil. At higher dissolved oxygen levels, soil micro organisms, as well as iron and manganese, reduce the dissolved arsenic level significantly. The claim of eco-friendly treatment technique of arsenic removal, that can ensure safe irrigation and potable water supply at an affordable cost, by the 'Queen's University researchers in Belfast', needs verification and on field application, before the technique is accepted for large scale adaptation.

The available arsenic removal technologies require refinement to make them suitable and sustainable for their large scale effective uses.

Surface waters are free from arsenic contamination. Although usages of surface water sources with minor treatment through organized piped water supply system seems to be very expensive, it has been proved to be a feasible solution to supply potable water in many places in West Bengal, where surface water availability is assured. Moreover, investigations have revealed that deeper aquifers underneath the contaminated shallow aquifers are free from arsenic contamination. The deeper aquifers, which are risk free from future threat of contamination from the overlain aquifer, can provide a sustainable source of potential groundwater withdrawal. Groundwater arsenic contamination zones in most of the arsenic affected areas are in localized patches. Areas around the arsenic affected patches are free from arsenic contamination. Because of hydrogeological features and fluvial characteristics of the groundwater domain, in many cases all those freshwater zones are free from threat of intruding contaminants from the nearby infected zones. Possibility of tapping all those shallow freshwater zones can be explored. The top most layers of the shallow aquifers are recharged annually by monsoon rainfall. This recharge water remains free from arsenic for quite a long time till they are mixed up by natural processes or by any external intervention. Most of the arsenic affected areas in the Gangetic flood plains are along linear track of river courses. River water is free from arsenic and the river banks possess unique properties of filtration, storage and transmission of water. Exploring possibility of tapping top fresh water zones by radial collector wells and river banks storage by intake wells can be one of suitable propositions to investigate. Over and above, as such no comprehensive maps delineating arsenic vulnerable zones and potential freshwater zones of the arsenic vulnerable areas are available.

The suggested framework of problem-solving curriculum linking one issue to another, one's favoring and posing condition to another and resolve those systematically in a judicious manner to achieve the target of human-land-water resources management in the arsenic affected areas can be envisaged as follows:

- **R & D activities to ensure sustainable solutions** : there is a need to prepare database, improvise and translate understanding of causes, geochemistry, genesis, aggravation, mobilization and dissolution processes of arsenic in groundwater for different hydro-geological settings to derive methods for in-situ remedy for decontaminating aquifers from arsenic; to devise cost effective, eco-friendly and socially accepted arsenic removal devices; to investigate feasibility of alternate sustainable water management (SW & GW) strategies to meet demand of water in the arsenic affected and vulnerable areas, to assess impact of arsenic in food chain and related health hazards, to ascertain health impact of arsenic contaminated groundwater, etc.

- **Ensuring supply of Arsenic free water:** in order to provide arsenic free potable water to the populace in the arsenic affected areas, the following alternate measures as a stopgap arrangement can be initiated: (i) in areas where population density is relatively more and the area is under the grip of arsenic effect and there are limited scope for alternate freshwater supply; arsenic removal devices, by choosing the best working model among the existing devices under the public-private partnership with community participation in the O and M, would be a suitable proposition to adopt, (ii) in areas where freshwater aquifers can be tapped using hand pump with no risk of arsenic contamination; installation of new hand pumps can provide a reasonable solution, (iii) the areas where deeper aquifers can be tapped with no future risk of contamination from the overlain aquifer; supply of potable groundwater by exploration of deeper aquifers can provide a sound solution, and (iv) the places where the surface water supply can be ensured as an alternate source of groundwater; fitting piped surface water supply scheme (although expensive) can be a reasonable proposition to adopt.

- **Capacity Building and Social Empowerment**: most of the arsenic removal technologies, rolled over to the field, have failed because of ignorance in O & M, and inadequate awareness in the society. The general notion of the society with regard to water and about water related schemes are: (i) water is in plenty and god gifted, and it has no threat from any unforeseen hazards rather it is the cleaner of all pollutants; and (ii) society has no responsibility, control and accountability on the provisions/schemes created by the government. While the effectiveness and benefits of a facility do not come merely by its creation rather by nurturing the created facility from time to time to derive its long term benefits. Thus, in water related schemes giving direct benefit to the society, and which bothers the society on its non-functioning or non-existence; involvement of the society in the O & M and making society responsible and knowledgeable can solve many problems associated with the water scarcity issues in the arsenic affected areas. In many rural areas, there is a belief that groundwater is plenty and can be drawn on demand and is also risk free from any contamination.

9. Summary & Conclusions

In India, seven states namely, West-Bengal, Jharkhand, Bihar, Uttar Pradesh in the flood plain of Ganga River; Assam and Manipur in the flood plain of Brahamaputra and Imphal rivers and Rajnandgaon village in Chhattisgarh state have so far been reported affected by arsenic contamination in groundwater above the permissible limit of 50 μg/L. People in these affected states have chronically been exposed to arsenic drinking arsenic contaminated hand tube-wells water. With every new survey, more arsenic affected villages and people suffering from arsenic related diseases are being reported, and the problem resolving issues are getting complicated by a number of unknown factors. It is now generally accepted that the source is of geological origin and percolation of fertilizer residues may have played a modifying role in its further exaggeration. Identification of parental rocks or outcrops is yet to be recognized, including their sources, routes, transport, speciation and occurrence in Holocene aquifers along fluvial tracks of the Ganga-Brahmaputra-Barrak valley. It is reported that the contaminated waters are enriched in Fe, Mn, Ca, Mg, bicarbonates, and depleted in sulphate, fluoride, chloride; pH ranged from 6.5 to 8; redox condition usually in reducing; high on organic matter content; lodged mostly in sand coatings, or sorbed on clays, HFOs, and organic matters. It has been proved that arsenic has affinity with iron in groundwater both positively and negatively, depending upon the condition. This gives a positive hope of devising *in situ* remediation of the problem of **As** contamination by removal of Fe from groundwater before withdrawal. Varieties of arsenic removal devices have been developed, based on different working principles, and have been extended to fields. Many of those could not produce satisfactory performance or failed due to lacks in O & M or due to sludge disposal problems. Among the various removal technologies, lime softening and iron co-precipitation have been reported to be the most effective removal technologies, and observed running satisfactorily, where operation and maintenance problems were taken care of by public-private partnership. The available arsenic removal technologies require refinement to make them suitable and sustainable for their large scale effective uses.

Surface waters are free from arsenic contamination. The usages of surface water sources with minor treatment through organized piped water supply system has been proven to be a feasible solution to supply potable water in many places in West Bengal, where surface water availability is assured. Deeper aquifers underneath the contaminated shallow aquifers are found free from arsenic contamination. The deeper aquifers, which are risk free from future threat of contamination from the overlain aquifer, can provide a sustainable source of potential groundwater withdrawal. Involvement of the society in the O & M and making society responsible and knowledgeable can solve many problems associated with the water scarcity issues in the arsenic affected areas.

The framework of problem-solving curriculum for the arsenic affected areas can be envisaged under three categories of activities: (i) R & D activities to ensure sustainable solutions, (ii) ensuring supply of Arsenic free water, and (iii) capacity building and social empowerment.

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