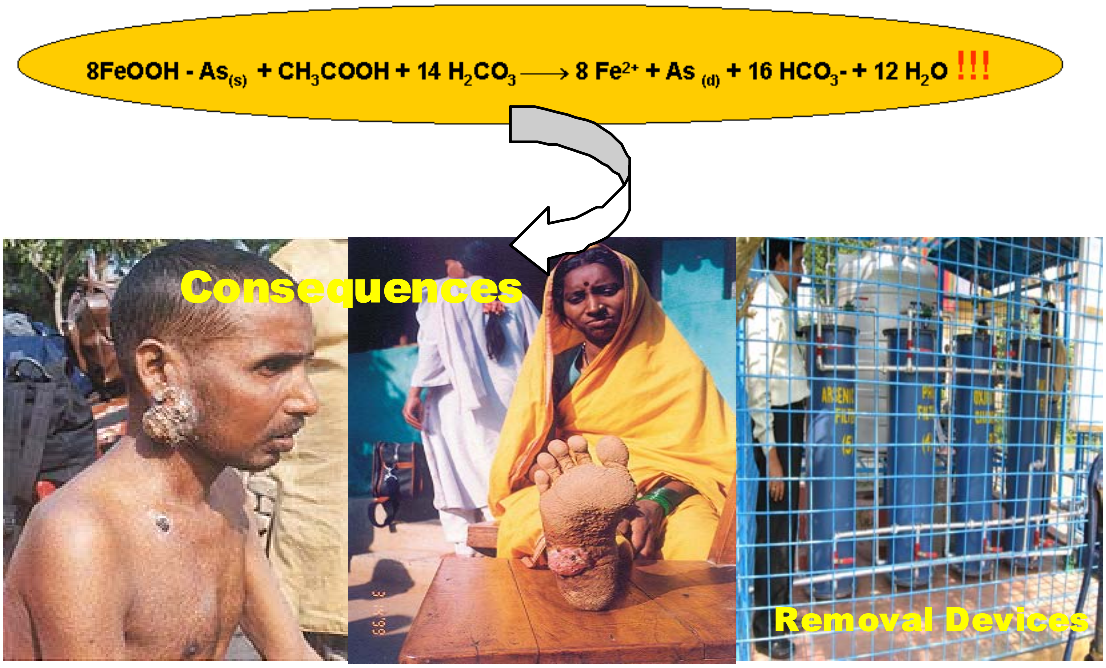
Mitigation and Remedy of Groundwater Arsenic Menace in India: A Vision Document



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

By:

National Institute of Hydrology, Roorkee
Central Ground Water Board, New Delhi

Under the aegis of:

Ministry of Water Resources
Government of India
New Delhi
June, 2010

Disclaimer

The document endeavoring a vision to **"Mitigate and Remedy of Groundwater Arsenic Menace in India"** gives a detailed outline emphasizing the gaps, focal areas of research, immediate measures to be taken up to provide arsenic safe potable water to the people in the arsenic vulnerable areas, other activities to be initiated for attaining a logical conclusion of the arsenic problem and also to develop a roadmap delineating as to how the suggested activities could be initiated, coordinated, undertaken, including framing out a budget estimate to fulfill those activities. The contents presented in this document are some scientific thoughts and analyses to encounter the groundwater arsenic menace in India. The roadmap and budget estimate outlined in the document are based on scientific perspectives only, not any committed proposition of the Government of India.

FOREWORD

Being a common pool and hidden resource, and because of a perpetual belief that groundwater is risk free from pollution and can easily be drawn on demand; exploitation of groundwater resources in many places in the Country has taken place indiscriminately without caring for hydrogeological features of aquifers and consequences that may emerge in the long run. One of the resulting effects has emerged in the form of deteriorated groundwater quality from the sources of hazardous contaminants of geogenic origin. Rise in deteriorated groundwater quality is emerging as the grave impinging issue to scarcity of fresh groundwater resources and thereby to demand management. Arsenic contamination in groundwater above the permissible limit of 50 g/L in scattered places reported from seven States particularly in the Holocene aquifers of Ganga-Brahmuptra alluvium plains is one of the major challenges of groundwater quality hazards before the Country that requires scientific solutions. The occurrence of arsenic in groundwater and its consequential health hazards to the people has been described as the biggest natural groundwater calamities in the World.

Since the arsenic contamination in groundwater was first reported from West Bengal in the late eighties and thereafter from six other States, a number of counteractive, preventive measures and R & D activities have been put in place, particularly in West Bengal. In other States, those remained scanty. Despite so many years passed over, however, the problem resolving issues have remained unresolved.

As a step towards that, the Follow up committee of the "Second Advisory Council for Artificial Recharge of Ground Water" has identified "Arsenic contamination in groundwater in India" as one of the focal areas to resolve by first bringing out a vision document emphasizing the present state-of-affairs of the problem, field actions and R & D works taken so far and their outcomes and shortfalls, the gaps, and areas in which further research and activities to be taken up, etc. To bring out a vision document, the Ministry of Water Resources, Govt. of India has entrusted the task to the National Institute of Hydrology (NIH), Roorkee and Central Ground Water Board (CGWB) with financial support. The Vision Document entitled **"Mitigation and Remedy of Groundwater Arsenic Menace in India"** is an outcome of the joint coordinated efforts of NIH and CGWB.

The Vision document contains a total of ten chapters: the chapters 1-5 explain knowledgebase, understanding and technological opportunities available, state-of-affairs of arsenic contamination in India and different corrective measures taken and shortcomings experienced; while the chapter-6 in fact, brings out a critical appraisal of chapters 1-5. The chapter-7 focuses the gaps and identifies areas requiring future initiatives. The Chapters 8-10 devise a "Comprehensive Plan of Actions" envisaging roadmap, financial requirement and the method as to how the mission can be coordinated and accomplished.

The texts presented in the document in the form of different chapters have been contributed by a number of resource persons conversant to the subject areas. The contributors were: Prof. K. J. Nath, Chairman-West Bengal Arsenic Task Force; Prof. Dipankar Chakraborty, School of Environmental Studies, Jadavpur University; Dr. S. P. Sinha Roy, Ex.-member, CGWB and Former Chairman, Arsenic Task Force, West Bengal; Mr. R. M. Mishra, Joint Secretary(Admn), MoWR; Dr. S. K. Sharma, Consultant (GW), MoWR; Dr. B. B. Basu, Director, School of Fundamental Research, Kolkata; Dr. N. C. Ghosh, Scientist-F, NIH-Roorkee; Dr. C. K. Jain, Scientist-F, NIH-Guwahati; Shri Abhijit Roy, Superintending Hydrogeologist, CGWB-ER, Kolkata; Dr. Dipankar Saha, CGWB-MER-Patna. Valuable contributions made by each of the experts are thankfully acknowledged. The services rendered by Dr. Nagendra Kumar, Associate Professor, Deptt. of Humanities and Social Sciences, IIT Roorkee in the form of professional editing of the document are also thankfully acknowledged.

The efforts of Dr. N. C. Ghosh, Scientist-F of National Institute of Hydrology, Roorkee, who has initiated, articulated and coordinated the tasks of the document, are highly appreciated.

Raj Deva Singh
(R. D. Singh)
Director,
National Institute of Hydrology.

(B. M. Jha)
Chairman,
Central Ground Water Board.

ACKNOWLEDGEMENT

The Government of India vide Resolution dated 17.04.2006 has constituted **"Artificial Recharge of Ground Water Advisory Council'** under the Chairmanship of Honorable Union Minister for Water Resources. The main objective of setting up the Council is to popularize the concept of artificial recharge among all stakeholders and its adoption. To follow-up the decisions of the Advisory Council, a Follow-up Actions Committee in the Ministry of Water Resources, GoI, headed by Joint Secretary (A) has been constituted.

In the second meeting of the Advisory Council, "Groundwater quality and related health problems" has been identified as one of the priority areas for meticulous government persuasion to control and remedy by deriving suitable action plans. Arsenic contamination in groundwater being a long standing unresolved issue, it is chosen as the focal area to confront its menace by identifying understanding and technological strength and gaps, and outlining suitable actions plans for mitigation and remedy. Being an area of highly complex and specialized contents on which enormous work have already been done both National and International level, it has thus been decided to develop a position document identifying knowledgebase, understanding and technologies available, gaps persist, and further works to be taken up, etc. Based on which, a comprehensive framework of activities to 'mitigate and remedy of groundwater arsenic contamination' can be derived. This vision document entitled **"Mitigation and Remedy of Groundwater Arsenic Menace in India"** is an outcome of the task assigned by the Follow-up Actions Committee.

On behalf of the National Institute of Hydrology, Roorkee and the Central Ground Water Board, I convey my gratitude to the Ministry of Water Resources, Govt. of India for entrusting this challenging task to NIH and CGWB, and also tender my earnest thanks to the officials of the Ministry of Water Resources for their support and guidance in different forms for successfully bringing out this document. A deep sense of gratitude is conveyed to the Follow-up Actions Committee for its suggestions and guidance, particularly to Shri Ram Mohan Mishra, Joint Secretary (A) and Chairman, Follow-up Actions Committee who has actually motivated and helped to take up this important task.

Effectiveness of a vision document labeling a comprehensive plan of actions depends on how critically and rigorously one has stirred and analyzed the existing state-of-affairs to tag the pertinent problem revolving issues. These objectives have been achieved from contributions of a select group of resource persons conversant on different themes of the subject area. The contributions made by Prof. K. J. Nath, Chairman-West Bengal Arsenic Task Force; Prof. Dipankar Chakraborty, School of Environmental Studies, Jadavpur University; Dr. S. P. Sinha Roy, Ex.-member, CGWB and Former Chairman, Arsenic Task Force, West Bengal; Mr. R. M. Mishra, Joint Secretary(Admn), MoWR; Dr. S. K. Sharma, Consultant (GW), MoWR; Dr. B. B. Basu, Director, School of Fundamental Research, Kolkata; Dr. N. C. Ghosh, Scientist-F, NIH-Roorkee; Dr. C. K. Jain, Scientist-F, NIH-Guwahati; Shri Abhijit Roy, Superintending Hydrogeologist, CGWB-ER, Kolkata; Dr. Dipankar Saha, CGWB-MER-Patna, Dr. S.K. Srivastava, Scientist-B, CGWB are gratefully acknowledged. The services rendered by Dr. Nagendra Kumar, Associate Professor, Deptt. of Humanities and Social Sciences, IIT Roorkee are also thankfully acknowledged. Without their expert contributions, it would not have been possible to bring out the document in the present form.

I also convey my sincerely thanks to all others who have extended their untiring support and help directly or indirectly during the course of the field work: to mention few names, Shri Biswajit Chakravorty, Scientist-E2, NIH-Patna; Shri Asit Kumar Ghosh, Hydrogeologist (Retd.), CGWB-ER, Kolkata; Dr. Dipankar Saha, Scientist-D, CGWB-MER-Patna; and Dr. Anupma Sharma, Scientist-C, NIH-Roorkee. Lastly, I would like to thank Director, National Institute of Hydrology, Roorkee for providing all administrative possible helps and supports for successfully completing the task.

Date : 18th June, 2010

(N. C. Ghosh)
Scientist-F and Head
Ground Water Hydrology Division
National Institute of Hydrology, Roorkee

ABSTRACT

Groundwater is a hidden and common pool resource. It is commonly believed that groundwater is omnipresent, and can be drawn on demand in any quantity wherever and whenever required. This conception has given rise to indiscriminate boom of groundwater withdrawal structures of various types namely, hand-pumps, bore-wells, tube-wells, etc. to meet ever increasing demands in individual household, community and social sector for different uses. Those, over the years, have triggered a number of invading issues such as; depletion of groundwater level and deteriorating groundwater quality. As a consequence of which have emerged a threat to scarcity of groundwater, failure of wells, severe health hazards, etc. Deterioration of groundwater quality is increasingly being recognized as the cause of water scarcity in many areas.

Groundwater, when it is in aquifer, possesses some fascinating features, such as; usually it travels very slowly and hence has long residence time. The space-time availability of groundwater is characterized by the porosity and permeability of the geological formations of the aquifer. The geological nature of the soil also determines the chemical composition of the groundwater. There is a misconception that the composition of groundwater does not change naturally. However, a common cause of change in water quality is interaction between aquifer material and the water flowing through them. Factors that control the dissolved minerals in groundwater include (i) the types of minerals that make up the aquifer, (ii) the length of time that the water is in contact with the minerals, and (iii) the chemical state of the groundwater. Different rocks have different minerals and groundwater in contact with those materials will have different compositions. The longer the contact time with minerals, the grater the extent of its reaction with those minerals and the higher will be the content of dissolved minerals. The chemical state of groundwater is generally defined in terms of three parameters: the temperature, pH, and oxidation-reduction potential. These factors are often influenced by chemical reactions between the groundwater and aquifer materials and in turn control the chemical composition of groundwater. If the aquifer material processed the toxic elements from weathered rocks, the changes in the chemical state of groundwater, which may be due to different water levels and annual recharge events, may trigger activation or dissolution of toxic elements in the groundwater.

Occurrence of Arsenic in groundwater, in excess to the permissible limit of 50 μg/L in the Ganges-Brahmaputra fluvial plains in India covering seven states namely, 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, is one such large scale groundwater quality disaster, described internationally as the World biggest natural groundwater calamity to the mankind after Bangladesh. These fluvial plains represent Holocene aquifers of recent alluvial sediments and have the routes originated from the Himalayan region. Since the groundwater arsenic contamination first surfaced in 1983 from

nearly 33 villages in 4 districts in West Bengal, up till 2008; 9 districts covering 3417 villages in 111 blocks in West Bengal, 15 districts covering 57 blocks in Bihar, 3 districts covering 69 villages in 7 blocks in Uttar Pradesh, 1 district covering 68 villages in 3 blocks in Jharkhand, 3 districts covering 9 blocks in Assam, 4 districts in Manipur, and 1 district covering 4 villages in 1 block in Chhattisgarh have been detected for groundwater arsenic contamination. 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. People in these affected states are chronically exposed to arsenic drinking arsenic contaminated hand tube-wells water. With every new survey, new 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. Further to those, 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. Whether the knowledgebase, understandings and technological options available are adequate to resolve the issues or, there are further needs of more investigations and studies to strengthen understanding of geochemical processes to mitigate and remediate arsenic from groundwater, are some of the concerns to be addressed for attaining sustainability in supply of arsenic safe groundwater to the affected areas.

Although the exact sources and mobilization processes of such large scale occurrence of arsenic in groundwater are yet to be established the cause 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 may have played a modifying role in its further exaggeration. There are numbers of hypotheses about the source of arsenic and probable reasons of its occurrence in groundwater. Among the hypotheses of sources, which have been described, Arsenic is transported : (i) by the River Ganges and its tributaries from the Gondwana coal seams in the Rajmahal trap area located at the west of the basin; (ii) by the north Bengal tributaries of the River Bhagirathi and the River Padma from near the Gorubathan base-metal deposits in the eastern Himalayas; and (iii) with the fluvial sediments from the Himalayas and chemical processes of arsenic in groundwater, the most accepted one is recognized as transport of arsenic from the Himalayas with the fluvial sediments. Regarding chemical processes of occurrence of arsenic in groundwater, out of two hypotheses, one describing oxidation of **As**-bearing pyrite minerals and the other one recognizing due to dissolution of **As**-rich iron oxyhydroxides (FeOOH), the later case is hypothesized as the most accepted one. Whether the reasons of dissolution of arsenic from soil to aqueous phases are excessive exploitation of groundwater is yet to be established.

Over the last 25 years, since the groundwater arsenic contamination first surfaced in the year 1983, a number of restorative and substituting measures coupled with action plans focusing mainly towards detailed investigations to understand the physiochemical process and mechanism, alternate arrangement to supply arsenic free water to the affected populace have been initiated mainly in West Bengal. Efforts have also been made in the development of devices for arsenic removal and their implementation at the field. While in other States, they are meager. Despite number of corrective and precautionary measures, the spread over of arsenic contamination in groundwater continues to grow and more new areas have been added to the list of contaminated area. The problem resolving issues, thus, seem to be partial and inadequate, that need to be strengthened by strategic scientific backing.

Numerous investigations have come out with number of findings, and alternatives propositions, varying from identification of shortfalls to success stories. Undoubtedly, each research study has its own merits and added new information; however, a need arises to translate all those research outcomes to problem resolving issues through framework of activities. The present state of affairs of the arsenic menace in India demands a systematic translation of success stories of one place/region to another, and overcoming the shortfalls by conceiving R & D studies in areas wherever they are 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 for groundwater tapping 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 deriving a comprehensive framework of activities leading to mitigation and remediation of the issues emerging out of arsenic menace.

Towards the supply of arsenic safe water by treatment of contaminated groundwater using arsenic removal filters and devices, a variety of treatment technologies, mainly based on oxidation, co-precipitation, adsorption, ion-exchange and membrane process, have been developed and extended to the field. However, the efficiency and applicability/appropriateness of the technologies have proved more conflicting than successful mainly because of disadvantages associated with them with regard to management of large amounts of toxic sludge produce from the devices and O & M difficulties. There is, therefore, a need for further refinement in those treatment devices besides their sustainability in terms of economic viability and social acceptability. To provide arsenic safe groundwater from alternate long distance sources piped water supply scheme, based on surface sources in feasible locations has been put in place and successfully operating in West Bengal. Tapping of deeper aquifers underneath the contaminated zones in many locations is proving feasible alternative. Numerous studies highlight different concepts with regard to mobilization processes and suggested for deriving alternative sources for supply of water to the affected areas, those include; watershed management, artificial groundwater recharge, tapping of deeper aquifers, etc. 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.

It is in these contexts; the Vision document entitled **"Mitigation and Remedy of Groundwater Arsenic Menace in India"** is envisaged. The document is designed to focus mainly on: (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, (vi) roadmap to achieve the targeted milestones, (vii) framework of activities to be taken up, etc. For figuring these concerns and issues, a total of ten different Chapters linking one to another are deliberated. Of which, first six chapters illustrate the knowledgebase, understanding, status , technologies available followed by a critical appraisal, while the other four chapters elaborate on further work required for achieving sustainable solution for arsenic menace, roadmap to achieve those along with an envisaged 'Plan of Actions' and financial requirement to achieve those targeted tasks. These chapters have been contributed by a number of resource persons from all over the Country.

The chapters are organized as follows: Chapter-1 discusses general aspects of Arsenic Source, occurrence and geochemistry; Chaper-2 brings out status of Arsenic menace in India with a critical appraisal; Chapter-3 explains the Sources and causes of groundwater Arsenic contamination in Ganga-Brahmaputra Plains along with results of different studies carried out by researchers; Chapter-4 highlights the mitigation and remediation measures initiated by different states and results achieved; Chapter-5 includes Technological options and Arsenic removal technologies available and practiced in the field and their performances and shortfalls; while Chapter-6 encompasses a critical appraisal of activities carried out so far and results achieved thereof with a suggested view of future risk, scope to remediate, technological competence, etc. Chapter 7 brings out the gap and identifies the areas on which further concentrated efforts would be required; Chapter-8 provides a roadmap of tasks to be initiated with a framework of activities including phasing their scope under the Government of India ongoing schemes; Chapter-9 details out the financial requirement and operation aspects of the activities emphasized in the document including proposition of Central-State sharing of finances; while Chater-10 figures out as to how the Mission can be managed to attain the targeted goals with an estimate of a time frame.

A framework of activities with an estimated financial target of **Rs.200 crores** for a period of five years has been envisaged to resolve arsenic menace exposed in seven States in India. It is believed, earnestly, that likely results from these elaborated scientific tasks will help building the strategy to mitigate and remove groundwater arsenic menace in India.

Contents

Chapter-7: Work Ahead: Critical Concerns and Key Challenges 125-138

Chapter- 8: Roadmap for Achieving Envisaged Targets 139-156

List of Figures

List of Tables

Elaboration of Abbreviations

AIIH&PH : All India Institute of Hygiene and Public Health
ARP : Arsenic Removal Plant
ARU : Arsenic Removal Unit
ARWSP : Accelerated Rural Water Supply Programme
BAMWSP : Bangladesh Arsenic Mitigation Water Supply Project
BARC : Bhabha Atomic Research Centre
BDP : Bengal Delta Plains
BIS : Bureau of Indian Standards
BTU : Bucket Treatment Unit
BUET : Bangladesh University of Engineering and Technology
CGWB : Central Ground Water Board
DPHE : Department of Public Health and Environment
GMB : Ganga-Meghna-Brahmaputra
INCOH : Indian National Committee on Hydrology
INCGW : Indian National Committee on Ground Water
JPOA : Joint Plan of Action
NGO : Non-Governmental Organization
NTU : Nephelometric Turbidity Unit
NREGA : National Rural Employment Guarantee Act
O & M : Operation and Maintenance
PFLT : Paint Filter Liquids Test
PHED : Public Health Engineering Department
PMGY : Pradhan Mantry Gramodaya Yojana
POU : Point of Use
POTW : Publicly Owned Treatment Works
PRB : Permeable Reactive Barrier
RO : Reverse Osmosis
R & D : Research and Development
SOES : School of Environmental Studies
SORAS : Solar Oxidation and Removal of Arsenic from Drinking Water
SPLP : Synthetic Precipitation Leaching Procedure
TBLL : Technically Based Local Limits
TCLP : Toxicity Characteristic Leaching Procedure
TC : Toxicity Characteristics
UCL : University College London
US-EPA : United States - Environmental Protection Agency
WHO : World Health Organization

Chapter -1

Arsenic: Source, Occurrence and Geochemistry

Arsenic that has the symbol 'As', and atomic number 33, atomic weight 74.92 is often referred to as a metal but, it is classified chemically as a nonmetal or metalloid belonging to Group-15 of the periodic table. The most common oxidation states for arsenic are : -3 (arsenides: usually alloy-like intermetallic compounds), +3 (arsenites (As(III)), and most organoarsenic compounds), and +5 (arsenates(As(V)): the most stable inorganic arsenic oxycompounds). Arsenic is always present as compounds with oxygen, chlorine, sulphur, carbon and hydrogen on one hand, and with lead, gold and iron on the other. It can exist in inorganic or organic form; inorganic arsenic is generally more toxic than organic arsenic. Inorganic arsenic occurs naturally in many kinds of rocks and it is most commonly found with sulfide ores as arsenopyrite. Inorganic arsenic compounds are known to be human carcinogens. Arsenic combined with carbon and hydrogen is classified as organic arsenic. Both inorganic and organic compounds are typically white to colorless powders. Arsenic in element form is insoluble in water. It is soluble in oxidized from.

Arsenic is found in the natural environment in abundance in the Earth's crust and in small quantities in rock, soil, water and air. The average concentration of arsenic in the continental crust is 1-2 mg/kg. The mean concentration of arsenic in igneous rocks ranges from 1.5 to 3.0 mg/kg, whereas in sedimentary rocks it ranges from 1.7 to 400 mg/kg. About one third of the arsenic in the atmosphere comes from natural sources. Volcanic action is the most important natural source of arsenic. The next most important natural source is the arsenic-containing vapor that is generated from solid or liquid forms of arsenic salts at low temperatures. The rest two third comes from man-made sources. Mining, metal smelting, burning of fossil fuels and coal-fired powder plants are the major industrial processes that contribute arsenic contamination to air, water and soil. Elemental arsenic is produced commercially from arsenic trioxide. Arsenic trioxide is a by-product of metal smelting operations. Environmental contamination also occurs from pesticides used in agriculture and from chemicals used for timber preservation. About 70% of the world production of arsenic is used in timber treatment, 22% in agricultural chemicals, and the remainder in glass, pharmaceuticals and metallic alloys. Thus, the sources of arsenic can be categorized as: (i) geological (geogenic), (ii) anthropogenic (human activities), and (iii) biological (biogenic). Figure-1.1 depicts a schematic diagram of major sources and routes of arsenic in soil and aquatic ecosystem. Important arsenic bearing minerals are given in Table-1.1, in which, the most common is Arsenopyrite **(FeAsS)**.

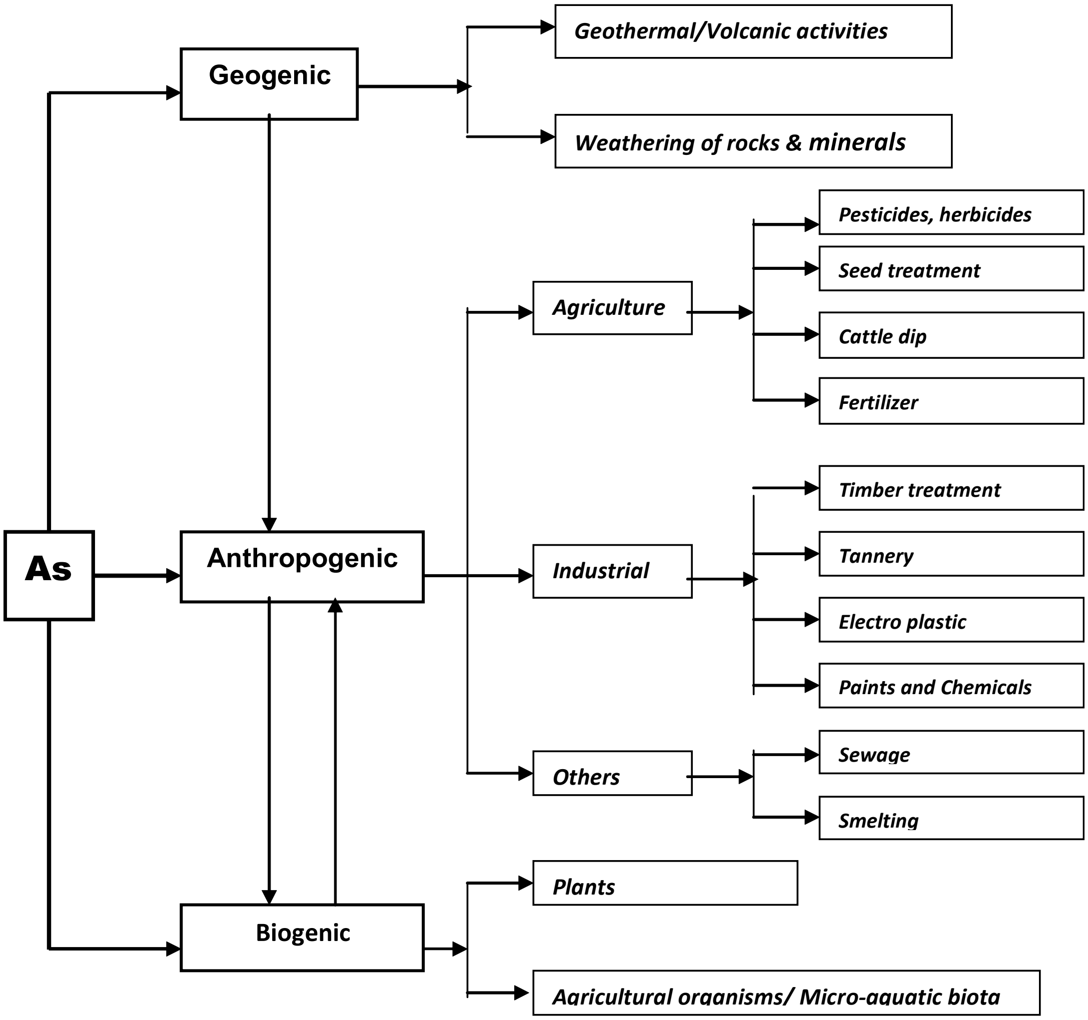


Figure 1.1: Major sources and routes of Arsenic in soils and aquatic ecosystem
(Source : Donald L. Sparks, 2005)

Table 1.1: Important Arsenic Bearing Minerals

Mineral	Arsenic content (%)
Arsenopyrite **(FeAsS)**	46
Lollingite **($FeAs_2$)**	73
Orpiment	61
Realger	70
Native Arsenic	90 – 100

The transport and distribution of arsenic in the environment is complex due to the many chemical forms in which it may be present and because there is continuous cycling of different forms of arsenic through air, soil and water. Arsenic dissolved in water can be present in several different forms. In well-oxygenated water and sediments, nearly all arsenic is present in the stable form of arsenate (V). Some arsenite (III) and arsenate (V) forms are less stable and are interchangeable, depending on the chemical and biological conditions. Some chemical forms of arsenic adhere strongly to clay and organic matter, which can affect their behavior in the environment. Weathered rock and soil, containing arsenic, may be transported by wind or water erosion. Arsenic releases into the atmosphere by industrial processes or volcanic activity and attaches to particles that are dispersed by the wind and fall back to the ground.

Long term exposure to arsenic in drinking water has variety of health concerns including several types of cancers, cardiovascular diseases, diabetes, and neurological effects. Many countries, including Bangladesh, India, Taiwan, Mongolia, Vietnam, Argentina, Chile, Mexico, Ghana and the United States, exposed to arsenic have problems because the sources of arsenic are primarily natural rather than anthropogenic or geothermal. Inorganic arsenic of geological origin has been recognized as the main form of arsenic in groundwater.

Different Countries have set different standards of arsenic content for drinking-water quality. WHO's norms for drinking-water quality go back to 1958; in that year, the international Standard for drinking-water was established at 200 µg/L as an allowable concentration for As. In 1963 the standard was re-evaluated and reduced to 50 µg/L. The WHO guidelines have been revised during the recent past and the permissible limits have been reduced from 50 µg/L to 10 µg/L (10 ppb) in year 1993 due to adverse health reports arising from different parts of the world where arsenic is causing severe health problems. India has set its maximum permissible limit for arsenic to 50 µg/L. The standards set by different countries for As for drinking-water quality are given in Table-1.2.

Table 1.2: Standards of Arsenic in potable water set by different Countries.

Country/Institution	Allowable level of Arsenic in drinking water
US-EPA, USA	10 µg/L or 10 ppb
Australia	7µg/L or 7 ppb
Canada	25 µg/L or 25 ppb
BIS, India	50 µg/L or 50 ppb
Latest, WHO’s norm (1993)	10 µg/L or 10 ppb

1.1 Occurrences in Groundwater

Arsenic 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. These sources are localized and therefore, important in some geologic settings; biogenic sources can be predominant in marine ecosystem, whereas natural sources are primarily from the parent (or rock) material from which they are derived and therefore, are main causes of concern. There is another mode of occurrence of arsenic, namely Organoarsenic, which is mostly less toxic than both As(III) and As(V) and therefore, less harmful than other two forms. In groundwater, inorganic arsenic commonly exists as arsenate [As(V)] and arsenite [As(III)] . Inter-conversion of As(V) and As(III) takes place by oxidation of As(III) to As(V) and reduction of As(V) to As(III). High concentrations of arsenic tend to occur in sulphide minerals and metal oxides, especially iron oxides. Many factors control arsenic concentration and transport in groundwater. An understanding of factors controlling the distribution of arsenic in groundwater requires knowledge of arsenic sources and of processes controlling arsenic mobility. This knowledgebase would help in guiding monitoring and remediation efforts.

1.2 Geochemistry of Arsenic

Geochemistry of arsenic is controlled by many factors, that include:

- Red-ox potential
- Adsorption/ desorption
- Precipitation/dissolution
- Arsenic speciation
- pH
- Biological transformation

In general, most naturally occurring arsenic compounds are insoluble in water.

1.2.1 Red-ox potential

Redox potential, symbolically termed as Eh is also known as reduction potential, means the tendency of a chemical species to acquire electrons and thereby to reach to a reduced state. Arsenic is a redox-sensitive element. This means that arsenic may gain or lose electrons in redox reactions. As a result, it may be present in a variety of redox states. Arsenate generally predominates under oxidizing conditions, while arsenite predominates when conditions become sufficiently reducing. Under the pH conditions of most groundwater, arsenate is present as the negatively charged oxyanions $H_2AsO_4^-$ or $HAsO_4^{2-}$, whereas arsenite is present as the uncharged species H_3AsO_3. Natural geochemical and biological processes play critical role in controlling the fate and transformation of arsenic in the subsurface. Arsenite is thermodynamically unstable in aerobic environments and oxidizes to As(V). Presence of other oxides such as FeO, Fe_2O_3, MnO_2 and even clay minerals is capable of oxidizing As(III).

1.2.2 Adsorption/ Desorption

Two categories of processes largely control arsenic mobility in aquifers: (i) adsorption and desorption reactions, and (ii) solid-phase precipitation and dissolution reactions. Attachment of arsenic to an iron oxide surface is an example of an adsorption reaction. The reverse of this reaction i.e., detachment of arsenic from such a surface, is an example of desorption. Arsenic adsorption and desorption reactions are influenced by changes in pH, occurrence of redox (reduction/oxidation) reactions, presence of competing anions, and solid-phase structural changes at the atomic level.

Arsenate and arsenite adsorb to surfaces of a variety of aquifer materials, including iron oxides, aluminum oxides, and clay minerals. Adsorption and desorption reactions between arsenate and iron-oxide surfaces are important controlling reactions because arsenate adsorbs strongly to iron-oxide surfaces in acidic and near-neutral-pH water. However, desorption of arsenate from iron-oxide surfaces becomes favored as pH values become alkaline. As a result of the pH dependence of arsenic adsorption, changes in groundwater pH can promote adsorption or desorption of arsenic. Similarly, redox reactions can control aqueous arsenic concentrations by their effects on arsenic speciation and hence, arsenic adsorption and desorption. Arsenic adsorption can also be affected by the presence of competing ions. Structural changes in solid phases at the atomic level also affect arsenic adsorption and desorption.

1.2.3 Precipitation and Dissolution

The various solid phases (minerals, amorphous oxides, volcanic glass, and organic carbon) of aquifer material can exist in a variety of thermodynamic states. Solid-phase precipitation is the formation of a solid phase from components present in aqueous solution. Precipitation of the mineral calcite, from calcium and carbonate present in groundwater, is an example of solid-phase precipitation. Dissolution of volcanic glass within an aquifer is an example of solid-phase dissolution. At any given time, some aquifer solid phases undergo dissolution, whereas others precipitate from solution. Arsenic contained within solid phases, either as a primary structural component or an impurity in any of a variety of solid phases, is released to groundwater when those solid phases dissolve. Similarly, arsenic is removed from groundwater when solid phases containing arsenic precipitate from aqueous solution. As an example, arsenic often co-precipitates with iron oxide; iron oxide, in such case, may act as an arsenic source (case of dissolution) or a sink (case of precipitation) for groundwater. Solid-phase dissolution contributes not only arsenic contained within that phase, but also any arsenic adsorbed to the solid-phase surface. The process of release of adsorbed arsenic, as a result of solid-phase dissolution, is distinct from the process of desorption from stable solid phases. Solid-phase precipitation and dissolution reactions are controlled by solution chemistry, including pH, redox state, and chemical composition.

1.2.4 Arsenic Speciation

Speciation of an element in water sample means determination of the concentration of different physico-chemical forms of the element which together make up its total concentration in the sample. The speciation of arsenic in environmental material is of interest because of the different levels of toxicity exhibited by various species. Species illustrate the various oxidation states that arsenic commonly exhibits (-3, 0, +3, +5) and the resulting complexities of its chemistry in the environment. Nearly two dozen arsenic species are present in the environmental and biological systems. Arsenic in groundwater is present in various species like, H_3AsO_3, H_2AsO_3, $HAsO_3$, H_3AsO_4, H_2AsO_4, and $HAsO_4$. Arsenic species are generally present as arsenate [As(V)] or arsenite [As(III)] for Eh conditions prevalent in most groundwater. Both As(V) and As(III) form protonates oxyanions in aqueous solutions and the degree of protonation depends on pH. Differences in their toxicity, biochemical and environmental behaviors require the determination of these individual arsenic species.

1.2.5 Influence of pH

Alteration in the state of arsenic oxidation is usually influenced by Eh and pH. The most suitable pH for arsenic dissolution is low acidic ($pH<2$), but it can be dissolved in other pH ranges from 2 to 11 under suitable chemical and physical conditions. Arsenious acids, usually formed at low pH under mildly reduced conditions, are easily replaced by H_2O_3 when pH increases. $HAsO_3$ is usually formed at very high alkaline $pH > 12$.

1.2.6 Influence of competing ions

Other intrinsic factors of a system which can also exert marked influence on the concentration and speciation of arsenic include: solution composition, competing ions especially, the ratio of Phosphorous to As, and Selenium to As, nature and composition of solid phases present, reaction kinetics and flow regime.

1.2.7 Biological transformation

Arsenic undergoes a series of biological transformations in the aquatic environment, yielding a large number of compounds, especially organo-arsenicals. Certain reactions, such as oxidation of As(III) to As(V), may occur both in the presence and absence of microorganisms, whereas other reactions such as methylation, are not thermodynamically favorable in water and can occur only in the presence of organisms, which indicates that many aquatic organisms are capable of accumulating arsenic and may catalyse the oxidation of As(III) to As(V). Biological transformation is significantly important in marine ecology.

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 the 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.

1.3 Hypotheses on Mechanism of Arsenic Mobilization

Widely accepted mechanisms of arsenic mobilization in groundwater are still to be established. 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.

1.4 Summary

Arsenic **(As)** in soil and aquatic ecosystem can occur from: (i) geological (geogenic), (ii) anthropogenic (human activities), and (iii) biological (biogenic) sources. In soil and groundwater, it can be introduced during weathering of rocks and minerals followed by subsequent leaching and runoff or from anthropogenic sources. Biogenic sources are predominant in marine ecosystem. The most common Arsenic bearing mineral is Arsenopyrite (FeAsS). In sediments and waters, **As** can be present in the form of arsenite (As(III)) and arsenate (As(V)). As(III) is normally 60 times more toxic than As(V). In groundwater, arsenic species can be present in various forms of arsenic acids, such as; H_3AsO_3, H_2AsO_3, $HAsO_3$, H_3AsO_4, H_2AsO_4, and $HAsO_4$. The standards of arsenic for drinking-water quality set by WHO and BIS are: 10 μg/L and 50 μg/L, respectively. Many factors control arsenic concentration, distribution and transport in groundwater. The factors, which govern the geochemistry of arsenic, are: red-ox potential, adsorption/desorption, precipitation /dissolution, arsenic speciation, pH, presence and concentration of competing ions, and biological transformation. These factors vary from aquifer to aquifer that depend upon the geological settings, geo-chemistry and eco-environmental conditions.

Out of three hypotheses describing (i) oxidation of **As**-bearing pyrite minerals and subsequent release of As(III) , (ii) dissolution of **As**-rich iron oxyhydroxides (FeOOH) and resulting release of Fe(II), As(III), and As(V), and (iii) release of **As** sorbed to aquifer minerals by competitive exchange with phosphate ions as probable mechanisms of **As** mobilization in groundwater specially with reference to Holocene aquifers, the second hypothesis is believed to be the probable reason for excessive accumulation of **As** in groundwater. The oxidation model is the one in which As(III) is oxidized to As(V) while in the reduction model As(V) is reduced to As(III).

Questions thus to be answered are:

(i) Whether the available literatures are adequate to resolve the issues of arsenic contamination in groundwater in India or, there is further need for investigation and study to strengthen understanding of geochemical processes for different hydrogeological conditions?

(ii) Whether suggested hypotheses of **As**-mobilization in groundwater hold well for all hydro-geological and geochemical settings or for a select few?

(iii) Whether occurrences of **As** in groundwater and their chemical composition contain similar proposition?

(iv) What are the controlling factors for **As** in different geochemical environments?

Chapter-2

Arsenic Menace in India- An Appraisal

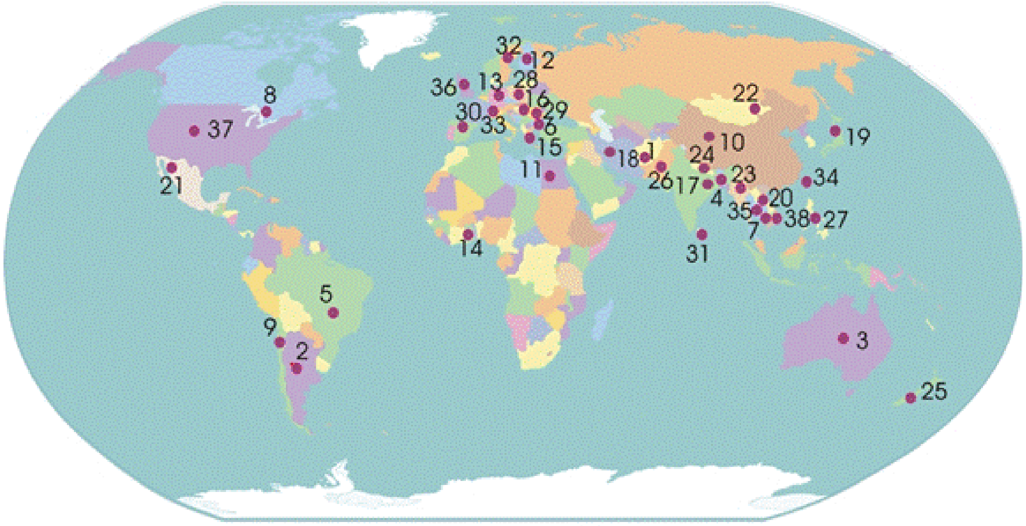
Groundwater arsenic contamination in India from the states of West-Bengal, Jharkhand, Bihar, Uttar Pradesh is in flood plain of Ganga River; in Assam and Manipur it is in flood plain of Brahamaputra and Imphal rivers. Groundwater of Rajnandgaon village in Chhattisgarh state is also arsenic contaminated and some people had arsenical skin lesions but the source of arsenic in Chhattisgarh is not from flood plains of Newer Alluvium (Holocene) as in Ganga, Brahmaputra, and Imphal rivers. The magnitude of arsenic contamination in Chhattisgarh state is much less compared to flood plain contamination in Ganga-Brahmaputra plain. People in these affected states are chronically exposed to drinking arsenic contaminated hand tube-wells water. Since the groundwater arsenic contamination first surfaced in 1983 from nearly 33 villages in 4 districts of West Bengal, up till 2008; 9 districts covering 3417 villages in 111 blocks in West Bengal, 15 districts covering 57 blocks in Bihar, 3 districts covering 69 villages in 7 blocks in Uttar Pradesh, 1 district covering 68 villages in 3 blocks in Jharkhand, 3 districts covering 9 blocks in Assam, 4 districts in Manipur, and 1 district covering 4 villages in 1 block in Chhattisgarh have been detected for groundwater arsenic contamination above permissible limit of 50 µg/L. Many more North-Eastern Hill States in the flood plains are suspected to have the possibility of arsenic in groundwater. Even, after twenty-five years, with every new survey, new arsenic affected villages and people suffering from arsenic related diseases are being reported. 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.

Analysis of 169698 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. And a preliminary survey screening 100,731 people by SOES from arsenic affected villages of West Bengal, Jharkhand, Bihar, Uttar Pradesh, and Chhattisgarh; reported 10118 patients with different kinds of arsenical skin lesions. Arsenic neuropathy as well as adverse pregnancy outcomes such as spontaneous abortion, still-birth, preterm birth and low birth weight were also reported along with other arsenic related diseases. Infants and children drinking arsenic contaminated water were also found severely effected. Analyses of biological samples from arsenic affected areas showed elevated level of arsenic in both patients and non-patients indicating that many are sub-clinically affected (SOES, 2008). It has been estimated that in Ganga-Meghna- Brahmaputra plain (including Bangladesh) alone around 100 million people are at risk from groundwater arsenic contamination above WHO guideline. People in newly arsenic identified states could be in more danger, as many are not aware of their arsenic contamination in hand tube-wells and unknowingly continue drinking arsenic contaminated groundwater. In arsenic contaminated areas often arsenic contaminated groundwater is used for agricultural irrigation resulting in excessive amount of available arsenic in the crops in that area. It has been reported that second to the ingestion of arsenic, after the direct consumption as drinking arsenic contaminated water, is through food chain, particularly use of contaminated rice followed by vegetables. This eventually indicates that the effects of this occurrence are far-reaching; sooner we search sustainable solutions to resolve the problem, lesser be its future environmental, health, socioeconomic and socio-cultural hazards.

Even after spending huge amount of money for providing arsenic safe water to the villagers from contaminated hand tube-wells and other sources, the overall result suggests requirement of more concentrated and focused efforts in planning and management to cope up with such gigantic calamity. Attempts made so far to combat the menace of groundwater arsenic contamination, like, to identify the causes, to provide arsenic free drinking water to people dependent on groundwater supply, to reduce the arsenic related social and socio-economic problems and to develop cost effective technology for eradication of arsenic contamination have proven inadequate, fragmented and less responsive, as evident from the rise in number of arsenic affected areas with every new survey. There is, therefore, a need for adopting holistic approach to resolve solution considering management of science-society-resources together, but not merely healing the pain externally. Proper watershed management, possibility of tapping of freshwater aquifer linking to proper aquifer management, in-situ remediation of the problem and economical utilization of all available alternative safe sources of water need to be explored. To combat the arsenic crises we need to aware and educate the villagers the dangers of arsenic toxicity and importance of using arsenic safe water. This can only be achieved by active community participation and whole-hearted support from government and arsenic researchers.

2.1 Global Arsenic Scenario

Most of the cases of arsenic toxicity in the medieval and early modern age were due to arsenic intake through medicine, smelting or genocide activities. Around the middle of 20th century arsenic poisoning surfaced from some countries where people ingested arsenic contaminated water. This toxicity manifested on mass scale rather than the mere individual cases. The major affected countries were Argentina, Chile, Mexico and Taiwan. Close to the end of 20th century groundwater arsenic contamination and sufferings of people came to lime light from three more Asian countries (West-Bengal-India, China and Bangladesh). The source of arsenic was contaminated hand tube-wells. In global arsenic contamination scenario 38 countries are affected at present **(Figure 2.1)**. In Asia alone 13 countries are arsenic affected and Asian countries are worse arsenic affected in global arsenic scenario. In Bangladesh alone out of its total 64 districts, 60 districts have groundwater arsenic contamination above WHO guideline value (10µg/L) . In India, flood plains of all the states in Ganga and Brahamaputra rivers are arsenic affected. **Figure 2.2** shows the major arsenic affected regions in Asia.



1. AFGANISTHAN
2. ARGENTINA
3. AUSTRALIA
4. BANGLADESH
5. BRAZIL
6. BULGARIA
7. CAMBODIA
8. CANADA
9. CHILE
10. CHINA
11. EGYPT
12. FINLAND
13. GERMANY
14. GHANA
15. GREECE
16. HUNGARY
17. INDIA
18. IRAN
19. JAPAN
20. LAO PDR
21. MEXICO
22. MONGOLIA
23. MYANMAR
24. NEPAL
25. NEW ZEALAND
26. PAKISTHAN
27. PHILIPPINES
28. POLAND
29. ROMANIA
30. SPAIN
31. SRI LANKA
32. SWEDEN
33. SWITZERLAND
34. TAIWAN
35. THAILAND
36. UNITED KINGDOM
37. USA
38. VIETNAM

Figure 2.1 : Global Scenarios of Arsenic Contamination Affected Countries

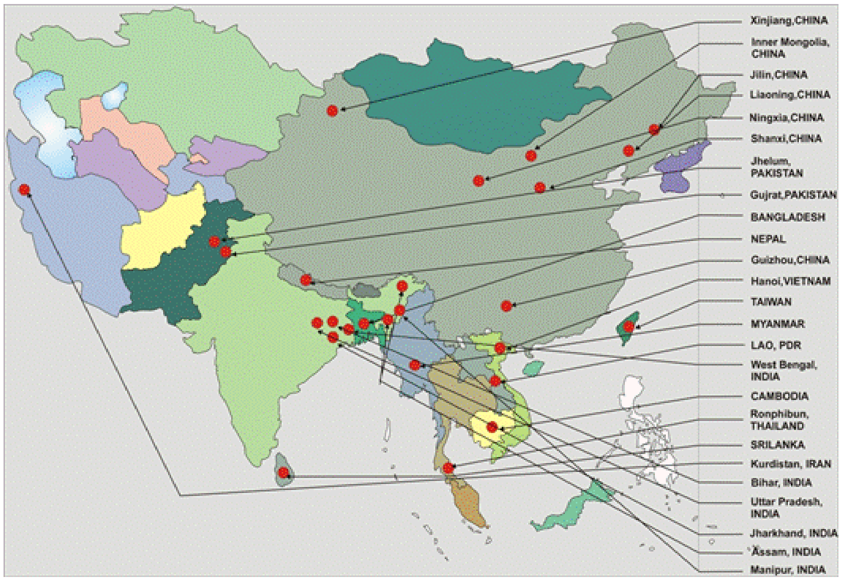


Figure 2.2 : Major Arsenic Affected Regions in Asia (Source : British Geological Survey, 2001).

Most of the world's high-arsenic in groundwater is the result of rock water interaction. The majority of large-scale high-arsenic provinces are in young unconsolidated sediments usually of Quaternary age and often belong to Holocene (<12 thousand years). These sedimentary deposits holding the arsenic contaminated aquifers can broadly be grouped into two: (i) large alluvial and deltaic plains (eg., Bengal delta, Yellow River plain, Irrawaddy delta, Red River delta), and (ii) inland closed basins in arid or semi-arid setting (eg. Argentina, Mexico, south-western United States). The most interesting fact is that these aquifers do not appear to contain abnormally high concentration of arsenic bearing minerals, but, do have geochemical and hydrogeological conditions favorable for mobilization and retention of arsenic in solution.

2.2 Background of Groundwater Arsenic Contamination in India (1976-2008)

During the middle of 20th century, South Asian countries like India and Bangladesh (then East Pakistan) had two major problems. The first was providing food for the huge population and the second was preventing water contaminated diseases like diarrhoea, cholera, typhoid, dysentery, etc. The yearly rainfall, though among the highest in the world in Bangladesh and in West Bengal, India, was not potent enough to satisfy the needs. Moreover, India and Bangladesh, with plenty of available surface water, did not have the necessary infrastructure for the preservation, distribution, and purification facilities. The overall watershed management was poor. The farmer had to plea desperately for the rains in order to grow a harvest. The annual rainfall allowing a single harvest a year was not enough for the population and the situation would be even worse if there was a drought. Such circumstances called for alternative remedies. Sometime during the year 1950, in Charmajdia, a small village of the district Nadia, West-Bengal, the first induction of groundwater by pump created a furor. Villagers fled at the sight of water gushing out from the earth. They shrieked, 'Devil Water' is coming. They believed underground was the proverbial Hell where Satan resided. Hence, they refused to use that water. Nevertheless, this water came at a trying period for the struggling people. These trusting people, thoroughly advised by the government and aid-agencies, finally decided to use the forbidden water. They were given assurance that with this groundwater, the bliss of God would bring green revolution and good health. The revolution did come and the discovery of devil water became mere annals of history. The underground water survived the test of time and faith. It overcame the stigma of being a tool of the devil. The villagers drank cold water during the summer and moderately warm water during winter by merely pushing the handle of a small machine known as a Tube-Well.

In 1976, Dr D V Dutt from Chandigarh, North India, while treating patients in Chandigarh and surrounding areas noticed some patients suffering from noncirrhotic portal hypertension (NCPH). He came to know that the drinking water used by those patients came from arsenic contaminated tube wells. In 1982, six years after the Chandigarh incident, a patient from North-24 Pargana district of West Bengal came to the Dermatology Department of Calcutta, School of Tropical Medicine (CSTM). Dermatologist Dr. K,C.Saha noticed that the patient's skin lesions were not like the usual skin diseases. Dr Saha learnt from the patient that many people in his village suffered from such afflictions in soles of their feet, palms of their hands, and bodies. Then soon another patient arrived with similar symptoms but more severe and he had an ulcer on his finger. After biopsy Dr Saha diagnosed cancer. Then Dr Saha visited the village from which such diseases were being reported. Together with Dr A K Chakrabarti and Dr Garai of All India Institute of Hygienic and Public Health (AIIH&PH), and Dr A K Saha, Professor of Geology, Presidency College, Calcutta, Dr Saha conducted a thorough research in that village for one year. He concluded that the tube well water used for drinking in the village was heavily arsenic contaminated, and was responsible for such diseases. After that, Dr D N Guha Majumdar diagnosed Liver Fibrosis among arsenic patients in the SSKM Hospital, Calcutta, and the same disease that was indicated by Dr D. V. Dutt in 1976. Soon the disease was found to exist in districts like South 24 Pargana, North 24 Pargana, Nadia, and Murshidabad. Nearly 33 villages in these four districts were reported affected by this malady. It was Dr. Saha who brought out first document on Arsenic menace in groundwater in four districts of West Bengal.

From 1983 onwards a number of organizations in West-Bengal are working on the groundwater arsenic contamination investigations, problem identification and mitigation. They are largely: (a) School of Tropical Medicine (STM), (b) All India Institute of Hygiene and Public Health (AIIH&PH), (c) Central Ground Water Board (CGWB), (d) Centre for Study of Man and Environment (CSME), (e) School Environmental Studies(SOES), JU, (f) WB Government Public Health Engineering Department (PHED), (g) School of Fundamental Research (SOFR), (h) Seth Sukhlal Karnani Memorial Hospital, and (i) WB Directorate of Health Services, Government of West Bengal, etc. In addition to these organizations, there may be a number of other Institutions/units working on Arsenic problem in West Bengal across the Country. Recently Government of West-Bengal has started a project worth Rs. 2100 crores to supply arsenic safe water to the arsenic contaminated districts of West-Bengal.

In continued surveys and investigations after 1983 in West Bengal, in every additional survey, more and more arsenic affected areas and districts have been added to the list of arsenic affected areas. Year wise addition of detected arsenic affected areas, compiled from database of SOES, is given in the following table that could help recognize the progression of this menace:

Year	No of district & Name of district	No. of villages (Blocks)
Year, 1983	4 (South 24 Pargana, North 24 Pargana, Nadia, and Murshidabad)	33 (*)
Up to 1991	6 (North 24-Pargana, South 24-Pargana, Nadia, Murshidabad, Malda, and Bardhaman)	93 (*)
Up to 1994	6 (North 24-Pargana, South 24-Pargana, Nadia, Murshidabad, Malda, and Bardhaman)	312 (37)
Up to 1995	6 (North 24-Pargana, South 24-Pargana, Nadia, Murshidabad, Malda, and Bardhaman)	405 (37)

Up to 1997	9 (Malda, Murshidabad, Bardhaman, Nadia, Howrah, Hooghly, North 24-Parganas, South 24-Parganas and Kolkata.)	830 (58)
Up to 1999	9 (Malda, Murshidabad, Bardhaman, Nadia, Howrah, Hooghly, North 24-Parganas, South 24-Parganas and Kolkata.)	985 (69)
Up to 2002	9 (Malda, Murshidabad, Bardhaman, Nadia, Howrah, Hooghly, North 24-Parganas, South 24-Parganas and Kolkata.)	2700 (*)
Up to 2004	9 (Malda, Murshidabad, Bardhaman, Nadia, Howrah, Hooghly, North 24-Parganas, South 24-Parganas and Kolkata.)	3200 (85)
Up to 2008	9 (Malda, Murshidabad, Bardhaman, Nadia, Howrah, Hooghly, North 24-Parganas,South 24-Parganas and Kolkata.)	3417(111)

(*) Not reported

Since 1983 when there were only 33 affected (As > 50 µg/L) villages in four districts, the number of villages has increased to 3417 in 111 blocks in nine districts in till 2008 in West Bengal alone. There can be several other lists of arsenic affected areas prepared by different organizations, which may differ from one to another, because of number of reasons, e.g.,(i) number of samples analyzed, and different sampling locations (ii) compilation of information may be different, etc. However, the fact is that during last 25 years, with every additional survey, an increasing number of contaminated villages and more affected people have been identified. Those raise questions: whether all those identified areas were already under the grim of arsenic contamination but not got exposed; or they resulted from the mobilization from the adjoining contaminated areas or triggered from the in-situ source material by the excessive groundwater exploitation over the passage of time. It needs a mention here that in 1992, the problem of arsenic groundwater contamination, and people suffering from arsenical skin lesions were also reported in Padma-Meghna-Brahmaputra (PMB) plain of Bangladesh. Bangladesh is considered worst affected in global arsenic contamination scenario.

In 1999, the arsenic groundwater contamination and its health effects in Rajnandgaon district were also identified from the analysis of water samples from Rajnandgaon district of Chhattisgarh by SOES.

In 2002, the arsenic contamination was also reported in Bihar in middle Ganga plain. It was also apprehended in adjoining areas of Uttar Pradesh. In Bihar, two villages, Barisban and Semaria Ojhapatti, in Bhojpur district, located in the western part of the Bihar state, were reported having contamination exceeding 50 µg/L. As of now, according to CGWB and PHED, Govt. of Bihar, 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 50 µg/L.

During 2003, 25 arsenic affected villages of Ballia district in Uttar Pradesh and people suffering from skin lesions came to limelight.

During 2003-2004, the groundwater arsenic contamination and consequent suffering of hundreds of people were reported by SOES in 698 hand tube-wells from 17 villages of the Sahibgunj district of Jharkhand state, India, in the middle Ganga plain.

In 2004, arsenic concentration above 50µg/L was also reported in Assam in pockets of 2 districts. In 2007, arsenic groundwater contamination from Manipur state, one of the seven North-Eastern Hill States, came to limelight. It is also apprehended by SOES that groundwater of flood plains of all the seven North-Eastern Hill states of India (Arunachal Pradesh, Meghalaya, Assam, Tripura, Nagaland, Manipur, Mizoram) may have the possibility of arsenic. **Table 2.1** shows the demography and appreciable groundwater arsenic contamination situation in Indian states at a glance and **Figure 2.3** shows the positions of arsenic affected states in India. **Figure 2.4** shows position of arsenic affected areas in Ganga Plains in India with reference to the Ganga-Meghna-Brahmaputra Plains

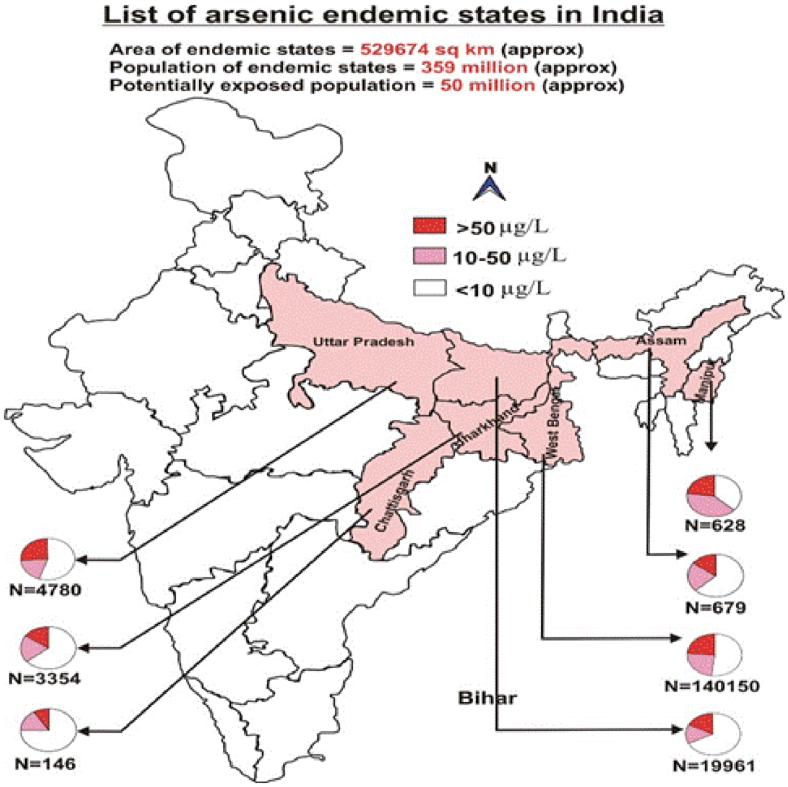


Figure 2.3: Arsenic Affected Areas in Different States in India.

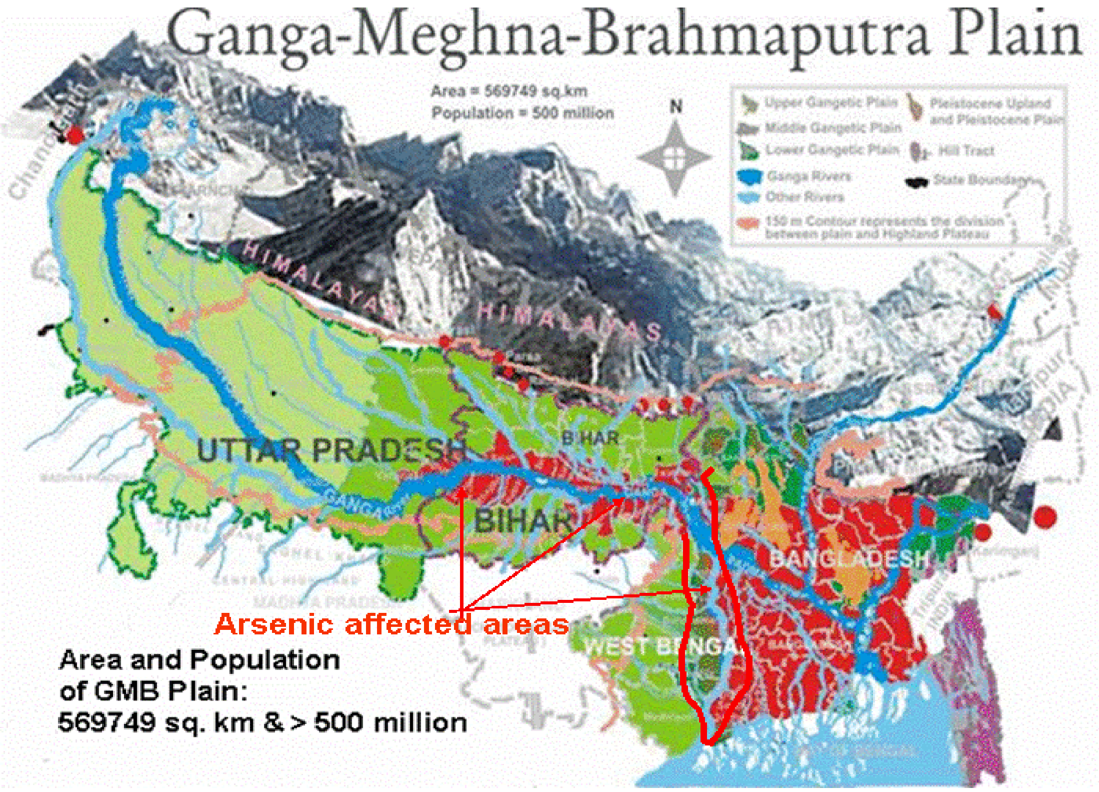


Figure 2.4: Arsenic affected stretches in Ganga Plains in India with reference to Ganga-Meghna-Brahmaputra Plains.

The demographic survey of the affected areas and analysis of water samples by many organizations (SOES alone analyzed nearly 211955 water samples; CGWB, State PHED, WB and Bihar, and other organizations also analyzed quite a large number of water samples) estimated that more than 13.85 million people could be under the threat of contamination level above 10 µg/L, in which more than 6.96 million people could be above 50 µg/L, against the total population of those areas of the order of 50 million. And a huge number of live-stock has also been exposed to arsenic contaminated groundwater. Arsenic contaminated groundwater is also in use for agricultural irrigation in the arsenic affected areas. 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. 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 source, 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.

2.3 Magnitude of Groundwater Arsenic Contamination and its Effects on Health in Arsenic Affected States of India

2.3.1 Impacts of arsenic on human health in chronically exposed population

Arsenic can exert its toxic effects through impairment of cellular respiration by inhibition of various mitochondrial enzymes and uncoupling of oxidative phosphorylation. The As(III) species can react with -SH group of protein and enzymes, thereby making them inactive and increase reactive oxygen species in the cells causing cell damage. It is also reported that arsenic could inhibit 200 enzymes in the body. It has been regarded that multisystemic non-cancer effect could be due to deactivation of essential enzymatic functions by trivalent arsenic compounds and subsequent oxidative stress to cell.

More recent studies have detected along with all the 4 species [As(III), As(V), MMA(V), DMA(V)] also the presence of MMA(III) and DMA(III) in urine. It is also considered that inorganic As(III) and the reduced forms of MMAIII and DMAIII formed during methylation are highly reactive and contribute to the observed toxicity of inorganic arsenic.

So far no evidence has been found that inorganic arsenic directly causes genetic mutations affecting cancerous cells. However, it appears that inorganic arsenic indirectly enhances susceptibility to cancer inducing chromosomal alterations, inhibition of DMA repair process, oxidative stress and cell proliferation.

Arsenate (AsO_4^{3-}) has similar structure as phosphate (PO_4^{3-}) and thus can substitute PO_4^{3-} in adenosine diphosphate (ADP). This substitution prevents conversion of ADP to ATP (adenosine triphosphate) which produces energy to cell.

The available health effect reports, after ingestion of arsenic contaminated groundwater, are mainly from the epidemiological study of chronic arsenic exposure. Number of incidents and studies related to acute arsenic toxicity are meager compared to chronic arsenic exposure. During the last decade plenty of chronic arsenic exposure incidents have been reported from Asian countries due to use of arsenic contaminated groundwater and associated health effects. More and more studies have been carried out to know various health effects due to chronic exposure. During the last decade 4 monographs (IARC 2004, IPCS 2001, NRS 1999, NRS 2001) along with large number of reports and special issues have been published to include the research activities of chronic arsenic exposure and various carcinogenic and non-carcinogenic health effects.

It is evident now that inorganic arsenic exposure deactivates the function of enzymes, some important anions, cations, transcriptional events in cells and causes other direct or indirect effects. Such activities of inorganic arsenic result in numerous illnesses that have been also confirmed by repeated epidemiological investigations. Examples of the same are :(i) Dermal effects, (ii) Cardiovascular effects, (iii) Respiratory effects, (iv) Gastrointestinal effects, (v) Endocrinological effects (diabetes mellitus), (vi) Neurological effects, (vii) Reproductive and developmental effects, (viii) Cancer effects, and (ix) other effects. Symptoms of arsenicosis are primarily manifested in the form of different types of skin disorders such as skin lesions, hyper keratosis and melanosis.

2.3.2 Arsenical health effects in India

West Bengal's groundwater arsenic contamination and health effects surfaced in 1983. West-Bengal is one of the worst arsenic affected areas in the world arsenic scenario. During last 25 years, more scientific and medical investigations have been carried out in this state by (a) School of Tropical Medicine (STM), (b) All India Institute of Hygiene and Public Health (AIIH&PH), (c) Central Ground Water Board (CGWB), (d) Centre for Study of Man and Environment (CSME), (e) WB Government Public Health Engineering Department (PHED), (f) Arsenic group in Seth Sukhlal Karnani Memorial Hospital, and (g) WB Directorate of Health Services, Government of West Bengal (h) Kolkata Medical College, etc. In very preliminary work, medical group of SOES examined around 96,000 individuals, including children (age range: infants to 11 yr), for arsenic toxicity from arsenic affected villages of West Bengal and 9,356 of them showed skin lesions; in children, these numbers were 5.6% ($n = 14,000$). 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.

Neurological examination was generally done for arsenocosis patients whose skin lesions were already diagnosed by experienced dermatologist. 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.

Arsenic exposure during pregnancy can adversely affect several reproductive endpoints. In several studies the association between arsenic exposure and adverse pregnancy outcome, including spontaneous abortion, preterm birth, stillbirths, low birth weight and neonatal and pre-natal mortality have been documented from arsenic affected villages of West-Bengal and other states in India.

2.3.3 Other multi-systemic common features in arsenic affected areas.

The following features were commonly noted (1983-2006) mainly from the arsenic endemic areas of India and Bangladesh. Most of the population suffering from arsenic skin lesions is from a poor socio-economic background.

(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%. As reported by the villagers, the unique sound of "cough of arsenicosis" was reported from adjacent village homes at night to create an unusual atmosphere. The cough may be painful and sputum may contain blood to be misdiagnosed as pulmonary tuberculosis. In late stages, shortness of breath might predominate.

(iii) Gastrointestinal symptoms of anorexia, nausea, dyspepsia, altered taste, pain in abdo men, enlarged liver and spleen, and ascites (collection of fluid in abdomen) were also observed in 50% patients.

(iv) Moderate to severe anemia was evident in some cases.

(v) Conjunctival congestion, Leg edema was less common.

2.3.3.1 West Bengal

Table 2.2 shows an overview of arsenic contamination status in West Bengal up to 2008 (Chakraborti, 2008a). Out of 140150 samples analyzed for arsenic, 48.1% had found arsenic above 10 µg/L and 23.8% above 50 µg/L. Importantly, 3.3% of the analyzed tube-wells had arsenic concentrations above 300µg/L, the concentration predicting overt arsenical skin lesions. A total of 187 (0.13%) hand tube-wells were reported highly contaminated (> 1000 µg/L). The maximum arsenic concentration (3700 µg/L) was found in Ramnagar village of GP Ramnagar II, Baruipur block, in South 24-Parganas district. This tubewell was a private one. **Figure 2.5** depicts groundwater arsenic contamination status of all 9 districts of West Bengal.

Table 2.3 represents the survey report by SOES for all the 19 districts (including Kolkata) in West Bengal. Based on the arsenic concentrations found in the 19 districts of West Bengal the severities have been classified into three categories: Severely affected (>300 µg/L), mildly affected (between 10 and 50 µg/L, and unaffected (< 10 µg/L). Nine districts (Malda, Murshidabad, Nadia, North 24-Parganas, South 24-Parganas, Bardhaman, Howrah, Hooghly and Kolkata), where more than 300 µg/L arsenic concentrations was found in tube-wells are categorized as severely affected. Out of 135,555 samples analyzed from these nine districts 67,306 (49.7%) had arsenic concentrations above 10µg/L and 33,470 (24.7%) above 50 µg/L.

It can be noted from **Figure 2.5** that all 9 severely affected districts (concentration > 50 µg/L) are in a linear track along the river Bhagirathi (the stretches of the river Ganga passed through Kolkata). Most of the affected areas lie along the left hand side of the river along the direction of groundwater flow. The groundwater flow direction in those areas is towards south-east direction, and the affected areas also swell mostly along the same direction. The geological formations in those areas are of thick recent alluvial deposits of Quaternary age. Arsenic contaminated ground water strata lies largely in the intermediate zone depth that ranges between 15m to 50 m.

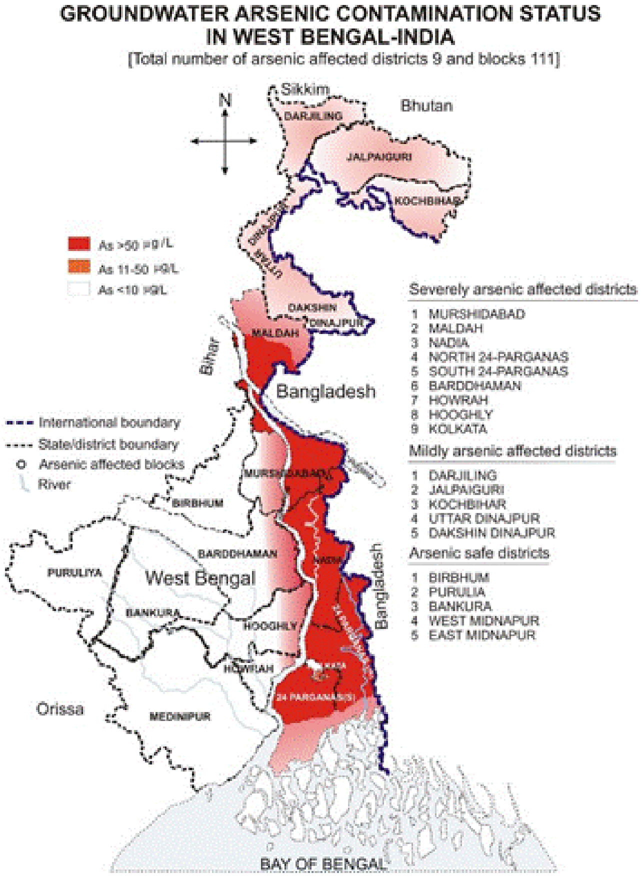


Figure 2.5 : Groundwater Arsenic Contamination status in West Bengal up to the year 2008.

2.3.3.1.1 A detailed study on groundwater arsenic contamination and its effects on health in Murshidabad, one of the nine arsenic affected districts in West Bengal.

A detailed study was conducted by SOES for 3 years in Murshidabad, one of the nine highly arsenic affected districts of West-Bengal, to know the magnitude of arsenic contamination situation and its effects on health. Murshidabad lies between the latitudes of $23^{0}43^{/}30^{//}$ to $24^{0}50^{/}20^{//}$ N and longitudes of $87^{0}49^{/}17^{//}$ to $88^{0}44^{/}$ E. The river Ganga forms its northern and eastern boundaries and separates it from Bangladesh. The river Bhagirathi flows across the district and divides it into two equal parts. The area and population of the district is 5324 km^2 and 58,66,569 respectively. There are 26 blocks in this district and all the 26 blocks were surveyed. A total of

29,668 hand tubewell water samples from 1833 villages/wards of 2414 villages/wards from all the 26 blocks were collected and analyzed. On the basis of the analysis, arsenic concentration in 25 blocks was found above the WHO guideline value of arsenic in drinking water (10 µg/L). **Table 2.3** shows the detailed block wise distribution of arsenic concentration. It was observed that 46.2% of the tube-wells could meet the WHO guideline value (10 µg/L) while 73.3% could meet the Indian standard (50 µg/L). Overall 4.5% of the samples exceeded 300 µg/L limit (the concentration predicting overt arsenical skin lesions). It was also observed that arsenic contamination in Jalangi block was worst where 78% of the total samples (n=1917) exceeded the WHO limit (10 µg/L) and 2% (n=38) samples were found to be contaminated above 1000 µg/L. **Figure 2.6** shows the situation of arsenic contamination in all the 26 blocks of the district.

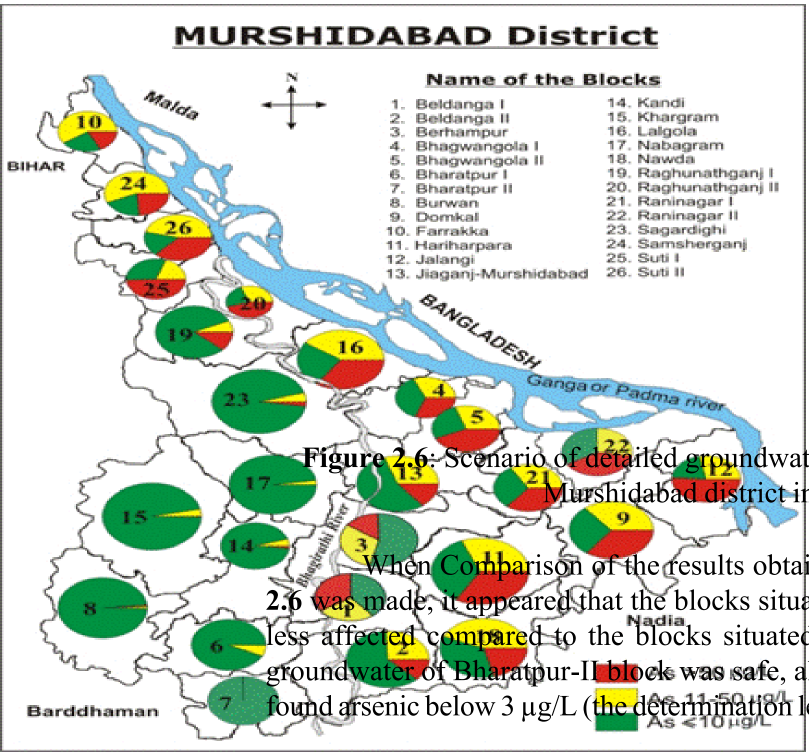


Figure 2.6: Scenario of detailed groundwater arsenic contamination study carried out in Murshidabad district in West Bengal by SOES.

When Comparison of the results obtained from water analysis **Table 2.4** with **Figure 2.6** was made, it appeared that the blocks situated in the western side of river Bhagirathi were less affected compared to the blocks situated on the eastern side. It was observed that the groundwater of Bharatpur-II block was safe, all the samples (n=625) analyzed from this block found arsenic below 3 µg/L (the determination level of our instrument with 95% confidence limit.

2.3.3.2 Bihar

In 2002, groundwater arsenic contamination first surfaced in two villages, Barisban and Semaria Ojhapatti in the Bhojpur district of Bihar in the Middle Ganga Plain. The area is located in the flood-prone belt of Sone-Ganga inter-fluve region. Investigations by Central Ground Water Board and Public Health Engineering Department, Bihar indicated contamination as high as .178 µg/L in the surrounding villages, affecting the hand pumps, which are generally at 20-40 m below ground surface. With ongoing study, more and more contaminated districts have surfaced. It was reported (CGWB, 2008) that by the year 2008, out of 38 districts, 15 districts covering 57 blocks are exposed to groundwater arsenic contamination above 50 µg/L. These districts are: i) Buxar ii) Bhojpur, iii) Patna, iv) Lakhisarai v) Saran, vi) Vaishali vii) Begusarai, Samastipur, ix) Munger, x) Khagaria, xi) Bhagalpur xii) Darbhanga, xiii) Purnea xiv) Katihar xv) Kishanganj **(Figure-2.7)**. These districts are mostly distributed along the course of the river Ganga in Bihar except three; (i) Darbhanga, (ii) Purnea and (iii) Kishanganj, which are in isolated and scattered places showing no distinct routes of connection to one-another **(Figure 2.7)**. It was also predicted that the districts lying in the area where Ganga and other tributaries, originating from the Himalaya, shifted in course of time, would be arsenic contaminated **(Figure 2.8)**. The blocks identified as arsenic affected in each district are given in **Table-2.5** (CGWB, 2008). The geological formations in the affected areas are of Quaternary deposits of multi-aquifer systems mixed with medium to fine sands having occasional coarse grained followed by medium sand, pebble and gravel, etc. **Figure 2.9** shows some arsenic patients from arsenic affected districts of Bihar.

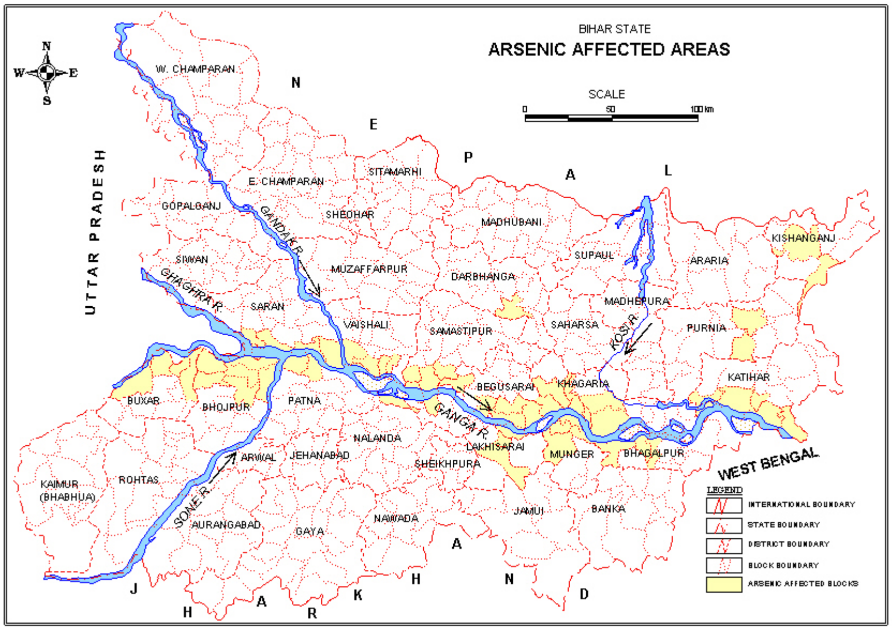


Figure 2.7 : Location of 15 Arsenic affected districts in Bihar.

Figure 2.8: Arsenic affected districts along the Ganga river course in Bihar.

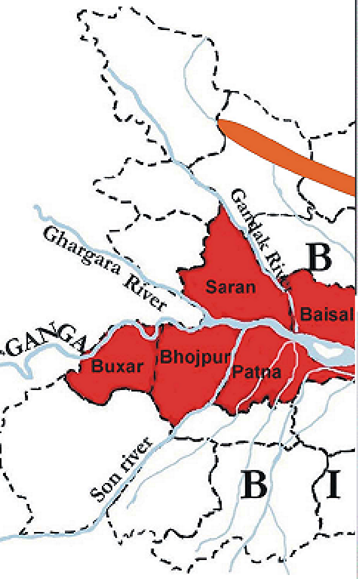


Figure 2.9: Photographs showing Some arsenic patients from arsenic affected districts of Bihar (Source : SOES)

2.3.3.3. Uttar Pradesh (UP)

Groundwater arsenic contamination in UP was first exposed in 2003 by SOES from survey of 25 villages in Ballia district. Thereafter, with continued survey two more districts, Gazipur and Varanasi were detected for arsenic groundwater contamination. As of 2008, 3 districts covering 69 villages in 7 blocks in Uttar Pradesh were found affected by arsenic groundwater contamination and people suffering from arsenical skin lesions. The used to drink water of hand pump operated tube wells. All those tube wells tap groundwater from shallow aquifer below about 20-30 m. **Figure 2.10** and **Table 2.6** show the arsenic contamination situation in UP. Ironically it was interesting to note that, all the arsenic affected districts in UP and 12 districts in Bihar are aligned along the linear track of the river Ganga, so is the position in West Bengal where it is along the river Bhagirathi. Questions are: whether are they from same genesis and are of same outcrops and sources? What are the reasons of activation along the flood plains of the river course? Etc. A thorough survey is required to understand the root causes and magnitude of arsenic contamination in UP, as well. Areas of UP adjacent to arsenic contaminated Terai region need investigations. **Figure 2.11** shows some arsenic affected patients from UP.

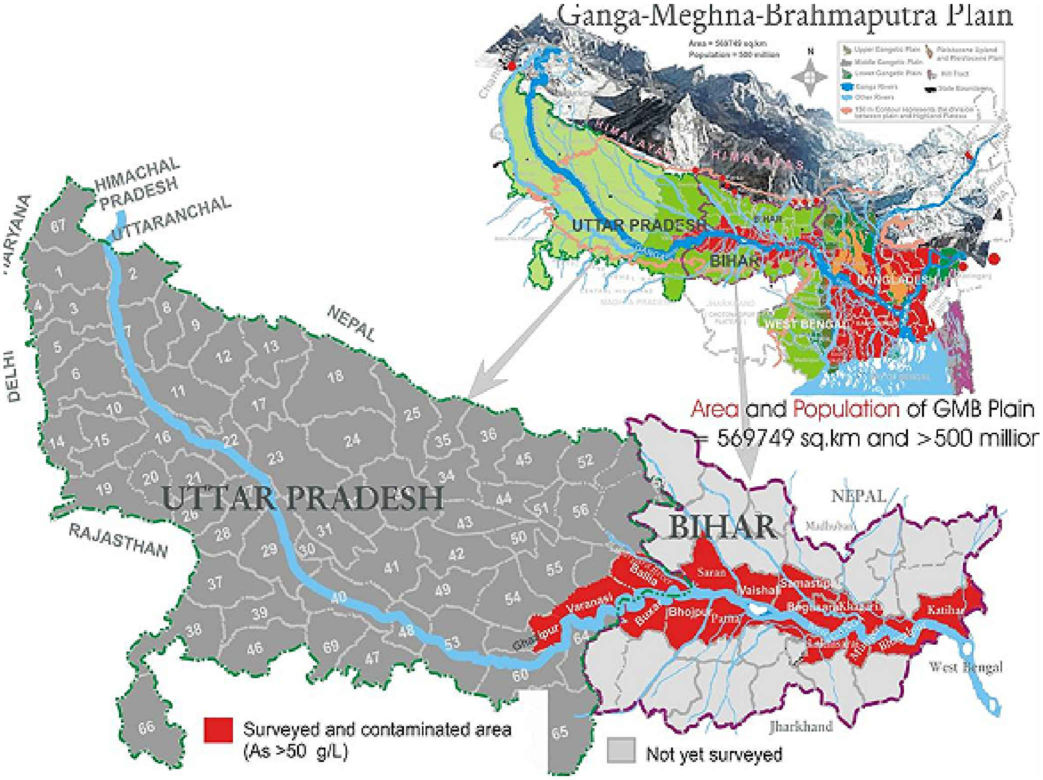


Figure 2.10 : Arsenic affected districts in UP and Bihar along the river course of the Ganga (Source: SOES).

Figure 2.11: Photograph showing some arsenic affected patients from UP (Source : SOES)

2.3.3.4. Jharkhand

During 2003-2004, groundwater arsenic contamination above 50 µg/L was first reported by SOES in the Sahibganj district of the Jharkhand, in the middle Ganga plain. Later on (2006-07), it was confirmed by CGWB through detailed investigation. Arsenic contamination is close to the Ganga River and in those areas from where the Ganga River shifted during recent past. The hand pump tube-wells of depth range 25-50 m were reported to be contaminated, and the affected areas had similar geological formations as in adjacent Bihar and West Bengal. The dug wells were reported free from arsenic contamination (CGWB, 2008). **Figure 2.12** and **Table 2.7** show the arsenic contamination situation in Jharkhand.**Figure 2.13** shows cancer patient with arsenical skin lesions from Jharkhand.

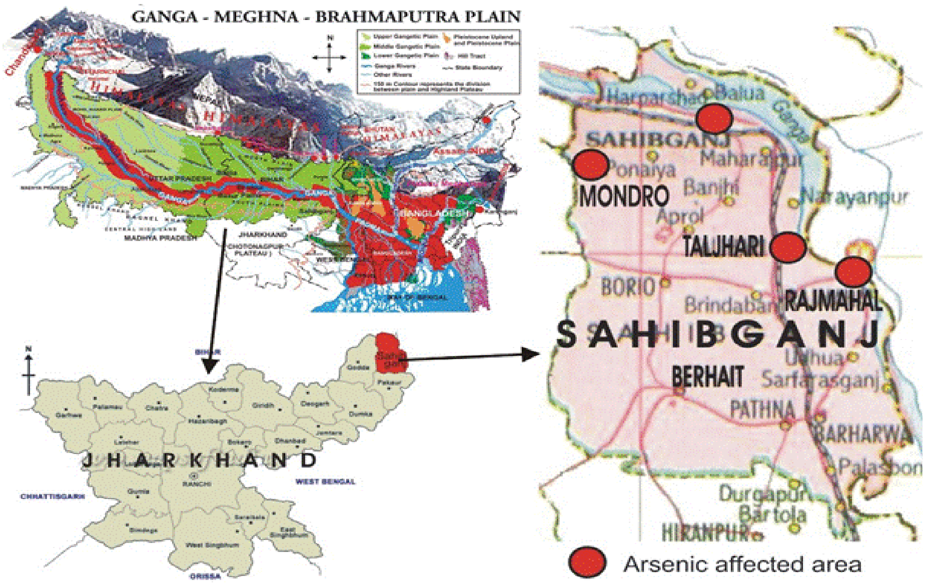
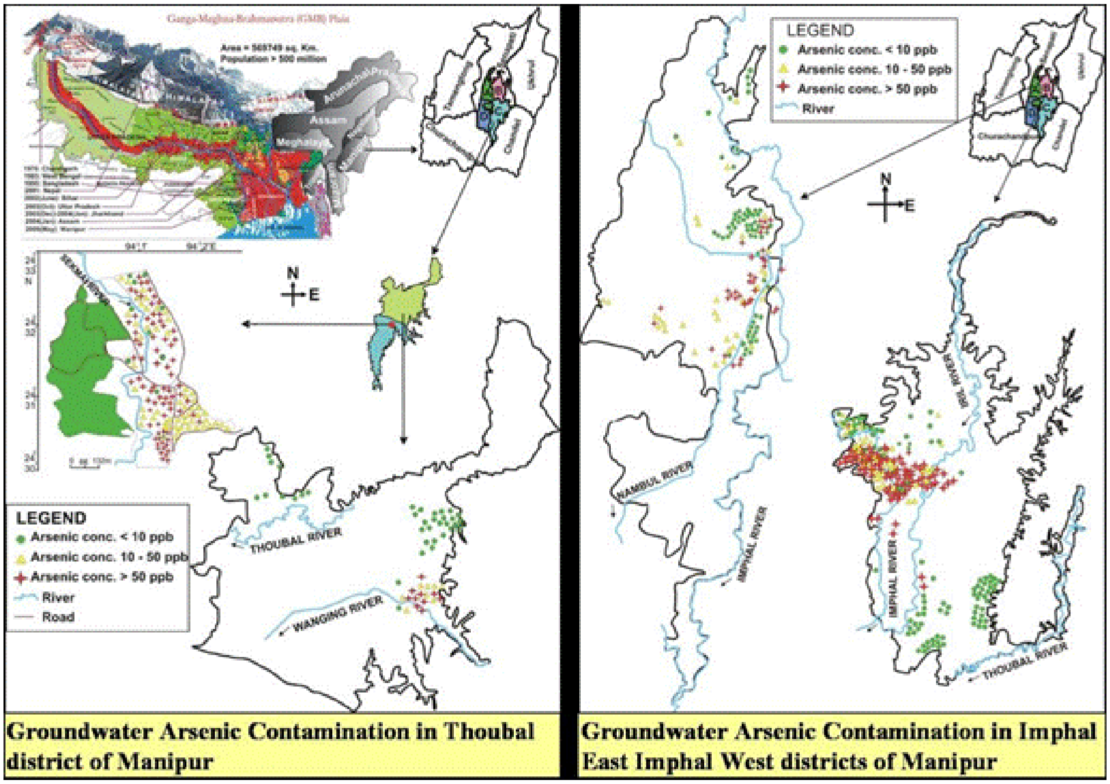


Figure 2.12 : Arsenic affected areas in Jharkhand (Source: SOES)

Figure 2.13: Photograph showing cancer patient with arsenical skin lesions from Jharkhand state (Source: SOES)

2.3.3.5. Assam & Manipur in North Eastern Hill states

There are seven states in North Eastern Hills. They are Manipur, Mizoram, Assam, Tripura, Arunachal Pradesh, Nagaland, and Meghalaya. Groundwater arsenic contamination was reported from Assam and Manipur states. A preliminary survey indicated that hand tube-well water in flood plains of these two states had some arsenic contamination above 50 µg/L and the magnitude was much less compared to Ganga-Padma- Meghna plain. Recently UNICEF reported arsenic contamination from Assam and found arsenic contamination in 18 out of 23 districts of Assam above 50 µg/L. **Table 2.8** shows the results. Recently SOES reported groundwater arsenic contamination situation from Manipur state. Mainly valley districts of Manipur are arsenic contaminated. These districts are Kakching, Imphal east, Imphal west, Bishnupur. The area of these 4 districts is 10% of total area of Manipur but about 70% of total population lives in these 4 districts. In Manipur at present people are not using hand tube-wells water for drinking, cooking and agricultural purposes. **Figure 2.14** and **Table 2.9** show the arsenic groundwater contamination situation in Manipur state. Arsenic patients have not been yet identified from states of Manipur and Assam.



Groundwater Arsenic Contamination in Thoubal district of Manipur

Groundwater Arsenic Contamination in Imphal East Imphal West districts of Manipur

Figure 2.14: Arsenic affected areas in Manipur (Source: SOES)

2.3.3.6 Chhattisgarh

Other than above flood plain areas of Ganga-Brhamaputra-Barak rivers, groundwater arsenic contamination was detected from Rajnandgaon district of Chhattisgarh state. **Table 2.10** shows the study report of SOES. A few hundred people were suffering from arsenical skin lesions from affected villages. One cancer patient (with arsenical skin lesions) and many patients with keratosis were identified **(Figure 2.15).**

Figure 2.15: Photograph showing arsenical skin lesions patients with keratosis from Chattisgarh state (source: SOES).

2.4 Effect of Arsenic Poisoning in Children

Infants and children are often considered more susceptible to the adverse effects of toxic substances than adults.

Normally children under 11 years of age do not show arsenical skin lesions although their biological samples contain high level of arsenic. However exceptions are observed when (i) arsenic content in water consumed by children is very high (≥1000 μg/l) and (ii) arsenic content in drinking water is not so high (around 500 μg/l) but the children's nutrition is poor. High arsenic content in their biological samples prove that children in the arsenic affected areas of the GMB plain have a higher body burden, though dermatological manifestations are few.

The children in the arsenic contaminated areas are often more affected than the adults. Children's body try very hard to expel the poison from their systems, but in trying to do so; their internal organs become badly damaged. That in turn retards their further growth, both physical and mental. The sufferings of children in arsenic affected areas in GMB plain had also been reported in many literatures. **Figure 2.16** shows a group of children and 60% of these children had arsenical skin lesions.

Figure 2.16 : Showing susceptible children affected by arsenical skin lesions.

2.5 Arsenic in Food Chain

In most of the developing countries including India, as such, there is no regulation imposing restriction in withdrawal of groundwater. As a result, groundwater is exploited excessively, leading to a substantial wastage of water especially that which is used for agriculture. For the summer crops, we depend totally on groundwater. In the arsenic-affected areas the water used from tube wells for irrigation is often arsenic contaminated. 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. When arsenic contaminated groundwater is used for crops irrigation, a part of this arsenic becomes incorporated into the food chain.

Many investigators consider water-soil-crop-food transfer, cooking water, and direct ingestion of arsenic contaminated water as the major exposure pathways of arsenic. Over 75% of this arsenic present in the crops is inorganic in nature **(Figure 2.17)**. Arsenic gathers first of all in the roots, then in the stem and after that in the crop proper.

Figure 2.17: Effect of Arsenic in food chain.

The effects of this occurrence are far-reaching. First, as the people take in contaminated water along with contaminated food, the chances of damage become greater. Secondly, the food crops are sold off to other places, including uncontaminated regions where the inhabitants may consume arsenic from the contaminated food. Thirdly, the domestic animals, like cattle etc. in arsenic-affected areas regularly take in arsenic along with their drinking water and food, like straw. If human beings consume the meat from such infected animals, they may consume arsenic as well. A full-grown cow eats 10-12 kg straw and drinks 30-40 litres of water per day. From this example, it is possible to calculate how much arsenic cattle consume every day. Almost all of Southeast Asia uses rice as its staple food. Due to irrigation with contaminated water, rice grains could have excessive amounts of arsenic. According to a leading scientist, this contamination of rice with arsenic may give rise to a new danger in the South -East Asia.

2.6 Socio-economic Effects of Arsenic Contamination

A good portion of 500 million people, living in the 5 69749 sq km of the Ganga-Meghna-Brahmaputra belt, live in danger of drinking arsenic contaminated water. Around 30 % of this populace is constituted of illiterate inhabitants who live below the poverty line. Affected populace are those who are economically backward and lack in nutritious food. Women are affected the most compared to men. Further, infants and children are adversely affected than the adults. An arsenic patient loses his strength and cannot work outdoors, but his family incurs more expenses than before because of his illness. Many of them borrow money from the local moneylender who charges them a high rate of interest, i.e. 5-10% monthly compound interest. Often villagers lose all their earthly possessions including the roof over their heads, trying to pay the moneylender back. Society too, turns an arsenic patient into an outcast. The arsenic problem, thus, has a major effect on the socioeconomic structure. People often mistake symptoms of arsenic poisoning for leprosy or other contagious skin diseases, and thus marriage, employment, and even the simplest social interaction become impossible for the victim. Thus, an arsenic patient often becomes depressed and sometimes even tries to commit suicide.

2.7 Summary

Up till 2008, 9 districts covering 3417 villages in 111 blocks in West Bengal, 15 districts covering 57 blocks in Bihar, 3 districts covering 69 villages in 7 blocks in Uttar Pradesh, 1 district covering 68 villages in 3 blocks in Jharkhand, 3 districts covering 9 blocks in Assam, 4 districts in Manipur, and 1 district covering 4 villages in 1 block in Chhattisgarh have been detected for groundwater arsenic contamination above permissible limit of 50 µg/L. Many more North-Eastern Hill States in the flood plains are suspected to have the possibility of arsenic in groundwater Even, after twenty-five years since 1983, with every new survey, new arsenic affected villages and people suffering from arsenic related diseases are being reported. 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. All the arsenic affected river plains have the river 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 socioeconomic dissolution besides its sprawling with movement, and exploitation of groundwater.

Thus the Questions arise and whose answers are to be amalgamated to find logical solutions are:

(i) What are the sources, genesis, causes and mechanisms of groundwater arsenic contamination?

(ii) How the problem has been triggered in many hydrogeological conditions along a fluvial track and in different scattered places in the Ganga and Brahmaputra plains and deltas?

(iii) What technological, scientific understanding and knowledgebase are required to combat such a large scale groundwater related disasters/menace?

(iv) How could people, livestock and groundwater dependant usages be safeguarded from hazards of arsenic contamination?

(v) What short-term and long-term planning and management of water resources are rquired for ensuring supply of arsenic-free water both for drinking and irrigation requirement in those affected and vulnerable areas?,

(vi) What remediation/corrective measures are necessary to restore the affected aquifers? These are some of key issues that need to be addressed. Proper watershed management coupled with deep aquifer tapping, sustaining efforts to evolve and provide cost effective and eco-friendly arsenic treatment techniques for supply of drinking water along with the water education of the villagers and their active participation appear to be potential solutions to resolving the present arsenic crisis, till a sustainable groundwater arsenic mitigation strategy is scientifically perfected.

Table 2.1: Groundwater arsenic contamination in states of India (according to latest survey report up to January, 2006 by SOES)

** According to CGWB assessment in 2008: In Bihar No. of affected district = 25, No. of affected blocks = 57 having population about 10 million.*

Table 2.2: Summary of groundwater arsenic contamination status in West Bengal, India (Chakraborti et al 2008a)

Parameters	West Bengal
Area in sq. km.	88,750
Population in million	80.2
Total number of districts (no. of district surveyed)	19 (19)
Total number of water samples analyzed	1,40,150
% of samples having arsenic > 10 μg L^{-1}	48.1
% of samples having arsenic > 50 μg L^{-1}	23.8
Maximum arsenic concentration so far we analyzed (μg/L)	3700
No. of severely arsenic affected districts *	9
No. of mildly arsenic affected districts*	5
No. of arsenic safe districts*	5
Total population of severely arsenic affected 9 districts in million	50.4
Total area of severely arsenic affected 9 districts in sq. km.	38,861
Total number of blocks/ police station	341
Total number of blocks/ police station surveyed	241
Number of blocks / police station having arsenic >50μgL^{-1}	111
Number of blocks / police station having arsenic >10μgL^{-1}	148
Total number of village	37910
Total number of village surveyed	7823
Number of villages/paras having arsenic above 50 μgL^{-1}	3417
People drinking arsenic contaminated water >10 μgL^{-1} (in million)	9.5
People drinking arsenic contaminated water >50 μgL^{-1} (in million)	4.6
Population potentially at risk from arsenic contamination > 10 μg L^{-1} (in million)	26
No. of districts surveyed for arsenic patients	9
No. of districts where arsenic patients found	7
Villages surveyed for arsenic patients	602
Number of villages where we have identified people with arsenical skin lesions	488

Table 2.3: Block wise distribution of arsenic concentration in West Bengal (Chakraborti et. al. 2008b)

Districts	Area in km^{2}	Population	Total no. of blocks	No. of blocks surveyed	No. of blocks with As >10 µg/L	No. of blocks with As >50 µg/L	No. of samples analyzed	Distribution of total samples in different arsenic concentration (µg/L) ranges									Max. As. conc. (µg/L)
								≤3	4 -10	11-50	51-100	101-200	201-300	301-500	501-1000	> 1000	
Highly affected																	
North-24-PGS	4094	8934286	22	22	22	21	54368	22221	3129	13001	6403	5531	2249	1308	477	49	2830
South-24-PGS	9960	6906689	29	17	12	11	8333	4407	427	1141	743	741	327	305	212	30	3700
Murshidabad	5324	5866569	26	26	25	24	29668	11471	2244	8042	3267	2366	941	884	382	71	3003
Nadia	3927	4604827	17	17	17	17	28794	11431	2613	9810	2265	1520	630	360	152	13	3200
Maldah	3733	3290468	15	14	13	9	4449	1754	373	810	488	559	183	163	97	22	1904
Haora	1467	4273099	14	12	12	7	1471	889	226	192	87	41	22	12	1	1	1333
Hugli	3147	5041976	18	17	16	11	2212	1469	346	251	77	52	14	2	1		600
Kolkata	185	4572876^{a}	141^{b}	100^{b}	65^{b}	30^{b}	3626	2224	855	345	85	75	27	10	5		800
Bardhaman	7024	6895514	31	24	12	7	2634	2091	79	244	86	89	27	11	6	1	2230
Sub Total	38861	**50386304**	172	149	129	107	135555	57957	10292	33836	13501	10974	4420	3055	1333	187	
Mildly affected																	
Koch Bihar	3387	2479155	12	5	4	1	474	403	57	13	1						54
Darjiling	3149	1609172	12	4	3	0	562	502	50	10							19
Dinajpur (N)	3140	2441794	9	7	6	2	990	817	57	112	4						68
Dinajpur (S)	2219	1503178	8	6	2	1	452	398	47	6	1						51
Jalpaiguri	6227	3401173	13	7	4	0	445	355	74	16							27
Sub Total	18122	**11434472**	54	29	19	4	2923	2475	285	157	6						
Unaffected																	
Bankura	6882	3192695	22	17	0	0	279	279									<3
Birbhum	4545	3015422	19	11	0	0	718	718									<3
Purulia	6259	2536516	20	15	0	0	314	314									<3
Medinipur (E)^{c}	14081	9610788	25	10	0	0	182	182									<3
Medinipur (W)			29	10	0	0	179	179									<3
Sub Total	31767	**18355421**	115	63	0	0	1672	1672									
Grand Total	88750	**80176197**	341	241	148	111	140150	62104	10577	33993	13507	10974	4420	3055	1333	187	

Table 2.4 : Block wise distribution of hand tubewells against arsenic concentration ranges (g/L) in Murshidabad district of West-Bengal, India.

Block	Total samples analysed	Distribution of total samples in different arsenic concentration (µg/L) ranges								%of Samples with As >10µg/L	% of Samples with As >50µg/L	Max. conc. µg/L (samples with As >1000µg/L
		=3	4 -10	11-50	51-100	101-200	201-300	301-500	501-1000			
Beharampur	1821	797	180	560	180	79	15	7	3	46.3	15.6	635
Beldanga I	1396	459	86	368	194	126	52	64	45	61.1	34.7	1700 (2)
Beldanga II	1037	529	130	248	78	39	12	1		36.5	12.5	345
Bhagowangola I	1775	592	96	544	170	256	72	33	10	61.2	30.6	1285 (2)
Bhagowangola II	819	137	96	234	134	83	51	57	23	71.6	43.0	1852 (4)
Bharatpur I	616	533	47	34	2	-	-	-	-	5.8	0.3	82
Bharatpur II	625	625	-	-	-	-	-	-	-	-	0	<3
Burwan	702	684	10	6	2	-	-	-	-	1.1	0.3	64
Domkal	3371	729	295	1166	429	392	161	139	58	69.6	35.0	1300 (2)
Farrakka	489	84	33	285	81	6	-	-	-	76.1	17.8	150
Hariharpara	1520	436	123	453	182	117	88	93	27	63.2	33.4	1160 (1)
Jalangi	1917	317	109	516	288	233	129	178	109	77.8	50.9	2040 (38)
Jiaganj	1235	492	205	360	123	49	6	-	-	43.6	14.4	286
Kandi	932	832	64	28	7	1	-	-	-	3.9	0.9	140
Khargram	715	670	22	20	3	-	-	-	-	3.2	0.4	75
Lalgola	1030	180	98	397	174	138	16	14	12	73.0	34.5	1028 (1)
Nabagram	705	656	41	8	-	-	-	-	-	1.1	0	40
Nawda	1208	420	17	516	141	63	18	20	12	63.8	21.1	3003 (1)
Raghunathganj I	515	394	21	34	36	9	9	6	1	19.4	12.8	3003 (5)
Raghunathganj II	1233	266	40	371	355	146	26	23	6	75.2	45.1	875
Raninagar I	778	132	116	253	122	123	24	6	1	68.1	35.6	1018 (1)
Raninagar II	2219	489	261	610	189	253	165	191	54	66.2	38.7	1652 (7)
Sagardighi	707	637	28	25	15	1	-	-	1	5.9	2.4	560
Samsherganj	878	120	69	480	111	77	21	-	-	78.5	23.8	287
Suti I	443	130	9	85	104	67	30	17	1	68.6	49.4	700
Suti II	982	131	48	441	147	108	46	35	19	81.8	36.9	1852 (7)
Total	29668	11471	2244	8042	3267	2366	941	884	382	53.8	26.7	3003 (71)

Table 2.5: Arsenic affected blocks in 15 districts in Bihar (Source: CGWB, 2008)

Sl. No	District	Block	Population of affected Block
1	**Patna**	1.Maner	201345
		2.Danapur	325457
		3.Bakhtiarpur	172531
		4.Barh	162381
2	**Bhojpur**	1.Barhara	194439
		2.Shahpur	185911
		3.Bihea	139374
		4.Koilwar	169564
		5.Udwant Nagar	132258
		6.Arrah	369644
3	**Begusarai**	1.Matihani	127090
		2.Begusarai	418614
		3.Barauni	228026
		4.Balia	148155
		5.Sabehpur Kamal	155057
		6.Bachwara	153699
4	**Khagaria**	1.Khagaria	295480
		2.Mansi	74297
		3.Gogri	243303
		4.Parbatta	192212
5	**Samastipur**	1.Mohiuddin Nagar	142472
		2.Mohanpur	88930
		3.Patori	143832
		4.Vidyapati Nagar	122240
6	**Bhagalpur**	1.Jagdishpur	471457
		2.Sultanganj	200123
		3.Nathnagar	122120
7	**Saran**	1.Sonepur	220271
		2.Dighwara	107912
		3.Chapra Sadar	363036
		4.Revelganj	99010
8	**Munger**	1.Jamalpur	181751
		2.Dharhara	104037
		3.Bariarpur	92406
		4.Munger	297741
9	**Katihar**	1.Mansahi	62581
		2.Kursela	52997
		3.Sameli	67261
		4.Barari	220955
		5.Manihari	149250
		6.Amdabad	132107
10	**Buxar**	1.Brahmpur	163855
		2.Semary	181003
		3.Chakki	34133
		4.Buxar	229521
11	**Vaishali**	1.Raghopur	187722
		2.Hajipur	349694
		3.Bidupur	207421

		4.Desri	77741
		5.Sahdei Buzurg	90459
12	**Darbhanga**	1.Biraul	233029
13	**Kishanganj**	1.Kishanganj	185535
		2.Bahadurganj	205888
14	**Purnea**	1.Purnea East	349118
		2.Kasba	143784
15	**Lakhisarai**	1.Lakhisarai	261620
		2.Pipariya	31020
Total Population			**10,471869**

Table 2.6: Summary of groundwater arsenic contamination status in Uttar Pradesh, India (Chakraborti et. al. 2008a)

Physical parameters	Uttar Pradesh
Area in sq. km.	238000
Population in million	166
No. of districts surveyed so far	3 (Ballia, Gazipur & Varanasi)
Arsenic affected area in sq. km.	10375
Total population in arsenic affected 3 districts (in million)	6
Number of arsenic affected districts where groundwater arsenic >50µg/L	3
No. of blocks surveyed so far	10
Number of arsenic affected blocks where groundwater arsenic >10 µg/L	9
Number of arsenic affected blocks where ground water arsenic >50 µg/L	7
Total number of hand tube-well water samples analyzed	4780
Number of arsenic affected blocks where groundwater arsenic >10 µg/L	45.48
Number of arsenic affected blocks where ground water arsenic >50 µg/L	26.51
% of hand tube-wells having arsenic concentration >300 µg/L	10
Maximum arsenic concentration so far we analyzed (µg/L)	3192
Number of arsenic affected villages with ground water arsenic >50µg/L	69
Number of arsenic affected villages with ground water arsenic >10µg/L	100
Population potentially at risk from arsenic contamination > 10 µg L^{-1} (in million)	3

Table 2.7: Summary of the arsenic contamination scenario in Jharkhand (Chakraborti et. al. 2008a)

Table 2.8: Summary data on arsenic in groundwater in Assam (Nickson et. al. 2007).

District	No. blocks affected	Total sources tested	Sources 10-50 μgL^{-1}	Sources > 50 μgL^{-1}	% Sources > 50 μgL^{-1}	District population	Projected population at risk
Barpeta	5	130	21	7	5.4	1,647,201	-
Bongaigaon	3	100	15	6	6.0	904,835	-
Cachar	7	210	68	59	28.1	1,444,921	-
Darrang	4	254	92	9	3.5	1,504,320	-
Dhemaji	5	539	128	83	15.4	571,944	-
Dhubri	6	435	130	21	4.8	1,637,344	-
Goalpara	2	145	11	3	2.1	822,035	-
Golaghat	5	268	67	30	11.2	946,279	-
Hailakandi	4	159	45	11	6.9	542,872	-
Jorhat	6	224	96	24	23.1	999,221	-
Kamrup	1	261	39	1	0.4	2,522,324	-
Karimganj	6	811	150	61	7.5	1,007,976	-
Lakhimpur	5	218	50	9	4.1	889,010	-
Marigaon	1	271	40	2	0.7	776,256	-
Nagaon	1	314	55	1	0.3	2,314,629	-
Nalbari	5	148	25	14	9.5	1,148,824	-
Sibsagar	3	206	72	15	7.3	1,051,736	-
Sonitpur	3	227	34	6	2.6	1,681,513	-
TOTAL	72	4920	1138	362	7.4	22,413,240	-

Table 2.9: Summary of present groundwater arsenic contamination status in Manipur (Chakraborti et. al., 2008c)

Parameters	Manipur
Area in sq. km.	22327
Population in million	2.29
Total number of districts (no. of district surveyed)	9 (4)
Arsenic affected area in sq. km.	2238
Total population of arsenic affected 4 districts in million	1.35
Total number of water samples analyzed	628
% of samples having arsenic > 10 μg L^{-1}	63.3
% of samples having arsenic > 50 μg L^{-1}	23.2
Maximum arsenic concentration analyzed (μg/L)	502
Total number of village surveyed	88

Table 2.10: Summary of groundwater arsenic contamination status in Rajnandangaon district Chhattisgarh state, India (Chakraborti et. al. 1999)

Parameters	Rajnandangaon
Area in sq. km.	6396
Population in million	1.5
Total number of water samples analyzed	146
% of samples having arsenic > 10 μg L^{-1}	25.34
% of samples having arsenic > 50 μg L^{-1}	8.22
Maximum arsenic concentration so far we analyzed (μg/L)	880
Total number of blocks/ police station surveyed	1
Total number of village surveyed	22
Number of villages having arsenic above 10 μgL^{-1}	8

Chapter-3

Sources and Causes of Groundwater Arsenic Contamination in Ganga-Brahmaputra Plains

Arsenic (As) in groundwater has been reported, mostly in areas formed by recent alluvial sediments, describing Holocene aquifers (< 12 thousand years of age) of the Ganga-Brahmaputra Plains, where the concentration is exceeding from acceptable level, that is, 50 μg/L. Almost all the identified arsenic affected areas, in the Gangetic plains, are in a linear track on either side of the River Ganga in UP, Bihar, and Jharkhand, or the River Bhaghirathi in West Bengal, except areas in Chhattisgarh and 3 districts of Bihar namely, Darbhanga, Purnea and Kishanganj. The areas in Assam and Manipur are in the flood plains of the Brahmaputra and Barack, respectively. Ironically, all the arsenic affected river plains have the river routes originated from the Himalayan region. Whether the source material has any bearing on the outcrops or not 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.

Though the exact geochemical processes are yet to be established, arsenic in groundwater in the Holocene aquifer is believed to be released from soil, under conditions, conducive to dissolution of arsenic from solid phase on soil grains to liquid phase in water. The constituents and environmental conditions of the soils have, thus, a greater influence on arsenic speciation and mobility than the total concentration in soils. The occurrence of **As** in soils and aquifer formations is, thus, a subject matter of greater interest.

3.1 Probable Natural Sources

There is no proof regarding the natural emission of **As** in the Ganga-Brahmaputra plains so far. 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. Arsenic concentration (NAS, 1977; Crecelius and Bothner, 1975) in different sediments could be as high as 490 mg/kg. 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 source of groundwater arsenic contamination, in the Ganga-Brahmaputra basin, is yet to be established. Weathering of As-rich sulphides, such as pyrite, releases bivalent Fe, which readily forms amorphous oxy-hydroxides in an oxidizing environment that would strongly sorb co-weathered arsenic (Mok and

Wai, 1994; Thornton, 1996). Groundwater of the reducing sedimentary aquifers is characterized by high concentrations of dissolved iron due to the reductive dissolution of iron oxy-hydroxides that mobilize the sorbed arsenic. Studies on the hydro-geochemistry of the BDP groundwater (Chakraborti et al., 2003; Acharyya, et al., 1999; Bhattacharya et al., 2002) have revealed elevated concentrations of Fe (145-8624 μg/l) in groundwater, whereas iron concentration in groundwater in Bihar ranges from below detection limit to 700 μg/L. Irrespective of the concentration of Fe in groundwater, the process for its release is triggered by the reduction of Fe oxy hydroxides in the Ganges sediments, with consequent release of arsenic.

As concentrations in groundwater of the Bengal Basin vary widely, it generally ranges from less than 5 μg/L to 3200 μg/L (CGWB, 1999; BGS and DPHE, 2001). But in certain areas, concentration up to 4100 μg/L, has been identified (Ghosh and Mukherjee, 2002). 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 (distriburtary 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 Jamuna in the northeast (Acharyya et al., 2000).

There has been much speculation about the primary source of arsenic in the Bengal basin. The total amount of solid-phase arsenic, which ranges from 1 to 30 mg/kg, in the soil and sediment, is not significant (McArthur et al., 2001; Harvey, 2002). Several investigators have reported that the contamination is natural and is intensified by anthropogenic interferences (Acharyya et al., 1999, 2000; Ray, 1999). 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.

3.2 Anthropogenic Sources

The release of arsenic from different sources is often cited in the literature (Boyle and Jonasson, 1973; Berdowski et al., 1997), but there is still lack of information on atmospheric emission of arsenic in eastern regions of the Indian subcontinent. Average concentration of arsenic in Indian coal ranges up to 3.72 mg/kg, with a maximum value of 40 mg/kg (e.g. Sohagpur coalfield, Northeastern India) (Khandekar et al., 1999; Warwick et al., 2001). Hence, it is believed that coal combustion in Eastern India is one of the major sources of anthropogenic arsenic emission in the environment. There are several metallurgical plants, cement factories, incineration and chemical industries in eastern and Northeast India which contribute to the emission of arsenic into the environment. However, there is no data available, on the exact tonnage of arsenic entering the environment. A secondary leading industry near greater Kolkata, West Bengal, releases arsenic to the environment. The maximum concentration in soil of that area was reported to be 9740 ± 226 mg/kg while the minimum was 17.5 ± 0.52 mg/kg (Chatterjee and Banerjee, 1999). Leaching of arsenic in groundwater is also expected in the vicinity of areas of landfills containing waste and hazardous waste piles (Boyle and Jonasson, 1973; Tripathi et al., 1997; Pandey et al., 1998). The use of fertilizers and insecticides also causes high concentration of arsenic in soil compartments. There is a lack of information on the anthropogenic deposition of arsenic, within the extensive alluvial tract of the Ganga-Brahmaputra river basin. The arsenic-affected areas are the parts of the lower delta plain of the Ganges and foothills of Brahmaputra and Barak valley. 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. However, it has been contemplated that the Ganges-Brahmaputra basin has rather been undisturbed by anthropogenic sources compared to industrialized countries, where river basins have generally been affected by industrial activities (Huang et al., 1992).

3.3 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.*

3.4 Mechanisms of As Mobilization

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 (after Smedley and Kinniburgh, 2002).

Oxidation of sulphide minerals (pyrite-FeS2) 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. The process can be explained as: the large-scale withdrawal of groundwater causes rapid diffusion of oxygen within the pore spaces of sediments and, thereby, increases dissolved oxygen in the upper part of groundwater. The newly introduced oxygen oxidizes the arseno-pyrite and forms hydrated iron arsenate compound known as pitticite in presence of water. This compound being very soft and water-soluble, the light pressure of tube-well water breaks the pitticite layer into fine particles and make it readily soluble in water. It then seeps like drops of tea from the teabag and percolates from the subsoil into the water table. When the tube-well is in operation, it comes out with the extracted water (Safiuddin and Karim, 2001). Such oxidation processes could explain possible mechanism of **As** mobilization in some parts of the aquifers, particularly at the shallowest levels but may not be the main cause of groundwater arsenic contamination in the Ganges-Brahmaputra river basin. *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)*. According to this process, a series of changes in the water and sediment chemistry as well as in the structure of iron oxides take place at the onset of reducing conditions in aquifers. Many of these changes are poorly understood on a molecular scale. *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); and reduction in such case involves a net release from adsorption sites. *Dissolution of the iron oxides themselves under reducing conditions is another potentially important process*. Under aerobic and acidic to neutral conditions, adsorption of arsenic (As (V)) to iron oxides is normally strong and aqueous concentrations are usually low. However, the sorption is less strong at high pH.

Increases in pH (especially above pH 8.5 or so) will, therefore, result in desorption of arsenic from oxide surfaces that, in turn, will increase arsenic in dissolved concentrations. Such processes are considered responsible for the release of arsenic in oxidizing Quaternary sedimentary aquifers. In addition, the role of microorganisms in the leaching of arsenic from sediments can not be over ruled. In this process, arsenic mobilization occurs by microbial degradation in the presence of organic substrates in reducing aquifers (Bhattacharya et al., 1997; Bhattacharya et al., 2001). Burial of organic matter along with the sediments facilitates microbial activity, which plays an important role in the generation of reducing conditions (BGS and DPHE, 2001; McArthur et al., 2001). The rates of arsenic release under such conditions depend on a number of factors, including rates of sedimentation, diffusion of gases and microbial reactions, but could be relatively rapid on a geological timescale. The onset of reducing conditions and release from iron oxides is believed to be the main process controlling high arsenic concentrations in sedimentary aquifers. The nature of the organic matter involved in the generation of reducing conditions in arsenic- affected aquifers has been disputed in recent years (BGS and DPHE, 2001; McArthur et al., 2001; Harvey et al., 2002). The shallow groundwater system in the Bengal delta plain is more complicated due to the presence of organic matter, which governs the biogeochemical processes of arsenic mobilization (McArthur et al., 2001). Whatever be the nature of the organic matter present, its importance in controlling the redox conditions in reducing aquifers such as those of the Bengal basin is widely acknowledged. The surface reactivity of iron (Fe) and aluminum (Al) plays an important role in adsorbing the bulk of arsenic in the sedimentary aquifers in the Ganges-Brahmaputra basin. *However, the theory lacks in explaining increasing arsenic concentration in existing tube-wells, which were previously safe but progressively contaminated over time (Roy Chowdhury et al., 1999). Sediment analyses showed that extensive groundwater withdrawal for agricultural purposes favored the oxidation of arsenic-rich iron sulphide and thereby mobilization of arsenic in the Bengal Basin (Nickson et al., 2000; Das et al., 1996; Roychowdhury et al., 1999).* Adsorption to hydrous aluminum and manganese oxides may also be important, in case they are present in significant quantity (Peterson and Carpenter, 1983; Brannon and Patrick, 1987). It was speculated that phosphate concentrations in groundwater of the BDP resulted from application of fertilizers (Acharyya et al., 1993; Acharyya et al., 1999; Sikdar 2003). But it seems to be unconvincing because the amount of dissolved and sorbed phosphate in the aquifer volume is found exceeding the amount of phosphate applied as fertilizer (Bhattacharya et al., 2002). *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.* Since phosphate is bound strongly onto these surfaces, As^{5+} can be mobilized in groundwater (Acharyya et al., 1993). It is also observed that phosphorus in groundwater cannot contribute to arsenic pollution (Manning and Goldberg, 1997).

Sikdar and Banerjee, (2003) attributed cause *of arsenic to the extensive use of lead arsenate and copper arsenite as rhodenticides and pesticides rather than geological or* *geo-morphological settings.* The redox balance tilted towards a reducing environment, due to the organic rich argillaceous sediments deposited in fluvio-deltaic marshes and triggered by recent heavy groundwater abstraction and use of phosphate fertilizers.

XRD analysis revealed that illite was the dominant clay mineral in the clay/silty clay partings. No arsenic bearing mineral phase was identified in the clay or in the sands in the arsenious zone. The concentration of arsenic in sediments generally decreased with depth. And arsenic showed high positive correlation with iron, manganese, copper and lead and low correlation with zinc based on multiple correlation analysis. These observations were related with extensive use of lead arsenate and copper arsenite as rhodenticides and pesticides in jute cultivation.

A study carried out by Sikdar and Chakraborty (2008) in the western part of the alluvium-filled gap between the Rajmahal hills on the west and the Garo hills on the east to understand the importance of hydro-geochemical processes involved in the groundwater evolution, with special emphasis on the genesis of arsenic in the aquifer system using statistical methods, indicated 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 oranthropogenic 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.* From another PCA (Principal component analysis) with geologic, geomorphic, anthropogenic, geochemical and land-use factors indicated that arsenic concentration in groundwater increased with increasing area of mango orchards, sand lithofacies and nitrate. The organic carbon, available from decomposition of waste material undergone oxidative carbon degeneration by different oxidants, increased the concentration of CO_2 in the aquifer. The reducing condition, thus, developed in the aquifer helped dissolve the arsenic adsorbed on iron hydroxide or oxy-hydroxide coated margins of sand, iron rich heavy mineral grain margins, clay minerals and Fe-Mn concretions present in the aquifer matrix.

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. Therefore, a need arises for integrated research in order to understand sources, release mechanisms, and mobilization of arsenic in sedimentary aquifers.

The natural **As**-pollution in Bangladesh has been reported to be from reductive dissolution of sedimentary iron oxide (FeOOH) (Nickson et al. 1998), which strongly sorbs arsenic, although details of the process continue to emerge (e.g. Tufano and Fendorf, 2008). What controls the distribution of arsenic-pollution in an aquifer is less clear, but of greater importance for aquifer development, health, and remediation. Early work (DPHE, 1999) showed that sea-level change strongly influenced the distribution of arsenic-pollution, apparently confining it to sands deposited after the low-stand of sea-level at the Last Glacial Maximum (LGM; ≈20 ka; Umitsu 1993, Lambeck et al. 2002); wells screened in underlying older sands were believed in 1999 to be arsenic-free. But of wells in the post-LGM aquifers, only 50% are polluted by arsenic above the concentration level of 50 μg/L, and a full 75% contained less than the local drinking-water limit of 50 μg/L, so sea-level variations alone could not explain the distribution of arsenic-pollution.

Polizzotto et al., (2008) using hydrologic and (bio)geochemical measurements, showed that on the minimally disturbed Mekong delta of Cambodia, arsenic is released from near-surface, river-derived sediments and transported, on a centennial timescale, through the underlying aquifer back to the river. Owing to similarities in geologic deposition, aquifer source rock and regional hydrologic gradients their results represented a model for understanding pre-disturbance conditions for other major deltas in Asia. Furthermore, the observation of strong hydrologic influence on arsenic behavior indicated that release and transport of arsenic are sensitive to continuing and impending anthropogenic disturbances. In particular, groundwater pumping for irrigation, changes in agricultural practices, sediment excavation, levee construction and upstream dam installations will alter the hydraulic regime and/or arsenic source material and, by extension, influence groundwater arsenic concentrations and the future of this health problem. This model was supported by Harvey (2008) who postulated that the arsenic originally came from eroded Himalayan sediments, had been washed down into low-lying regions. It is widely believed that this arsenic dissolves and enters the groundwater under anaerobic conditions. It is, therefore, unsurprising to find that highly contaminated groundwater originates from pond sediments: the steady settling and decomposition of organic material at the bottom of tropical ponds take up all the oxygen that diffuses, or is carried by downward flow, into the sediment. Water passing through pond sediments could also contain organic carbon that, on decomposition, might help liberate arsenic from deeper sediments, adding to the contamination. But any organic carbon that is already contained in deeper aquifer sediments probably contributes less to biogeochemical processes because it is not replenished, and what remains is typically of low reactivity.

The model proposed by Polizzotto and Harvey was contradicted by Sengupta et al., (2008) from their analysis of time-series data collected over two years for $\delta^{18}O$, $\delta^{2}H$, and Ca, Mg, K, and Cl, concentrations for 10 ponds in, and upflow of, an arsenic-polluted region of southern West Bengal. They compared the compositions of As-polluted groundwater from wells with the compositions of waters in ponds upflow and within the range of influence of the wells; and revealed that conservative tracers ($\delta^{18}O$, $\delta^{2}H$, K), and other tracers (Ca, Mg) of pond-water and groundwater were distinct and there were no overlaps between the composition of two sources. These indicated that water from ponds was not the source of arsenic in the contaminated groundwater.

3.5 Transport modeling to understand arsenic movement

Geochemical, physicochemical and biological characteristics usually explain chemistry of arsenic with regard to its occurrence, release, dissolution, sorption, mechanism, etc. in soil-water phases at local scale. Groundwater, being dynamic, when it is in a specific hydro geologic setup, fate assessment of point values of arsenic concentration in terms of distribution and transport in a groundwater domain on a regional scale could provide a good insight to understand movement of arsenic in that domain. Numerical groundwater flow and transport modeling is one of the powerful techniques by which one can determine spatial and temporal distribution of arsenic mobilization, understanding of transport phenomena, zoning of fresh and contaminated water, etc. that can help evolve management strategies of an aquifer for different stress conditions under a framework of hydro-geological setting. Modeling is a framework of computational tool, basically derived from the conceptualization of processes, which are otherwise known, but modeling itself cannot explain the physical processes. Numerous studies have been attempted by many investigators related to modeling of groundwater arsenic contamination, however, the findings of numerical modeling has 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.

National Institute of Hydrology (NIH) and CGWB in year 2001 carried out a modeling study in the Yamuna sub-basin, Nadia, and North 24-Paraganas districts to quantify spatial and temporal variation of arsenic contaminated groundwater for different geo-hydrologic settings and to suggest possible remedial measures for the arrest of spreading. It was reported from the study that the distributions of observed arsenic concentration have local high peaks with spreading in their surroundings implying localized in-situ sources spread over in the vicinity of the source by the influence of groundwater movement exaggerated by exploitation. And their localized activation has no bearing on the influence of sources from other domain or by the mobilization of arsenic from one pocket to another: those had been propagated by the local disturbances. From another analysis, it was shown (Majumdar et al., 2002) that by appropriately locating pumping wells in the freshwater zone, within the scattered zones of arsenic contaminated water, one can withdraw arsenic free groundwater without influencing movement of arsenic in the contaminated zones. In other words, it indicated that by adopting appropriate aquifer management strategies, fresh groundwater tapping from the scattered zones of fresh water, adjoining to the zones of arsenic contaminated water is possible without perturbing movement of arsenic from the contaminated zones.

Michael and Voss (2008) derived a method for reducing the concentration of arsenic in the Bengal Basin's water supply, from a groundwater modeling study, which could provide the population with safer water for drinking and irrigation. As an alternate to other solutions such as ex-situ treatment of arsenic contaminated water by filters, the authors performed a quantitative, large-scale hydro geologic analysis and numerical simulation of the entire Bengal Basin, looking at the benefits of water wells that pump from depths where the water is less contaminated. The authors showed that by installing wells to depths >150 m and using that water only for households could provide 90% of the region with low-arsenic water for 1,000 years. Water for irrigation would continue to be taken from near the surface because using the deep aquifers for both purposes could stress the resource, potentially drawing surface arsenic into the deeper reservoirs. Simulations provided two explanations: deep domestic pumping would slightly perturb the deep groundwater flow system, while substantial shallow pumping for irrigation would form a hydraulic barrier for protecting deeper resources from shallow arsenic sources. The analysis, further, indicated that this simple management approach could provide arsenic-free drinking water to >90% of the arsenic-impacted region for a period over 1,000-year.

Paul and Sikdar (2008) carried out numerical modeling of groundwater arsenic contamination movement for the English Bazar Block, Malda District, West Bengal. The study indicated that high abstraction of groundwater because of irrigation requirement has led to both horizontal and downward vertical movement of arsenious water within the aquifer towards the fresh water zones. The pattern of path-lines of groundwater flow was delineated quite different from the pre-development case. It was recommended from the above studies that if the abstraction rate is increased to 100m3/hr then within 50 years, there is a possibility of the aquifer getting contaminated but if the rate is decreased to 30m3/hr then the aquifer may remain uncontaminated at least for the next 50 years.

There are several other groundwater arsenic modeling studies. 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.

3.6 Chemical processes of arsenic contamination

Although there are number of hypotheses explaining chemical processes groundwater arsenic contamination, however, the most commonly believed chemical processes are dissolution.

Iron arsenate ($FeAsO_4$) may be tentatively regarded as the direct and immediate source of arsenic, because it is easily formed from scorolite [$FeAs_4$, $2H_2O$] and pitticite (hydrated mixture of arsenate and sulphate), that are common alternation products of arsenopyrite. Since arsenopyrite can contain As (III) ions in small proportion with ions of As (V), which is the dominant constituent, it is quite likely that arsenic in the alluvium occurs as ferric arsenate ($FeAsO_4$), with ferric arsenite ($FeAsO_3$) in minor proportion. Due to hydrolysis under conditions of low pH and high Eh, ferric arsenate is dissociated into the strongly poisonous arsenic acid (H_3AsO_4)

Ferric hydroxide is soluble in acidic aqueous environment, but it is precipitated in alkaline and reducing conditions at low Eh. Thus, if the acidity of the solution decreases (pH increases), colloidal precipitation of ferric hydroxide takes place. Some As (V) and As (III) ions being absorbed on the particles of Fe $(OH)_3$, may be co-precipitated with the latter. This reduces arsenic content of water. However, precipitation of As (V) and As (III) is not simultaneous because As (III) is 5 to 10 times more soluble than As (V) and its stability in aqueous solution increases with the alkalinity of water and reducing character of the environment. Thus, even after colloidal precipitation of As (V) ions with ferric hydroxide, the aqueous solution may contain As (III) ions in large amount. In mildly acid to neutral solution ($pH \leq 7$) or even in mildly alkaline solution under oxygenated condition at $Eh > 0$, breakdown of ferric arsenate and ferric arsenite by hydrolysis can produce As (V) bearing arseneous acid ($HAsO_4^{-2}$) and As(III) bearing arsenious acid (H_3AsO_3) respectively, together with ferric hydroxide in both cases. The relevant equations are:

$$FeAs^{3+}O_4^{-} \xleftrightarrow{(2H_2O+O)} HAsO_4^{2-} + Fe(OH)_3$$

$$FeAs^{3+}O_3 \xleftrightarrow{3(H_2O)} H_3As^{3+}O_3 + Fe(OH)_3$$

Arseneous acid ($HAs^{5+}O_4^{2-}$) is the commonest of arsenate compounds in natural water as aqueous solution. In a mildly reducing environment, $HAsO_4^{2-}$ is converted into As (III)-bearing arsenious acid ($H_2AsO_3^{1-}$) and in a strongly reducing condition into arsenious acid (H_3AsO_3). The change can be shown by the following equations:

$$HAsO_4^{2-} \xrightarrow{3H} H_2AsO_3^{1-} + H_2O,$$

$$HAsO_4^{2-} \xrightarrow{2H_2} H_3AsO_3 + H_2O.$$

In the absence of As (III) in the source material ($FeAsO_4$), As(V)-bearing arseneous acid ($HAsO_4^{2-}$) can be formed by the hydrolysis of $FeAsO_4$ in a mildly alkaline and oxygenated environment and ferric hydroxide is produced at the same time.

In the biomethylation process, arsenic in the sediment is hydrolysed to arseneous acid and is further reduced by bacteria to $As^{3+}O\ (OH)$ that form arsenite in solid state. Thus, the first role of bacteria is to increase the ratio of As (III)/As (V) in the sediment. This As (III) readily goes into aqueous solution to increase arsenic toxicity of water. The next step of change brought about by bacteria is biomethylation of $As^{3+}O\ (OH)$, resulting in the formation of $CH_3As^{5+}O\ (OH)_2$ or methyl arsenic acid and $(CH_3)_2\ As^{5+}O(OH)$, i.e. dimethyl arsenic acid or cacodylic acid, which is an extremely toxic compound. In each step, these substances are soluble in water to increase toxicity. In the fourth step, cacodylic acid is again biomethylated to form $(CH_3)_3As^{3+}$ or trimethylarsine by aerobic bacteria under oxidizing condition, whereas, anaerobic bacteria under reducing condition convert cacodylic acid to $(CH_3)_2HAs^{3+}$ or dimethyl arsine. Both are soluble in water and are toxic. The biomethylation process increases the proportion of organo-arsenic, which is readily absorbed by plants and animals through soil and water. Thus, the arsenic content of soil and water is reduced. However, the unabsorbed part of the organo-arsenic being toxic pollutes the soil and water. Hence, the practice of drawing arsenic contaminated groundwater from tube wells for irrigation purposes may ultimately lead to poisoning of surface soil and surface water, which are normally arsenic-free even in arseniferous regions of West Bengal.

The Brahmaputra alluvial basin is bounded by lower Himalayan Mountains in the north and northeast. High intensity of rainfall in the catchments and plain areas has contributed to high sediment loads, which have developed the valley into a long stretch of recent and old alluvium. The alluvium near the river is sandier and periodic fluviatile action keeps the alluvium stratified. However, its influence has been gradually obliterated by climate as one move from recent flood plains to old flood plains and then upland. As a result, there is deposition of coarse sand and coarser river-borne materials along with plant cells and other organic materials cells which may contain considerable amount of arsenic and other toxic elements. During the course of time, arsenic elements get released in the reducing environment by the process of biomethylation and get shelter within silty and clayey sediments. Some studies (Bhattacharya et al., 1997; Nickson et al., 1998 and others) also put forward the hypothesis that the burial of sediments, rich in organic matter, led to strongly reducing conditions in groundwater aquifer, which is facilitated by high water table, fine grained surface layers and widely practiced wetland paddy cultivation, as well as microbial oxidation of sedimentary organic matter, depleting, thereby, the dissolved oxygen in groundwater. Arsenic is released when arsenic rich iron oxyhydroxides, which are efficient arsenic scavengers, are reduced in anoxic groundwater. Such reduction is driven by concentrations of sedimentary organic matter.

Many experts agreed that the source of such high arsenic, anomaly in groundwater is geological rather than from pesticides or other artificial sources. It is postulated that arsenic bearing sulphide minerals, the commonest of which in nature is arsenopyrite (FeAsS) and/or its alternation products, *had been transported in the geologic past possibly from those occurring along the foothills of the Himalayas and deposited with the alluvium in* *the Ganges-Brahmaputra basin. These extraneous arsenic minerals buried under the recent alluvium are considered to be responsible for contamination. However, arsenopyrite and its alternation products are less toxic and normally insoluble in water. Over and above this, high arsenic anomaly has suddenly appeared in recent times, as no report of arsenic contamination of groundwater can be traced earlier than the late seventies.* In the present condition of emergence of greater area with arsenic pollution, the relation between chemistry of arsenic and high arsenic anomaly in groundwater is an interesting subject of study.

3.7 Observations, Analysis and Appraisal

Arsenic contaminations in groundwater have affected highly fertile and thickly populated Bengal Delta, Middle Ganga Plain, parts of Brahmaputra Plain and some alluvial areas of North-Eastern Regions. It is by and large influenced by common geomorphological setting and sedimentation pattern associated with Pleistocene-Holocene sea level changes. Shallow level arsenic contaminated aquifers of Holocene age are extensive over low-lying Bengal Delta and discontinuously along narrow entrenched channels in the Middle Ganga Plain. The oxidised Pleistocene sediments are generally free from arsenic. The Late Pleistocene and associated oxidized sediments constituted the interfluve areas of organic rich Holocene flood plain and deltaic sediments in the Bengal Delta and Middle Ganga Plain and the Barind. The presence of Late Pleistocene palaeosol aquitard apparently protects the underlying sediments from the downward movement of arsenic bearing and organic rich groundwater which might cause arsenic contamination. The arsenic contaminated aquifers in the Terai belt, Nepal, are closely comparable in nature and age to that of the Bengal Delta. The sediments in the Middle Ganga Plain and in the Bengal Delta are mainly derived from the Himalaya with minor contribution from the Peninsular India. In the Dongargarh Proterozoic rift-zone, in Chhattisgarh, arsenic concentration was enriched in acid magmatic rocks. In some of its local areas, arsenic and iron were enriched further in weathered rocks and soils, where Arsenic is adsorbed on hydrated-iron-oxide (HFO), which occurs as coating on clay minerals, biotite, and chlorite. In the Bhagirathi-Ganga Delta, Middle Ganga Plain and other arsenic-affected alluvial basins, Arsenic bearing pyrite or any other arsenic minerals are virtually absent in their aquifer sediments. Arsenic generally occurs as adsorbed on HFO, which preferentially enriched fine grained, fluvial and deltaic sediments and occur as coatings on quartz, clay, ferromagnesian clastic grains and organic matter.

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.

The oxidation hypothesis considers that due to heavy withdrawal of groundwater, aquifer was aerated and oxygen entering into the aquifer oxidised the pyrites rich in arsenic and acid released in the oxidation process leached the arsenic in soluble form in groundwater. While some scientists believe that the reductive desorption and dissolution of arsenic adsorbed onto iron oxyhydroxides in recent sediments is the most probable mechanism of arsenic mobilization in groundwater.

The oxidation hypotheses lack the merit as no arsenopyrite or pyrite rich in arsenic could be detected in widespread areas. Very low concentration of sulphate in groundwater is also contrary to pyrite oxidation hypothesis. On the other hand, the reduction hypothesis is getting considerable support from various studies. The soils in deeply submerged areas promote growth of aquatic weeds and increased agricultural wastes, most of which are mixed up with soil and buried underground and finally decay anaerobically. The anaerobic process provides a reducing environment of low redox condition for dissolution of iron and arsenic from solid phase to the liquid phase in groundwater.

Microbial arsenic reduction is also emerging as a potentially important factor in aquatic arsenic mobility. Bacterial action e.g. Thiobacillus Ferroxidant can assist the oxidation of Fe^{2+} (aq) in the presence of dissolved oxygen. Investigations have revealed microbial transformations of As (V), a form that absorbs strongly sediment solids to As (III), a form that is often much more mobile. As this process generates energy for the microbes involved, it has the potential to modify arsenic speciation of a system both rapidly and extensively.

Some scientists argued that arsenic contamination has been created by imprudent human interventions on nature. The modern system of agriculture has introduced an environment in which huge amount of fertilizers, pesticides, agrochemicals and groundwater for irrigation caused physical interventions changing the natural flow of irrigation setting of the country.

From the available information and results of various research works, it is considered that a combination of oxidation and reduction phenomena coupled with changes introduced by organic matter present in the sediments might have contributed largely for such high mobilization of arsenic. Large scale groundwater withdrawal during summer months causes lowering of Water table and enhances oxidized zone. During monsoon months the sediments are subjected to reducing environments with large quantities of rainfall recharge. As redox conditions become increasingly reducing, the ferric iron is reduced to, resulting in mobilization of some of the adsorbed arsenic. The Wetland cultivation with increased microbial activity further aggravates the problem.

Ground water in Bengal Deltaic Plain is anoxic in nature and mostly Calcium bicarbonate type in which sedimentary iron [both Fe (II) and Fe (III)] deposited by the meandering river carries arsenic. Sediment mineralogy and texture along with organic matter play crucial role in release of As in groundwater. High redox sensitive species (As, Fe and Mn), high alkalinity and absence of dissolved oxygen and nitrates suggest the microbial mediated and thermodynamically favoured redox processes (denitrification→ iron reduction). The presence of amorphous Fe-oxide together with surface bound phosphate in hotspot areas, and Fe-oxides as well as carbonate and phosphate minerals are also playing significant role in arsenic mobilization. It has been observed that As (III) is more dominant in near-surface aquifers rich in organic matter.

Release of arsenic to groundwater is mainly caused by reductive dissolution of hydrated iron oxide (HFO) and corresponding oxidation of organic matter. Groundwater flow, particularly during recharge of aquifers brings dissolved organic matter, in contact with HFO, promoting its bio-mediated reductive dissolution and consequent release of iron and arsenic to groundwater. High concentrations of arsenic are common in alluvial aquifers of the Bengal Basin and Mid Ganga Plain and arise because erosion of Himalayan region supplies immature sediments with low sulphate loadings of FeOOH on mineral grains, to a depositional environment that is rich in organic matter so that complete reduction of FeOOH is common. The role of human interventions, in increasing recharge of groundwater consequent to groundwater withdrawal during pre-monsoon period and enhancing the process of reduction, may also be quite significant.

Although level of information in Lower Ganga Plain is quite substantial, research work on mobilization of arsenic in Mid Ganga Plain and Brahmaputra Plain has to be geared up to arrive at a more precise understanding on the processes involved.

3.8 Summary

Findings of many research studies are yet to explain precisely actual causes, sources and mechanisms in a boarder perspective. The studies have mostly remained in search of causes, mechanisms and in identification of 'pros and cons' at micro-level. Groundwater flow and contaminant transport modeling studies could settle down suggesting different options of aquifer management to provide arsenic free groundwater from a contaminated aquifer without influencing much mobilization of arsenic contaminated water. Efforts for in-situ remediation of arsenic contaminated aquifer have already been initiated in West Bengal. It is strongly believed that there is a need for integrated research to identify genesis of arsenic and its mechanism of release and mobilization in the soil-water system. There is also a need for developing methods for in-situ remediation and groundwater management strategies in arsenic contaminated areas.

The primary source or the parental outcrops of arsenic in the Ganga-Brahmaputra basin is yet to be established. However, 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. Two hypotheses recommending mechanism of arsenic mobilization in the groundwater, one - oxidation of arsenopyrite or arsenic rich pyrite in soil strata, and the other, reductive dissolution of arsenic from soils, the later case 'the reductive dissolution' is recognized as the most potential reason than the former as the dominant mechanism of arsenic groundwater contamination. The mechanism states that the As derives from reductive dissolution of Fe oxyhydroxide (FeOOH) and release of its sorbed As. The Fe oxyhydroxide exists in the aquifer in dispersed phases, such as coatings on sedimentary grains. Reduction of the Fe is driven by microbial metabolism of sedimentary organic matter present in the system as C. Identification of the mechanism of As release to groundwater would help to provide a frame work to guide the placement of new water wells having acceptable concentrations of As.

Chapter-4

Mitigation and Remediation Update from West Bengal and Bihar : Studies and Projects Initiated

4.1 West Bengal

Though, the groundwater arsenic contamination first surfaced in the year 1983, the initiative to combat the menace of arsenic hazards, in true sense, came into existence in the year 1992 from the Government of West Bengal with the constitution of a state level expert committee. By then, as against 33 villages in 4 districts namely, South 24 Pargana, North 24 Pargana, Nadia, and Murshidabad reported in the year 1983 as many as 93 villages covering 6 districts namely, Murshidabad, Nadia, North 24 Parganas, South 24- Parganas, Barddhaman and Malda were identified as arsenic contaminated. The expert committee was formed to investigate the causes and sources of arsenic contamination in groundwater and to suggest possible remedial measures to combat the growing hazards. 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 has operationalized number of schemes spending a sum of nearly **Rs. 2100 crores**. 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. As of 2008, 9 districts covering 3417 villages in 111 blocks have been reported as the groundwater arsenic contaminated. These contaminated areas are in patches and encompass the districts of Murshidabad, Nadia, North 24 Parganas, South 24- Parganas and Kolkata to the east and Howrah, Hoogli, Barddhaman to the west of River Bhagirathi/ Hugli, and Malda to the north of the River Ganga. Even with every additional survey, more new areas are being added to the list of groundwater arsenic contamination from the state. Although the occurrences of groundwater arsenic contamination are in patches within shallow depth measuring 100m bgl., people staying around those affected areas are not abated from the potential risk of arsenic contamination owing to use of contaminated groundwater in different forms. About 16.26 million population (35.48% of the total population of the State) covering 17533 number of habitats are located in the potential risk zone of groundwater arsenic related threat and diseases. The basis of categorizing the contaminated areas are groundwater sampling from hand pumps and tube wells located in those places. Therefore, a hand pump or a tube well identified as arsenic affected means denial of use of that hand pump or tube well for further usages. It may be mentioned here that in most of the arsenic affected areas people are largely dependent on the hand pumps and tube wells for their potable and irrigation water requirement. Thus, scarcity of potable and irrigation water in the affected areas has become inevitable. Usages of those contaminated wells, to meet the basic need of water, mean accelerating the process of arsenic hazards and aggravation of its spreading.

In order to combat arsenic menace in the state, a number of counteractive measures, steps and research studies have been initiated and put into practice broadly as per the recommendations of the expert committee constituted by the Government. 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. 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) Research & Development studies for devising cost effective remediation techniques and for developing sustainable ground water resources management strategies.

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.

4.1.1 Steps and measures taken by the Government

Since 1992 the Govt. of West Bengal has taken a number of counteractive steps and measures to combat the natural calamity of groundwater arsenic menace like; public awareness programs, devising and demonstrating some of the results acquired from scientific analysis. Some of the important steps taken by the govt. are as follows:

(i) As the first step, 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 'Ar senic 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 con taminated 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.

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. 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.

4.1.2 Findings of initiated R & D studies

A number of research studies have been pursued to investigate extent, mobilization process, geochemistry, hydro-geological properties and processes by different organizations. Findings of various research studies have broadly been discussed in chapter-3. The Central Ground Water Board-Eastern Region (CGWB-ER), in addition to the above aspects, undertook tasks to identify potential arsenic safe zones aquifer. Findings of CGWB-ER are given below:

(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 is further observed that when the deeper aquifer is pumped creating a drawdown of 6 m, there is 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 viceversa. 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 (<1µg/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. In order to evaluate the performance of different arsenic removal devices, installed by various agencies in the arsenic affected areas in the West Bengal, the CGWB and United Nations Industrial Development Organization (UNIDO) jointly studied 16 community-based arsenic removal units en compassing six different removal technologies and 40 domestic units relied on four different removal technologies. It is observed that although, by and large, the arsenic removal devices are effective in bringing down the concentration of contaminated water to less than 50 g/L, there are instances when they failed to produce desirable outputs. It is mainly found attributed to poor maintenance and monitoring than any inherent weakness in the technology itself.

(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.

4.1.3 Projects Initiated/Implemented as Remedial Measures

The source of arsenic in groundwater is of geogenic origin, whose immediate restoring solution may not be feasible, unless physicochemical process is adequately understood. Thus, the possible remedial measures have been to find alternate source or to adopt suitable technological options to ensure supply of potable water in the arsenic affected areas. 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.

4.1.4 Uses of surface water sources

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 with estimated cost of **Rs. 1254.2 crores**. Out of them the main five schemes are: (i) Malda water supply scheme of 75 MLD capacity covering 1.43 million population; (ii) South 24 Parganas water supply scheme of 145.31 MLD capacity covering 2.951 million population; (iii) North 24 Parganas water supply scheme of 34 MLD capacity covering 0.751million population; (iv) Mahyampur water supply scheme in Murshidabad district for 3.95 MLD capacity covering 68,975 populations; and (v)) Balupur water supply scheme in Malda district of 5.23 MLD capacity for 72,883 populations. Photographs of two such schemes, one at Malda, and another at North 24 Paraganas, which are successfully running, are shown in **Figs. 4.1 and 4.2**, respectively. 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.

Figure 4.1: Malda surface water supply scheme, West Bengal

Figure 4.2: North 24 Paraganas surface water supply scheme, West Bengal

Surface water based schemes are constrained by the following factors:

a) ***Water availability:*** Surface water sources, that can be harnessed, are not omnipresent, and, therefore, cannot be located and extended everywhere. Moreover, water in some of the flowing/ stationary bodies remains only for a specific period of a year and cannot form the regular source for public water supply system. In addition to that, due to changes in the river discharges and its flow course, it is difficult to keep a sustainable intake point of water for the whole year.

b) ***Maintenance of water treatment units:*** Periodical maintenance of water treatment units, generally installed at various sites, requires a close monitoring. Efficacy of any treatment unit depends not only on the merit of technology but also on the regular maintenance and vigilance.

c) ***Networking/Transportation:*** A long transportation is required for supply of surface water from intake point/ treatment unit to the delivery points, particularly in the areas where water is to be supplied. This would involve: i) maintenance to avoid leakage damage in pipe lines during transportation ii) considerable cost of pipe line & its maintenance, iii) upholding of pressure for long transportation, etc.

d) ***Acceptability of using surface water for drinking purposes:*** Generally, rural people are habitual in using groundwater for drinking purposes and use of treated surface water, specially chlorinated water & its smell, is not conventionally practiced. There fore, switching over from routine groundwater uses to surface water sources, particularly for potable water would need an effort for social empowerment.

4.1.5 Uses of arsenic free groundwater by tapping deep aquifers

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. The deeper aquifer is separated by a thick clay layer of appropriate composition from the shallow aquifer. From the isotopic studies carried out in West Bengal, it is observed that there is no hydraulic connection between the shallow and deep aquifers as they belong to different age groups. Those deep arsenic free aquifers have the potential to yield nearly 5 to 20 lps of water, which is largely adequate to meet demand of water in the domestic sector. It is observed in the field studies 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. Similar experiences are observed from coastal areas where fresh deeper aquifer is separated from upper saline/brackish water by a thick clay layer. For example number of wells constructed using cement sealing techniques could yield fresh water for a very long period. However, in some cases, the deep tube wells are reported to be contaminated with arsenic, which might have attributed due to the following reasons:

(i) Tube wells constructed in the past might have not been properly designed with cement sealing techniques,

(ii) Tube wells constructed in the past might have been designed to screen both the upper and deeper aquifer to get higher discharge,

(iii) Tube wells constructed with cement sealing might have not been constructed properly.

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.

The successful implementation of deep aquifers, tapping from underneath arsenic contaminated shallow aquifer and freshwater zones in the shallow aquifer, could provide scope for an alternate option of dependability on groundwater resources. In arsenic affected areas, where the underneath deep aquifer possesses the characteristics of potential groundwater yields, and is risk free from potential arsenic threat by tapping deeper aquifer with proper sealing of the upper arseniferous aquifer for prevention of leaking arsenic contaminated water from the overlain aquifer groundwater withdrawal can provide an alternate sustainable solution to meet water demand.

In order to delineate potential deep aquifers and their prospect of harnessing, CGWB-ER, Kolkata, has started and continued groundwater exploration, down below the depth of 350 m bgl (maximum) in a number of arsenic affected districts in the State. By 2008, nearly 120 exploratory wells have been constructed and most of production wells have been handed over to the State Govt. department for operation. While carrying out the explorations, some interesting results are noted, which could help researchers and planners for future planning and management of groundwater resources in those areas. They are:

- A three layer aquifer system comprising thickness within 100 m bgl, 120 to 160 m bgl and 200 to 250 m bgl exists in the Bengal Delta Plains. The top layer (shallow aquifer) within 100 m bgl is mostly arseniferous, while the other two deep aquifers (120 to 160 m bgl, and 200 to 250m bgl) are separated from the overlying aquifers by clay layers of thickness above 10 m. They are arsenic free. The clay layer acts as a barrier to arrest the transport of arsenic from shallow arseniferous aquifer to the deep aquifers.

- A properly designed well with screen length tapping the desired aquifer, along with cement sealing of interface of shallow arseniferous aquifer and deep aquifer, is proficient in safe withdrawal of water from the deep aquifer having no risk of arsenic rich water. A schematic of two such exploratory wells, constructed at Beldanga village in Murshidabad district in West Bengal, is shown in **Fig.4.3.**

- Arsenic free deeper aquifers have the potential to yield 5 to 20 liter water per second and can cater to the need of potable water for large section of affected populace. By considering the capacity of each tube well, constructed in the arsenic affected areas of North 24 Parganas district, against a projected demand of 10 liters per capita per day for drinking & cooking purposes, a conservative estimate shows that about 48 tube wells could meet water requirement. The estimated figures are given in Table-4.1.

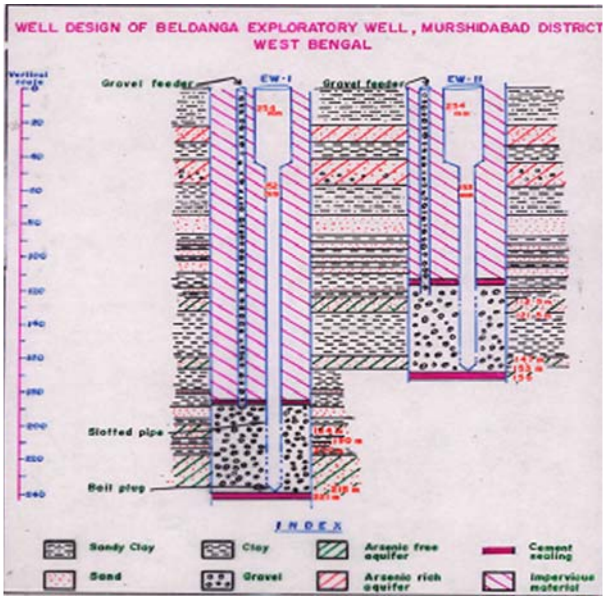


Figure 4.3: Schematic of two exploratory wells constructed at Beldanga in Murshidabad district in West Bengal to tap arsenic free deep aquifers.

Table 4.1: A conservative estimate, showing requirement of a number of deep tube wells for tapping arsenic free groundwater to meet domestic requirement in the North 24 Parganas district, West Bengal.

lock	Expected yield of arsenic free water (litre per sec)	Supply of arsenic free water, if run for 8 hrs in a day (litres)	Population in arsenic risk areas	Water requirement for drinking purposes (litre per day)	No of tube Well required for arsenic mitigation in the block
arasat I	13	3,74,400	2,38,000	23,80,000	6
abra I	17	4,89,600	1,88,000	18,80,000	4
abra II	15	4,32,000	1,50,000	15,00,000	4
ongaon	8	2,30,400	3,44,000	34,40,000	15
arrackpur I	15	4,32,000	1,57,000	15,70,000	4
arrackpur II	10	2,88,000	1,59,000	15,90,000	6
aighata	12	3,45,600	3,00,000	30,00,000	9
otal		25,92,000	15,36,000	1,53,60,000	48

A hydrogeological map showing formations and characteristics of potential deep aquifers, underneath of arsenic affected areas in West Belgal, prepared by CGWB-ER, is shown in Fig. 4.4. However, in order to ascertain responses of overlain contaminated zone and the probable threat of contamination to the deep aquifers, due to different stresses in the groundwater domain, a multi-aquifer system based flow and contaminant transport modeling need to be carried out to secure the fate of the groundwater domain before such schemes are planted.

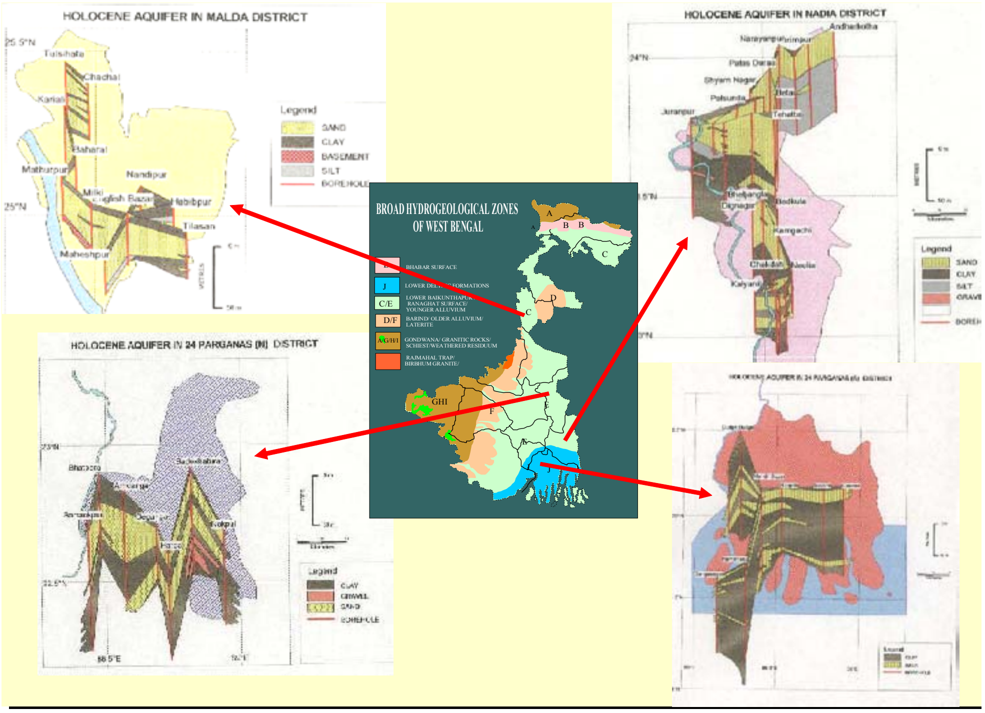


Figure 4.4: Disposition of delineated arsenic free deep aquifers in some parts of arsenic infested areas in West Bengal (Source: CGWB-ER, Kolkata)

4.1.6 *Use of arsenic removal filters for supply of arsenic free groundwater*

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 come forward with arsenic removal devices and implemented them 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 crores 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. A photograph of an ARP connected with an existing piped water supply scheme is shown in **Fig.4.5.**

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. As a measure to render services to the people and for water quality surveillance, PHED has established 17 chemical laboratories at the district level. Besides that, United Nation International Children Emergency Fund (UNICEF) entered into a strategic alliance with the Govt. of West Bengal in a Joint Plan of Action (JPOA) to address issues related to the arsenic menace in the State. The JPOA includes testing of tube well water yielding arsenic free water, taking appropriate mitigation measures by way of construction of deep hand pump fitted with tube well, development of arsenic removal filters, supporting research & development facilities, providing platform for information sharing and creating awareness programme. The proposed plan of action under the JPOA is given in Table-2.

Figure 4.5: Arsenic Removal Plant (ARP) connected to an existing piped water supply schemes (PWSS).

Table 4.2: Scheme wise coverage and estimated cost of the schemes planned to cover for the arsenic affected areas under JPOA (Joint Plan of Actions) with UNICEF.

Sl. no.	Type of scheme	No. of schemes	Nos. of Mouza covered.	Population as per 2001 census , (lakh)	Population covered (lakh)	Estimated Cost (Rs. lakh)
1	Surface water based scheme	8	1266	38.510	58.875	125420.38
2	New groundwater based scheme with ARP	361	1579	44.710	68.97	74976.07
3	New groundwater based scheme without ARP	21	39	0.924	1.433	1380.07
4	ARP in existing ground water based scheme	165	663	28.840	36.62	8269.23
	TOTAL	**555**	**3547**	**112.984**	**165.898**	**210045.75**

4.1.7 Rain Water Harvesting/Watershed Management

Rain water harvesting and conserving, by appropriate conservation structure to facilitate collection on ground or recharging to aquifer in order to use it later, is being practiced successfully in many water scarce regions of the country. Rain water harvesting, by watershed management practices in arsenic affected areas, where groundwater withdrawal has been restricted by overexploitation of the aquifer, can prove to be a promising alternative for managing water demand. This approach, besides increasing surface water accumulation and reduction of stresses on the use of groundwater, will enhance to recharge the underneath aquifer, that in turn will arrest decline of groundwater table. Water conservation, by this practice, will also require filtration and disinfections before put into use for public supply. Artificial recharge of rain water into overexploited/ overstressed aquifers through suitable recharging structures may also be a favorable proposition for permissible hydro-geological conditions.

4.1.8 Social Responses and Impacts

Social responses, in terms of socio-economic, socio-culture and socio-composite structure consequent to the affect of groundwater arsenic contamination, in the arsenic infested areas have not been worked out quantitatively in scientific terms. Few non-governmental organizations have made some qualitative analyses, which are as follows:

- Number of arsenic infected patients was more in the past (during eighties & early part of nineties) as compared to the number being reported in the later periods.
- Economically under privileged persons in the arsenic affected areas are more affected. This could be because of their low intake of protein & vitamin through food items.

Supply and usages of arsenic free water, and the awareness, generated through various campaigns and awareness programmes, are helping people in the affected areas to overcome the adverse impact on their health to a large extent.

- Earlier people suffering from arsenic related diseases used to get indifferent treatment from the rest of the people in the area as the disease was considered to be an infectious one. Based on this baseless apprehension that prevailed for a long time, even the mar riage alliance to a family, having arsenic patient, was rejected. Gradually, with the help of social and health awareness programmes, people started believing that the disease is purely water borne and not infectious; this in turn, helped people to re-store social acceptability .
- With the help of awareness programmes and water quality analysis facilities, people can be identified having arsenic related disease by the local health workers. They can also differentiate the tube wells yielding arsenic free water with blue mark.

4.2 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. Findings of some of the studies carried out by CGWB-MER, Patna are given below:

(i) From investigations, carried out to understand the pattern and extent of arsenic distribution in groundwater, physicochemical constituents of groundwater, lithologic characteristics and hydraulic properties of the aquifer materials, in the arsenic affected areas, it is observed that spatial variability in arsenic contamination have patchiness in distribution around the affected wells (Hand Pumps), with depth wise variation within top 50m bgl. Only newer alluvial deposits are found to have been arsenic affected, and the Pliestocene deposits are free from arsenic contamination. In the Sone-Ganga inte fluves region covering Bhojpur and Buxar districts, the deeper aquifer of depth ranges from 100-120m to 230-260m bgl. This is separated from the shallow contaminated zone by an aquitard, which has been found risk free from arsenic. If tapped through deep tube wells, deeper aquifer is estimated to have yield about 150-200 m3/hr of water. The geological map and lithological features of the arsenic affected areas are shown in **Figs. 4.6 and 4.7**, respectively. The lithological features **(Fig. 4.7)** showed that top soils of thickness about 2-5 m comprise clay, sandy clay and silty clay followed by fine to medium sand with occasional sand layers, having disconnected lenses of coarse to very coarse sand with occasional gravel beds. The geological units **(Fig.4.6)** of these formations can be linked to Siwaliks, Rajmahal traps, and Vindhayans ranges.

(ii) A joint study, by CGWB-MER, Patna and BARC, Mumbai, has been carried out to investigate hydrodynamic behavior of arsenic affected aquifers, age of arsenic contaminated groundwater, its relationship with the age of aquifer water, and to study the mechanism of arsenic mobilization. From the analysis of major chemical and environmental isotopes like Tritium, O_{16}/O_{18} and radio carbon, it was found that the shallow aquifers, influenced by arsenic contamination, are replenished by rainfall recharge, and, therefore, shallow aquifers with young groundwater is contaminated (< 40 years). Deeper aquifers, which posses' water of much older age (> 3000 years), are arsenic-free. This indicates that deeper aquifers are not influenced by direct vertical percolation of over lain strata. A positive correlation between arsenic and iron, and a concentrated distribution of arsenic in bicarbonate rich water, are also observed.

(iii) In addition to the above studies, several other studies have also been initiated by various organizations. GSI-Patna has initiated a study, covering 2400 sq. km in Bhojpur, Buxar and Patna districts and 1200 sq km area in Saran and Vaishali districts, to examine distribution and physiochemical behavior of arsenic in soil-water and mineral phases. Deptt. of Environment and Water Management, A N College, Patna, is studying effects of arsenic in food chain considering crop plants, like; wheat, maize, and rice irrigated by groundwater arsenic contaminated water.

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

(a) Groundwater arsenic contamination is confined to Newer alluvial belt along the river Ganga,

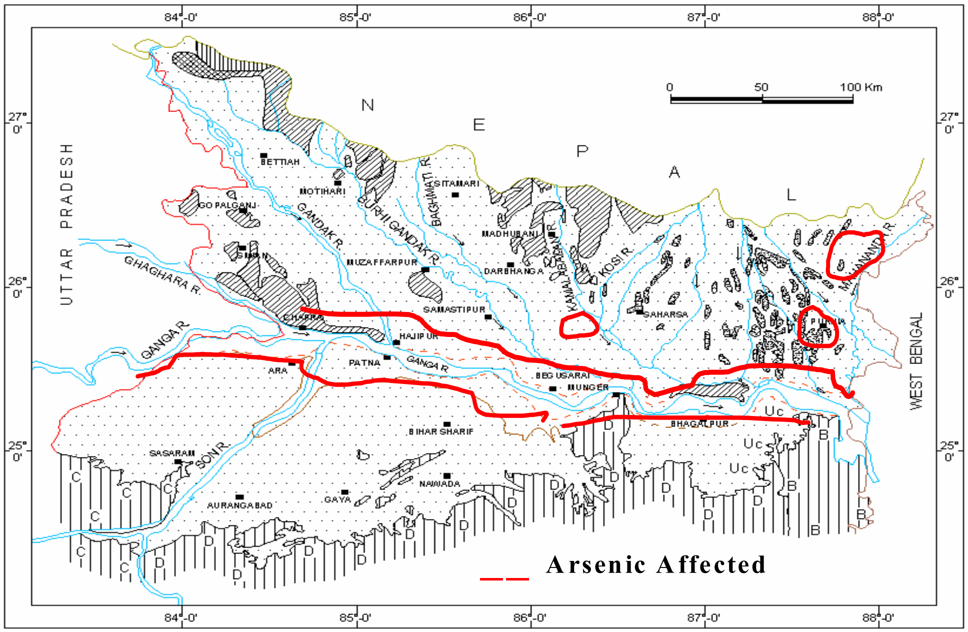
(b) Arsenic contamination is mostly in shallow aquifer (<50 m bgl) of young groundwater (< 40 years old), and is in localized pockets,

(c) Dug wells are free from arsenic contamination,

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

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

(f) The deeper arsenic-safe aquifer has potential to yield about 150-200 m3 /hr, which can be taped through heavy duty deep tube wells.



LEGEND

	GEOLOGICAL UNIT	GEOMORPHIC UNIT	DOMINANT LITHOLOGY
⁘	Diara/Kamla Formation Vaishali/Jaynagar/Kosi-Mahananda/Fatwa/Ganga Formation	Present(active) flood-plain & Older flood-plain	Unoxidised to feebly oxidised sediments, usually lacking soil cover, dominantly sand and silt with clay in flood basins.
⬭	Purnea (Alluvial fan) Formation	Relict dissected alluvial fan	Partly oxidised sediments with thin soil cover, dominantly sandy.
▨	Hazipur Formation/Khajauli Formation & Madhubani Formation.	Relict older alluvial surfaces	Partly to moderately oxidised sediments with significant soil cover, dominantly clayey at top with ferruginous concretions and minor kankar, underlain by sand.
⁘ Uc	Jamui/Nawada/Older alluvial Formation (South of the Ganga)/unclassified part	Older alluvial surface of the south Ganga plain	Feebly to highly oxidised sediments with soil cover of variable thickness, dominantly clayey at top, often with profuse kankar.
▩	Ganauli Terrace Formation	High level terrace sediments	Highly oxidised sediments with ferrolitic soil cover, dominantly pebbles, cobbles and minor boulders in sand, silt or clay matrix.
▥	Pre-Quaternaries A. Siwaliks B. Rajmahal traps C. Vindhyans D. Proterozoics and Archaeans	Pediplains, Hills etc	Sedimentaries, traps, metasedimentaries, grieisses, grsnite etc.

- - - Formational contact

≈ Ganga Meander Belt

Figure 4.6 : The Quaternary geological map of the Middle Ganga Plain, Bihar *(Source: Bihar Nepal earth Quake, GSI Special publication, 31).*

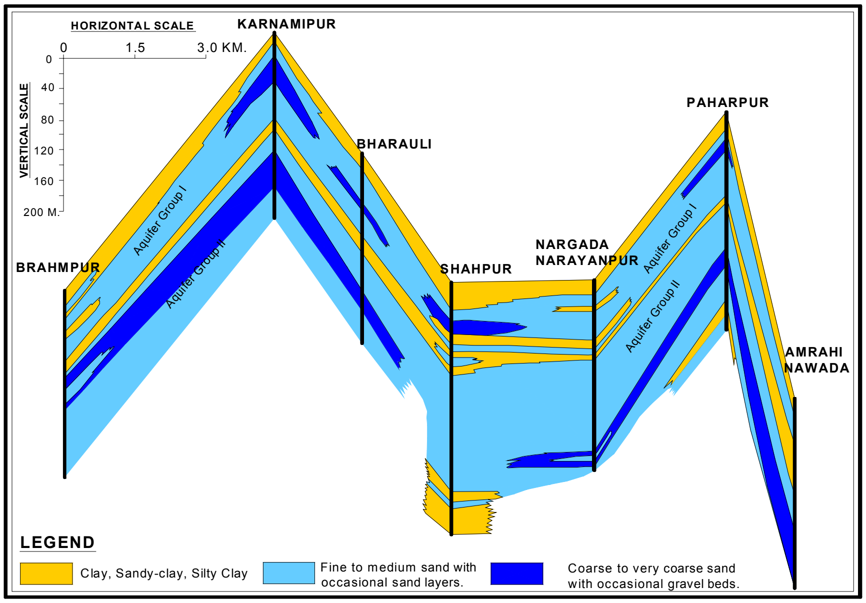


Figure 4.7 : Lithological formations of the arsenic affected areas.

4.2.1 Schemes Initiated on Remedial measures

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 Lsupply 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:

a) Mauzanpur, Bhojpur district, covering 39 villages,

b) One in Bidupur in Vaishali district; and one in Simri block in Buxar district for which work is about to start,

c) 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 order to identify and assess the potentiality of deeper aquifers and their sensitivity towards overlain contaminated shallow aquifer, CGWB-MER, Patna, has carried out the task of exploration through drilling in the affected districts. Twenty deep tube wells, in different locations in 6 districts, have been constructed with proper sealing to prevent any vertical percolation of contaminated water from the overlain aquifer. These tube wells have been handed over to PHED for use as groundwater production well. These wells are as given in Table-4.3.

Table-4.3: Arsenic-free exploratory well constructed by CGWB-MER, Patna in different places in Bihar as on 31st March 2009.

Sl. no.	Location	District	Sl. no.	Location	District
1	Barisban	Bhojpur	12	Barh	Patna
2	Shahpur		13	Gyaspur	
3	Paharpur		14	Maner	
4	Nargada Narayanpur		15	Madudabad	Samastipur
5	Bharauli		16	Vidyapati Nagar	
6	Karnamipur		17	Kancha	
7	Amrahi Nawada		18	Shahpur Patori	
8	Arjurnpur		19	Gangajal	Saran
			20	Sitabdiara	
9	Brahmpur	Buxar		Narapur	Begusarai
10	Churawanpur				

4.2.2 Social Responses and Impacts

Due to lack of awareness about the ill effects of consuming arsenic contaminated groundwater, on the one hand, and unknowingly and compellingly (because of no other option) , on the other, the rural people in the arsenic affected areas are continually using arsenic contaminated groundwater. Nevertheless, due to some spiritual notions, rural people are in normal habit of using groundwater. Furthermore, people using arsenic contaminated groundwater were not aware that the diseases and health hazards, they were experiencing, originated from water being used. To avoid societal fears and rejections, arsenic affected people used to hide their diseases. These eventually have given rise to aggravation of the problem both in terms of health hazards and spreading the contamination in the groundwater domain. Continuous efforts, to make people aware about the ill effect of consuming arsenic poisonous groundwater, helped some of the village heads to realize importance of taking precautionary measures against emerging threats. They facilitated PHED, Govt. of Bihar to implement the following:

(i) Community based surveillance system for arsenic groundwater monitoring, in some of the affected villages, has been provided, equipping these villages with Field Test Kits for regular water quality testing.

(ii) In order to generate social awareness about the uses of contaminated water and hygiene practices of water, PHED, in collaboration with CGWB-MER, Patna, has organized a number of mass awareness programmes particularly, in Maner and Sampat chawk in Patna district, Shahpur, in Bhojpur district, Mohiuddinnagar in Samastipur district, etc.

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 in comparison to the scale up of the problem. Unless a comprehensive and socially relevant programme, on a war footing, is conceived and implemented, the arsenic related problems in the State would multiply many folds.

4.3 Summary

Even after 25 years, since first surfacing of arsenic groundwater contamination in West Bengal, the problem resolving steps are still not sufficient and there is no sustainable solution. Neither, the understanding and knowledge base, accomplished from R & D activities, is adequate to resolve the problem completely. Nor the counteractive and precautionary measures initiated by the government, are sufficient to provide sustainable solution to meet the water demands of the rural populace. Numerous investigations have come out with a number of findings, alternatives and propositions, which varied from identification of shortfalls to success stories. Undoubtedly, each research study has its own merits and adds new information; however, there is a need to translate research outcomes to problem resolving issues through a framework of activities. Now, the present state of affairs of the problem, exposed in many States of 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 they are deemed fit. 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, are 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 for groundwater tapping 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.

The calamity of groundwater arsenic contamination in the state of Bihar is not as old as, and as serious as it is in West Bengal, however, scaling up and surfacing of groundwater arsenic with every new additional survey, in a number of districts, pose a serious threat towards further exploitation and usages of those contaminated aquifers. It also poses a threat to the people using the contaminated groundwater in different forms. Studies, carried out, and action, taken so far in the State of Bihar to understand the problem resolving issues, counteractive measures, etc., are meager 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. Thus, these meager findings from the state of Bihar, together with the experiences and knowledgebase acquired so far, from West Bengal, will help to evolve a framework of activities and sustainable mitigation strategies for the state of Bihar as well.

Chapter-5

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. Most of the existing efforts are relied on ex-situ remediation of arsenic, which have various degrees of success and failure as well. 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. Based on this approach, Government of West Bengal has developed some schemes to supply drinking water to some of the arsenic affected areas.

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. The subsequent sections give details of scientific and technical know how about arsenic removal technologies from water and their effectiveness.

5.1 Scientific Standing of Arsenic Treatment Technologies

A variety of treatment technologies, based on oxidation, co-precipitation, adsorption, ion-exchange and membrane process, have been developed and are available for removal of arsenic from contaminated water. However, question, regarding the efficiency and applicability/ appropriateness of the technologies, remains, particularly because of low influent arsenic concentration and differences in source water composition. Some of these methods are quite simple, but the disadvantage, associated with them, is that they produce large amounts of toxic sludge. This needs further treatment before disposal into the environment, besides the sustainability of these methods in terms of economic viability and social acceptability.

Many of these technologies can be reduced in scale and conveniently applied at household and community level, for the removal of arsenic from groundwater. During the last few years, many small scale arsenic removal technologies have been developed, field tested and used in various countries including India. Various technologies available for removal of arsenic from contaminated water are based mainly on five principles:

i) **Oxidation and filtration**
ii) **Co-precipitation:** Oxidation of As (III) to As (V) by adding suitable oxidizing agent followed by coagulation, sedimentation and filtration (co-precipitation).
iii) **Adsorption:** Activated Alumina, Iron filings (zero valent iron) and hydrated iron oxide.
iv) **Ion exchange** through suitable action and anion exchange resins.
v) **Membrane technology:** Reverse osmosis, nanofiltration and electrodialysis.

Arsenic is normally present in groundwater in As (III) and As (V) states in different proportions. Most treatment methods are effective in removing arsenic in pentavalent state and, hence, include an oxidation step as pretreatment to convert As (III) to As (V). Following oxidizing agents are used for conversion of As (III) to As (V):

- Oxygen (process is very slow),
- Powdered active carbon and dissolved oxygen (catalytic oxidation),
- UV irradiation,
- Chemicals (free chlorine, hypochlorite, bleaching powder, ozone, permanganate, hydrogen peroxide etc.), and
- Sunlight.

Although, As (III) can be oxidized to As (V) by various methods like oxygen, catalytic oxidation, UV irradiation, chemicals (free chlorine, hypochlorite, bleaching powder, ozone, permanganate, hydrogen peroxide, etc.) and sun light , air oxidation of arsenic is very slow and can take weeks for oxidation (Pierce and Moore, 1982). Chlorine dioxide and monochloramine are ineffective in oxidizing As (III) to As (V). Ultraviolet (UV) light, by itself, is also ineffective. However, if the water is spiked with sulfite, UV photo-oxidation shows promise for As (III) conversion (Ghurye and Clifford, 2001). Based on these considerations, only chlorine, permanganate and ozone are effective oxidizing agents for oxidizing As (III) to As (V), over wide range of working condition.

5.2 Conventional Technologies

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 5.1** and shown in **Figure 5.1.**

Table 5.1: Arsenic removal devices applied for removal of arsenic from contaminated groundwater

Name of the device	Operation principle	Filter media	Price	System	Performance
RPM/ Alcan AAFS -50 media by RPM Marketing Pvt. Ltd., Kolkata	Adsorption	Activated Alumina + AAFS-50.	Rs.44,300 + Rs.20,000 per charge.	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 design and model is 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	Rs.92,300 + Rs.39,000 per charge	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)	Rs. 74,100 + Rs.25,000 per charge	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	Rs. 47,300 + Rs.14,400 per charge	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 50 installed places. Company guarantees 2 years O & M, training including performance.
ADHIACON : AFDWS 2000 – Arsenic Removal Plant	Catalytic precipitation/ Electron Exchange	AFDWS - 2000	Rs. 75,000	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	Field performance of the system was below satisfactory level.

				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.	
Handpump Attached Arsenic Removal Plant by AIIH&PH, Kolkata	Oxidation + Coagulation + Flocculation/ Precipitation and filtration	Chlorinating agent (BP) + Ferric Alum	Rs. 35,000 + periodic chemical reagents	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	Rs. 39,000	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 $\beta FeOOH$. When Hand Pump is operated, the pressurized raw water 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.	Regular backwashing of iron filter is essential, which caused problem of operation and maintenance. Otherwise, the performance remained satisfactory.
Apyron Arsenic Treatment Units by Apyron Technologies (P) Ltd. Representing of Apyron Technologies Inc., USA	Adsorption	Aqua Bind (Activated Alumina +)	Rs. 80,000 + Rs. 15,000 per charge	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	Rs. 27,000	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,	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

				quartz and dual media (Sand-Activated Alumina), respectively.	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	Rs. 8000 + Rs.1200 per charge	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. Out of the above arsenic removal technologies, only a few could prove satisfactory performance at the field level like Granular Ferric Hydroxide (GFH) of Pal Trockner (P) Ltd., Kolkata - a German Technology, Arsenic Removal Plant by Oxide India (Catalysts) Pvt. Ltd, Durgapur, and Apyron Arsenic Treatment Units by Apyron Technologies (P) Ltd. representing Apyron Technologies. 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 ?

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. Scientific details of these five operating principles and their different applications are explained here.

5.2.1 Oxidation and Filtration

Oxidation and filtration normally refer to the processes that are designed to remove naturally occurring iron and manganese from water. These processes involve the oxidation of the soluble forms of iron and manganese to their insoluble forms and then removal by filtration. If arsenic is present in the water, it is removed via two primary mechanisms: adsorption and co-precipitation. First, soluble iron and As (III) are oxidized. The As (V) then adsorbs onto the iron hydroxide precipitation that are ultimately filtered from solution.

The arsenic removal efficiency is strongly dependent on the initial iron concentration and the ratio of iron to arsenic. In general, the Fe: As mass ratio should be at least 20:1. These conditions customarily result in an arsenic removal efficiency of 80-95%. In some cases, it may be appropriate to add ferric coagulant, in the beginning of the iron removal process, to optimize arsenic removal.

The effectiveness of arsenic co-precipitation, with iron, is relatively independent of source water pH, in the range 5.5 to 8.5. However, high levels of organic matter, orthophosphates and silicates, weaken arsenic removal efficiency by competing for sorption sites on iron hydroxide precipitates (Fields et al., 2000a, b).

In-situ Oxidation: In-situ oxidation of arsenic and iron in the aquifer was tried under DPHE-Danida Arsenic Mitigation Pilot Project in Bangladesh. The aerated tube well water was stored in a tank and released back into the aquifers, through the tube well, by opening a valve in a pipe connecting the water tank to the tube well pipe under the pump head. The dissolved oxygen content in water oxidizes arsenite to less mobile arsenate and also the ferrous iron in the aquifer to ferric iron causing a reduction in arsenic content of tube well water. Experimental results showed that arsenic in the tube well water following in-situ oxidation has been reduced to about half due to underground precipitation and adsorption on ferric iron.

Solar Oxidation: SORAS is a simple method of solar oxidation of arsenic in transparent bottles to reduce arsenic content from drinking water. The Department of Sanitary Engineering of AIIH&PH, Kolkata has studied the efficacy of arsenic removal by solar oxidation and precipitation and achieved 85 to 95% arsenic removal. The method is only applicable if the iron content in the groundwater exists beyond permissible level so as to adsorb the arsenate from water. Wegelin et al. (2000) have also used solar oxidation to reduce arsenic content of drinking water. Ultraviolet radiation can be used to catalyze the process of oxidation of arsenite in the presence of other oxidants like oxygen (Young, 1996). Experiments in Bangladesh have shown that the process on average could reduce arsenic content of water to about one-third.

Passive Sedimentation: Passive sedimentation also received considerable attention because of rural people's habit of drinking stored water from pitchers. Oxidation of water, during collection and subsequent storage in houses, may cause a reduction in arsenic concentration in stored water (Bashi Pani). Experiments, conducted in Bangladesh, showed zero to high reduction in arsenic content by passive sedimentation. Arsenic reduction, by plain sedimentation, appears to be dependent on water quality particularly the presence of precipitating iron in water. Ahmed et al. (2000) have shown that more than 50% reduction in arsenic content is possible by sedimentation of tube well water containing 380-480 mg/L of alkalinity as C_aCO_3 and 8-12 mg/L of iron. But this cannot be relied upon to reduce arsenic to desired level. Most studies showed a reduction of zero to 25% of the initial concentration of arsenic in groundwater. In rapid assessment of technologies, passive sedimentation has failed to reduce arsenic to the desired level (BAMWSP, DFID, Water Aid, 2001).

5.2.2 Co-precipitation

Co-precipitation has been the most frequently used method to treat arsenic contaminated water in numerous pilot- and full-scale applications. This technology can typically reduce arsenic concentrations to less than 50 µg/L and in some cases below 10 µg/L. In order to remove arsenic by co-precipitation, coagulant is to be added. Water treatment with coagulants, such as alum [Al_2 $(SO_4)_3$.18H2O], ferric chloride [$FeCl_3$] and ferric sulfate [Fe_2 $(SO_4)_3.7H_2O$], are effective in removing arsenic from water. Ferric salts have been found to be more effective in removing arsenic than alum on a weight basis and effect over a wider range of pH. In both cases, pentavalent arsenic can be more effectively removed than trivalent arsenic. The following steps are involved in the co-precipitation process for removal of arsenic:

- Addition of bleaching powder / hypochlorite,
- Addition of alum / ferric sulphate,
- Rapid mixing of chemical followed by slow mixing,
- Sedimentation, and
- Filtration.

In the coagulation-flocculation process, aluminum sulfate or ferric chloride or ferric sulfate is added and dissolved in water by stirring for few minutes. Aluminum or ferric hydroxide micro-flocs are formed rapidly. The water is, then, gently stirred for few minutes for agglomeration of micro-flocs into larger easily settable flocs. During this flocculation process, all kinds of micro-particles and negatively charged ions are attached to the flocs by electrostatic attachment. Arsenic is also adsorbed onto coagulated flocs. As trivalent arsenic occurs in non-ionized form, it is not subject to significant removal. Oxidation of As (III) to As (V) is, thus, required as a pretreatment for efficient removal. This can be achieved by addition of bleaching powder (chlorine) or potassium permanganate. The following three chemical precipitation processes are normally used:

i) Enhanced Lime Softening,
ii) Conventional Gravity Coagulation/Filtration, and
iii) Coagulation Assisted Micro-filtration.

5.2.2.1 Enhanced Lime Softening

Lime softening is a chemical-physical treatment process used to remove calcium and magnesium from solution. The addition of lime increases the pH of solution, thereby, causes a shift in the carbonate equilibrium and the formation of calcium carbonate and magnesium hydroxide precipitates. These precipitates are amenable to removal by clarification and filtration.

Lime softening solely, for arsenic removal, is uneconomical and is generally considered cost-prohibitive. However, for water systems that use lime softening to reduce hardness, the process can be enhanced for arsenic removal. To remove As (V), additional lime is added to increase the pH value above 10.5 units. In this range, magnesium hydroxide precipitates and As (V) is removed by co-precipitation with it. As (V) removal by co-precipitation, with calcium carbonate (i.e., below a pH of 10.5), is poor (less than 10%).

The amount of waste residual, produced by lime softening, is dependent on the hardness removed. While the total volume of waste, produced from lime softening, is typically higher than that produced by coagulation/filtration and co-precipitation processes, the arsenic concentration, in the sludge, is generally lower because more solids are produced. Prior to disposal, this waste residual will require thickening and dewatering, most likely via mechanical devices. Previous studies have indicated that typical lime sludge should not exceed toxicity characteristics limits, enabling it to be disposed in a municipal solid waste landfill (Fields et al., 2000a, b).

5.2.2.2 Conventional Gravity Coagulation/Filtration

Coagulation is the process of destabilizing the surface charges of colloidal and suspended matter to allow agglomeration of particles. This process results in the formation of large, dense floc, which is amenable to removal by clarification or filtration. The most widely used coagulants for water treatment are aluminum and ferric salts, which hydrolyze to form aluminum and iron hydroxide particles, respectively.

Conventional gravity coagulation/filtration processes use gravity to push water through a vertical bed of granular media, that retains the floc and are typically used within surface water treatment plants. They are less commonly used for treatment of groundwater supplies as these sources usually contain much lower concentrations of suspended solids, organic carbon and pathogenic microorganisms. Installation and operation of a conventional gravity coagulation/filtration process, solely for arsenic removal, is uneconomical.

Coagulation/filtration processes can be optimized to remove dissolved inorganic As (V) from water. The mechanism involves adsorption of As (V) to an aluminum or ferric hydroxide precipitate. The As (V) becomes entrapped as the particle continues to agglomerate. As (III) is not effectively removed because of its overall neutral charge under natural pH conditions. Therefore, pre-oxidation is recommended. The efficiency and economics of the system are contingent upon several factors, including the type and dosage of coagulant, mixing intensity and pH. In general, however, optimized coagulation-filtration systems are capable of achieving over 90% removal of As (V) and producing water with less than 5 µg/L of As (V). Influent As (V) levels do not appear to impact the effectiveness of this treatment process.

Iron-based coagulants, including ferric sulfate and ferric chloride, are more effective for removing As (V) than that of aluminum-based. This is because iron hydroxides are more stable than aluminum hydroxides, in the pH range 5.5 to 8.5. A fraction of the aluminum, which remains as a soluble complex, is incapable of adsorbing As (V) and this can pass through the filtration stage. The optimal pH ranges for coagulation, with aluminum and ferric salts, are 5 to 7 and 5 to 8, respectively. At pH values above 7, the removal performance of aluminum-based coagulants drops markedly. Feed water pH should be adjusted to the appropriate range, prior to coagulant addition. Post-filtration pH adjustment may be necessary to optimize corrosion control and comply with other regulatory requirements.

Several batch studies have demonstrated that As (V) removal is positively related to coagulant dosage. However, specific dose requirements, needed to meet As (V) removal objectives, were contingent upon the source water quality and pH. Effective coagulant dosage ranges were 5-25 mg/L of ferric chloride and as much as 40 mg/L of alum.

5.2.2.3 Coagulation Assisted Micro-filtration

Coagulation-assisted micro-filtration uses the same coagulation process described above. However, instead of the granular media filtration step, the water is forced through a semi-permeable membrane by a pressure differential. The membrane retains the As (V) laden floc formed in the coagulation step.

The use of pre-engineered coagulation assisted microfiltration package plants is a realistic possibility for new installations, where water quality precludes the use of sorption treatment. The membrane must be periodically backwashed to dislodge solids and restore hydraulic capacity. Backwash water is typically a high-volume, low solids (less than 1.0%) waste stream. The specific amount of solids will depend on several factors, including coagulant type, dosage, filter run length and ambient solids concentration.

The co-precipitation technique for removal of arsenic has been applied in the following systems:

- Central Arsenic Removal Plant (ARP) attached with tube wells for piped water supply,
- Arsenic Removal Plant (ARP) attached with Hand Pump, and
- Domestic Arsenic Removal Units using Earthen Pots, Plastic Buckets, Bucket Treatment Units, Modified BTUs, Stevens Institute Technology, Fill and Draw Units, Naturally Occurring Iron, Chemical Packages, etc.

5.2.3 Adsorption

Adsorption technology has been widely used to treat groundwater and drinking water containing arsenic. The technology can reduce arsenic concentrations to less than 50 μg/L in general and in some cases even below 10 μg/L. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It is used less frequently than precipitation/co-precipitation technologies, and is most commonly used to treat groundwater and drinking water.

In adsorption technology, solutes (contaminants) concentrate at the surface of a sorbent, thereby, reducing their concentration in the bulk liquid phase. The adsorption media is usually packed into a column. Contaminants are adsorbed, as the contaminated water is passed through the column. When adsorption sites get filled, the column must be regenerated or disposed of and replaced with new media.

Several adsorbents are available for removal of arsenic from water, viz., activated alumina, activated carbon, iron and manganese coated sand, kaolinite clay, hydrated ferric oxide, activated bauxite, titanium oxide, silicium oxide and many natural and synthetic ones. The efficiency of sorptive media depends on the use of oxidizing agent as aids to sorption of arsenic. Saturation of media, by different contaminants and components of water, takes place at different times of operation, depending on the specific sorption affinity of the medium to the given component.

Adsorption is probably the most prospective technology for removal of arsenic. It largely depends on capital cost, operation and maintenance cost, operational procedure and user-friendliness. The following media are commonly used for removal of arsenic through adsorption technique:

i) Activated alumina (AA),
ii) Activated Carbon (AC),
iii) Iron Based Sorbents (Granular Ferric Hydroxide, Iron Coated Sand, etc.),
iv) Indigenous Filters, and
v) Cartridge Filters.

5.2.3.1 Activated Alumina (AA)

Activated Alumina (AA), Al_2O_3, is a porous, granular material having good sorption properties. The media, aluminum trioxide, is prepared through the dehydration of aluminum hydroxide at high temperatures. AA grains have a typical diameter of 0.3 to 0.6 mm and a high surface area for sorption. Activated alumina is commonly used to remove arsenic from drinking water and ground water (EPA, 2000a, b). The reported adsorption capacity of AA ranges from 0.003 to 0.112 grams of arsenic per gram of AA. It is available in different mesh sizes and its particle size affects contaminant removal efficiency. Up to 23,400 bed volumes of wastewater can be treated before AA requires regeneration or disposal and replacement with new media.

When water passes through a packed column of activated alumina, the impurities including arsenic present in water are adsorbed on the surfaces of activated alumina grains. The selectivity of AA towards As (III) is poor, owing to the overall neutral molecular charge at pH levels below 9.2. Therefore, pre-oxidation of As (III) to As (V) is critical. Several different studies have established the optimum pH range as 5.5-6.0, and demonstrated greater than 98% arsenic removal under these conditions. AA column runs operated under acidic pH con ditions are 5 to 20 times longer than under natural pH conditions (6.0-9.0).

Several constituents can interfere with the adsorption process, either by competing for adsorption sites or clogging the media with particulate matter. The presence of suspended solids in the feed water could gradually clog the media and, therefore, pre-filtration is recommended for sources where the turbidity exceeds 0.3 NTU.

Activated Alumina media can either be regenerated on-site or disposed of and replaced with fresh media. Regeneration of saturated alumina is carried out by exposing the medium to 4% caustic soda, NaOH, either in batch or by flow, through the column, resulting in high arsenic contaminated caustic waste water. On-site regeneration of AA media produces 37 to 47 bed volumes of caustic soda waste (EPA, 2000a, b) generally. The residual caustic soda is, then, washed out and the medium is neutralized with 2% solution of sulfuric acid rinse. During the process, about 5-10% alumina is lost and the capacity of the regenerated medium is reduced by 30-40%. The activated alumina needs replacement after 3-4 regeneration. Like coagulation process, pre-chlorination improves the column capacity dramatically.

Activated Alumina is a low cost chemical (Rs. 100/- to Rs. 110/- per kg.) and it can be regenerated by washing with acid and alkali. It has a useful life expectancy and after which fresh activated alumina will replace the exhausted alumina. Bengal Engineering College, Shibpur, has developed both hand pump attached model and domestic model. A good number of hand pumps attached arsenic removal plants, with activated alumina as adsorbent, have been installed in West Bengal through various initiatives.

The technologies and market for alumina-based adsorptive media are continuously expanding. There are several emerging proprietary media, commonly referred to as modified AA, which contain alumina in a mixture with other substances such as iron and sulfur. In some instances, these media have greater overall adsorptive capacities, enhanced selectivity towards arsenic, and/or greater overall operational flexibility than conventional AA, thus, making them more cost-effective. Some of the activated alumina based sorptive media include:

- BUET Activated Alumina,
- Alcan Enhanced Activated Alumina,
- Arsenic Removal Units (ARUs) of Project Earth Industries Inc., USA, and
- Apyron Arsenic Treatment Unit.

The BUET and Alcan activated alumina have been extensively tested in field condition in different parts of Bangladesh and found very effective in arsenic removal (BAMWSP, DFID, Water Aid, 2001). The Arsenic Removal Units (ARUs) of Project Earth Industries Inc., USA uses hybrid aluminums and composite metal oxides as adsorption media. They are able to treat 200-500 Bed Volume (BV) of water containing 550 mg/L of arsenic and 14 mg/L of iron (Ahmed et al., 2000). The Apyron Technologies Inc. (ATI) also uses inorganic granular metal oxide based media that can selectively remove As (III) and As (V) from water. The Aqua-Bind TM arsenic media, used by ATI, consists of non-hazardous aluminum oxide and manganese oxide for cost-effective removal of arsenic. The proponents have claimed that the units, installed in India and Bangladesh, are consistently reducing arsenic to less than 10μg/L.

5.2.3.2 Activated Carbon (AC)

Activated carbon is an organic sorbent, commonly used to remove organic and metal contaminants from water and waste water. Activated carbon media are normally regenerated using thermal techniques to desorb and volatilize contaminants. However, regeneration of activated carbon media, used for the removal of arsenic from water, might not be feasible. The arsenic might not volatilize at the temperatures, used in activated carbon regeneration. In addition, off-gas, containing arsenic from the regeneration process, may be difficult or expensive to manage. The reported adsorption capacity of activated carbon is 0.020 grams of As (V) per gram of activated carbon. As (III) is not effectively removed by activated carbon. Activated carbon, impregnated with metals such as copper and ferrous iron, has a higher reported adsorption capacity for arsenic. The reported adsorption capacity for As (III) is 0.048 grams per gram of copper impregnated carbon and for As(V) is 0.2 grams per gram of ferrous iron-impregnated carbon.

5.2.3.3 Iron Based Sorbents (IBS)

Adsorption on IBS is an emerging treatment technique for arsenic removal. Examples of IBS products, currently available in the market, include granular ferric hydroxide, iron coated sand, modified iron, iron/sulfur, and iron oxide. The sorption process has been described as chemisorption (Selvin et al., 2000), which is generally considered to be irreversible. It can be applied in fixed bed pressure columns, similar to those for AA.

The studies, conducted with IBS media, have revealed that the affinity of this media for arsenic is strong under natural pH conditions, relative to AA. This feature allows IBS to treat much higher bed volumes, without the need for pH adjustment. However, similar to AA, optimal IBS performance is obtained at lower pH values. Phosphate has been shown to compete aggressively with As (V) for adsorption sites. Each 0.5 mg/L increase in phosphate above 0.2 mg/L will reduce adsorption capacity by roughly 30%. The exhausted IBS media can be disposed in a municipal solid waste landfill (MacPhee et al., 2001).

Granular Ferric Hydroxide: Ferric hydroxide is an excellent adsorbent for removal of arsenic. A few manufacturers have already installed a considerable number of hand pumps attached arsenic removal plants, in West Bengal. M/S Pal Trockner (P) Ltd, India and Sidko Limited, Bangladesh, have installed several Granular Ferric Hydroxide based arsenic removal units, in India and Bangladesh. The Technical University, Berlin, Germany, has also developed Granular Ferric Hydroxide (AdsorpAs®) based adsorbent for arsenic removal. The unit requires iron removal as pre-treatment to avoid clogging of filter bed. The proponents of the unit claim to have very high arsenic removal capacity and produces non-toxic spent granular ferric hydroxide. As iron content in ground water is generally high, all hand pump attached arsenic removal plants working under adsorption principles require regular backwashing/cleaning for removal of arrested iron particles. Such backwashing needs to be done in alternate days for optimal operation of ARP.

Iron Coated Sand: BUET has constructed and tested iron coated sand based small scale units, for the removal of arsenic from ground water. Iron coated sand has been prepared following a procedure similar to that adopted by Joshi and Choudhuri (1996). The iron content of the iron coated sand has been found to be 25 mg/g of sand. Raw water having 300 μg/L of arsenic, when filtered through iron coated sand, becomes essentially arsenic-free. It has been found that 350 bed volumes could be treated, satisfying the Bangladesh drinking water standard of 50 μg/L. The saturated medium is regenerated by passing 0.2N sodium hydroxide through the column or soaking the sand in 0.2N sodium hydroxide, followed by washing with distilled water. No significant change in bed volume, in arsenic removal, has been found after 5 regeneration cycles. It is interesting to note that iron coated sand is equally effective in removing both As (III) and As (V). Iron coated brick dust has also been developed in Bangladesh for arsenic removal from drinking water.

Read-F Arsenic Removal Unit: Read-F is an adsorbent produced and promoted by M/s Shin Nihon Salt Co. Ltd., Japan (2000), for arsenic removal in Bangladesh. Read-F displays high selectivity for arsenic ions under a broad range of conditions and effectively adsorbs both arsenite and arsenate without any pretreatment. The Read-F is Ethylene-vinyl alcohol copolymer (EVOH)-borne hydrous cerium oxide in which hydrous cerium oxide (CeO2 • n H2O) is the adsorbent. The material contains no organic solvent or other volatile substance and is not classified as hazardous one. Laboratory test at BUET, and field testing of the materials at four sites, under the supervision of BAMWSP, has showed that the adsorbent is highly efficient in removing arsenic from ground water.

5.2.3.4 Indigenous Filters

There are several filters available that use indigenous material as arsenic adsorbent. Red soil, rich in oxidized iron, clay minerals, iron ore, iron scrap or fillings and processed cellulose materials, is known to have capacity for arsenic adsorption. Some of the filters manufactured using these materials include:

- Sono 3-Kolshi Filter,
- Granet Home-made Filter,
- Chari Filter,
- Adarsha Filter,
- Shafi Filter, and
- Bijoypur Clay/Processed Cellulose filters.

The Sono 3-Kolshi filter uses zero valent iron fillings and coarse sand in the top Kolshi, wood coke and fine sand in the middle Kolshi while the bottom Kolshi is the collector of the filtered water (Khan et al., 2000). Nikolaidis and Lackovic (1998) showed that 97 % arsenic can be removed by adsorption, on a mixture of zero valent iron fillings and sand. The Sono 3-Kolshi unit has been found to be very effective in removing arsenic, but the media has over growth of microorganism (BAMWSP, DFID and Water Aid, 2000). If ground water contains excessive iron, the one-time use unit becomes quickly clogged.

The Garnet home-made filter contains relatively inert materials like brick chips and sand, as filtering media. No chemical is added to the system. Air oxidation and adsorption on iron-rich brick chips and flocs of naturally present iron in ground water can be the reason for arsenic removal from ground water. The unit has produced inadequate quantity of water and has not shown reliable results in different areas of Bangladesh, under different operating conditions. The Chari filter also uses brick chips and inert aggregates, in different Charis as filter media. The effectiveness of this filter in arsenic removal is not known.

The Shafi and Adarshs filters use clay material as filter media in the form of candle. The Shafi filter has been reported to have good arsenic removal capacity but has suffered from clogging of filter media. The Adarsha filter has participated in the rapid assessment program but has failed to meet the technical criterion of reducing arsenic to acceptable level (BAMWSP, DFID and Water Aid, 2000). Bijoypur clay and treated cellulose have also been found to adsorb arsenic from water (Khair, 2000).

5.2.3.5 Cartridge Filters

Filter units with cartridges, filled with soptive media or ion-exchange resins, are readily available in the market. These units remove arsenic like any other dissolved ions present in water, but are not suitable for water, having high impurities and iron content. Presence of ions, having higher affinity than arsenic, can quickly saturate the media requiring regeneration or replacement. Two household filters, tested at BUET laboratories, include:

- Chiyoda Arsenic Removal Unit, Japan, and
- Coolmart Water Purifier, Korea.

The Chiyoda Arsenic Removal Unit can treat 800 BV, meeting the WHO guideline value of 10 µg/L and 1300 BV, meeting the Bangladesh Standard of 50 µg/L, when the feed water arsenic concentration is 300 µg/L. The Coolmart Water Purifier can treat only 20 L of water with an effluent arsenic content of 25 µg/L (Ahmed et al., 2000). The initial and operation costs of these units are high and beyond the reach of the rural people.

5.2.4 Ion Exchange

Ion exchange is a physical-chemical process in which ions are swapped between a solution phase and solid resin phase. The solid resin is typically an elastic three-dimensional hydrocarbon network, containing a large number of ionizable groups electrostatically bound to the resin. These groups are exchanged for ions of similar charge in solution that have a stronger exchange affinity (i.e., selectivity) for the resin. In drinking water treatment, this technology is commonly used for softening and nitrate removal. This technology can reduce arsenic concentrations to less than 50 µg/L in general and in some cases to below 10 µg/L. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It is used less frequently than precipitation/co precipitation. And it is most commonly used to treat ground water and drinking water.

Arsenic removal is accomplished by continuously passing water, under pressure through one or more columns, packed with exchange resin. As (V) can be removed by the use of strong-base anion exchange resin, in either chloride or hydroxide form. These resins are insensitive to pH in the range 6.5 to 9.0 (EPA, 2000a, b).

Different categories of synthetic resins can be used for arsenic removal. The process is similar to that of adsorption; just the medium is a synthetic resin of more well defined ion exchange capacity. Few manufacturers have developed synthetic resins suitable for arsenic removal. However, the resins need to be replenished after use and renewal interval is dependent on the quantity of arsenic in water. The hand pump attached arsenic removal plants working with ion exchange principle need meticulous attention for operation as well as for regular backwashing.

The arsenic removal capacity is dependent on sulfate and nitrate contents of raw water as sulfate and nitrate are exchanged before arsenic. The ion exchange process is less dependent on pH of water. The efficiency of ion exchange process is radically improved by pre-oxidation of As (III) to As (V) but the excess of oxidant often needs to be removed before the ion exchange in order to avoid the damage of sensitive resins. Development of ion specific resin for exclusive removal of arsenic can make the process very attractive.

The exchange affinity of various ions is a function of the net surface charge. Therefore, the efficiency of the ion exchange process for As (V) removal depends strongly on the solution pH and the concentration of other anions, most notably sulfates and nitrates. High levels of total dissolved solids (TDS) can adversely affect the performance of an Ion Exchange system. In general, the Ion Exchange process is not an economically viable treatment technology if source water contains over 500 mg/L of TDS (Wang et al., 2000) or over 50 mg/L of sulfate. The presence of suspended solids in the feed water could gradually plug the media, thereby increasing head loss and necessitating more frequent backwashing. Therefore, pre-filtration is recommended if the source water turbidity exceeds 0.3 NTU.

Tetrahedron ion exchange resin filter tested under rapid assessment program in Bangladesh (BAMWSP, DFID and Water Aid, 2000) showed promising results in arsenic removal. The system needs pre-oxidation of arsenite by sodium hypochloride. The residual chlorine helps to minimize bacterial growth in the media. The saturated resin requires regeneration by re-circulating sodium chloride (NaCl) solution. The liquid wastes, rich in salt and arsenic, produced during regeneration require special treatment. Some other ion exchange resins have also been tried in Bangladesh but sufficient field test results are not available on the performance of those resins.

5.2.5 Membrane Technology

Membrane technology can remove a wide range of contaminants from water. This technology typically can reduce arsenic concentrations to less than 50 µg/L and in some cases to below 10 µg/L. However, its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It also produces a larger volume of residuals and tends to be more expensive than other arsenic treatment technologies. Therefore, it is used less frequently than precipitation/co precipitation, adsorption and ion exchange.

Membrane techniques are capable of removing all kinds of dissolved solids including arsenic from water. They can address numerous water quality problems while maintaining simplicity and ease of operation. In this process, water is allowed to pass through special filter media which physically retain the impurities present in water. The water, for treatment by membrane techniques, should be free from suspended solids and the arsenic in water shall be in pentavalent form. Most membranes, however, can not withstand oxidizing agent.

There are four types of membrane processes: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). All the four processes are pressure-driven and are categorized by the size of the particles that can pass through the membranes or by the molecular weight cut off (i.e., pore size) of the membrane (EPA, 2000a, b). The force required to drive fluid across the membrane depends on the pore size; NF and RO require a relatively high pressure (50 to 150 psi), while MF and UF require lower pressure (5 to 100 psi). The low pressure processes primarily remove contaminants through physical sieving and the high pressure processes through chemical diffusion across the permeable membrane (EPA, 2000a, b).

Because arsenic species dissolved in water tend to have relatively low molecular weights, only NF and RO membrane processes are likely to effectively treat dissolved arsenic (EPA, 2000a, b). MF has been used with precipitation/co precipitation to remove solids containing arsenic. MF generates two treatment residuals from the influent waste stream: a treated effluent (permeate) and a rejected waste stream of concentrated contaminants (reject).

RO is a high pressure process that primarily removes smaller ions typically associated with total dissolved solids. The molecular weight cut off for RO membranes ranges from 1 to 20,000, which is a significantly lower cut off than that for NF membranes. The molecular weight cut off for NF membranes ranges from approximately 150 to 20,000. NF is a high pressure process that primarily removes larger divalent ions associated with hardness (for example, calcium [Ca], and magnesium [Mg] but not monovalent salts (for example, sodium [Na] and chlorine [Cl]). NF is slightly less efficient than RO in removing dissolved arsenic from water (EPA, 2000a,b).

Reverse Osmosis (RO) units can be used as stand-alone arsenic treatment under most water quality conditions. Most RO membranes are made of cellulose acetate or polyamide composites cast into a thin film. The semi-permeable (non-porous) membrane is then constructed into a cartridge called an RO module, typically either hollow-fiber or spiral-wound. It is a pressure-driven membrane separation process capable of removing dissolved solutes from water by means of particle size, dielectric characteristics and hydrophilicity/hydrophobicity. Reverse osmosis is capable of achieving over 97% removal of As (V) and 92% removal of As (III) in a single pass (NSF, 2001a; NSF 2001b). As an added benefit, RO also effectively removes several other constituents from water including organic carbon, salts, dissolved minerals and color. The treatment process is relatively insensitive to pH. In order to drive water across the membrane surface against natural osmotic pressure, feed water must be sufficiently pressurized with a booster pump. For drinking water treatment, typical operating pressures are between 100 and 350 psi. Water recovery is typically 60-80%, depending on the desired purity of the treated water.

Most RO modules are designed for cross-flow filtration, which allows water to permeate the membrane while the retentate flow sweeps rejected salts away from the membrane surface. In many cases, pre-filtration (commonly through sand or granular activated carbon) is worthwhile. This minimizes the loading of salt precipitates and suspended solids on the membrane surface, thereby extending run length, improving system hydraulics and reducing O&M requirements.

Some membranes, particularly those composed of polyamides, are sensitive to chlorine. In such cases, feed water should be dechlorinated. Another potential concern associated with RO treatment is the removal of alkalinity from water, which in turn could affect corrosion control within the distribution system. If feasible, this problem can usually be avoided by conducting side-stream treatment for arsenic removal. Residual can be discharged either to a treatment plant or on-site sewerage system.

MRT-1000 and Reid System Ltd.: M/s Jago Corporation Limited promoted a household reverse osmosis water dispenser MRT-1000 manufactured by B & T Science Co. Limited, Taiwan. This system was tested at BUET and showed As (III) removal efficiency more than 80%. A wider spectrum reverse osmosis system developed by M/s Reid System Limited was also promoted in Bangladesh. Experimental results showed that the system could effectively reduce arsenic content along with other impurities in water. However, the capital and operational costs of the reverse osmosis system are relatively high.

Reverse Osmosis and Low-pressure Nanofiltration: Oh et al. (2000) applied reverse osmosis and nanofiltration membrane processes for the treatment of arsenic contaminated water applying low pressure by bicycle pump. A nanofiltration membrane process coupled with a bicycle pump could be operated under condition of low recovery and low pressure range from 0.2 to 0.7 MPa. Arsenite was found to have lower rejection than arsenate in ionized forms and hence water containing higher arsenite requires pre-oxidation for reduction of total arsenic acceptable level. In tube well water in Bangladesh the average ratio of arsenite to total arsenic was found to be 0.25. However, the reverse osmosis process coupled with a bicycle pump system operating at 4 Mpa can be used for arsenic removal because of its high arsenite rejection. The study concluded that low-pressure nanofiltration with pre-oxidation or reverse osmosis with a bicycle pump device could be used for the treatment of arsenic contaminated ground water in rural areas (Oh et al., 2000; Rahman and Rahaman, 2000).

5.3 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. A brief description of these technologies is given below.

5.3.1 Permeable Reactive Barriers (PRBs)

PRBs are walls containing reactive media that are installed across the path of a contaminated groundwater plume to intercept the plume. The barrier allows water to pass through while the media remove the contaminants by precipitation, degradation, adsorption or ion exchange. PRBs are used to treat groundwater in-situ. This technology tends to have lower operation and maintenance costs than ex-situ (pump and treat) technologies, and typically requires a treatment time of many years.

PRBs are applicable to the treatment of both organic and inorganic contaminants. The former usually are broken down into carbon dioxide and water, while the latter are converted to species that are less toxic or less mobile. The most frequent application of PRBs is the in-situ treatment of groundwater contaminated with chlorinated solvents. A number of different treatment media have been used, the most common being zero valent iron (ZVI). Other media include hydrated lime, slag from steel making processes that use a basic oxygen furnace, calcium oxides, chelators (ligands selected for their specificity for a given metal), iron oxides, sorbents, substitution agents (e.g., ion exchange resins) and microbes (EPA, 1998; Smyth et al., 2000).

PRBs are being used to treat arsenic in groundwater at full scale at only few sites. Although many materials for the reactive portion of the barrier have been tested at bench scale, only zero valent iron and limestone have been used at full scale. The installation techniques for PRBs are established for depths less than 30 feet, and require innovative installation techniques for deeper installations. The following chemicals and reactive media are used in PRBs to treat arsenic:

- Zero valent iron (ZVI),
- Limestone,
- Basic oxygen furnace slag,
- Surfactant modified zeolite, and
- Ion exchange resin.

As groundwater reacts with ZVI, pH increases Eh decreases and the concentration of dissolved hydrogen increases. These basic chemical changes promote a variety of processes that impact contaminant concentrations. Increases in pH favor the precipitation of carbonates of calcium and iron as well as insoluble metal hydroxides. Decreases in Eh drive reduction of metals and metalloids with multiple oxidation states. Finally, an increase in the partial pressure of hydrogen in subsurface systems supports the activity of various chemotrophic organisms that use hydrogen as an energy source, especially sulfate-reducing bacteria and iron-reducing bacteria.

Arsenate ions bind tightly to the iron filings, causing the ZVI to be oxidized to ferrous iron, aerobically or anaerobically in the presence of water. The process results in a positively charged iron surface that sorbs the arsenate species by electrostatic interactions (Su and Puls, 2001). In systems where dissolved sulfate is reduced to sulfide by sulfate-reducing bacteria, arsenic may be removed by precipitation of insoluble arsenic sulfide (As2S3) or co-precipitated with iron sulfides (FeS).

PRBs can be constructed by excavating a trench of the appropriate width and backfilling it with a reactive medium. Commercial PRBs are built in two basic configurations: the funnel-and-gate and the continuous wall. The funnel-and-gate uses impermeable walls, for example, sheet pilings or slurry walls, as a "funnel" to direct the contaminant plume to a "gate(s)" containing the reactive media, while the continuous wall transects the flow path of the plume with reactive media (EPA, 1998).

PRBs are a passive treatment technology, designed to function for a long time with little or no energy input. They produce less waste than active remediation, as the contaminants are immobilized or altered in the subsurface. PRBs can treat ground water with multiple contaminants and can be effective over a range of concentrations. PRBs require no above ground equipment, except monitoring devices, allowing return of the property to economic use during remediation. PRBs are best applied to shallow, unconfined aquifer systems in unconsolidated deposits, as long as the reactive material is more conductive than the aquifer (EPA, 2001a,b).

The technology relies on the natural movement of ground water; therefore, aquifers with low hydraulic conductivity can require relatively long periods of time to be remediated. In addition, PRBs do not remediate the entire plume, but only the portion of the plume that has passed through the PRB. Because cleanup of ground water contaminated with arsenic has been conducted at only few sites, the long-term effectiveness of PRBs for arsenic treatment has not been demonstrated fully (EPA, 2001a,b).

5.3.2 Phytoremediation

Phytoremediation is an in-situ technology applicable to contaminated soil and ground water. It is designed to use plants to degrade, extract, contain or immobilize contaminants in soil, sediment or ground water (Zhang et al., 2001). Typically, trees with deep roots are applied to ground water and other plants are used for shallow soil contamination. This technology tends to have low capital, operating and maintenance costs relative to other arsenic treatment technologies because it relies on the activity and growth of plants.

The mechanisms of phytoremediation include phytoextraction (also known as phytoaccumulation, the uptake of contaminants by plant roots and the translocation/accumulation of contaminants into plant shoots and leaves), enhanced rhizosphere biodegradation (takes place in soil or ground water immediately surrounding plant roots), phytodegradation (metabolism of contaminants within plant tissues), and phytostabilization (production of chemical compounds by plants to immobilize contaminants at the interface of roots and soil). Most applications of phytroremediation for arsenic removal include phytoextraction and phytostabilization.

Experimental research into identifying appropriate plant species for phytoremediation is ongoing. It is generally applicable only to shallow soil or relatively shallow ground water that can be reached by plant roots. In addition, the phytoremediating plants may accumulate high levels of arsenic during the phytoremediation process, and may require additional treatment prior to disposal.

The selection of the phytoremediating species depends upon the species' ability to treat the contaminants and the depth of contamination. Plants with shallow roots (e.g. grasses) are appropriate only for contamination near the surface, typically in shallow soil. Plants with deeper roots, (e.g. trees) may be capable of remediating deeper contaminants in soil or ground water plumes.

Examples of vegetation, used in phytoremediation, include sunflower, Indian mustard, corn, and grasses (such as ryegrass and prairie grasses) (EPA, 2001b). Some plant species, known as hyperaccumulators, absorb and concentrate contaminants within the plant at levels greater than the concentration in the surrounding soil or ground water. The ratio of contaminant concentration in the plant to that in the surrounding soil or ground water is known as the bioconcentration factor. A hyperaccumulating fern (Pteris vittata) has been used in the remediation of arsenic-contaminated soil, waste and water. The fern can tolerate as much as 1,500 ppm of arsenic in soil, and can have a bioconcentration factor up to 265. The arsenic concentration in the plant can be as high as 2% (dry weight) (Ma et al., 2001; Zhang et al., 2001).

5.3.3 Biological Treatment

Although biological treatments have usually been applied to the degradation of organic contaminants, some innovative techniques have applied biological remediation to the treatment of arsenic. This technology involves biological activity or micro-organisms that promote precipitation/co precipitation of arsenic from water and leaching of arsenic in soil. Biological precipitation/co precipitation processes for water create ambient conditions intended to cause arsenic to precipitate/co precipitate or act directly on arsenic species to transform them into species that are more amenable to precipitation/co precipitation. The microbes may be suspended in the water or attached to a submerged solid substrate.

An adequate nutrient supply should be available to the microbes to enhance and stimulate growth. If the initial solution is nutrient deficient, nutrient addition may be necessary. Iron or hydrogen sulfide may also be added. For biologically enhanced iron precipitation, iron must be present in the water to be treated. The optimal iron level depends primarily on the arsenic concentration.

Biological treatment for arsenic is used primarily to treat water above-ground in processes that use microorganisms to enhance precipitation/co precipitation. This technology may require pretreatment or addition of nutrients and other treatment agents to encourage the growth of key microorganisms. The leachate from bioleaching requires additional treatment for arsenic prior to disposal.

Another process uses anaerobic sulfate-reducing bacteria and other direct arsenic-reducing bacteria to precipitate arsenic from solution as insoluble arsenic sulfide complexes. The water containing arsenic is typically pumped through a packed-bed column reactor, where precipitates accumulate until the column becomes saturated. The arsenic is then stripped and the column is biologically regenerated. Hydrogen sulfide has also been used in suspended reactors to biologically precipitate arsenic out of solution. These reactors require conventional solid/liquid separation techniques for removing precipitates. Removal of arsenic from soil biologically via "accelerated bioleaching" has also been tested on a bench scale. The microbes in this system produce nitric, sulfuric and organic acids which are intended to mobilize and remove arsenic from ores and sediments. This biological activity also produces surfactants, which can enhance metal leaching.

5.3.4 Electrokinetic Treatment

Electrokinetic treatment is an emerging remediation technology designed to remove heavy metal contaminants from soil and ground water. It is an in-situ treatment technology and therefore does not require excavation of contaminated soil or pumping of contaminated ground water. Fine-grained soils are more amenable to electrokinetic treatment due to their large surface area, which provides numerous sites for reactions necessary for electrokinetic processes (Acar and Gale, 1995; Evanko and Dzomback, 1997). However, its effectiveness may be limited by a variety of contaminants and soil and water characteristics. In addition, its treatment depth is limited by the depth to which the electrodes can be placed. The technology has limited number of applications for arsenic.

Electrokinetic remediation is based on the theory that a low density current will mobilize contaminants in the form of charged species. A current passed between electrodes is intended to cause water, ions and particulates to move through the soil, waste and water (Will, 1995). Contaminants arriving at the electrodes can be removed by means of electroplating or electrodeposition, precipitation or coprecipitation, adsorption, complexing with ion exchange resins, or by pumping of water (or other fluid) near the electrode.

The chemicals used in electrokinetic process for arsenic removal include sulfuric acid, phosphoric acid and oxalic acid. In situ electrokinetic treatment of arsenic uses the natural conductivity of the soil (created by pore water and dissolved salts) to affect movement of water, ions and particulates through the soil (Will, 1995). Water and/or chemical solutions can also be added to enhance the recovery of metals by electrokinetics. Positively charged metal or metalloid cations, such as As (V) and As (III) migrate to the negatively-charged electrode (cathode), while metal or metalloid anions migrate to the positively charged electrode (anode) (Evanko and Dzomback, 1997). Extraction may occur at the electrodes or in an external fluid cycling/extraction system. Alternately, the metals can be stabilized in situ by injecting stabilizing agents that react with and immobilize the contaminants. Arsenic has been removed from soils treated by electrokinetics using an external fluid cycling/extraction system.

This technology can also be applied ex-situ to groundwater by passing the water between electrodes. The current causes arsenic to migrate toward the electrodes, and also alters the pH and oxidation-reduction potential of the water, causing arsenic to precipitate/co precipitate. The solids are then removed from the water using clarification and filtration (Pensaert, 1998).

A pilot-scale test of electrokinetic remediation of arsenic in ground water was conducted in Belgium in 1997. This ex situ application involved pumping groundwater contaminated with zinc, arsenic and cadmium and treating it in an electrokinetic remediation system with a capacity of 6,600 gpm. The treatment system precipitated the contaminants and the precipitated solids were removed using clarification and filtration. The electrokinetic treatment system did not use additives or chemicals. The treatment reduced arsenic concentrations in groundwater from 0.6 mg/L to 0.013 mg/L. The reported costs of the treatment were \$0.004 per gallon for total cost, and \$0.002 per gallon for O&M (Pensaert, 1998).

5.4 Waste Disposal / Sludge Management

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

The arsenic-rich sludge should be disposed in a controlled manner. 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.

The adsorbed media rich in arsenic can also be mixed with concrete as an additional aggregate but in a controlled proportion. Liquid wastes must have lower concentrations than the toxicity characteristic in order for the waste to be classified as non-hazardous. The arsenic toxicity characteristic is 5.0 mg/L. Those liquid wastes that contain more than 5.0 mg/L of arsenic would, therefore, be classified as a hazardous waste. Many of the arsenic removal technologies also remove other constituents and therefore the liquid waste must also be analyzed for other substances that may be present in concentrations above their respective toxicity characteristics. Because of the cost implications, on-site treatment or off-site disposal of hazardous waste is likely to be infeasible for small water systems. Indirect discharge through sewer to treatment plants may be viable option for waste disposal. There are five realistic methods for the disposal of arsenic wastes.

5.4.1 Landfill Disposal

Historically, municipal solid waste landfills have been commonly used for the disposal of Non-hazardous solid wastes emanating from treatment processes. However, the hazard potential of arsenic may limit the feasibility of this alternative.

Dewatered sludge and spent media can be disposed in a municipal solid waste landfill if the waste passes both the Paint Filter Liquids Test (PFLT) and the TCLP. The PFLT is used to verify that there is no free liquid residual associated with the waste. However, if the TCLP extract contains arsenic or any other contaminant (e.g., chromium) above the TC, the waste residuals must be disposed in a designated hazardous waste landfill. As such, the costs of disposal are relatively high. As with municipal solid waste landfill disposal, waste sludges must not contain free liquid residuals.

5.4.2 Direct Discharge to Surface Waters

Direct discharge refers to the disposal of liquid wastes to nearby surface waters, which act to dilute and disperse the waste by-products. The primary advantage of direct discharge is to reduce capital and operations and maintenance costs due to the elimination of residuals treatment. The feasibility of this disposal method is subject to provisions of the guidelines for waste disposal. The allowable discharge is a function of the ability of the receiving water to assimilate the arsenic without exceeding water quality criteria established under the Govt. regulations. Different water quality criteria exist depending on the classification of the receiving water. For specific criteria, conditions and limits, the appropriate agency should be contacted, because the conditions and limits can vary according to the receiving water's particular characteristics.

5.4.3 Indirect Discharge

The discharge of liquid wastes to a treatment plant is a potential disposal alternative. In this case, the wastes can be discharged to sewer systems. The arsenic limit is usually on the order of 50 to 10 µg/L. The TBLLs are computed for each POTW to take into account the background levels of contaminants in the municipal wastewater. The background level will change because of the drinking water treatment process, which may lead to revised TBLLs. The revised TBLL can be used to determine if the liquid waste stream could be discharged to the POTW.

5.4.4 Land Application

Land application of concentrated sludge may be allowed under certain conditions depending on the state law and regulations. As per USEPA guidelines, sewage sludge (also called "biosolids") containing <41 mg As/kg biosolids can be land-applied with no restrictions. Biosolids with arsenic concentrations between 41 and 75 mg/kg can be land-applied, but must track arsenic accumulation. The lifetime arsenic accumulation limit is 41 kg As/hectare of land.

5.4.5 On-site Sewerage

Liquid wastes from Reverse Osmosis POU devices can suitably be disposed in on-site sewerage or septic system. Arsenic is concentrated in the RO retentate during normal process operation. However, eventually this retentate is combined with other domestic wastewater in the septic tank. Because the amount of water consumed is small relative to the total flow entering the dwelling, the concentration of arsenic in the blended wastewater is nearly identical to that in the influent stream.

5.5 Alternative Options

West Bengal-India and Bangladesh are lands of rivers. The average annual rainfall in these two areas is 2000 mm. West Bengal has about 7,000 m3 and Bangladesh has 11,000 m3 of available surface water per capita. Besides this, West Bengal has about 4000 km2 of wetland and vast river basin is flooded almost every year, but due to the negligence most of these water goes as waste. Therefore, there is an urgent need for a proper watershed management so that the vast surface and rain water resource could be used to combat with the situation. A proper watershed management approach with active participation from the people can also prove to be a possible alternative to resolve problem of freshwater availability arising out of arsenic groundwater contamination.

5.6 Performance Audit, Evaluation and People's Participation

As per the performance audit of arsenic alleviation programme (PHED, 2005), the Govt. of West Bengal took up measures to combat arsenic poisoning in potable ground water since 1992-93. However, the schemes for arsenic alleviation were not executed in a mission mode as warranted by the situation and there was inadequate monitoring. Despite 13 years of effort and expenditure of Rs. Rs.832.46 crores on arsenic alleviation measures, only 43% of the at risk population was supplied with arsenic free drinking water as of March 2005 against the capacity created to cover 56%. As of June 2005, no comprehensive mapping of arsenic affected areas was done. Screening of results of 1.20 lakh out of 1.31 lakh tube wells in the eight affected districts revealed that 27% (0.32 lakh) of them were yielding water with arsenic concentration even above 50 µg/L. In spite of execution of the short term, long term and medium term programmes at a cost of Rs 721.24 crore to combat arsenic poisoning, 21.47 lakh people continued to remain exposed to arsenic contamination due to non-adherence to the stipulated performance standards. Out of 2396 Arsenic Removal Units (ARUs) and 77 PWSS installed with Arsenic Removal Plants (ARPs), 135 ARUs and 32 PWSS were yielding water contaminated beyond 50µg/L while 989 ARUs remained non-functional due to use of defective adsorption media, non regeneration and non replacement of adsorption media affecting 7.89 lakh people. Arsenic rich sludges generated in ARUs were also not disposed scientifically leaving substantial risks of environmental hazards (PHED, 2005).

Arsenic removal plants (ARPs) could be one possible option to provide arsenic-free drinking water to the affected people. However, these technologies need evaluation in respect of effectiveness in arsenic removal and community acceptance. The ARPs are mainly based on adsorption, co-precipitation, ion exchange and membrane techniques. Installation of ARPs in West Bengal, India, started at the end of 1998. The West Bengal government and other organizations have already invested about 3 million dollars in installing ARPs purchased from both national and international manufacturers (1900 ARPs were set up at an average price of US$1500 for each ARP) in mainly 5 out of 9 arsenic affected districts of West Bengal.

School of Environmental Studies of Jadavpur University had initiated investigations on the efficiency of arsenic removal plants (ARPs) in West Bengal in late 1998. They have evaluated the efficiency of 577 ARPs in the districts of North 24 Parganas, Murshidabad and Nadia of West Bengal and submitted their evaluation reports to the Government of West-Bengal, manufacturers of ARPs and other concerned NGOs for their information and follow-up action (SOES, 2000, 2001, 2003a,b, 2004).

Hossain et al. (2005) evaluated efficiency of arsenic removal plants (ARPs) in removing arsenic and iron from raw ground water covering 18 ARPs from 11 manufacturers, both from India and abroad, installed in Baruipur Block of South 24 Parganas district under a project titled 'Technology Park Project' implemented by All India Institute of Hygiene and Public Health (AIIH&PH), Govt. of India, Kolkata, in partnership with a number of NGOs under the financial support from India-Canada Environment Facility (ICEF), New Delhi. Immediately after installation of ARPs on August 29, 2001, the villagers began using filtered water for drinking and cooking even though first analysis on September 13, 2001 found that ten out of 13 ARPs failed to remove arsenic below the WHO provisional guideline value of 10 µg/L, while six plants could not even achieve the Indian standard value of 50 µg/L. The highest concentration of arsenic in filtered water was observed to be 364 µg/L. Two years study showed that none of the ARPs could maintain arsenic in filtered water below the WHO provisional guideline value and only two could meet Indian standard value of 50 µg/L throughout where the users were able to recognize the ARPs as an asset for the community and maintained it properly. Standard statistical techniques also showed that ARPs from the same manufacturers were not equally efficient. During the study period almost all the ARPs have undergone minor or major modifications to improve the performance and after the study, 15 out of 18 ARPs were no longer in use. The study concluded ineffectiveness and poor reliability of the ARPs. It is further reported that in most cases authorities installed the ARPs abruptly without checking the ground realities. Lack of awareness and relevant information is one of the major hurdles in arsenic mitigation program. Without cost sharing it is difficult to inculcate in users' mindset a sense of 'belonging' (Hossain et al., 2005).

Hossain et al. (2006) also evaluated effectiveness of arsenic removal plants (ARPs) as a remediation approach to provide safe water based on systematic study of 577 ARPs installed in 3 districts out of 1900 total ARPs installed in five arsenic affected districts of West Bengal, India. Overall study showed that 475(82.3%) of the ARPs installed in the arsenic affected areas were not useful. The reasons for ineffectiveness and low performance included improper maintenance, sand gushing problem, lack of user friendliness and absence of community participation. A comparative study of ARPs in two different blocks Domkol in Murshidabad district and Swarupnagar in North 24 Parganas showed that 39(80%) and 38(95%) ARPs, respectively, were not useful. A micro-level study in a Gram Panchayat, Kolsur, Deganga block, North 24 Parganas showed that 14(87.5%) ARPs were not useful (Hossain et al., 2006).

There are few examples where ARPs were able to run successfully through community participation. These include two ARPs of BE College, one installed in Village Parpatna, GP Chakla, Block Deganga, District North 24 Parganas and another installed in Village Sangrampur Paschimpara, GP Sangrampur Sibhati, Block Bosirhat 1, District North 24 Parganas. Another example of successful ARP is of Pal Trockner installed near Ichhapur Ayurbedic Hospital, GP Ichapur 1, Block Gaighata, District North 24 Parganas. One ARP of Oxide India Plant in Chandranath Basu Sebasangha, in Betai of Dangapara GP, Block Tehatta, District Nadia is also running successfully with people's participation.

Based on the above observations, it is strongly recommended that awareness amongst the people and their whole hearted participation is very much essential to achieve success at field level. The technologies found effective and safe for arsenic removal from contaminated water should be promoted for wider implementation in the acute arsenic problem areas to avoid ingestion of excessive arsenic through water. The arsenic removal technologies may improve further through adaptation in rural environment through people's participation.

5.7 Observations, Analysis and Appraisal

The main technological options for the remediation of arsenic are: i) decontaminate aquifers from arsenic by in-situ treatment of soil-water system, or (ii) switch over to alternative, arsenic-free water sources; instead of opting exclusively for ex-situ arsenic removal technologies. Former case is the best option when complete understanding of the physico-chemical processes and system behavior are methodically known; while the later case could be considered as a potential alternative when sustainable surface water and groundwater flows are ensured. However, in either case, extensive feasibility studies would be necessary. Ex-situ arsenic removal technologies can be a suitable option when the dimension of the problem is small and short lived, such as the source is anthropogenic. For a large scale groundwater arsenic problem, as in different states in the Country where demand of and dependability on ground water resources both for drinking and irrigation water in such places are continuum, ex-situ treatment of tapped groundwater by arsenic removal technologies could merely be thought to be a stopgap arrangement to meet the requirement of drinking water to the people in the arsenic affected area. Requirement of agricultural irrigation water in rural areas is far more than the drinking water. Irrigation water requirement cannot be sustained by the ex-situ arsenic removal devices. Use of arsenic contaminated groundwater in agriculture has far reaching consequences in terms of contamination through food chain and environmental aspects. Further, in ex-situ treatment technologies another additional problem is arsenic sludge management. The key issues thus emanate as: whether to adopt strategy for in-situ remediation of arsenic from soil-water system, or switching over to alternate surface water-groundwater management strategies letting remediation of arsenic groundwater menace undisturbed in its existing state-of-affairs, or to adopt mixed management strategies such as; supply of drinking water through arsenic removal technologies and irrigation water through conjunctive use of surface water and fresh aquifer tapping? To ensure non-hazardous supply of drinking and irrigation water to the people in the arsenic affected areas, a suitable water management strategy on scientific footings needs to be evolved.

If it is considered that arsenic removal technologies can be one of the technological options to ensure supply of drinking water in the arsenic affected areas, the questions generally raised are: sustainability of the technologies in terms of cost, O & M, and efficiency. Most of the existing devices showed unsatisfactory results in terms of cost (total and per capita), operation and maintenance and expected sustainability. Although a remarkable technological development in arsenic removal processes has taken place during last few years, however, very few in which O & M has been taken care, could show potential field satisfaction. The technologies and its field applications, which could prove satisfactory results, can be thought for promotion with improvisation for long term sustainability. One should also realize that arsenic mitigation strategy is location specific. A method suitable for a specific area can not be generalized for the other affected regions due to i) geographical and geomorphological variations, and ii) different socio-economic and literacy conditions of people. Therefore, a considerable R & D is necessary to evolve eco-friendly, cost effective and user friendly arsenic removal technology. A comparison of different arsenic removal processes is shown in Table 5.2.

Table 5.2: Comparison of conventional arsenic removal technologies

Technologies	Advantages	Disadvantages
Oxidation/Precipitation: - Air Oxidation - Chemical oxidation	- Relatively simple, low-cost but slow process - Relatively simple and rapid process - Oxidizes other impurities and kills microbes	- The processes remove only a part of arsenic
Coagulation/Co-precipitation: - Alum Coagulation - Iron Coagulation	- Relatively low capital cost - Relatively simple operation - Common Chemicals available	- Produces toxic sludges - Low removal of As(III) - Pre-oxidation required
Sorption Techniques: - Activated Alumina - Iron Coated Sand - Ion Exchange Resin - Other Sorbents	- Relatively well known and commercially available - Well defined technique - Plenty possibilities and scope of development	- Produces toxic solid waste - Replacement/regeneration required - High tech operation and maintenance - Relatively high cost
Membrane Techniques: - Nanofiltration - Reverse osmosis - Electrodialysis	- Well defined and high removal efficiency - No toxic solid wastes produced - Capable of removal of other contaminants	- Very high capital and running cost - High tech operation and maintenance - Toxic wastewater produced

5.8 Summary

All the technologies described in this document have their own merits and demerits and should be refined to make them suitable and sustainable for a particular situation. The modifications should be based on the pilot-scale implementation of the technologies with objectives to:

- Improve effectiveness in arsenic removal,
- Reduce the capital and operation cost of the system,
- Make the technology user friendly,
- Overcome maintenance problems, and
- Resolve sludge and arsenic concentrates management problems.

Arsenic removal technologies have to compete with other technologies in which cost appears to be a major determinant in the selection of a treatment option by the users. The rural people habituated in drinking tube well water may find arsenic removal from tube well water as a suitable option for water supply. In many arsenic affected areas, arsenic removal may be the only option in the absence of an alternative safe source of water supply. Awareness amongst the people and their whole hearted participation is very much essential to achieve success at field level. A proper watershed management approach with active participation from the people can also prove to be a possible alternative in many areas to meet requirement of water for drinking and irrigation purposes.

RPM /ALCAN AAFS-50 MEDIA

BUCKET OF RESINS OF WRI

GRANULAR FERRIC HYDROXIDE - PAL TROCKNER

ARSENIC REMOVAL PLANT – OXIDE INDIA

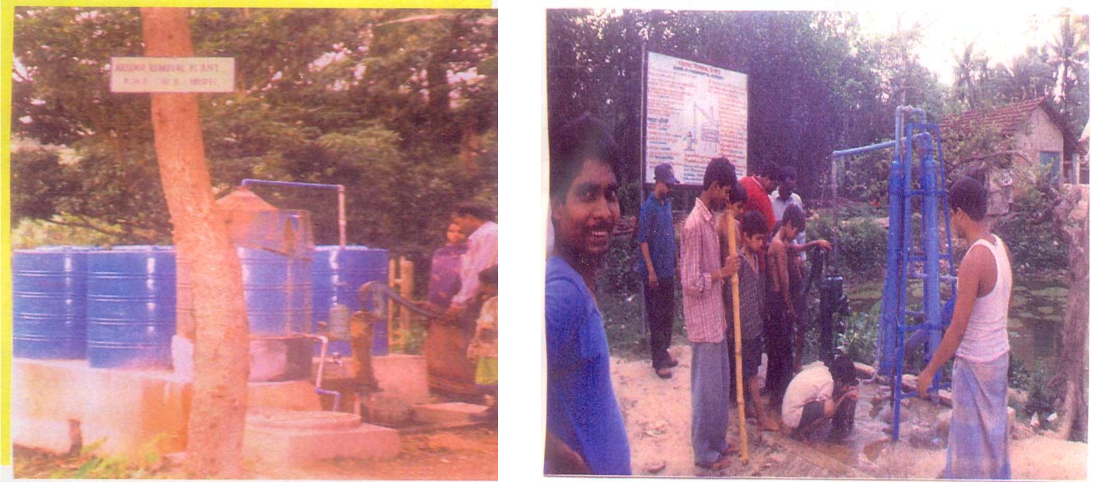
ADHIACON-AFDWS 2000

HANDPUMP ATTACHED ARSENIC REMOVAL PLANT-AIIH & PH

Figure 5.1: Arsenic Removal Devices Developed and Promoted by Different Organizations in various places in West Bengal.

IONOCHEM- ARSENIC TREATMENT UNIT

APYRON ARSENIC TREATMENT UNIT



ARSENIC TREATMENT PLANT-PHED MODEL

ARSENIC AND IRON REMOVAL SYSTEM-SFR MODEL

Figure 5.1: Arsenic Removal Devices Developed and Promoted by Different Organizations in various places in West Bengal.

Chapter- 6

A Critical Appraisal- Future Risk, Scope to Remediate, Technological Competence, etc.

6.1 Appraisal on Source and Mobilization in the Bengal Basin

After the first detection of arsenical dermatitis and its causal connection with the drinking of high-As groundwater by the affected agglomerations of population, in a few districts of West Bengal (1983-84), it was only natural that the initial systematic studies on the problem were clinical, epidemiological and chemical-analytical in technique and orientation (Chakraborty et al., 1982; Saha, 1984; Chakraborty and Saha, 1987; Chatterjee et al., 1995; Das et al., 1996; Mondal et al., 1996). One fallout of this initial perception of the looming threat was the formulation of the question as to whether this arsenic contamination has been caused and is being caused by anthropogenic factors (e.g., large-scale use of chemical fertilizers, pesticides, herbicides, and excessive withdrawal of groundwaters) or by natural (geogenic) factors. It is now generally agreed that the source is of geological origin, being the top strata of the Bengal Basin, underlying the Bengal Delta Plain (WHO, 2008). The percolation of fertilizer residues can have only a modifying role on a limited scale, that too in the very upper strata. The question of the possible role of excessive withdrawal of groundwater, however, continues to divide the opinion.

Initial studies of this natural source and pathways of the metalloid came to centre on delineation of spatial extents of the contamination (reported, till the1990s, as confined to the regions east of the Bhagirathi-Hugly River), and the stratigraphic level of occurrence (reported as confined to the Meander Belt of the Upper Delta Plain of the Late Quaternary). Based on the argument that the contamination occurs in the pore-waters of the terrigenous sediments of the Ganga-Brahmaputra-Meghna (GBM) delta, it was naively felt that the contaminant (arsenic) has an inland source. The chief interest has been put in locating the possible inland source. And the speculations have ranged from the sulphide belts of Bihar, Uttar Pradesh, North Bengal to the coal seams of the neighbouring Godwana Basins, the basic rocks of the Rajmahal Traps, the metamorphic schists of the Lesser Himalaya, even as far to a common source as in the Qamdo-Siman volcanic and ophiolite province in China for the whole mosaic of arsenic show-ups in the entire south-east Asia (e.g.,PHED,1991; Chakraborty et al., 1994; Das et al., 1996; Bhattacharya et al., 1997; Dhar et al., 1997; Saha, 1998; Nickson et al., 1998; Acharya et al., 1999; Stanger, 2005). The main thrust of these studies was, however, on the chemical characterization of groundwater, with elevated levels of arsenic concentration, redox state, arsenic speciation, age of waters, depth control, etc. All of this leads to the conclusion that the contaminated water is enriched by Fe, Mn, Ca, Mg, bicarbonates, and depleted in sulphate, fluoride, chloride. The pH, in this water ranges from 6.5 to 8. The redox condition is usually reducing. It is high on organic matter content; lodged mostly in sand coatings, or sorbed on clays, HFOs, and organic matters. As-concentration, in this water, is diminishing down-depth.

Widening and deepening of the knowledge base has now pushed forth the question as to how does arsenic mobilize into the aqueous phase from the aquifer solid phase. Early opinions are divided into two schools: oxidation model and reduction model. Kinniburgh et al. (1994) have postulated that the high quantum of groundwater withdrawal in Bangladesh and India has been causing the widening of the zone of aeration, resulting in oxidation of the source arsenian sulphides (pyrite and arsenopyrite, especially), in the aquifer sediments. And the acid so released has been reacting to liberate cations, including arsenic, into the aqueous phase. Soon, however, the euphoria subsided when (i) search for source clastic (detrital) arsenian sulphides proved elusive; (ii) any pyrites present were found to have framboidal structure, indicative of their diagenetic origin; (iii) aqueous phase was bicarbonate- enriched (alkaline), not acidic (e.g., Maynard et al. 1997; McArthur, 1999; BGS, 1999).

The favor of support has now tilted to the reduction model, with a host of workers proposing that arsenic is initially sorbed on HFOs, clays, ferromagnesian phyllosilicates , organic matter, or is lodged in the lattices of some crystalline oxide phases (magnetite, haematite,etc.), carbonates (siderite, rhodochrosite, etc.), and silicates (grunerite, etc.). Under appropriate reducing conditions, especially with Fe-3 reducing to Fe-2 and release to the aqueous phase, the sorbed arsenic (now reduced) desorbs and dissolves, in the aqueous phase in amounts, controlled by equilibrium conditions. It co-precipitates with Fe-2, or if the crystalline oxides and/ or carbonates and/or silicate phases dissolve, it comes along into the aqueous phase. If and when the redox state of the aqueous phase reverses, with changing micro- environment, precipitation occurs back to the solid phases. It is warranted that the cycle may repeat, in space and time, or should change in the micro-environment. The presence of arsenical pyrite shows that sulphate reduction occurred after, or at the same time as, Fe reduction, in micro-environments. The latter yield arsenic, for incorporation into diagenetic pyrite, which is a sink for, not a source of, arsenic (Jekel, 1994; McArthur, 1999). With significant corroboration coming from field, laboratory and theoretical studies, this reduction origin of arsenic has now gained the status of the standard model among workers in this field (Matisoff et al.,1982; Saha, 1984; Welch et al., 1988; Belzile and Tessier,1990; Saha and Chakraborty, 1995; Sullivan and Aller, 1996; Chen et al., 1997; Dutta and Subramanium,1997; Manning and Goldberg, 1997; McArthur 1997; CGWB, 1999; Jain et al., 1999; Nickson et al., 2000; Chowdhury et al., 2000; Gotkowitz et al., 2000; Acharya et al., 2001; BGS and DPHE, 2001; Pal et al., 2001; Ravi Shankar et al.,2001; Achyuthan and Baker, 2002; Harvey et al., 2002; Price and Picher, 2002; Rowland et al., 2002; Smedley and Kinniburgh, 2002; Ta TKO et al., 2002; Bhattarchyya et al., 2003; McArthur et al., 2004; Pal et al., 2003; Swartz et al., 2004; Adel Miah, 2005; Stanger et al., 2005; Gurung et al., 2006; Lipfert et al., 2006; Mukherjee, 2007; Hasan et al., 2007; Rowland et al., 2007; Banning et al., 2008; Hoque et al., 2008; Purakait and Mukherjee, 2008; Sengupta et al., 2008). On the other hand, the oxidation model is considered relevant only locally, occasionally and insignificantly.

The major controls of arsenic mobilization have thus been specified. The question of source has been relegated to the backburner. Briefly put, arsenic is present initially in the solid phase. Under reducing conditions, it mobilizes. It is being largely mediated, perhaps, by microbial activity. In presence of high concentrations of S, it precipitates as sulphides. That is, only the general conditions of mobilization have been defined. The more intriguing questions of the mechanism of mobilization are yet to be understood i.e., the nature of specific reactions involved and the micro-environmental controls of these reactions, in terms of aquifer sedimentary lithic properties (physical and geometrical), mineralogical attributes, organic matter contents and microbial activities, groundwater flux, and so forth. And, if this is true, then the mineralogical-phase form (s) of the source of arsenic, the initial pattern of dispersal of the source-assemblage(s), and, especially, the relation of this dispersal pattern to the geological evolutionary history of the delta, must be taken into account alongside and in full measure. Due to the lack of knowledge base, neither we cant explain the specificities of the observable pattern of distribution of arsenic in the aqueous phase at present, nor the variance for concentration values in time series in a given region, e.g., in the Bengal Basin. More importantly, the real reason of the alarming fact of gradual spread-out and newer show-ups of arsenic in groundwater, over time in newer tracts of this deltaic basin, will remain elusive to undermine all mitigation programmes, in not distant future. Accumulating reports on widespread occurrence of arsenic, its potential health hazards, have drawn worldwide attention. As a result, arsenic research has been accorded recognition as a thrust area. The focus has been turned on to the specifics of microbially mediated reduction, sorption mechanism, reaction kinetics, hydrostratigraphic and hydrochemical modeling, laboratory simulation, effects of groundwater flux, site specificity, thermodynamics of arsenic incorporation in pyrite, isotopic probe, besides mitigation. That is, all ramifications but the vital of a natural holistic approach.

In this backdrop, the present arsenic research group of the School of Fundamental Research of Kolkata conducted a two-year investigation into the problem of arsenic presence, in Nadia district of West Bengal, and reached the definitive conclusions that: (i) presently observable distribution-pattern of arsenic, in aqueous phase in the Bengal Basin, defines the picture, obtaining at the present stage of an ongoing hydrochemical evolutionary process, modified by anthropogenic interventions; (ii) specifics of this pattern become evident, only if and when, considered with reference to a natural frame of reference; (iii) there exists a definite and regional correlation, both positive and negative, between arsenic (total) and iron (total). It demonstrates that other than desorption reactions, there must have been more reaction; (iv) memories of the micro-environmental Eh and pH states of some of the preceding evolutionary stages, at least, are preserved in the diagenetic-phase mineral parageneses present in the aquifer sediments (Berner, 1981); (v). study of the aquifer solid phase arsenic and iron by sequential extraction (Keon,et al., 2001), along with studies on oxidation states of **As** and **Fe** and on the diagenetic phases and their parageneses, will yield the basic information to making possible the reconstruction of the past and present reaction regimes, the ones that induced arsenic and iron mobilization--- in short, the mechanism and triggers; (vi) nature of initial source of arsenic, in the deltaic sediments-in terms of pattern of distribution (whether dispersed throughout or concentrated in thin bands), reactive forms, and mineral association --- definitely bears on the evolutionary changes, leading to the present picture, i. e., the question of source pertains, it needs to be addressed (Chatterjee et al., 2005; Basu et al., 2007; Ghatak, 2007; Roy et al., 2007).

6.2 Appraisal on Arsenic Removal Technologies

Widespread variations, in the projected costs of arsenic removal, are partially attributed to the large number of possible arsenic removal technologies. All of the methods are intended to remove arsenic in the As (V) state. As (III) can be oxidized to As (V) by using ferric chloride, potassium permanganate, or chlorine. Ferric sulfate coagulation works well, for removing arsenic at nearly neutral pH values, but sludge disposal can be a problem. Lime softening is effective, especially at pH > 10.5. This could initially be a good step, but extremely low arsenic concentrations cannot be achieved. Activated aluminum is very good for water, with high total dissolved solids (TDS) concentrations, but ion competition and regeneration difficulties must be overcome. Ion exchange drawbacks include ion competition and iron precipitate clogging. Reverse osmosis can remove 95% of the arsenic; however, a significant amount of water is concentrated with arsenic and, therefore, is wasted. Nano filtration can be > 90% effective, but 80% of the water is wasted. Iron coagulation and filtering work well, given tight control of parameters, most notably iron content, time, and pH. Arsenic often is bound to iron or manganese, so traditional Fe/Mn removal methods work well for some waters (Water World, 2000). In 1978, Jones and others suggested Fe (II) and lime, for the removal of As (V) from acidic solutions (Prasad, 1994). At present, lime softening and iron co-precipitation appear to be the most effective removal technologies, barring the wasteful membrane separation methods. Arsenic removal methods and their effectiveness are shown in Table 6.1. The approaches of arsenic removal from contaminated water can be summarized as follows:

6.2.1 Arsenic Removal Technologies

(i) It is proved that arsenic has affinity with iron. Under restricted Eh-pH conditions, arsenic dissolved in water, gets adsorbed onto iron and precipitates as oxyhydroxide. So if a volume of oxygenated water is injected into arseniferous aquifers, the concentration of arsenic in water may be proportionately depressed. This technique would work effectively in areas, where arsenic in groundwater correlates positively with iron, and prior knowledge of arsenic distribution pattern and flow direction has been gathered to facilitate grids for sinking injection wells.

ii) The second alternative is to remove arsenic from arsenic-contaminated water by suit able filtration techniques. If we can solve the related problems of sludge disposal effectively, and maintenance is ensured locally, this appears to be the indigenously viable practical solution. There are various kinds of filter manufacturers, who claim their success in making arsenic contaminated water into water of standard potable type. These are:

Oxidation of As (III) to As (V) by free Cl, ferric chloride, potassium permanganate, ozone, hydrogen peroxide. Each process of oxidation has its limitation and drawbacks.

Coagulation-precipitation process: Aluminum and ferric salts are commonly used in drinking water treatment, for coagulation of particles and colloids in the water. If the As content in water is in the range of 0.1 to 1 ppm, under optimized condition of Fe dosage and pH, precipitation efficiency and the elimination process may be as high as 99%,. With change in Eh / pH ratio efficiency varies appreciably.

Lime softening: This treatment is used for reducing hardness of water, and is also an effective process for As (V) removal. The use of activated charcoal powder increases the efficiency as it induces oxidation of As (III). But effectiveness decreases in alkaline condition.

The biggest problem of the above three processes is concerned with the separation of the precipitate and disposal of arsenic contaminated coagulated sludge.

Ion exchange: It can remove As (V) more efficiently than As (III). In some recent studies, it has been established that by this process, As5+ level can be reduced to 2 mg/L and the brine regeneration can be done several times without any adverse impact on As removal. TDS, selenium, sulphate, fluoride and nitrate, present in water, affect the life of resin adversely. Suspended solid and precipitated iron cause clogging of resin bed. Another disadvantage is that As (III) is hardly removed.

Activated alumina: It is a porous oxide with large surface area and it adsorbs As5+ under favorable pH condition of 5.5 to 6, but it is also susceptible to various interfering chemicals as in the case of ion exchange process.

The great advantage of activated alumina is its simple operation, with regeneration operation at intervals of one to three months. Unfortunately, activation efficiency decreases fast. As (III) cannot be removed efficiently. The biggest problem is disposal of highly concentrated sludge with high contents of toxic dissolve solid.

Granular ferric hydroxide: It is poorly crystallized B-FeOOH, with very large specific surface of 250-300 m^2/g and porosity of 75-80%, which is capable of high adsorption. The grain size ranges from 0.2 to 2 mm. It also acts as fixed bed absorbers, with best efficiency between pH ranges of 5.5 to 9.

In addition to As (V), As (III) can also be adsorbed by granular ferric hydroxide. The presence of sulphates in raw water has little influence on adsorption capacity. Depending on As concentrations, the treatment efficiency ranges from 5 to 25g/m^3 of water. The residue is solid and the spent absorbent is non-toxic and can withstand temperature of 950°C without release of As from the granules. So disposal is less problematic. Phos phate, in raw water, reduces the arsenate adsorption due to interference.

Activated carbon: It may be helpful, to some extent, in removing arsenate, specially As (V) from water, but its efficiency is very low and cost inhibitive.

Conventional Fe-Mn removal process: It is effective only in case of raw water, with less concentration of As.

Natural oxides: Crushed hematite and feldspar can be used for adsorption of arsenic, in the particle size, range of 200 um; but the maximum capacity is only 2.6 umol/g.

There are some other plausible methods of separation of As in laboratory scale.

Reverse osmosis and nano-filtration: Efficiency may be as high as 95% in ideal situations, but water rejection is very high, 25-40%, and discharge of large volume of reject-water, with higher concentrations of As. This may pose a problem.

Electro dialysis reversal: Removal efficiency of As (V) crosses 80%, but As (III) can hardly be removed.

Table 6.1: Arsenic removal methods and their effectiveness (from Torrens, 1999)

Arsenic removal in drinking water: summary of available data

Treatment technology	Arsenic in (ppb)	Arsenic out (ppb)	% removal
Chemical precipitation			
Oxidation/iron co-precipitation	110	10-85	23-91
Oxidation/iron co-precipitation	200	80-200	0-60
Oxidation/iron co-precipitation	1100	<5	>99
Lime softening	220	30	86
Lime softening (pH>10.5)	75	<5	>95
Lime softening	100	<5	>95
Oxidation/iron co-precipitation	50	<5	>90
Oxidation/iron co-precipitation	21	<2	>90
Oxidation/iron co-precipitation	377	11	95

Adsorption			
Activated alumina	88	<50	>43
Activated alumina	103	<50	>51
Ion exchange	92	<50	>45
Ion exchange	103	<50	>51
Manganese green sand	110	6.8-37.7	64-94
Membrane separation			
Reverse osmosis	91	1	99
Electrodialysis	85	23	73
Reverse osmosis	260	2.6	99
Coagulation/micro-filtration	50	<5	>90

6.3 Future of Remediation Approaches

6.3.1 In-situ Treatment of Arsenic in Aquifer by Removing Dissolved Iron

There is wide-scale report of the presence of dissolved iron, in arsenic contaminated groundwater in many countries, and of co-precipitation of iron and arsenic under oxidizing condition. In the investigated region of Nadia District, West Bengal, it has been found that As correlates with Fe in groundwater both positively and negatively, depending upon the condition. This raises the hope of a plausible way of *in situ* remediation of the problem of As contamination by removal of Fe from groundwater before withdrawal.

In situ Fe removal has proved to be a viable technique for diminishing Fe concentration in groundwater. The technique involves a cyclic injection of oxygenated water, in which Fe and Mn concentrations are lower than in the native groundwater. It is applied in a number of European countries and in the US (Hallberg and Martinell, 1976; Rott et al. 1978; Booch and Barovich, 1981; Van Beek, 1983; Rott and Lamberta, 1993; Meyerhoff, 1996). The reaction involves the displacement of ferrous iron exchange and sorption sites and subsequent oxidation by oxygen. Clogging has not been observed and appears to be unimportant, by virtue of self-regulatory nature of Fe^2 exchange and sorption mechanism. (Appelo et al., 1999) Increasing oxygen concentration in injected water is useless, because efficiency is limited by exchangeable Fe2, capable of consuming the oxidant during the injection stage.

Quantification of the reaction mechanism allows assessment of operational conditions. The gross mechanism of *in situ* oxidation appears to be simple as a given amount of oxidant is injected and is consumed by reduced substances in the aquifer. The problem is how the dissolved oxidant, such as O_2, in injected water reaches the dissolved reductant, Fe^2, in groundwater, while the latter is being displaced during injection. The essence of *in situ* treatment is, in fact, the iron removal, and hence, arsenic removal, it continues even after the complete withdrawal of the injected water. The resulting ferric iron is highly insoluble and precipitates as an oxyhydroxide. It has been found that clogging does not occur, even in the case of systems, operating for more than 30 years. The lack of clogging suggests that precipitation takes place at a distance away from the well and possibly at varying locations in time.

In the aquifer, the fronts spread out due to dispersion and the combined effects of transport and reaction. When a new run is started with the injection of oxygenated water, the concentration of iron increases gradually in the well on pumping, and its efficiency depends on the limiting concentration of Fe^2. With each cycle 1000 cubic meter of oxygenated water may be injected and 7000 cubic meter pumped out. The ensuing runs show a delayed rise of iron concentration, in the pumped water. In other words, the efficiency increases with the number of runs. The efficiency can better be improved, by optimizing the well arrangement, for example, by installing separate injection and pumping wells, to prevent the last part of oxygenated water, being withdrawn without reaction.

Groundwater pH should be above 6 for in situ iron removal, because rapid decrease of oxidation rate of Fe^2 occurs when pH is below 6. Moreover, if the aquifer contains lot of sulphides, the oxidation acidifies the system. And aquifers should be as homogeneous as possible. And this should be without extremely coarse layers to prevent preferential flow of injected water, through the most permeable parts, which generally have low exchange capacity. Thus, planning for *in situ* remediation, with injection of oxygenated water (pH ~7.5), four times a year, is a plausible long lasting mitigation technique for decontamination of arsenic in groundwater.

Researchers in the Queens University, Belfast, claimed to have developed a low-cost technology, which offers chemical-free groundwater arsenic treatment technology to provide arsenic-free water to rural communities for drinking and farming needs. The technology is based on recharging a part of the groundwater, after aeration, into a subterranean aquifer (permeable rock), which is 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. Based on this concept, a trial plant in Kasimpore near Kolkata was planted and its performance was found satisfactory.

6.3.2 Limestone-based Arsenic Removal Methods

Experiments have been performed, using Limestone to remove arsenic from water. This approach is supported by previous research, regarding the removal of arsenic by the formation of calcium arsenate (Bothe and Brown, 1999). Mobilization of arsenic, from sediment, is most likely when the sediment is low in iron and calcium carbonate (Brannon and Patrick, 1987). A reasonable conclusion is that arsenic is immobilized in iron and/or calcium compounds. Work on arsenic-rich mine drainage and the subsequent decrease of arsenic content, down gradient from where discharges crossed limestone outcrops, indicated that limestone is a possible arsenic removal medium (Davis et al., 1999). Surface area of the limestone is a key parameter, controlling the efficiency of the process. The smaller grain sizes have provided a greater surface area per unit weight. Thus, better arsenic removal has been demonstrated.

The areas of major concern, regarding feasibility of a limestone-based arsenic removal process, are ionic interference, the stability and disposal of arsenic-saturated limestone, and the rate at which the process can treat water. Each of these concerns should be addressed. The process should be studied at the molecular level, regarding what compound is formed on or within the limestone. A better understanding of the entire process and the composition of the arsenic-rich limestone waste product would likely result from such a study. Perhaps a material, other than limestone, needs to be added to the process to enhance waste product stability. Based on previous research, iron oxide seems an appropriate choice. Other lime stones should be tested. A rock unit can contain various constituents and still qualify for classification as limestone. One of these minor constituents could greatly enhance the process. Various other natural waters should be used in upcoming work with a batch reactor. Chemical analyses of these natural waters should be done in an attempt to identify as to which ions preferentially interfere. Column experiments, using a constant flow rate, are needed. Understanding the flow mechanics of the process will be essential to the development of a prototype.

A prototype cartridge must be designed. Experimental data regarding mass adsorption ratios and necessary residence times, indicating an appropriate cartridge size and flow rate, would assist in the design of a prototype. The intent of any design should be to maximize the efficiency of the limestone-based arsenic removal process, with regard to both limestone mass and water volume or flow rate. This assumes the use of 58 smallest feasible limestone grain sizes. Cost and availability factors could affect that assumption. Initial experimental work has been successful in demonstrating the use of limestone to reduce the arsenic concentrations of a prepared standard solution. Prototype design and arsenic-rich limestone disposal must be addressed, before the ultimate feasibility of applying limestone-based arsenic removal systems, can be determined. Further work should focus on expanding the applications of the process, namely, to include removing arsenic from natural waters as well as standard solutions.

6.3.3 Remediation of Arsenic contaminated Soils by in situ Chemical Fixation

Subsurface soils, from several industrial facilities, are contaminated with arsenic because of the application of arsenic containing herbicide. Low cost *in situ* chemical fixation treatment is designed to react with contaminated soils directly, against the treatment solutions to cause the formation of insoluble arsenic-bearing phases, and thereby, decreases the environmental leachability of arsenic (Xang, Li *et al*). Combinations of ferrous sulfate, potassium permanganate and calcium carbonate are used as major reagents for the chemical fixation solutions. Sequential leaching, with an extraction fluid described in the EPA synthetic precipitation leaching procedure (SPLP), has been used to simulate the long-term leaching behavior of treated soils under natural conditions. The results indicate that the fixation solution, with only ferrous sulfate, have the best effect among all the reagent combinations, reducing SPLP-leachable arsenic by as much as 90%.

A modified 4-step sequential extraction procedure can be used to further study the chemical fractionation of soil **As**, before and after chemical treatment. Sequential extraction data would likely show that the soil treatment has greatly reduced the most readily labile portion of arsenic which is extracted in the 1st step of the sequential extraction, with its value lowered to less than one tenth than that of untreated soil. The potentially mobile fraction of soil arsenic, extracted in the 2nd step of the sequential extraction, is also considerably smaller. It is shown that after treatment; most of the As in the soil is transferred to amorphous Fe oxyhydroxides which are the major phases extracted in the 3rd step. X-ray absorption near edge spectra show As is present as As (V) in the treated soil. Extended X-ray absorption fine structure (EXAFS) spectral analysis indicates that a large portion of the total soil arsenic is co-precipitated and incorporated into newly formed amorphous Fe oxides after treatment.

6.4 Experiences during Arsenic Removal Technology Evaluation in Technology Park

School of Fundamental Research has been entrusted to conceptualize, execute and manage the evaluation programme of Arsenic Removal Technologies, using an Arsenic Technology Park during August 2001 to September 2003. It has gained some knowledge about the problems and genesis of arsenic mitigation in dynamic field conditions. Some of which are mentioned below.

(i) **Tube-well:** The probable scenario has been in operation for more than a decade, with most of the tube-wells, which have been selected, based on their contamination level, and has practically concluded their critical life span. These have been found to be the same in all cases. Re-sinking of all the tube wells, due to sudden heavy drawl of water, becomes a necessity.

Since most of the lift pumps are used to pump water for gravitational drawdown through the media column natural system, resistance seems to affect the performance of the tube wells, which are otherwise meant for free lifting of water without any resistance in the path. Thus, difference in pull-push process interaction within the tube well generates a resultant back-pressure. Continuous over use disturbs the performance of the lift pumps as well as creates an impact on the interface mechanism. It is one of the critical issues that seem to affect the overall performance of ARPs.

(ii) **Fluctuation:** Some of the major issues for fluctuation are high level of arsenic fluctuation in raw water in subsequent weeks, fine silvery colloidal sand, pollution due to unstabilised sub-surface condition and old under-used tube-wells. They have created many initial problems for the technology park programme and are a common scenario in most of the sites in lower deltaic region. Operation and maintenance have, thus, become quite a difficult task for obvious reasons. Erratic behaviour of arsenic, in raw water, is quite baffling as observed in each week and even on daily fixed time study. The fluctuation ranges from 11% to 35.6%, as observed. Some units tend to increase the pH and conductivity in the filtered water. Some units also show increase in hardness in the filtered water. All are capable of lowering Iron to permissible level. Backwashing is quite a regular feature for all the units. The suppliers of devices shall have to take note of the high level of arsenic fluctuation and *in situ* sub-soil condition for future device making as they seem to affect and alter the performance of media in both short term and long term interest.

(iii) **As (III) & As (V) speciation:** Although it is generally felt that As (V) is better removed in the adsorption approach, for which in the design concept of most of the ARPs a primary oxidizing-interface for converting As(III) species to pentavalent status is ensured. The speciation studies have observed that all the As (III) species, present in the raw water, get converted or removed through the media interface. This may not be essentially true for the removal or adsorption in the process for As (V). In fact, whatever Arsenic remains after filtration is of As (V) species. Besides, it is to be noted, with interest, that this phenomenon is also repeated with even non-oxidant interface like the units with only Activated Alumina. One of such units has been installed by Oxide India.

(iv) **Sludge:** 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.

(v) **Operation & Maintenance:** The maintenance of the systems requires double attention for the ARPs and the tube wells. Majority of the operation and maintenance issues are related to tube wells, that have nothing to do with the ARP or its chemical media. In the resultant scenario, whole programme of operation and maintenance shall continue to suffer till design changes are ensured for the lift pumps. This can be done by releasing the back pressure through an outlet before it can exert cumulative pressure on the inlet valve.

In fact, 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 programme can be envisaged. This aspect holds good for the best performing devices too.

(vi) **People's Participation:** In a scenario, rural community has come to believe that getting free water is their fundamental right and getting pipe supply water at the door step is a matter of priority expectations. This poses serious concerns to planners of community based systems in maintenance and fund mobilization for the upkeep of the facilities at the time of media replacement. A fundamental change in community perception can only ensure the success of these endeavors. Although it will continue to suffer but the chances of getting *free* water from governmental agencies are still quite bright. *By executing the programme of establishing the Technology Park and evaluating the critical performance parameters, it was understood that beyond fund mobilization through motivation, the community participation, in a programme of high technical na ture, requires continuous physical involvement of manufac turers' representative at site, otherwise quality of filtered water cannot be ensured. This matter needs to be appreciated in reality.*

(vii) ***Sludge Treatment :*** 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. In this way a large amount of slurry is obtained in concentrated form for treatment.

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.

6.5 Alternate approach for ensuring supply of arsenic-free water

It is important to note that in most of the areas, the arsenic contaminated zone is at the shallow/intermediate depth ranged largely between 20m and 50m. The groundwater in deeper aquifer ≥ 100 m has been reported arsenic-free, and has potential prospect of tapping. Though our studies at School of Fundamental Research in Nadia district showed tube wells up to 250 meters are affected. In alluvial formations, possibility of having confined aquifer is a chance phenomenon, and if at all, it would be on a very limited local scale. The aquifers are normally of unconfined to semi-confined types. Therefore, threat of downward mobilization of arsenic, from shallow to deeper zones over the years always, prevails. Further, the source being *in-situ* at localized pockets, a large part in a spatially distributed groundwater domain has uncontaminated groundwater reserves, which may not be under the influence of arsenic groundwater mobilization due to some obvious chemical portioning leading to self-purging, etc.. Areas barring large scale fluvial deposits, accumulated formations of clays, shifted river courses, already exposed by arsenic mobilization, etc. are normally expected to have uncontaminated reserves or accumulations. Modeling studies of arsenic contamination transport by various researchers showed that judicious and scientific management of fresh zones of aquifer, both shallow and deep, can sustain withdrawal of fresh groundwater resources for a long period without much aggravation of arsenic contaminated zones. For identification and design of safe locations of groundwater withdrawal, wells modeling studies can be the right tool. The caution that one has to take is analysis of post groundwater development scenarios, particularly with respect to transformed groundwater direction and movement.

Watershed is considered to be the basic unit of land-water management practices. From hydrological point of view, watershed possesses all characteristics generally required for conservation and development of water resources. Surface water is arsenic-free, and it is more so when rainwater is harvested as surface storage. Harnessing, developing and appropriate management of surface water, on a watershed basis, in arsenic affected areas and their usages in irrigation and other domestic purposes, can be a potential alternative. This can be noted that the major application of watershed based approaches and harnessing surface was not a traditional practice in alluvial tracts in Bengal, - major part of which is scourged with Arsenic contamination. On the contrary, in the western part of Bengal and mostly in drier zones and hard rock areas, use of surface water, was a natural option and practice.

Supply and usage of surface water exclusive from other sources, particularly due to distributive rain fall pattern, are no doubt a viable alternative, when availability of water from the source is assured and sustainable. The demand management of some areas from resources of other areas is linked to certainty of many factors. Creation of alternate surface water system may involve considerable money. Conjunctive use of surface water (either from watershed development or from other sources) and *in-situ* groundwater can be another potential alternative. A technical feasibility study, considering risk, cost and benefit of each alternative, would form an important task.

Whatever technological options we adopt, the success and effectiveness of that task can not be achieved unless end-users and beneficiaries of the schemes are debugged from concern and responsibility. No strategic planning of availability of safe and wise use of water can be sustained by delinking user community and their effective participation in the management of traditional and new resources. Obviously, for the success of the program, people's awareness, regarding importance of water, its know-how on 'dos and don'ts and rightful uses, need to be tagged as a mandatory task.

6.6 Summary

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 Godwana 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. 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. It appears that the reductants and oxidants were transported / accumulated / diagenetically precipitated components of the process of build-up of the sediment sequence of the delta. The oscillations owe their origin either to resetting of oxidants / reductants as a result of diffusion-dispersion-flux, or combined with, initial variation of As-Fe contents of the solid phases in the aquifer sediments.

It is also to be understood that the arsenic contamination of groundwater in the 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.

A variety 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.

Chapter - 7

Work Ahead: Critical Concerns and Key Challenges

7.1 Unfinished Agenda

Arsenic was first detected in India in the early 80s, in a village in West Bengal, where some of the villagers developed symptoms of Arsenicosis and skin pigmentations. At that time, the cause for sickness and symptoms were not known to the medical professionals. Neither the Public Health Engineers nor the community water supply sector professionals were aware of the danger posed by such a serious chemical contaminant as Arsenic. There was absence of even the rudimentary facilities of water quality monitoring and surveillance in the rural areas of the country at that time. The people continued drinking arsenic contaminated water for years, got sick and hospitalized and then only the cause and source of water contamination was identified. Since then, during the last three decades, substantial amount of work has been done to enrich our knowledge in respect of the following.

(i) *The source and cause of Arsenic contamination of ground water.*
(ii) *Extent and magnitude of the same.*
(iii) *Mechanism of dissolution of Arsenic from soil to ground water.*
(iv) *Impact on Community Health: Diagnosis of sickness and symptoms.*
(v) *Development of technologies for removal of arsenic from ground water.*
(vi) *Analytical techniques for detecting arsenic from ground water.*

It is needless to say that a comprehensive understanding of the above aspects would go a long way in developing immediate, interim and long term strategy, to address the problem. The first decade, that is, the 80s, when the arsenic problem was first detected, was conspicuous by slow response of the administration in identifying the problem and assessing the extent and magnitude of the same. The R&D studies, water quality monitoring and epidemiological assessment, were all too inadequate to measure up the situation. Till date, except the state of West Bengal, no other states in India, and a very few countries, 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. The basic agenda is of ensuring a sustainable and affordable supply of arsenic free water to all segments of community, in the geographical areas, where concentration of arsenic in ground water is high and above permissible limit. This agenda still remains largely unfinished in most of the countries. In the next few paragraphs in this chapter, we will discuss the current knowledge gaps, critical concerns and key challenges, facing the country and also the factors which are impeding the progress of mitigatory programmes.

7.2 Critical Concerns

The National Governments in many of the Asian countries, affected by high Arsenic in groundwater, are trying to meet the challenges with varying degrees of success. The primary task of providing Arsenic safe water to millions of people needs to address the following critical concerns.

- Water quality monitoring
  - * *District & Block level Capacity Building.*
- Identification of Arsenic contaminated as well as safe sources: both public & private
- Provision of alternate sources of Arsenic free safe drinking water.
- Village specific GIS Database and Action Plan and sharing the same with all stakeholders.
- Establishing a transparent system of information sharing by all stakeholders
  - * *Health Education.*
  - * *Awareness Generation.*
- Health Risk Assessment and estimation of disease burden :
- Provision of Medical Relief for the critically affected people :
  - * *Training of Medical Practioners in Govt, as well as outside the same.*
- Long-term change in agriculture and Irrigation practice:
  - * *Restricting the use of Groundwater.*

7.2.1 National Standard for Arsenic in Drinking Water

In addressing the key-concerns and developing a National Plan of Action, for providing Arsenic safe water to the community, the 1st key-step is to establish a National Standard for Arsenic in Drinking Water.

The WHO is helping the countries in developing their own national standards. The present guideline value of Arsenic in groundwater of WHO is 10ppb, but as could be seen below in the table, many countries are still adhering to the standard of 50 ppb of Arsenic.

Country standard for Arsenic in Ground water

Countries	Standard Mg/L	Countries	Standards Mg/L
Australia	0.007	Bolivia (1997)	0.05
European Union (1998)	0.01	China	0.05
Japan (1993)	0.01	Egypt (1995)	0.05

Jordan (1991)	0.01	India	0.05
Laos (1999)	0.01	Indonesia (1990)	0.05
Mongolia (1998)	0.01	Oman	0.05
Namibia	0.01	Mexico	0.05
Syria (1994)	0.01	Philippines (1978)	0.05
USA (2001)	0.01	Saudi Arabia	0.05
Canada	0.025	Sri Lanka (1983)	0.05
Bahrain	0.05	Vietnam (1998)	0.05
Bangladesh (1997)	0.05	Zimbabwe	0.05

In setting national Standard for Water Quality parameter like Arsenic, Fluoride etc, the National Govts. need to consider various issues related to the social, cultural, health and other benefits related to the standard and the cost of compliance of the same. The table below depicts a case study for Bangladesh. The situation in Indian states, particularly, West Bengal is similar and the cost of implementing a higher standard is of the same order.

Estimated Health benefit and costs of compliance of present Bangladesh standard and WHO GV for arsenic in drinking water

Arsenic Level in Drinking Water	**Present Level**	**<50 μg/L.**	**<10 μg/L.**
Total Risk of Skin Cancer	377,000	55,000	15,000
Percent of population	0.290	0.042	0.012
No. of TWS to be abandoned	-	2.0 million	3.5 million
Cost of abandoned TWs (Taka)	-	9.1 billion	15.5 billion
Cost of alternative water supply (Taka)	-	12 billion	24 billion
Cost of monitoring remaining safe tube wells (Taka/year)		170 million	800 million

Note: Assumptions, No. of shallow tube well = 7.5 million; cost of a shallow tube well=4,500.
Source; Prof. F. Ahmed, BUET, Dacca

But the above case study is based on the EPA model, which as stated earlier, possibly over estimates the health risk associated with Arsenic. As a matter of fact, many Health Scientists in India, China and Bangladesh, believe that the additional health benefit of lowering the standard from 50 ppb to 10 ppb, would be marginal and does not justify the huge expenditure required. On the other hand, many health scientists strongly feel that standard should be strictly based on health risk and no compromise should be made on economic consideration.

It is, therefore, recommended that the standard for water purification units, the standard of Arsenic in treated water should be 10 ppb. But the threshold value for rejection of a water source could continue to be 50 ppb for sometime. BIS and the Dept. of Consumer Affairs should take an unequivocal stand in this matter.

7.2.2 Identification of Contaminated Sources and Creation of District, Block and Village Level Databases: Key Challenges

In West Bengal, all public tube wells have been tested through a net work of rural laboratories. Near about 150,000 water samples have been analyzed in the block level laboratories. And GIS Database has been created at the district, block and habitation level. However, the most challenging task, which is yet to be accomplished, is the testing of near about 500,000 private sources. Adding to the menace, the identification of contaminated public tube wells remains incomplete in other states like Bihar, UP, Jharkhand, Chhattisgarh, Assam etc. Though organizations, like SOES, Jadavpur University, Sriram Institute and quite a few others have done remarkable work, the basic task of identifying all arsenic contaminated sources, public as well as private, remains largely incomplete. If we consider the tube wells' use for irrigating and vegetable plants, in the arsenic affected districts, the task becomes more difficult and complex.

7.2.2.1 Field Testing Kit vis-à-vis Network of Laboratory

The magnitude of the tasks involved raises the question of use of field kits vis-à-vis creation of network of block/village level laboratories. In West Bengal, considering the risk of false positive and false negative data, by the use of field test kits, the Arsenic Task Force opted for creation of a network of rural laboratories, at the rate of one laboratory for every three blocks, through Public Private Partnership. As a matter of fact, the Arsenic crisis in West Bengal has been a blessing in disguise, in the sense that it has resulted in development of institution and capacity, at the block and village level Panchayatiraj organizations, for water quality monitoring and surveillance.

It must, however, be noted that though the above system has been successful in monitoring public sources, the big question remains on the monitoring of water quality of the private sources. In Bangladesh, a community based approach, using field kits, has created a very large database covering both public and private sources. However, the precision and dependability of the same is always open to question. The challenge is to produce field test kits, which are robust, reliable, cheap and simple enough to be used by relatively unskilled users in the villages of India and Bangladesh. It is also imperative to say tat these field kits and supplies should be readily available for the rural markets. Misclassification of arsenic contaminated drinking water sources is a real risk, considering the large number of wells, having arsenic concentrations close to the existing national drinking water standard. However, giving the private well owners full information, about the test result of his well, will alert them to a considerable degree, regarding the contamination of their water supply. This will also enable them to make their own decisions regarding the use of the tube wells, owned by them.

7.2.3 Provision of Arsenic Safe Water to the Community: The Key Challenge of Sustainability

In West Bengal, the Master Plan envisages supply of arsenic safe water, to all the affected habitations, through a system of piped water supply, which would be fed from treatment plants after appropriate treatments. 40% of the villages would be supplied from mega water treatment plants, drawing water from large perennial rivers like the Ganga. They would supply water through kilometers of water distribution system after appropriate treatment for bacteriological purification. 60% of the villages would be served by mini-piped water supply network, which would be fed from large diameter tube wells after removing arsenic by using appropriate technology. This is the most ambitious long term mitigatory programme undertaken by any State Govt. for the arsenic affected rural community. The implementation of the master plan is expected to be completed by 2011. But the progress of work indicates delay in project execution. The more vital question that remains to be answered is that, whether such a capital intensive approach could be sustainable in the long run. Effected operation and maintenance of the system, through people's participation in cost sharing and maintenance, could go a long way in ensuring sustainability. The success of West Bengal experience could set a model for nation wide replication. However, to make a community based scheme sustainable, the Govt. effort needs to be supplemented. These efforts can be community based approaches through the implementation of decentralized small scale community maintained rural water supply projects, based on traditional surface water sources, that are largely supported by rain water harvesting. There are millions of traditional surface water sources like ponds and dighis in states, like West Bengal, Bihar, UP, Jharkhand, Chhattisgarh, Assam etc, which could be rejuvenated, conserved and utilized.

7.3 Existing Knowledge Gaps

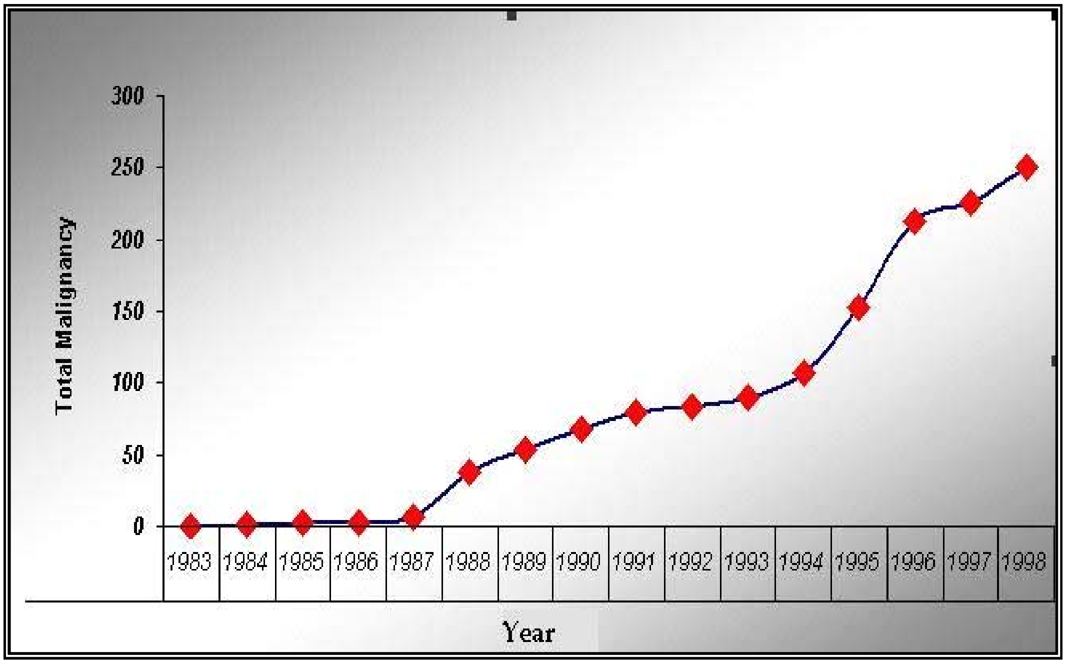
7.3.1 Health Impact: Scientific Health Risk Assessment and Rational Estimation of Disease Burden

Though near about 30 million people are living in the hydrogeologically risk zones (79 affected rural blocks and 12 urban communities) in West Bengal and substantial population in Jharkhand, Bihar, Chhattisgarh, Uttar Pradesh and Assam, the exact number of people, drinking arsenic contaminated water and suffering from Arsenicosis, is yet to be established scientifically and epidemiologically. Considerable confusion and contradiction persists in this matter. While the official statistics of the Dept. of Health, Govt. of West Bengal, reports Arsenic related disease burden to be <15000, unofficial sources put the same between 200,000 to 300,000. The impact and symptoms of arsenic contamination differ in severity between individuals, population groups and geographical areas. The severity and manifestation of symptoms also depend upon the concentration of arsenic in water, the daily average intake, overall health and nutritional level of the person and many other factors. This makes assessment of the burden on an individual's health on account of arsenic consumption a complex exercise. A scientific epidemiological assessment of the extent and magnitude of the problem is yet to be made. High concentrations of arsenic in community water sources do not always co-relate with high levels of Arsenicosis symptoms in the community. According to a multistage model, applied by EPA to estimate life-time risk of skin cancer (based on an Epidemiological study in Taiwan), WHO guideline value of 10 ppb Arsenic in drinking water is associated with a life time excess skin cancer risk of 6 per 10,000 people. The same for the National Standards 50 ppb, followed in India, Bangladesh and many other Asian countries, is 29 per 10,000 people (0.29%).

Estimated incidence of excess lifetime skin cancer in Bangladesh

Source; Prof. F. Ahmed, BUET, Dacca

It appears that the model over estimates the actual risk of skin cancer than it actually exists. This over estimation could be due to the conservative assumptions made in the model. Melanosis and Keratosis are considered as 1st & 2nd stages of Arsenicosis, which may turn into skin cancer if Arsenic ingestion continues. The primary identification of Arsenicosis is generally diagnosed by the visible symptoms of Arsenic related skin lesions. In Bangladesh, health surveys have been conducted in 58 upazilas covering about 12% of the population. The prevalence of Arsenical skin lesions has been found to be 0.086%, which is much lower than the estimated excess skin cancer risk at the present level of contamination in the country. The data of the health survey also presents a rather poor relationship between prevalence of Arsenical skin lesions and average Arsenic content in the tube well water. Limited information is available, regarding the disease burden due to arsenicosis in West Bengal. In an epidemiological survey carried out by Dr. Guha, Majumdar et al (1998), in one of the affected districts of West Bengal (South 24 Parganas), where 7683 people were examined in 57 arsenic affected villages, the prevalence of arsenical skin lesion was found to be 4.6%. Further, Saha (2003) reported the incidence of arsenic related cancer to be 5.1%, among 4865 cases of arsenicosis examination, during the period of 1983 to 2000. However, the data of the former study represents information in a highly exposed region of the state, while the later data were compiled from cases, examined in a tertiary referral centre and some scattered survey, carried out in the affected districts of the state.



(Source: Dr. K.C. Saha, Ex-Prof. of Dermatology, School of Tropical Medicine, Calcutta)

Figure 7.1: Increasing malignancy due to Arsenic contamination in West Bengal

Existing situations suggest that considerable knowledge gap exists, in respect of Health Impact of Arsenic contamination of groundwater in India. Dept. of Health & Indian Council of Medical Research should consider undertaking an Epidemiological Survey in all the affected states, with adequate sample size to find out the prevalence of Arsenicosis among the affected population and correlate the same, if possible with the Arsenic concentration in the well water. More effective collaboration and co-ordination is necessary between the Departments. of Health, Panchayat & Rural Development, Public Health Engineering to assess the health risk, associated with Arsenic in groundwater and plan mitigatory measures.

7.3.2 Arsenic Contamination in Agriculture: A Threat to Water - Soil- Crop - Animal - Human Continuum

Efforts are being aimed at ensuring safe drinking-water, either through mitigation techniques or through finding alternative sources of water. Even if supply of an arsenic-free drinking-water is ensured, arsenic-contaminated groundwater will continue to be used for irrigation purposes, posing a significant risk of this toxic element accumulating in the soil and, consequently, entering into the food-chain through plant uptake and consumption by animals and humans. Thirty to forty percent net cultivable land is under irrigation, and more than 60% of this irrigation is met from groundwater. Thus, the risk of arsenic-contaminated water, being used, is high.

During the past 10 years, researchers have mainly focused on ingestion of arsenic through contaminated drinking-water, but the incidence of Arsenicosis, in the population, is not consistent with the concentration of arsenic in drinking-water, obtained from groundwater. The figure below depicts the findings of a study in Bangladesh, which highlights the lack of correlation between the arsenic concentration in tube well water and arsenic related skin lesions, amongst the population using the same.

Figure 7.2: Relationship between arsenical skin lesion and average arsenic content in drinking water.

This inconsistency has raised questions on potential pathways of ingestion of arsenic. According to Dr. F. Ahmed of BUET, Bangladesh, while there is a very weak relationship between the number of patients and the average arsenic content in drinking-water at a local level, there is a stronger relationship at the regional level. These findings are consistent with observations of many researchers that people using water from the same source are not equally affected and that people from the same household ingesting water from a common tube well may not be equally affected.

The observed clinical symptoms of arsenic toxicity vary significantly, which poses a challenge in relating the potential pathways of transfer of arsenic from groundwater to human metabolic system through food-chain. Although there may be several other factors involved in the relationship between ingestion of arsenic and epidemiology of arsenicosis, the significance of groundwater-arsenic ingested through the food route is not adequately shown. Along with intake of food, it is also possible that incidental ingestion and inhalation of dust containing arsenic may be a significant pathway of exposure, particularly for the rural community and agricultural workers.

Present knowledge about the impact of use of arsenic contaminated water for agricultural practices is rather scanty. A WHO supported study by the Bidhan Chandra Agricultural University in West Bengal, on a limited scale, arrived at the following findings.

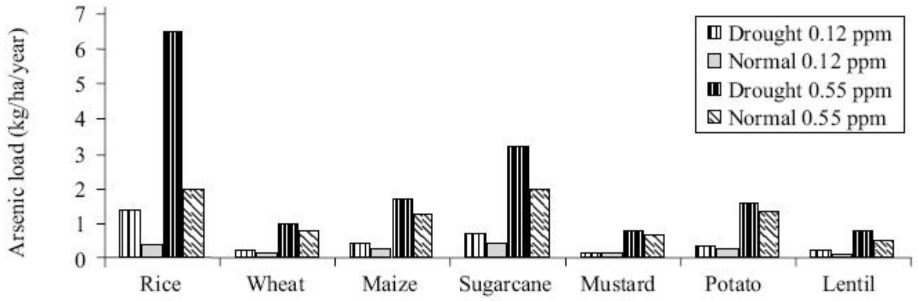
i. *The total arsenic loading of groundwater (used for irrigation) varied from 0.10 to 0.59 mg* L^{-1}.

ii. *The total and extractable arsenic content of soils varied from 2.56 to 16.87 and 1.08 to 9.30 mg* kg^{-1} *respectively.*

iii. *Average arsenic loading in grains and other edible parts of pre-kharif rice, pulses, oilseeds, vegetables and fruits under study were 2.66, 3.13, 2.01, 19.39 and 10.20 mg* kg^{-1}*, respectively.*

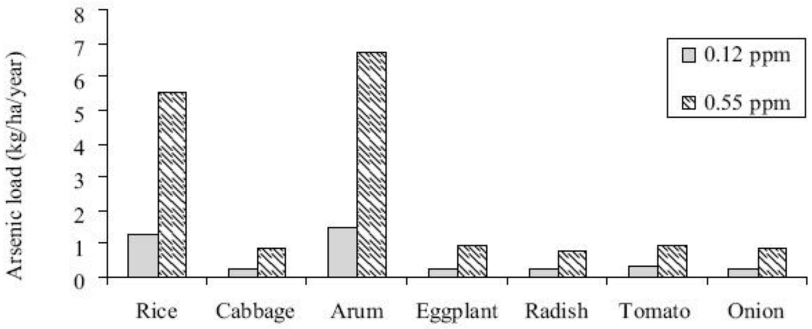
Another study, carried out by Bangladesh Agricultural Research Council, indicated that concentration of Arsenic in water, used for irrigation, varied from 0.136 to 0.55 mg/l and the total loading of Arsenic in irrigated soils for Boro rice that requires 1000 mm of irrigation water per season, ranged from 1.36 to 5.5 kg/hectare/year. Similarly, for winter wheat that requires 150mm irrigation water per season, loading of arsenic from irrigation ranged from 0.12 to 0.82 kg/hectare/year. The figures below depict arsenic load from irrigation water for rice and some other cash crops and also the dynamics for arsenic transfer through water soil crop root.

Arsenic load from irrigation-water for some cash crops



Irrigation data obtained from Bangladesh Agricultural Research Council
Arsenic in water from laboratory analysis

Arsenic load from irrigation water for some crops compared to that for rice



Irrigation data obtained from Bangladesh Agricultural Research Council
Arsenic in water from laboratory analysis

From the findings of the above two studies, it is difficult to assess adequately the phototoxic impact of use of arsenic contaminated groundwater and the dietary impact of the same on human health. More elaborate studies are required to adequately assess the situation and formulate policies and practices for agricultural methods and selection of crops in arsenic affected areas.

7.4 Critical Needs for Research and Capacity Building

A careful analysis of the present situation, in respect of arsenic contamination in groundwater, in various states in India, would lead us to the inevitable conclusion that while lot of information and knowledge has been generated through large number of research studies, the findings of the same have not been consolidated in a replicable model to address the sufferings of the people. To sum up, the critical needs for further research and human resource development, the following areas need to be addressed on a priority basis.

i. A scientific and epidemiological assessment of the health impact and disease burden and identification of hot spots for prioritizing action plan.

ii. Consolidation of the knowledge regarding arsenic removal technologies, indigenous as well as imported, and development of designs for appropriately scaled up models for community supply systems and developing a national policy on technology options.

iii. Developing a robust, simple and user friendly, yet scientifically precise and sensitive device for field test kits, which could be used by the community for testing millions of private sources in the country

iv. Studies should be undertaken urgently to asses the impact of arsenic in agricultural and irrigation water and the transportation of the same in the plant and food chain.

v. Capacity building and skill development in the Panchayatiraj organizations in the district, block and habitation level and also in the NGOs and civil society organizations for quality monitoring and surveillance as well as mitigatory actions in support of the Govt. programmes.

vi. Long term change in agriculture and irrigation practice: Restricting the use of groundwater.

7.5 Technology Options: Critical Constraints and limiting factors

Based on the experiences in countries like India, China, Bangladesh etc, the following are the major technology options for providing Arsenic safe water in the affected areas.

- Tapping ground water from alternate arsenic-free aquifers at a higher depth and proper sealing-off of the arsenic bearing aquifer from the same. (>100m).
- Large scale piped water supply for the rural communities by drawing water from the rivers and treating them for removal of pathogenic microbes.
- Conservation and quality up gradation of traditional surface water sources like ponds, dug-wells etc. in the villages. These sources are generally free from Arsenic but grossly contaminated with fecal pollution.
- Removing arsenic from the ground water, by using technologies like, adsorption (activated alumina/Iron oxide), co-precipitation (oxidation, coagulation & filtration) or ion exchange. These technologies could be applied in community plants attached to hand pump tube-wells or large dia tube-wells. Otherwise domestic filters could also be developed on the basis of these technologies.

Of various options stated, Tapping of Arsenic free aquifers is restricted by the absence of clay barrier between the upper arseniferrous aquifer and the deeper Arsenic free aquifers, as has been found in parts of West Bengal, India. In some places, the water bearing aquifer is restricted to 80 to 90 m only, due to presence of hard rock beneath the same. The use of Arsenic Treatment Units fitted to hand pumps, are also facing the problem of sustainability because of the problem of operation & maintenance. A community based system of O&M, and active participation and cost sharing by the people, are essential for these to be successful. So far as domestic units are concerned, experience suggests low acceptability by the people. Considering that in the long run, use of ground water must be restricted in the Arsenic affected areas. The most appropriate technology option, for countries with high annual rainfall and large perennial surface water sources, appears to be the surface water based piped water supply systems. However, it is also the most capital intensive among all the options. Sustainability of such systems would be assured by people's participation in the operation and maintenance & cost sharing.

7.6 Key Factors Impeding the Progress of Mitigatory Programmes in the Arsenic Affected States.

Given the experience, in the developing countries of Asia, where Arsenic in groundwater is posing a great challenge to the health of a large number of people, the following could be mentioned as the major factors impeding the progress of the projects to address the problem.

- *Gap between the perceived need of the people and approach of the implementing agencies.*

- *Long period of completion for large capital-intensive government project / lack of interim relief.*
- *In general, rural populations are largely unaware of the technologies developed by various institutions and organizations due to poor promotional activities.*
- *Lack of knowledge among the people regarding the health impact of the arsenic problem.*
- *Lack of facilities at the grass root level for water quality monitoring.*
- *Lack of a transparent system of information sharing between all stakeholders.*

7.7 Establishing a Transparent System of Information sharing by all Stakeholders

There is an urgent need for awareness generation among the people regarding the problem and efforts undertaken by the Government and agencies in alleviating people's suffering. The people and Media must have easy access to scientific information. But under no circumstances scientific information should be used for creating unnecessary panic among the people. With a significant proportion of the population of India and Bangladesh, in extreme social and economic deprivation, competing environmental Health Risk exists in the society. Without diluting the gravity of the situation, it must be emphasized that we need to be objective and realistic in making political and economic decisions in relation to the current problem of Arsenic or Fluoride Contamination of Ground Water and people should have the opportunity of an in formed choice of options, through a transparent system of information sharing.

Chapter- 8

Roadmap for Achieving Envisaged Targets

8.1 Important Milestones

Milestones are the events, which are envisaged as future course of actions to achieve the targeted goals. The targeted goals in this case are: (a) to make arsenic contaminated aquifers conducive to preserve groundwater quality and produce arsenic free groundwater to meet drinking and irrigation demands, (b) to find sustainable techniques and technologies for decontamination of aquifers from arsenic and for the removal of arsenic from contaminated water, (c) to scale up scope for unveiling alternate sources of water to meet the demand of potable water in the arsenic affected and vulnerable areas, (d) to eradicate health hazards, originating from ingestion of arsenic contaminated water, and (e) to make society responsive to unconscious usages of water. The milestones to achieve the above goals, as emerged from the chapter- 7: 'Work Ahead: Critical Concerns and Key Challenges,' can broadly be categorized as: (i) R & D work to be undertaken to reach at logical solutions to the arsenic calamity, (ii) immediate measures to provide arsenic free potable water to the people in the arsenic vulnerable areas, and (iii) activities to be undertaken for Capacity Building and Social Empowerment, and (iv) revisit to revise the National Standard for Arsenic in drinking water. The details of these envisaged tasks are as follows:

(i) **Emerging R & D Activities -** 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.

(ii) **Ensuring Arsenic Free Water-** activities and plan of actions to provide arsenic free drinking water to the people in affected and vulnerable areas,

(iii) **Capacity Building and Social Empowerment -** activities to promote public awareness, capacity building and social empowerment about importance of water and its effective usages, health related issues, ill-effects of using contaminated water, etc.

(iv) **Revisit to revise National Standard for Arsenic in drinking water:** to consider revision of the National Standard for Arsenic in drinking water in the light of the WHO's present guidelines.

8.1.1 Emerging R & D Activities

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

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

Although there are some commonly accepted hypotheses, explaining occurrences and mechanisms of arsenic in groundwater, however, causes, sources of parental materials including their geo-chemical behaviors and processes in different hydro-geological settings and speciation are still to be established. Techniques and technologies, available globally and indigenously, for arsenic removal mostly, deal with ex-situ arsenic removal methods i.e., removal of arsenic from contaminated water after it is taken out from contaminated aquifers. 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 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. Further, a variety of ex-situ treatment technologies, which are mainly based on oxidation, co-precipitation, adsorption, ion-exchange and membrane process, have their own merits and limitations, and are mostly found unwarranted; in terms of efficiency, operation and maintenance, applicability/appropriateness of the technologies. The main disadvantages associated with those are: (i) they produce large amounts of toxic sludge, which needs further treatment before disposal into the environment, and (ii) they lack in proper operation and maintenance policy guidelines. In addition to those, the treatment devices, in many cases, are not economically viable and socially acceptable. 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.

Recognizing the above needs and their importance, following three categorizes of R & D programmes are proposed to pursue simultaneously to achieve the goal against groundwater arsenic menace; these are: (i) Laboratory scale R & D programmes, (ii) Field level R & D programmes, and (iii) evolving strategies to translate the techniques and technologies to the benefit of the society. The laboratory scale R & Ds should aim at developing eco-friendly and economically viable arsenic removal treatment techniques, species identification and knowledgebase generation; while the field level R & D programmes should aim at developing appropriate methodologies for decontamination of aquifer from arsenic by improvising understanding of geo-chemical behavior, processes and mechanisms of mobilization, source identification, monitoring and mapping, management of aquifer. The third type of R & Ds could aim at developing strategies as to how techniques and technologies can be translated to the society for their acceptability and sustainability.

The detailed outlining of the three categories of R & D activities are illustrated in subsequent section:

(i) Laboratory scale R & Ds

The objectives of the laboratory R & D activities should primarily be to improve knowledgebase on physicochemical characteristics and behaviors of arsenic both in aqueous and solid phases, when it transforms from one condition to another by the attribution of other chemical constituents and to identify effective methods for removal/dissociation of arsenic from arsenic contaminated water or development of cost-effective and eco-friendly arsenic removal filters.

The laboratory based R &D activities could thus be focused on the following key areas:

- Identifying most promising arsenic removal devices among the existing techniques *(such as, Granular Ferric Hydroxide (GFH) of Pal Trockner (P) Ltd., Kolkata - a German Technology; Arsenic Removal Plant by Oxide India (Catalysts) Pvt. Ltd, Durgapur; and Apyron Arsenic Treatment Units by Apyron Technologies (P) Ltd. Representing of Apyron Technologies Inc., USA)* and improvising their defeats to make those eco-friendly, low-cost, efficient and socially acceptable;
- Developing alternate innovative eco-friendly, low-cost, efficient arsenic removal techniques & technologies;
- Study of behavior of arsenic with Fe, Mn, Ca, Mg, and bicarbonates and finding their characteristic behaviors for different physicochemical conditions;
- Development of eco-friendly and innovative methods for arsenic sludge treatment & management;
- Arsenic speciation and characterizing their environmental hazards under different hydrological, environmental, and ecological conditions; and translating scientific knowledgebase to resolve field problems;
- Laboratory analysis of samples to detect arsenic concentration, chemical compositions, characteristic behaviors, reaction and sorption kinetics, etc.
- Development of field kits, which are robust, reliable, cheap and simple enough to be used by relatively unskilled users in the villages.

(ii) Field level R & Ds

The primary objectives of the field level R & Ds should be to devise mechanisms and methods for remedy of contaminated aquifers from arsenic; to devise optimal aquifer management strategies; to explore possibility of developing alternate water management strategies in the arsenic affected areas; to study the effect of arsenic in food chains and on human health; to study the social responses and societal impact on groundwater arsenic contamination, etc.

The field level R & D activities could be in the following key areas:

- Diagnosis survey of the arsenic vulnerable areas and preparing thematic maps on GIS environs showing arsenic affected, arsenic vulnerable and freshwater zones;
- Delineation of arsenic free aquifers including deeper aquifers; and assessment of their yields and potential to tap, including preparation of thematic maps on GIS environs ;
- Detection of genesis of arsenic in Ganga-Brahmaputra flood plains and finding reasons of large scale activation in Holocene aquifers;
- Improving understanding of sorption kinetics of arsenic both in solid and water phases for different physicochemical and geo-chemical conditions, dissolution and reduction potential of arsenic in different state-of-affairs chemical composition and enhancing knowledgebase on arsenic mobilization processes under different hydro-geological settings;
- Development of appropriate sustainable in-situ remedial techniques employing innovative ideas/techniques including phyto-remediation and bioremediation;
- Modeling studies to evolve sound aquifer management strategies including arrest spreading, harness fresh aquifer zones, study of movement of arsenic in aquifers for different stresses in the groundwater domain, etc.;
- Evolving alternate water management strategies in arsenic vulnerable areas to meet demand of irrigation water requirement including feasibility studies for adaptation;
- Impact of fertilizers and pesticides infiltration to the arsenic contaminated aquifers;
- Pilot scale study to translate, test effectiveness and adaptation of the in-situ arsenic removal technique claimed by Queen's University, Belfast;
- Pilot scale study for in-situ removal of arsenic from As-Fe interrelationships or other innovative methods;
- Exploring possibility of tapping monsoon groundwater recharge (top most layer of shallow aquifer) using radial collector wells and river bank storages by infiltration galleries/ intake wells;
- Pilot scale studies to test efficiency and effectiveness of different technological advancements, propositions and concepts for in-situ arsenic remedy;
- Impact of arsenic in food chains and health risk assessment;
- Impact of arsenic groundwater contamination on health, society, environment, and socio-economic issues, etc.

(iii) R & Ds to roll-over

The techniques and technologies expected to be developed at the laboratory and field level R & Ds should finally roll over to the field. Most of the techniques and technologies fell short to produce satisfactory results because of many unforeseen and undefined factors, such as; implementing agencies do not even know as to how go about, social unacceptability, complicated O & M, etc. One has to have, therefore, a clear idea as to how the task is to be implemented and operated to get its targeted benefits. So, the R & D activity, in such case, could be to evolve methods as to how a socially acceptable public-private-people entrepreneurship for implementation, operation and maintenance of the schemes can be translated to the field to derive sustainable benefits.

8.1.2 Ensuring 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.

During the past few years, many small scale arsenic removal devices have been developed, field tested and used in West Bengal. Out of 10 such tested arsenic removal devices, few have proved satisfactory performances both in terms of arsenic removal efficiency, and O & M. The schemes in which regular O & M are entrusted with the local community are found to have produced successful results. Arsenic removal devices attached with Hand Pumps and tube wells developed and marketed by M/s Pal Trockner Foundation Ltd, India in association with Harbauer GmbH, Germany; by Oxide India (Catalysts) Pvt. Ltd, Durgapur; and by Apyron Technologies (P) Ltd. representing of Apyron Technologies Inc., USA are those devices and schemes, which have shown satisfactory performances in the field. Comparison of photographs (Figs. 8.1 and 8.2) taken during November, 2008 representing two similar type of schemes marketed by M/s Pal Trockner Pvt. Ltd. located in a kilometer distance apart, one with care of O & M, other one without care of O & M, clearly revealed that sustainability of a scheme mainly depends on how do one nurtures the scheme rather than the sophistication of the scheme.

The plan of actions under this task could be as follows:

(i) Reviving and strengthening of existing arsenic removal plants/units wherever possible by the replacement of components of successful system under the public-private partnership linking the community participation in the O & M;

(ii) Installation of new Arsenic removal plants (efficient and effective system among the existing) with existing hand pumps and tube wells in arsenic vulnerable areas where no such schemes exist, under the public-private partnership with community participation in the O & M;

(iii) Installation of new hand pumps to tap and provide fresh potable groundwater to the inhabitants residing in the arsenic vulnerable areas;

(iv) Installation of new tube wells to tap deeper aquifers and creating infrastructure to supply risk free potable water to the people in the arsenic vulnerable areas;

(v) Developing scope and infrastructure for piped surface water supply schemes ,wherever feasible, to ensure potable water to the people of arsenic vulnerable areas;

8.1.3 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. *To cite an example in this regard; a recent field investigation made to an arsenic affected area in Ojha Patti in Bhojpur District, Bihar, it was observed that village people preferred to drink hand pump operated tube well water from arsenic affected area than the bore well operated overhead tank water provided by the Govt. of Bihar. On query, villagers replied that overhead tank water is stored water and not regularly pumped, and therefore, is not fresh, whereas the hand pump water is drawn on demand and hence better than overhead tank water. These notions signal lack of adequate literacy and know-how.*

Figure 8.1 : Photograph showing a hand pump connected with Arsenic removal filter developed by M/s Pal Trockner Foundation Ltd, India, successfully operating under the community participation in O & M in Barasat, West Bengal.

Figure 8.2 : Photograph showing a hand pump connected with similar Arsenic Removal filter located at about one km. distance apart but not under the responsibility of community participation in O & M, found non-functional due to minor maintenance.

Efficiency, effectiveness and sustainability of a technologically challenged scheme can be achieved by capacity building among the human resources to be involved in development, implementation, and O & M of the system, whereas usages of water, water-literacy, and health related issues can be achieved through mass awareness programme.

The following tasks are thus proposed:

(i) Establishment of a network of water quality testing laboratories in each arsenic affected States, having provision of one level-II category laboratory in each district with scope to detect primary chemical constituents and selected toxic elements,

(ii) Training of personnel involved in the technological developments to acquire advanced knowledgebase and know-how,

(iii) Training of junior level personnel with the implementing agencies, NGOs involved in the area, Panchayat Officers; who in turn shall impart training to the personnel to be involved in O & M,

(iv) Mass awareness and campaign programme for the society through local Panchayati raj network.

8.1.4 Revision of the National Standard for Arsenic in drinking water

In addressing the key-concerns and in developing a National Plan of Action for providing Arsenic safe water to the community, the 1st key-step is to establish a National Standard for Arsenic in Drinking Water. It is strongly felt that the National Standard for Arsenic in drinking water is to be set linking the issues related to the social, cultural & health benefits in line as set by the WHO. Many health scientists strongly feel that standard should be strictly based on health risk and no compromise should be made on economic consideration. It is, therefore, recommended that the standard for Arsenic in treated water should be 10 ppb; but the threshold value for rejection of a water source could continue to be 50 ppb for sometime to come. BIS and the Dept. of Consumer Affairs should take an unequivocal stand in this matter

8.2 Approaches for Achieving Milestones

Government of India has launched a number of countrywide development schemes as Societal Missions emphasizing to provide basic amenities to the society for its multi-faceted development. These schemes are:

(i) Bharat Nirman, 2005-2009.

(ii) Accelerated Rural Water Supply Programme (ARWSP) & Pradhan Mantry Gramodaya Yojana (PMGY) - Rural Drinking Water.

(iii) National Rural Employment Guarantee Act-2005 (NREGA).

All these schemes have component and relevance dealing with providing safe drinking water to every habitation. It is proposed to link and operationalize the activities emerging from this mission of providing arsenic free groundwater and decontaminating aquifers from hazards of arsenic to the above Govt. of India societal schemes.

Ministry of Water Resources, Government of India, also provides financial assistance for R & D projects through its different 'National Committee'; the related committees are:

(i) Indian National Committee on Ground Water (INCGW) - Secretariat with the Central Ground Water Board,

(ii) Indian National Committee on Hydrology (INCOH) - Secretariat with the National Institute of Hydrology, Roorkee.

8.2.1 Bharat Nirman (2005-2009)

'Bharat Nirman' is a time-bound plan for action in rural infrastructure by the Govt. of India in partnerships with State Governments and Panchayat Raj Institutions in the areas of irrigation, road, rural housing, rural water supply, rural electrification and rural telecommunication connectivity.

The task envisaged under the 'Drinking Water' component of the 'Bharat Nirman' is to provide every habitation safe source of drinking water. In addition, all habitants, which have slipped back from full coverage to partial coverage due to failure of source and habitations, which have water quality problems, is to be addressed.

The Ministry of Rural Development, Department of Drinking Water Supply, is responsible for meeting this goal in partnership with State Governments. The programme instrument of the Government of India is a Centrally Sponsored Scheme of Accelerated Rural Water Supply Programme under implementation since 1972-73, which is funded on a 50% matching share basis between the Government of India and the State Governments. The norms set in the scheme are:

- 40 liters per capita per day(lpcd) of safe drinking water for human beings,
- 30 lpcd additional for cattle in the Desert Development Programme Areas,
- One hand pump or stand post for every 250 persons,
- The water source should exist within 1.6km in the plains and within 100 meters elevation in the hilly areas.

Water quality problems due to excess arsenic have got a special mention in the 'Bharat Nirman' document.

8.2.2 Accelerated Rural Water Supply Programme (ARWSP) & Pradhan Mantry Gramodaya Yojana (PMGY) - Rural Drinking Water.

The Rural Water Supply Programme of Government of India, Ministry of Rural Development, Department of Drinking Water Supply, provides scope for action plans institutionalizing community participation in the capital cost sharing, O & M and WQM& S for pilot schemes in the water quality affected habitations. Providing safe drinking water in the Arsenic affected areas is one of the priorities of the mission. The Rural Water Supply supportive activities are also aimed at: (i) to ensure sustainability in scientific methodologies, (ii) to human resource development for sustainable management of rural water supply schemes by community participation and empowerment together with adequately trained professional and sensitized planners, administrators and decision makers, and (ii) to research and develop for providing scientific and technological inputs to improve performance, cost effectiveness and management practices of ongoing programmes. Further a new initiative in the form of Pradhan Mantry Gramodaya Yojana (PMGY) for Rural Drinking water started from 2000-2001 provides scope for taking up Projects /schemes on sustainability. The rationale of funding should be based on following factors:

- Competing demand of groundwater for irrigation, industrial and other purposes,
- Excessive withdrawal of ground water without taking into consideration the recharge,
- Low electricity tariff for agricultural and industrial use,
- Lack of scientific input and management of ground water,
- Misuse of precious water and treating it as a free, ever lasting commodity,
- Lack of sustainability principle in withdrawal of ground water etc.

Under PMGY-Rural Drinking Water in water stressed area 25% fund of sub-mission programme of ARWSP has been earmarked for taking up projects /schemes based on rainwater harvesting, artificial recharge and sustainability.

8.2.3 National Rural Employment Guarantee Act-2005 (NREGA).

The National Rural Employment Guarantee Act-2005 (NREGA), operationalized under the Ministry of Rural Development, Department of Rural Development, Government of India, has the objective to enhance livelihood security in rural areas by providing at least 100 days of guaranteed wage employment in a financial year to every household, whose adult members volunteer to do un-skilled manual work. In addition, the Act also has provision of semi-skilled wages in the form of mate with educational requirements between class-5 and class-8. The financing patterns of wages as mentioned in the NREGA are as follows: the Central Govt. will bear; (a) entire cost of un-skilled manual workers, (b) 75 percent of the cost of material and wages for skilled and semi-skilled workers, and (c) administrative expenses as may be determined by the Central Govt. While the State Govt. will bear: (a) 25 percent of the cost of material and wages for skilled and semi-skilled workers, and (b) administrative expenses of the State Employment Guarantee Council.

One of the goals of the NREGA is the new way of doing business, as a model of governance reform anchored on the principles of transparency and grass root democracy. Water conservation and water harvesting is one of the works envisaged in the NREGA. The key stakeholders are: wage seekers, Gram Sabha, Panchyati Raj Institutions, Programme Officer at the Block level, District Programme Coordinator, State Government, Ministry of Rural Development. The operational aspects, rules of the NREGA and roles of Stakeholders are well defined in the Act.

8.3 Operational Framework

'Bharat Nirman' provides scope for action plan in rural infrastructural; 'Accelerated Rural Water Supply Programme (ARWSP) & Pradhan Mantry Gramodaya Yojana (PMGY) - Rural Drinking Water' provides scope for action plans institutionalizing community participation in the capital cost sharing, O & M and WQM& S for pilot schemes and taking up R & D Projects/schemes including human resource development and capacity building; INCGW and INCOH under the Ministry of Water Resources also provide financial assistance for R & D Programmes and Projects, and the National Rural Employment Guarantee Act-2005 (NREGA) gives scope to involve local semi-skilled/skilled persons for facilitating the activities in operation and maintenance of the system.

The provision of creating a network of water quality testing laboratories in each arsenic affected State having provision of one level-II category laboratory in each district is kept out of scope of the operational framework of activities. There is a need to evolve a policy decision and a National guideline for such activity to roll over.

The plan of activities can be pursued linking with the above mentioned GOI schemes as follows:

(i) Within the given scope of the 'Bharat Nirman' scheme, which has the provision of providing one hand pump or stand post for every 250 persons to ensure 40 liters per capita per day (lpcd) of safe drinking water for human beings, provision of new hand pumps in all arsenic fringe areas of affected States to tap arsenic free shallow aquifers and to ensure supply of potable groundwater with 50:50 financial share by the Central and the respective State Government can be extended.

(ii) The Accelerated Rural Water Supply Programme (ARWSP) under the Ministry of Ru ral Development, which provides scope for action plans institutionalizing community participation in the capital cost sharing; initiatives for installation of new schemes for safe drinking water supply in water quality affected habitations with capital cost sharing by the Central and the respective State Government, can be extended to install new arsenic removal plants and to create new tube wells to tap risk free deeper aquifers in the arsenic vulnerable areas for ensuring safe drinking water supply to the people in the arsenic affected areas in all seven States. The Stand posts along the roadside to facilitate supply of water can be extended from the provision of 'Bharat Nirman' scheme. The mechanism of capital cost sharing by the community participation can be similar as is being followed in ARWSP.

(iii) For reviving and strengthening the existing non-functional and defunct arsenic removal units/plants/schemes by the components or as a complete new setup of existing successful arsenic removal devices (applicable for West Bengal only), one-time financial aid on 50:50 capital cost sharing between the Central and the State

Government can be extended under the provision of Accelerated Rural Water Supply Programme (ARWSP).

(iv) Implementation of the schemes related installation of arsenic removal devices can be through public-private partnership with responsibilities of O&M on the local community, i.e., the executing agencies while framing the schemes should make sure that the O & M are adequately outlined through involvement of local community. This can be achieved by devising mechanism of charging very nominal price on arsenic treated water. This approach can help in two ways: one, some money will be generated, which in turn can be used for routine minor O & M, the other one, beneficiaries of the scheme will have the feeling of ownership and conscientiousness. This approach has been found success fully running in West Bengal wherever deployed.

(v) R & D schemes on demand driven areas can be entrusted to potential lined organizations/academic institutions under the Prime Minister's Gramodaya Yojana (PMGY) of Ministry of Rural Department, and INCGW & INCOH of Ministry of Water Resources. Joint R & D programmes in collaboration with foreign experts/ agencies (where foreign currency is involved) can be operated under the Rural Water Supply supportive programmes of Ministry of Rural Department, while the in-house R & D programmes can be supported from INCGW & INCOH of Ministry of Water Resources.

(vi) Training of personnel aboard to acquire specialized knowledgebase would be in accordance with the requirement of the joint R & D programmes with the foreign collaborators. Training of personnel of the implementing agencies, NGOs, skilled /semi skilled mates, etc. can be extended conceiving programmes under the Pradhan Mantry Gramodaya Yojana (PMGY) and INCGW & INCOH of Ministry of Water Resources. Mass awareness and social empowerment programmes can be supported under the ARWSP of Ministry of Rural Development and INCGW & INCOH of Ministry of Water Resources in the mission mode by the trained personnel of the implementing agencies, NGOs, etc.

(vii) Activities related to operation, routine supervision and care of the arsenic removal schemes can be supported under the **NREGA**. One semi-skilled mate for each arsenic removal scheme covering nearly 250 persons, and two semi-skilled mates for each arsenic removal scheme covering more than 250 persons can be involved for the purpose of operation, routine supervision and care. Material requirement for this purpose can be extended as per the provision laid down in the **NREGA**. While maintenance such as, change of filters, painting of the device, etc. can be done from the marginal tariff to be charged from the beneficiaries on the treated potable water. Any technical faults or unwarranted failure of the scheme can be supported from the scope of **NREGA**. Disposal of the used arsenic removal filters and the toxic sludge to a designated location could be one of the responsibilities of each mate besides other routine tasks.

The framework of activities and their operating linkages to various ongoing Government schemes are schematically shown in Fig. 8.3.

Figure 8.3: Framework of different activities and their operational linkages with Government of India schemes. *(Note: the mode of operation of the schemes shall be through joint ventures of Central Government and respective State Governments as per the provision laid down under different schemes).*

8.4 Mechanisms for Implementation of Envisaged Activities

The plan of actions envisaged in the document primarily deals with three aspects: (i) formulation and implementation of social sector schemes, (ii) promoting future R & D programmes, and (ii) programmes for mass awareness and social empowerment. The formulation and implementation of different social sector schemes as envisaged in section 8.4, can be through initiating dialogues between the Central Govt. and the State Govts., and largely can be based on mutually agreed terms & conditions. The formulation and implementation of the schemes shall be the sole responsibility of the respective State Governments. While the responsibilities in formulation and execution of R & D programmes on different demand driven areas shall solely rest on the Central Government. The programmes of mass awareness and social empowerment can be through joint initiative of Central and State sector departments with involvement of other public and private sector units.

The method of operation of different activities could be as follows:

A. Formulation and implementation of social sector schemes

- By initiation of dialogues between Central Govt. and the State Govts.
- State Government has the responsibility to formulate and implement the schemes; Central Government can provide technical inputs in formulation and implementation of the schemes, if necessary.

B. R & D Programmes

The R & D programmes on envisaged areas shall be by invitation of project from the resource persons/Institutions/Organizations in India. The R & D programmes involving foreign collaborators shall also be by invitation from selected Institutions/Organizations. Following are some of the resource/expert Institutions/ Organizations that can be entrusted with R & D programmes according to the areas of expertise and mutual interest.

Type of R & D programmes	Broad areas	Name of the Institutions/ Organizations
Laboratory Scale R & Ds	Arsenic removal filters & devises; innovative techniques for arsenic removal, Laboratory based research & chemical analysis, etc.	(i) All India Institute of Public Health & Hygiene, Kolkata. (ii) Bengal Engineering College, Howrah. (iii) Indian Toxicological Research Institute, Lucknow. (iv) Indian Institute of Technology Roorkee, Kanpur, Delhi. (v) Indian Institute of Sciences, Bangalore. (vi) School of Environmental Studies, Jadavpur University, Kolkata. (vii) Water Technology Mission, ICAR. (viii) School of Tropical Medicine, Kolkata (ix) Kalyani University, W.B
		(i) BARC, Trombay, Mumbai. (ii) Central Ground Water Board. (iii) Geological Survey of India, Kolkata (iv) Indian School of Mines, Dhanbad. (v) National Institute of Hydrology, Roorkee. (vi) National Geophysical Research Institute, Hyderabad.

Field level R & Ds	Monitoring, mapping, feasibility studies, modeling studies, pilot scale studies, deeper aquifers detection, source, age and genesis detection, Geochemical study, watershed management study, pilot study for in-situ remedy, etc.	(vii) State Public Health Engineering Departments. (viii) State Ground Water Departments. (ix) School of Water Resources Engineering, Jadavpur University, Kolkata. (x) School of Fundamental Research, Kolkata. (xi) A.N College, Magadh University, Patna (xii) Dept of Applied Geology, ISM University, Dhanbad (xiii) Dept of Geology, Sahebganj College, Sahibganj, Jharkhand (xiv) Centre for Ground Water Studies (NGO)
	Arsenic in Food Chains	(i) Bidhan Chandra Krishi Viswavidhalaya, West Bengal, (ii) Agricultural University, Bihar. (iii) Agricultural University, U.P.
	Social & environmental impact analysis, public-private entrepreneurship, etc.	(i) Indian Institute of Social Welfare & Business Management (IISWBM) (ii) Centre for Studies of Man & Environment, Kolkata, (NGO) (iii) Institute of Economic Studies, Patna,
Foreign Organizations	Collaborative studies	(i) CSIRO, Adelaide, Australia. (ii) Harbauer GmbH, Germany. (iii) Queen's University, Belfast, UK. (iv) Swiss Federal Institute for Aquatic Science & Technology, Switzerland. (v) University of Guelph, Canada. (vi) US-EPA & USGS. (vii) Department of Earth Sciences, University College of London, Gower Street, London WCIE 6 BT, UK. (viii) UNICEF (ix) WHO

C. Mass Awareness and Social Empowerment programmes

The mass awareness and social empowerment programmes can be implemented in a two tier process under the overall coordination of selective Central agencies and the State Public Health Engineering Departments. In the first tier, training of personnel from the State implementing departments, Panchayati Raj Institutions, and selected NGOs can be trained by expert group(s) devising suitable mechanisms; in the second tier, the trained personnel will disseminate the campaign and awareness programme to the rural masses. The programme can be operationalized by suitable outsourcing mechanisms.

Some of the resourceful institutions/NGOs who could be involved for mass awareness programmes are:

(i) Panchayati Raj Institutions - a Government Institution.
(ii) Centre for Environmental Studies, New Delhi - NGO.
(iii) Ram Krishna Mission Seva Sangh- NGO
(iv) Centre for Ground Water Studies, Kolkata - NGO.
(v) Paschim Bangya Bigyan Mancha -NGO
(vi) Loksiksha Parisad, Ramkrishna Mission -NGO

Chapter - 9

Financial Requirement

9.1 General

The detailed information about the arsenic menace, in different states in India, is given in Chapter-2: 'Arsenic Menace in India-An Appraisal'. In short, nine districts, covering 111 blocks (3417 villages), spread over 38,861 sq. km. of area, with total population about 50.4 million in West-Bengal; fifteen districts, covering 39 blocks (235 villages), spread over 21271 sq. km. of area, with total population about 24 million in Bihar, three districts, covering 9 blocks (69 villages), spread over 10375 sq. km of area, with population of about 6 million in Uttar Pradesh; one district, covering 3 blocks (68 villages), spread over 725 sq. km. of area, with population of about 0.6 million in Jharkhand; one district, covering 1 block (4 villages), spread over 6396 sq. km. of area, with total population of 1.5 million in Chhattisgarh; three districts, covering 9 blocks, spread over 8822 sq. km. of area, in Assam; and four districts, spread over 2238 sq. km. of area, with total population of about 1.35 million, in Manipur, have been reported under influence of arsenic vulnerability of concentration more than 50 μgL^{-1}. It is also suspected that many more areas, in the North-Eastern states and 17 more districts in Uttar Pradesh, may have arsenic in groundwater. In fine tuning, 4.6 million people, in 3417 villages in West Bengal, 1.7 million people in 235 villages in Bihar, 0.6 million people in 69 villages in Uttar Pradesh, and 0.06 million people in 68 villages in Jharkhand, have been reported under the grim of arsenic contaminated groundwater above 50 μgL^{-1},. In other states, exact count of population is not known. Largely, 7 states, in which large part of West Bengal, stretches in Bihar and Uttar Pradesh, scattered areas in Assam, pockets in Jharkhand, Chhattisgarh and Manipur, are in the list of arsenic contamination in aquifer exceeding concentration 50 μgL^{-1}.

In West Bengal, to combat the arsenic menace and to provide potable groundwater to the people in the arsenic affected area, a number of schemes have been put in place, which could cover about 43% of the arsenic risk people. About 57% of the arsenic risk people are still to be covered with the potable water supply. Nearly, 2252 Arsenic Treatment Units (ATUs), 77 Arsenic Removal Plants (ARPs), and number of hand pumps, without filtration devices, have been installed. Out of which, about 50% of the ATUs and 42% of the ARPs are either yielding groundwater contaminated arsenic beyond 50μg/L or non-functional. Thus, there seems to be requirement of reviving and strengthening more than 1125 ATUs and 30 ARPs, besides installation of number of new arsenic removal schemes and hand pumps or stand posts to ensure potable water to the people, in the arsenic affected areas.

In other arsenic affected States, as such no arsenic removal Units/Plants have been installed or operationalized, except some initiative for making alternate arrangement to provide potable groundwater supply. In order to ensure supply of safe drinking water to the people in the arsenic affected and vulnerable areas, the following field oriented schemes are proposed to take up. The planning of any scheme for a district should be based on the comprehensive groundwater quality maps and demography of the district.

(i) One Arsenic Treatment Unit (ATU) for every 250 persons in severely affected villages, where the scope of developing arsenic safe shallow and deeper aquifers is limited; and drinking water from other sources cannot be made available within a distance of 1.6 km,

(ii) One Arsenic Removal Plant(ARP) for population more than 1000 in severely affected villages or society, where the scope of developing arsenic safe shallow and deeper aquifers is limited; and drinking water source cannot be made available within a distance of 1.6 km,

(iii) One hand pump for every 250 persons in arsenic vulnerable areas, where drinking water source can be made available within a distance of 1.6 km from arsenic safe shallow aquifer,

(iv) One tube well for each village, covering population more than 5000 with provision of overhead storage tank and distribution line, having facility of one Stand post for every 250 persons in arsenic vulnerable areas, where drinking water source can be made available from exploration of arsenic safe deeper aquifers,

(v) Reviving and strengthening of existing 1125 ATUs and 45 ARPs in West Bengal, by new arsenic removal devices, which are showing successful performance.

(vi) One semi-skilled mate for each ATU and 2 semi-skilled mates for each ARPs.

With these provisions, State-wise allocation of ATUs, ARPs, hand pumps, tube wells and stand posts for 7 arsenic affected States are given below:

State	ATU	ARP	New Hand Pump	New tube wells with provision of Stand Post for supply of water *(number in parenthesis indicate Stand post)*	Number of Semi-skilled mate
West Bengal	2500 (includes 1125 reviving & strengthening)	100 (includes 30 reviving & strengthening)	500	50(500)	2700
Bihar	200	-	3000	110 (1100)	200
Uttar Pradesh	150	-	1200	70(700)	150
Jharkhand	35	-	500	15 (150)	35
Assam	-	-	1000	60 (600)	-
Manipur	-	-	300	10(100)	-
Chattisgarh	4	-	100	5(50)	4

The above allocation of additional infrastructural facilities, in the arsenic affected areas, would ensure arsenic safe potable water to about 10.75 lakhs in West Bengal, 10.5 lakhs in Bihar, 4.5 lakhs in Uttar Pradesh, 1.57 lakhs in Jharkhand, 3.50 lakhs in Assam, 1.00 lakh in Manipur, and 0.39 lakh in Chattisgarh, with employment generation of 3089 people and many more tangible benefits.

A. Cost of an ATU

ATU is hand pump operated. The cost of installation including material of an ATU fitted with a hand pump ranged from Rs. 1,50,000/- to Rs.1, 75,000/- as in the year 2005, depending upon the type of unit. Cost of filter was nearly Rs.12,000/-. For budget estimate. The total cost of an ATU is considered to be Rs. 2, 25,000/- (with cost escalation).

B. Cost of an ARP

ARP is mechanical pump operated. Cost of installation including material of an ARP was nearly Rs. 6, 00,000/- as in the year 2005. Annual maintenance cost of each ARP varies between Rs.30, 000/- and Rs.35, 000/-. For budget estimate, total cost of an ARP is considered to be Rs. 7, 00,000/- (with cost escalation).

C. Reviving & Strengthening cost of ATU, and ARP

Reviving and Strengthening cost of each ATU and ARP is considered 50% of their original cost, i.e., cost of each ATU is Rs. 1, 00,000/- & cost of each ARP is Rs. 3, 25,000/-.

D. Cost of a Hand Pump

Cost of installation of a hand pump, including material, is considered to be Rs.75, 000/-.

E. Cost of Tube well exploration i/c distribution lines with provision of 10 Stand Posts

Cost of developing of one tube well	: Rs. 1,50,000/-
Cost of distribution lines of 10 kms long for each unit	: Rs. 4,15,000/-
Cost for developing 10 Stand posts	: Rs. 2,50,000/-
Total cost of one unit	**: Rs. 8,15,000/-**

F. Semi-skilled Mate

Wages of semi-skilled mate would be as per the rate prescribes by the Govt. from time to time. For budget estimate, it is considered to be Rs.150/- per day.

Cost of material for O & M

In the operation of the ATU and ARP, to start with some material such as, bucket, water storing container, etc., would be required. For each ATU and ARP, it is considered to be Rs.500/- and Rs.1000/-, respectively.

H. Cost of one Training & Mass Awareness Programme.

Two types of training and mass awareness programmes are proposed. The first type would be to train the personnel of implementing agencies, Panchayati Raj Institutions and NGOs; and the second type would comprise the campaign and mass awareness programme for the rural masses by the trained personnel. Training programme of the first category can be of two days, at the respective State, with maximum number of 50 in each batch. Number of this category of training programme can be 5 for West Bengal, 5 for Bihar, 2 for Uttar Pradesh, 3 for Assam, 1 each for Jharkhand, Chhattisgarh and Manipur.

The mass awareness programme, for the rural masses, can be of half a day in each arsenic affected village by the trained personnel. Total number of mass awareness programme can be 100 for West Bengal, 200 for Bihar, 150 for Uttar Pradesh, 50 for Jharkhand; 100 for Assam, 10 for Manipur, and 10 for Chhattisgarh.

(a) Each training programme of first category is estimated to involve an approximate sum of Rs.1,10,000/- with following details:

i.	Training material @Rs.200/each	: Rs. 10,000/-
ii.	Travel @Rs.500/- each	: Rs.25,000/-
iii.	Stay & Hospitality for 2 days @ Rs. 1000/- each	: Rs.50,000/-
iv.	Miscellaneous	: Rs. 15,000/-
v.	Administrative expenses	: Rs.10, 000/-
	Total	: Rs.1, 10,000/-

(b) Each mass awareness programme is estimated to involve an approximate sum of Rs.40, 000/-with following details:

i.	Cost of demonstration material	: Rs. 15,000/-
ii.	Transportation	: Rs. 15,000/-
iii.	Refreshment	: Rs. 5,000/-
iv.	Administrative & Miscellaneous	: Rs. 5,000/-
	Total	: Rs. 40,000/-

H. R & D Programmes

R & D activities would be in three aspects: Laboratory based R & Ds; Field based R & Ds, and R & Ds to evolve mechanisms for roll-over.

9.2 Distribution of Financial Allocations under Different Schemes

The total budget requirement to achieve goals of different envisaged activities and their proportion under Governmental schemes are given below:

	Amount in lacs of Rupees.					
Activities	**Total Amount**	**Bharat Nirman**	**ARWSP**	**PMGY**	**NREGA**	**INCGW & INCOH of MoWR**
R & D programme	4500	---	1500	500	---	2500
ATU & ARP	7200	----	7200	----	----	-----
Hand Pumps	5000	5000	----	----	----	----
Deep tube wells with Stand Posts	2600	800	1800	---	----	-----
O & M	300	----	----	----	300	----
Training & Awareness Programme	400	----	----	50	----	350
	20000	**5800**	**10500**	**550**	**300**	**2850**

9.2.1 Distribution of Financial allocation between the Central Government and the respective State Governments

Except the R & D, Training and Mass awareness programmes, procedure of promoting tasks under all other schemes shall be based on Centre-State sharing of finances as prescribed under different schemes. For example, the Centre-State share for the 'Bharat Nirman' is 50:50; for the ARWSP, it is 75:25; and for the NREGA for skilled/semi-skilled wages and material cost it is 75:25.

With these provisions, the sharing of finances for the envisaged activities, under different schemes, are estimated and given in Table-9.1

Table 9.1: Sharing of Financial Responsibilities of Different Tasks between the Central Government and the respective State Governments

Activities	***Amount in lakhs of Rupees***								
	Central Govt.	West Bengal	Bihar	Uttar Pradesh	Jharkhand	Chhatisgarh	Assam	Manipur	**Total**
R & D Programme	4500	---	---	---	----	-----	---	---	**4500**
ATU & ARP	5400	1581	112.5	84.5	19.75	2.25	----	-----	**7200**
Hand Pumps	2500	190	1130	450	190	40	380	120	**5000**
Deep tube wells with Stand Posts	1750	133.5	287.5	187.5	40.75	13	160	27.75	**2600**
O & M	225	60	7	5	2	1	---	----	**300**
Training & Awareness Programme	400	---	---	----	----	---	----	---	**400**
Total	**14775**	**1964.5**	**1537**	**727**	**252.5**	**56.25**	**540**	**147.75**	**20000**

Of the total estimated financial outlay of **Rs. 200 crore**; the financial responsibility of the Central Government is figured out to be **Rs.147.75 crore**, and the remaining amount of **Rs. 52.25 crore** will be responsibility of different states with distribution of Rs.19.65 crore to West Bengal, Rs.15.37 crore to Bihar, Rs. 7.27 crore to Uttar Pradesh, Rs.2.52 crore to Jharkhand, Rs.0.56 crore to Chattisgarh, Rs. 5.40 crore to Assam, and Rs. 1.48 crore to Manipur. The overall percent share of financial responsibility between the Central Government and State Government stands as 73.87 % (Central Govt.) and 26.13% (State Govt.)

Chapter-10

Mission Management and Time Frame

10.1 Mission Management

In order to coordinate, facilitate and monitor the various tasks, envisaged in this document and to initiate dialogue and activities on other sphere of water quality related issues, it is proposed to constitute a National level Committee, which can be named as "National Task Force for Water Quality Management. This can comprise resourceful experts, renowned individual/organizations and Government officials from related departments. Since quantity shapes the fate of quality, the Ministry of Water Resources, Government of India, can be the nodal ministry for coordination and initiation of various activities related to 'Water Quality Management'. The proposed committee can be headed by the Secretary (WR). For effective functioning, coordinating and facilitating various activities, involvement of higher level officials from the following Ministries/Departments are mandatory:

- Planning Commission, GOI
- Ministry of Rural Development, GOI
- Department of Drinking Water Supply, GOI
- Ministry of Environment and Forest, GOI
- Ministry of Agriculture, GOI.
- Ministry of Water Resources, GOI.
- Ministry of Health and Family Welfares, GOI.

The project management committee for implementation, coordination, and monitoring of different activities, envisaged in this document, can be as shown in Fig10.1:

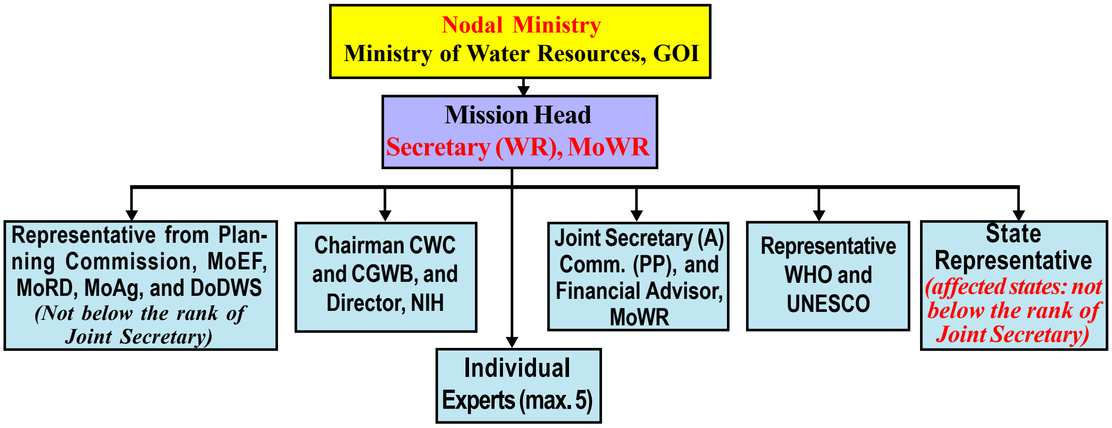


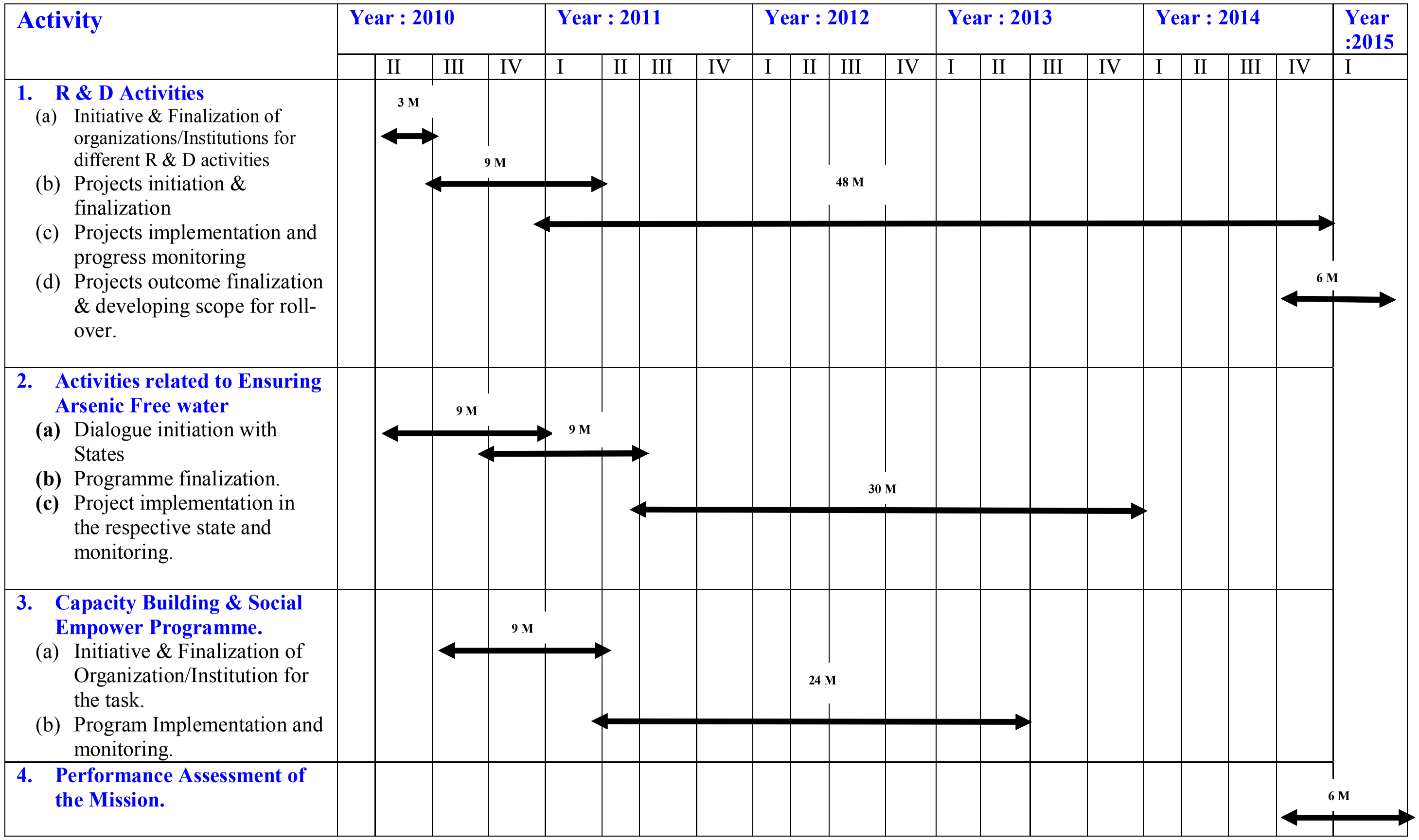
Figure 10.1: Mission Management Committee

10.2 Time Frame

Except the R & D component, all other components are field oriented, which can be taken up as a 'mission mode', initiating dialogue with respective state government. In fact, it is the respective State government, who has to take initiative for developing and implementing programmes. The Central government can provide technical assistance and guidance for development and implementation of the programmes. In two components, namely, the R & D and Mass awareness and training programmes, the Central government has the responsibility to initiate and implement the activities.

Keeping the above in view, the time frame for achieving the targeted goals is set to be 5 (Five) years from 2010 as per the following details:

Table 10.1 : Time schedule of different activities



Activity

1. **R & D Activities**
   - (a) Initiative & Finalization of organizations/Institutions for different R & D activities
   - (b) Projects initiation & finalization
   - (c) Projects implementation and progress monitoring
   - (d) Projects outcome finalization & developing scope for roll-over.
2. **Activities related to Ensuring Arsenic Free water**
   - **(a)** Dialogue initiation with States
   - **(b)** Programme finalization.
   - **(c)** Project implementation in the respective state and monitoring.
3. **Capacity Building & Social Empower Programme.**
   - (a) Initiative & Finalization of Organization/Institution for the task.
   - (b) Program Implementation and monitoring.
4. **Performance Assessment of the Mission.**

References

Abernathy, C.O., Calderon, R.L. and Chappell, W.R. (eds.) (1997). ARSENIC exposure and health effects. Chapman and Hall.

Abernathy, C.O., Liu, Y., Longfellow, D., Aposhian, H.V., Beck, B., Fowler, B., Goyer, R., Menzer, R., Rossman, T., Thompson, C., and Waalkes, M., (1999). Arsenic: health effects, mechanisms of actions, and research issues: Environmental Health Perspectives, July, v. 107, no. 7, pp.593-597.

Acar, Y. B. and Gale, R.J., (1995). Electrokinetic remediation: Basics and technology status, Journal of Hazardous Materials, 40, pp. 117-137.

Acharya et al., (1999). Nature, 401, pp.545-546.

Acharya et al., (2001). Environ. Geol., pp.1127-1137.

Acharyya, S. K., Lahiri, S., Raymahashay, B. C. and Bhowmik, A., (1993). Arsenic toxicity of groundwater in parts of the Bengal basin in India and Bangladesh: the role of Quaternary stratigraphy and Holocene sea-level fluctuation. Environ. Geol., 39, pp.1127-1137.

Acharyya, S. K., Chakraborty, P., Lahiri, S., Raymahashay, B. C., Guha, S. and Bhowmik, A., (1999). Arsenic poisoning in the Ganges delta. Nature, 401, pp. 545-546.

Acharyya, S.K., Lahiri, S., Raymahashay, B.C., Bhowmik, A., (2000). Arsenic toxicity of ground water in parts of the Bengal basin in India and Bangladesh: the role of Quaternary stratigraphy and Holocene sea-level fluctuation. Environ. Geol., 39, pp.1127?1137.

Achyuthan and Baker, (2002). Radiocarbon, 44, 1, pp.137-144.

Adel Miah, (2005). Jour. Water Health, 3, 4, pp.435-452.

Ahmed. F., Jalil, M. A., Ali, M. A., Hossain, M. D. and Badruzzaman, A. B. M. (2000). An overview of arsenic removal technologies in BUET. In: Bangladesh Environment-2000 (Ed. M.F. Ahmed), Bangladesh Poribesh Andolon, pp.177-188.

Ahmed, K. M., (1999). A review of available geochemical data and their implications to the origin of arsenic in Bangladesh groundwater. KTH/Dhaka University Seminar on Ground water Arsenic Contamination in the Bengal Delta Plains of Bangladesh: Book of Ab stracts, University of Dhaka, Bangladesh, 24p.

Amaya, A., (2002). Arsenic in groundwater of alluvial aquifers in Nawalparasi and Kathmandu districts of Nepal. Master's thesis, Dept. of Land and Water Resources Engineering, Kungl Tekniska Hogskolan, Stockholm.

Appelo et al., (1999). Ground Water, 37,6, pp.811-823.

Arsenic (Medical & Biological Effects of Environmental Pollutants). (1977). National Academy of Sciences, Washington DC.

Bamwsp, Dfid and Water Aid Bangladesh, (2001). Rapid Assessment of Household Level Arsenic Removal Technologies, Phase-I and Phase-II, Final Report, WS Atkins International Limited.

Banning et al., (2008). www. springerlink.com/content/e64475318415457.

Basu, B.B., (2003). Arsenic Technology Park and Critical Lessons of Arsenic Mitigation, SFR, Kolkata.

Basu, B. B. (2003). Lessons from arsenic technology Park and critical issues of arsenic mitigation. School of Fundamental Research, Kolkata.

Basu et al., (2007). Proc. Int. Workshop on Arsenic, Kolkata.
Ravenscroft, P., Brammer, H., and Richards, K. Arsenic Pollution. (2009). A Global Synthesis. RGS-IBG Book Series. Willey Blackwell 2009.

Belzile and Tessier, (1990). Geochim. Cosmochim. Acta, 54, pp.23-38.

Berner, (1981). Jour. Sed. Pet., 51, pp.359-365.

BGS and DPHE, (2001). As contamination in groundwater in WB, Report, Vol. 2.

Bhattarchyya et al., (2003). Appl. Geochem., 18, pp.1435-1451.

Bhattacharyya et al., (1997). Water Res. Dev., 13, 79-92.

Bhattacharya, P., Ramanathan, A.L., Mukherjee, A. B., Bundschuh, J., Chandrasekharam, D., and Keshari, A. K., (eds.) (2008). Groundwater for Sustainable Development. Problems, Perspective and Challenges. Taylor & Francis.

Bhumbla, D.K., and Keefer, R.F., (1994). Arsenic mobilization and bioavailability in soils, in Nriagu, J.O., ed., Arsenic in the environment part I: cycling and characterization: Wiley Series in Advances in Environmental Science and Technology, v. 26, p. 51-82.

Bothe, J.V., and Brown, P.W., (1999). Arsenic immobilization by calcium arsenate formation: Environmental Science and Technology, v. 33, no. 21, p. 3806-3811.

Booch and Banvica. (1981). Ground Water, 19.

Brannon, J.M., and Patrick, W.H., (1987). Fixation, transformation, and mobilization of arsenic in sediments: Environmental Science and Technology, v. 21, no. 5, p. 450-458.

BGS and DPHE (British Geological Survey and Bangladesh Department of Public Health Engineering). (2001). Arsenic Contamination of Groundwater in Bangladesh (four volumes), British Geological Survey.

BGS/MML, (1999). British Geological Survey/Mott MacDonald Ltd, Groundwater Studies for Arsenic Contamination in Bangladesh. Final report, Department of Public Health Engineering, Govt. of Bangladesh Dhaka.

Boyle, R. W. and Jonasson, I. R., (1973). The geochemistry of arsenic and its use as an indicator element for geochemical prospecting. J. Geochem. Explor., 2, 252-296.

Berdowski, J. J. M., Baas, J., Bloos, J. P. J., Vischedijk, A. J. H. and Zandveld, P. Y. J., (1997). The European emission inventory of heavy metals and persistent organic pollutants. Forschungsbericht, 104 02 672/03, Apeldoorn, the Netherlands.

Bhattacharya, P., Chatterjee, D. and Jacks, G., (1997). Occurrence of As contaminated ground water in alluvial aquifers from the Delta Plains, eastern India: option for safe drinking water supply. Int. J. Water Res. Dev., 13, 79-92.

Bhattacharya, P., Jacks, G., Jana, J., Sracek, A., Gustafsson, J. P. and Chatterjee, D., (2001).

Geochemistry of the Holocene alluvial sediments of Bengal Delta Plain from West Bengal, India: implications on arsenic contamination in groundwater. In Proceedings of National Seminar on Groundwater Arsenic Contamination in the Bengal Delta Plains of Bangladesh (eds Jacks, G., Bhattacharya, P. and Khan, A. A.), University of Dhaka, Bangladesh, TRITA-AMI Report, 3084, 21-40.

Bhattacharya, P., Jacks, G., Ahmed, K. M., Khan, A. A. and Routh, J., (2002). Arsenic in ground water of the Bengal Delta Plain aquifers in Bangladesh. Bull. Environ. Contam. Toxicol., 69,538-545.

Bhattacharyya, R., Jana, J., Nath, B., Sahu, S. J., Chatterjee, D. and Jacks, G., (2005).

Groundwater As mobilization in the Bengal Delta Plain. The use of ferralite as a possible remedial measure: a casestudy. Appl. Geochem., 18, 1435-1451.

Bose, P., and Sharma, A., (2002). Role of iron in controlling speciation and mobilization of arsenic in subsurface environment. Water Research, Vol. 36, 4916-4926.

Brannon, J. M. and Patrick, W. H., (1987). Fixation, transformation, and mobilization of arsenic in sediments. Environ. Sci. Technol., 21, pp.450-459.

Brookins, D. G., (1998). In "Eh-pH" diagram for geochemistry. Springer-Verlag, NY, 175p. CGWB, (1999), High incidence of arsenic in groundwater in West Bengal. Central Ground Water Board, Ministry of Water Resources, Government of India.

Chakraborti, D., Das, B., Nayak, B., Pal, A., Rahman, M. M., Sengupta, M. K., Hossain, M. A., Ahamed, S., Biswas, K. C., Sahu, M., Saha, K. C., Mukherjee, S. C., Pati, S., Dutta, R. N., Quamruzzaman, Q. Groundwater arsenic contamination and its adverse health effects in the Ganga-Meghna-Brahmaputra plain. Arsenic Calamity of Groundwater in Bangladesh: Contamination in water, soil and plants. Editor: Prof. Kingsuk Roy. Nihon University, Japan 2008a, pp 1352.

Chakraborti, D., Das, B., Rahaman, M. M., Chowdhury, U. K., Biswas, B., Goswami, A. B., Nayak, B., Pal, A., Sengupta, M. K., Ahamed, S., Hossain, A., Basu, G., Chowdhury, T. R., Das, D., Status of groundwater arsenic contamination in the state of West-Bengal, India: A 20 year study report. Molecular Nutrition and Food Research, 2008b .

Chakraborti, D., Singh, E. J., Das, B., Shah, B. A., Hossain, M. A., Nayak, B.Ahamed, S., Singh, N. R., Groundwater arsenic contamination in Manipur, one of the seven North Eastern Hill state in India: A future danger. Environmental Geology. 2008c.Vol.56; pp. 381 - 390.

Chakraborti, D., B. Das, B. Nayak, A. Pal, M.M. Rahman, M. K. Sengupta, Md. A. Hossain, S. Ahamed, M. Sahu, K.C.Saha, S. C. Mukherjee, S. Pati, R.N. Dutta, Q. Quamruzzaman. Groundwater Arsenic Contamination in Ganga-Meghna-Brahmaputra Plain, its Health Effects and an Approach for Mitigation. International Conference on Water Scarcity, Global Changes, and Groundwater Management Responses. 1-5 December 2008d. UNESCO UCI. California, USA (in press).

Chakraborti, D., Biswas, B. K., Chowdhury, T. R., Basu, G. K., Mandal, B. K., Chowdhury, U.K., Mukherjee, S. C., Gupta, J. P., Chowdhury, S. R., Rathore, K. C. Arsenic ground water contamination and sufferings of people in Rajnandgaon district, Madhya Pradesh, India. 1999. Current Science, 77(4), pp.502-504.

Chakraborti, D. et al., 2003, Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: a future danger? Environ. Health Perspect., 111, pp.1194-1201.

Chakraborti, D. et al., 2004, Groundwater arsenic contamination and its health effects in the Ganga-Meghna-Brahmaputra plain. J. Environ. Monit., 6, 74N-83N.

Chakraborty et al., 1982. Analyt. Chem.,H-17, pp.31-42.

Chakraborty and Saha,1987. Med.Res.,85, pp.326-324.

Chakraborty et al., 1994. Rep. Hydro. Studies in As affected areas of West Bengal,. Tech. Report, Sr D, 114.

Chappell, W.R., Abernathy, C.O. and Calderon, R.L. (eds.), (1999). ARSENIC exposure and health effects. Elsevier.

Chappell, W.R., Abernathy, C.O. and Calderon, R.L. (eds.) (2001). ARSENIC exposure and health effects IV. Elsevier.

Chappell, W.R., Abernathy, C.O., Calderon, R.L. (eds.) and Thomas, D.J. (eds.) (2003). ARSENIC exposure and health effects. Elsevier.

Chappell, W.R., Abernathy, C.O. and Cothern, C.R. (eds.) (1994). ARSENIC Exposure & Health. Science & Technology Letters.

Chatterjee et al., (1995). Analyst, 120, pp.643-650.

Chatterjee et al., (2005). Environ. Geol., 49, pp.188-206.

Chen et al., (1997). Quaternary Res., 47, pp.181-191.

Chowdhury et al., (1997). Nature, 401, pp.545-546.

Chatterjee, A. and Banerjee, R. N., (1999). Determination of lead and other metals in a residential area of greater Calcutta. Sci. Total Environ., 227, pp.175-185.

Crecelius, E. A. and Bothner, R., (1975). Geochemistries of arsenic, and antimony and related elements in sediments. Environ. Sci. Technol., 9, pp.325-333.

Cullen, W. R. (2008). Is Arsenic an Aphrodisiac? The Sociochemistry of an Element. RCS Publishing.

Das et al., (1996). Environ. Geochem. Health, 18/1, pp.5-15.

Davis, A.D., Webb, C.J., and Durkin, T.V., (1999). A watershed approach to evaluating impacts of abandoned mines in the Bear Butte Creek basin of the Black Hills: Mining Engineering, v. 51, no. 9, pp. 49-56.

Dhar et al., (1997). Curr. Sci., 73, pp48-59.

Dutta and Subramanium, (1997). Environ. Geol., 30, pp.181-185.

Das, D., Chatterjee, A., Mandal, B. K., Samanta, G., Chakraborti, D. and Chanda, B., (1995). Arsenic in groundwater in six districts of West Bengal, India: the biggest arsenic calamity in the world. Part II: Arsenic concentration in drinking water, hair, nail, urine, skinscale and liver tissues (biopsy) of the affected people. Analyst, 120, pp. 917-924.

Das, D. et al., (1994). Arsenic contamination in groundwater in six districts of West Bengal, India - The biggest arsenic calamity in the world. Analyst, 119, N168-N170.

Das, D., Samanta, G., Mandal, B. K., Chowdhury, R. T., Chandra, C. R. and Chowdhury, P. P., (1996). Arsenic in groundwater in six districts of West Bengal, India. Environ. Geochem. Health, 18, pp. 5-15.

Dahi, E. and Liang, Q. (1998). Arsenic removal in hand pumps connected iron removal plants in Noakhali, Bangladesh, International Conference on Arsenic Pollution of Ground Water in Bangladesh: Causes, Effect and Remedies, Dhaka, 8-12 February, 1998.

DPHE, (1999). Groundwater Studies for Arsenic Contamination in Bangladesh. Mott MacDonald International Ltd, BGS, Department of Public Health Engineering (Bangladesh) and Department for International Development, UK (6 vols).

DPHE-Danida Arsenic Mitigation Pilot Project, June 28, (2001), http://phys4.harvard.edu /~wilson 2bucket.html.

Environmental Health Criteria 224 (2001). ARSENIC & arsenic Compounds (2nd Edition); IPCS; WHO; Geneva.

EPA (1998). Permeable Reactive Barrier Technologies for Contaminant Remediation, Office of Research and Development, U.S. EPA, EPA-600-R-98-125. September 1998.

EPA (2000a). Technologies and Costs for Removal of Arsenic from Drinking Water, U.S.

EPA, EPA 815R00028, Prepared by Malcolm Pirnie, Inc. under contract 68C60039 for EPA ORD, December 2000. http://www.epa.gov/safewater/ars/treatments_and_costs.pdf.

EPA (2000b). Regulations on the Disposal of Arsenic Residuals from Drinking Water Treatment Plants, Office of Research and Development, U.S. EPA, EPA/600/R-00/025. May 2000. http:/ www.epa.gov/ORD/WebPubs/residuals/index.htm

EPA (2001a). Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat Systems and Permeable Reactive Barriers, U.S. EPA, Office of Solid Waste and Emergency Response, EPA-542-R-00-013, February 2001.

EPA (2001b). Treatment Technologies for Site Cleanup: Annual Status Report (Tenth Edition), Office of Solid Waste and Emergency Response, U.S. EPA, EPA-542-R-01-004, February 2001.

Evanko, C.R. and Dzomback, D.A. (1997). Remediation of Metals-Contaminated Soils and Groundwater, Prepared for the Ground-Water Remediation Technologies Analysis Center, Technology Evaluation Report TE-97-01, October 1997. http://www.gwrtac.org pdf/metals.pdf

Fields, K., Chen, A. and Wang, L. (2000a). Arsenic Removal from Drinking Water by Coagulation/Filtration and Lime Softening Plants, EPA 600R00063, Prepared by Battelle under contract 68C70008 for U.S. EPA ORD, June 2000.

Fields, K., Chen, A. and Wang, L. (2000b). Arsenic Removal from Drinking Water by Iron Removal Plants, EPA 600R00086, Prepared by Battelle under contract 68C70008 for

U.S. EPA ORD, August 2000.

Ghosh, A.R., and Mukherjee, A., (2002). Arsenic contamination of groundwater and human health impacts in Burdwan District, West Bengal, India. Geol. Soc. Am. Abstracts with Programs 34(2), 107.

Ghurye, G. and Clifford, D. (2001). Laboratory Study on the Oxidation of As(III) toAs(V), EPA 600R01021, Prepared under contract 8CR311-NAEX for EPA ORD, March 2001.

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, pp. 4300-4306.

Hossain, M.A., Mukherjee, A., Sengupta, M.K., Ahamed, S., Das, B., Nayak, B., 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), pp. 216-225.

Harvey, C. F. et al., (2002), Arsenic mobility and groundwater extraction in Bangladesh. Science, 298, pp. 1602-1606.

Harvey, C. F., (2008), Poisoned waters traced to source, Nature, 454, pp. 415-416.

Huang, W. W., Zhang, J. and Zhou, Z. H., (1992), Particulate element inventory of the Huanghe (Yellow River): a large-turbidity river. Geochim. Cosmochim. Acta, 56, pp. 3669-3680.

Kumaresam M., and Riyazuddin, P., (2001). Overview of speciation chemistry of arsenic. Current Science, vol 80 (7), April 10.

Khandekar, M. P., Bhide, A. D. and Sajwan, K. S., (1999). Trace elements in Indian coal and coal fly ash. In Biogeochemistry of Trace Elements in Coal and Coal Combustion Byproducts (eds Sajwan, K. S., Alva, A. K. and Keefer, R. F.), Kluwer Academic/Plenum Press, New York, 99-114.

Journal of Environmental Science and Health, (2003).. Special issue on arsenic: Environmental and health aspects with special reference to groundwater in South Asia (Part A), Volume A38; No. 1 .

Journal of Environmental Science and Health, (2007). Special issue on arsenic: Groundwater arsenic contamination and its effects in South East Asia (Part A) , Vol. 42; Issue 12.

Journal of Health, Population and Nutrition; (2006). Special issue on Arsenic: Arsenic contamination in developing countries: health effects, Vol. 24(2).

Joshi, A. and Chaudhuri, M. (1996). Removal of arsenic from groundwater by iron-oxide-coated sand, ASCE J. Env. Eng., 122(8), pp.769-771.

Khair, A. (2000). Factors responsible for the presence of arsenic in groundwater: Bangladesh context. In: Bangladesh Environment-2000 (Ed. M. F. Ahmed), Bangladesh Poribesh Andolon, pp. 198-209.

Khan, A.H., Rasul, S.B., Munir, A.K.M., Alauddin, M., Habibuddowlah, M. and Hussam, A. (2000). On two simple arsenic removal methods for groundwater of Bangladesh. In:

Bangladesh Environment-2000 (Ed. M. F. Ahmed), Bangladesh Poribesh Andolon, pp. 151-173.

Kohnhorst, A. and Paul, P. (2000). Testing simple arsenic removal methods. In: Water, Sanitation and Hygiene: Challenges of the Millennium, Pre-prints of the 26 WEDC Conference, Dhaka, Bangladesh, 177-181.

Lambeck K. et al. (2002). Links between climate and sea levels for the past three million years. Nature, 419, pp. 199-206.

Majumdar, P.K., Ghosh, N.C., and Chakravorty, B., (2002). Analysis of arsenic-contaminated groundwater domain in the Nadia district of West Bengal (India), Special issue : Towards Integrated Water Resources Management for Sustainable Development, Hydrological Sciences- Journal, 47(S), pp. S55-S66.

Mandal, B.K., Chowdhury, T.R., Samanta, G., Mukherjee, D.P., Chanda, C.R., Saha, K.C., Chakraborti, D., (1998). Impact of Safe Water for Drinking and Cooking on Five Arsenic Affected Families for 2 Years in West Bengal, India, The Science of Total Environment, 218, pp. 185-201.

Ma, L.Q., Komar, K.M., Tu, C., Zhang, W.H., Cai, Y. and Kennelly, E.D. (2001). A fern that hyperaccumulates arsenic, Nature, 409, 579.

MacPhee, M.J., Charles, G.E. and Cornwell, D.A. (2001). Treatment of Arsenic Residuals from Drinking Water Removal Processes, EPA 600R 01033, Prepared by Environmental Engineering & Technology, Inc. under contract 8CR613-NTSA for EPA ORD, June 2001.

Mandal et al., (1996). Curr. Sci., 70, 11, pp. 976-9786.

Manning and Goldberg, (1997). Environ.Sci.Technol.,31, pp. 2005-2011.

Matisoff et al., (1982). Ground Water, 18, 4, pp. 331-333.

Maynard et al., (1997). NRECA Report, Bangladesh.

Manning, B. A. and Goldberg, S., (1997). Adsorption and stability of arsenic(III) at the clay-mineral water interface. Environ. Sci. Technol., 31, pp. 200-201.

Master Plan to Tackle Arsenic Contamination of Groundwater in West-Bengal". May (2006). Public Health Engineering Directorate Government of West-Bengal.

McArthur, J. M., Ravenscroft, P., Safiulla, S. and Thirlwall, M. F., 2001, Arsenic in groundwater: Testing pollution mechanisms for sedimentary aquifers in Bangladesh. Water Resour. Res., 37,109-117.

McArthur, J. M. et al., 2004, Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. Appl. Geochem., 19, 1255-1293.

McArthur J.M. et al. 2008. How palaeosols influence groundwater flow and arsenic pollution: a model from the Bengal Basin and its worldwide implication. Water Resour. Res., 44, W11411, doi:10.1029/2007WR006552.

McArthur et al., 1997. Water Res. Research, 37, 109-117.

McArthur, 1999. Nature, 401, 546-547.

McArthur et al., 2004. Appl. Geochem., 19, 1255-1293.

Michael and Voss, 2008, Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the Bengal Basin, Proceedings of National Academy of Science, USA, 105(25), 8531-8536.

Mukherjee, A. B. and Bhattacharya, P., 2001, Arsenic in groundwater in the Bengal Delta Plain: slow poisoning in Bangladesh. Environ. Rev., 9, 189-220.

Mukherjee, S. C., Saha, K. C., Pati, S., Dutta, R. N., Rahman, M. M., Sengupta, M. K., Ahamed, S., Lodh, D., Das, B., Hossain, M. A., Nayak, B., Palit, Kaies, I., Barua, A. K., Asad, K. A., Mukherjee, A., and Chakraborti, D.. Murshidabad - one of the nine groundwater arsenic affected districts of West Bengal, India. Part II: dermatological, neurological and obstetric findings. Journal of Toxicology - Clinical Toxicology, 43, 2005, 835-848.

Mukherjee, A., Sengupta, M. K., Hossain, M. A., Ahamed, S., Lodh, D., Das, B., Nayak, B., Saha, K. C., Mukherjee, S. C., Pati, S., Dutta, R. N., Chatterjee, G., Chakraborti, D..Are some animals more equal than others? 2005. Toxicology 208, 165-169.

Meyerhoff. 1996. Appl. Geochem.

Morton, M.E., and Dunnette, D.A., 1994, Health effects of environmental arsenic, in

Nikolaidis, N. P. and Lackovic, J. (1998), Arsenic remediation technology -AsRT, International Conference on Arsenic Pollution of Ground Water in Bangladesh: Causes, Effect and Remedies, Dhaka, 8-12 February 1998.

NSF International (2001a), Environmental Technology Verification Report: Removal of Arsenic in Drinking Water - Hydranautics ESPA2-4040 Reverse Osmosis Membrane Element Module, NSF 0120EPADW395, March 2001.

NSF International (2001b), Environmental Technology Verification Report: Removal of Arsenic in Drinking Water - KOCH Membrane Systems TFC - ULP4 Reverse Osmosis Membrane Module, NSF 0125EPADW395, August 2001.

National Research Council (2001 update). Arsenic in Drinking water (2001 update). National Academy Press, Washington, DC.

National Research Council (1999). Arsenic in Drinking water. National Academy Press, Washington, DC.

NAS, 1977, Medical and biologic effects of environmental pollutants: arsenic. National Academy of Sciences, Washington DC.

National Institute of Hydrology(NIH) and Central Ground Water Board (CGWB), 2001. Arsenic pollution study in Yamuna sub-basin, Nadia and North 24-Paraganas Districts, West Bengal.134p.

Naidu, R., Smith, E., Owens, G., Bhattacharya, P., Nadebaum, P. (eds.) (2006). Managing Arsenic in the Environment. From Soil to Human Health. CSIRO Publishing.

Nriagu, O. (ed.) (1994). ARSENIC in the Environment (Part I): Cycling and characterization. Wiley Interscience Publication.

Nriagu, O. (ed.) (1994). ARSENIC in the Environment (Part II): Human health and ecosystem effects. Wiley Interscience Publication.

Nickson, R., Sengupta, C., Mitra, P., Dave, S. N., Banerjee, A. K., Bhattacharya, A., Basu, S.,Kakoti, N., Moorthy, N. S., Wasuja, M., Kumar, M., Mishra, D. S., Ghosh, A., Vaish, D. P., Srivastava, A. K., Tripathi, R. M., Singh, S. N., Prasad, R., Bhattacharya, S., Deverill, P. Current knowledge on the distribution of arsenic in groundwater in five states of India. 2007. Journal of Environmental Science and Health Part A 42, 1707-1718.

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

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

Oh, J. I., K., Urase, T., Kitawaki, H., Rahaman, M.M., Rahaman, M.H. and Yamamoto, K. (2000), Modelling of arsenic rejection considering affinity and steric hindrance effect in nonofiltration membranes, Water Science and Technology, 42(3-4), 173-180.

Pandey, P. K., Patel, K. S. and Subrt, P., 1998, Trace element composition of atmospheric particulate at Bhilai in central-east India. Sci. Total Environ., 215, 123-134.

Paul, P.K. and Sikdar, P.K., 2008, Assessment and Management of groundwater resources of English Bazar block, Malda district, West Bengal. Unpublished Report of Department of Science and Technology, New Delhi, 279p.

Pensaert, S. (1998), The Treatment of Aquifers Contaminated with Arsenic, Zinc and Cadmium by the Bipolar Electrolysis Technique, The Overpelt Project, 1998.

PHED (2005), Audit Report (Civil) for the year ended 31 March 2005, Public Health Engineering Department, Govt. of West Bengal, pp. 57-70.

Pierce, M.L. and Moore, C.B. (1982), Adsorption of arsenite and arsenate on amorphous iron hydroxide, Water Resources, 16, 1247-1253.

Polizzotto, M.L., Benjamin, D.K., Benner, S. G., Sampson, M. and Fendorf, S., 2008, Near-surface wetland sediments as a source of arsenic release to ground water in Asia,Nature, 454, 505-509.

Ray, A.K., 1999, Chemistry of arsenic and arsenic minerals relevant to contamination of ground water and soil from subterranean source. Everyman's Science 35(1).

Roychowdhury, T. et al., 1999, Arsenic poisoning in the Ganges delta. Nature, 401, 545-546.

Roychowdhury, T., Tokunaga, H. and Ando, M., 2003, Survey of arsenic and other heavy metals in food composites and drinking water and estimate of dietary intake by the villagers from anarsenic-affected area of West Bengal, India. Sci. Total Environ., 308, 15-35.

Safmiuddin, M. and Karim, M.M, 2001, Groundwater arsenic contamination in Bangladesh: Causes, Effects and Remediation, Proceedings of the 1st IEB international conference and 7th annual paper meet; 2001 November 2-3; Chittagong, Bangladesh: Institution of Engineers, Bangladesh.

Saha, K.C. (ed.) (2002). ARSENICOSIS in West Bengal (Environmental problems and solutions). Sadananda Prakashani; Kolkata, India.

Saha, A.K., 1991. Genesis of arsenic in groundwater in parts of West Bengal. Center for Studies on Man and Environment, Calcutta, Annual Volume.

Sengupta, S., McArthur, J . M., S arkar, A ., Leng, M. J., Ravenscroft, P., Howarth, R. J. and Banerjee, D. M., 2008, Do Ponds Cause Arsenic-Pollution of Groundwater in the Bengal Basin? An Answer from West Bengal. Environ. Sci. Technol, 40 (30).

Sexana, V. K., Sanjee Kumar, and Singh, V. S., (2004). Occurrence, behaviour and speciation of arsenic in groundwater. Current Science, vol 86(2), Jan. 25.

Sikdar, P. K. and Banerjee, S., 2003, Genesis of arsenic in groundwater of Ganga delta an anthropogenic model. Journal of Human Settlements April: 10-24.

Sikdar, P. K. and Chakraborty, S., 2008, Genesis of arsenic in groundwater of North Bengal Plain using PCA: A case study of English Bazar Block, Malda District, West Bengal, India, Hydrological Process. 22, 1796-1809.

Singh, A. K., 2004, Arsenic contamination in groundwater of Northeastern India. In Proceedings of 11th National Symposium on Hydrology with Focal Theme on Water Quality, National Institute of Hydrology, Roorkee, 255-262.

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

Smedley, P., 2004, Arsenic occurrence in groundwater in South and East Asia - Scale, causes and mitigation. Technical Report, Vol. II, The World Bank, Report no. 31303.

Sparks, Donald L., (2005). Advances in Agronomy, Vol 86. Elsevier Academy, 440p.

Thornton, I., 1996, Sources and pathways of arsenic in the geochemical environment: health implications. Environ. Geochem. Health, 113, 153-161.

Tripathi, R. M., Raghunath, R. and Krishnamoorthy, T. M., 1997, Dietary intake of heavy metals in Bombay city, India. Sci. Total Environ., 208, 149-159.

Tufano K.J. and Fendorf S., 2008, Confounding impacts of Fe-reduction on As-retention. Envir. Sci. Tech. 43, 4777 - 4783.

Umitsu M. 1993. Late Quaternary sedimentary environments in the Ganges Delta. Sedimentary Geology, 83, 177-186.

US-EPA, (1998). Locating and estimating air-emissions from sources of arsenic and arsenic compounds. EPA-454/R-98-013.

US-Geological Survey, (1999). Arsenic in groundwater of the Willamette Basin, Oregon: Geochemistry of arsenic. http://oregon.usgs.gov/pubs-dir/online /Html/WRIR98-4205.

World Health Organizations, (1993). Guidelines for drinking water quality, vol. 1-Recommendation (2nd Ed.) WHO, Geneva.

Warwick, P. D., Milici, R. C., Landis, E. R., Mukhopadhyay, A., Adhikari, S. and Hackley, P. C., 2001, Coal quality and trace element characteristics of samples from Sohagpur coal field, North Central India. In Coal Quality: Global Properties (eds Pierce, B. S., Dennen, K. O. and Finkelman, R. B.), Int. Conf. US Geol. Surv., Reston, Virginia, US Geological Survey Circulation 1272, 24-26 September 2001.

Rahman, M.M. and Rahaman, M.H. (2000), Application of low-pressure nanofiltration coupled with a bicycle pump for the treatment of arsenic-contaminated groundwater, Desalination, 132, 307-314.

Sarkar, A., Thogersen, Choudhury, Rahaman, Akhter and Choudhury (2000), Bucket treatment unit for arsenic removal. In: Water, Sanitation and Hygiene: Challenges of the Millennium, Pre-prints of the 26 WEDC Conference, Dhaka, Bangladesh, 308-310.

Selvin N., Messham G., Simms J., Pearson I. and Hall J. (2000), The Development of Granular Ferric Media - Arsenic Removal and Additional Uses in Water Treatment, Proc. AWWA Water Quality Technology Conference, Salt Lake City, USA.

Shin Nihon Salt Co. Ltd. (2000), Report on Performance of Read-F Arsenic Removal Unit (ARU), October 2000.

Smyth, D.J., Blowes, D.W. and Ptacek, C.J. (2000), Steel production wastes for use in permeable reactive barriers (PRBs), Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 20-23, 2000, Monterey, CA.

SOES (2000), Performance of Arsenic Removal Plants for Treating Ground Water with Community Participation, Report No.1, School of Environmental Studies, Jadavpur University, Kolkata, India.

SOES (2001), Fate of Three Crore Rupee Arsenic Removal Plants in Murshidabad, Report No. 2, School of Environmental Studies, Jadavpur University, Kolkata, India.

SOES (2003a), A Study Report on Efficiency of 259 Arsenic Removal Plants Installed in Ten Blocks of the District North 24 Parganas, West Bengal, Report No. 4, School of Environmental Studies, Jadavpur University, Kolkata, India.

SOES (2003b), Usefulness of Arsenic Removal Plants: A Case Study in Kolsur Gram Panchayet of Deganga Block in North 24 Parganas, West Bengal, India, Report No. 5, School of Environmental Studies, Jadavpur University, Kolkata, India.

SOES (2004), Physical Aspects of Arsenic Removal Plants (ARPs) Installed in 4 Different Blocks of North 24-Parganas, West Bengal (March-April 2004), Report No. 6, School of Environmental Studies, Jadavpur University, Kolkata, India.

Su, C. and Puls, R.W. (2001), Arsenate and arsenite removal by zerovalent iron: kinetics, redox transformation, and implications for in situ groundwater remediation, Environmental Science & Technology, 35, 1487-1492.

Wang, L., Chen, A. and Fields, K. (2000), Arsenic Removal from Drinking Water by Ion Exchange and Activated Alumina Plants, EPA 600R00088, Prepared by Battelle under contract 68C70008 for U.S. EPA ORD, October 2000.

Wegelin, M., Gechter, D., Hug, S., Mahmud, A., Motaleb, A. (2000), SORAS - a simple arsenic removal process (http://phys4.harvard.edu/~wilson /mitigation/SORAS_ Paper.html).

Will, F. (1995), Removing toxic substances from soil using electrochemistry, Chemistry and Industry, 376-379.

Young, E. (1996), Cleaning up arsenic and old waste, New Scientist, 14 December, 22,

Zhang, W., Cai, Y., Tu, C. and Ma, L.Q. (2001), Speciation and distribution of arsenic in an arsenic hyperaccumulating plant, Biogeochemistry of Environmentally Important Elements. Symposia, Papers Presented Before the Division of Environmental Chemistry, American Chemical Society, San Diego, CA, April 1-5, 2001.

Nickson et al., 2000. Appl. Geochem., 15, 403-413.

Pal et al., 2001. Gond. Res., 5, 2, 501-512.

Pal et al., 2002, 82, 5, 554-561.

PHED, 1991. Arsenic Pollution in Groundwater in West Bengal, Report.

Pontius, F.W., Brown, K.G., and Chen, C., 1994, Health implications of arsenic in drinking water: Journal of the American Water Works Association, September, p.52-63.

Price and Picher, 2002. EOS Trans., Am. Geophys. Union, 83, 47.

Purakait and Mukherjee, 2008. www.springerlink.com/contentfh74142443112421.

Ravi Shankar et al., 2001. J. Geol. Soc. India, 58,269-271.

Rott and Lamberth. 1993. Water Supply, 11,143-156.

Rowland et al., 2002. Water Res. Research, 38, 1-19.

Rowland et al., 2007. Geobiology, 5, 3, 281-292.

Roy et al., 2007. Proc. Int. Workshop on Arsenic, Kolkata.

Saha, 1998. CSME Publ., p. 189.

Sengupta et al., 2004. Environ. Geol., 45, 1071-1081.

Sengupta et al., 2008. http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/asap/abs/es702988m.html Smedly and Kinniburg , 2002. Appl. Geochem., 17, 517-568.

Stanger, 2005. Environ. Geochem. Health, 2005.

Stanger et al., 2006. Environ. Geochem. Health, 28.

Sullivan and Aller, 1996. Geochim. Cosmochim. Acta, 60, 9, 1-22.

Swartz et al., 2004. Geochim. Cosmochim. Acta, 68, 4539-4557.

Ta TKO et al., 2002. Sed. Geol., 152, 313-325.

Van Beek.1983. Ground Water, 21.

Welch, A.H., Lico, M.S., and Hughes, J.L., 1988, Arsenic in ground water of the western United States: Ground Water, v. 26, no. 3, p. 333-347.

WHO, 2008. www.who.int/mediacentre/factsheet/fs210/en/

Yang, Li, Donahoe, Rona J., and Graham, Elizabeth Y., Geological Sciences, Univ of Alabama, Box 870338, 202 Bevill Building, Tuscaloosa, AL 35487, yang003@bama.ua.edu

Important Websites dedicated to arsenic problem in India

1. http://www.soesju.org
2. http://bicn.com/acic/
3. http://www.wbphed.gov.in/Arsenicbackgroud.html
4. http://www.dngmresfoundation.org/
5. http://physics.harvard.edu/~wilson/
6. http://www.lehigh.edu/~aks0/arsenic.html
7. http://projectwellusa.org/

Contributors

1. **Basu, Biplab Bhusan, Dr.**
   Director
   School of Fundamental Research, Kolkata.
   Email : biplabbb@gmail.com

2. **Chakraborti, Dipankar, Prof.**
   Director
   School of Environmental Studies
   Jadavpur University, Kolkata.
   Email : dcsoesju@vsnl.com

3. **Das, Bhaskar, Dr.**
   School of Environmental Studies
   Jadavpur University, Kolkata.

4. **Ghosh, N. C., Dr.**
   Scientist-F & Head
   Ground Water Hydrology Division
   National Institute of Hydrology, Roorkee.
   Email : ncg@nih.ernet.in

5. **Jain , C. K., Dr.**
   Scientist-F
   Centre for Flood Management Studies (Guwahati),
   National Institute of Hydrology, Guwahati.
   Email : ckj_1959@yahoo.co.in

6. **Mishra, Ram Mohan, Mr.**
   Joint Secretary (A), Ministry of Water Resources
   Govt. of India, New Delhi.
   Email : jsadm-mowr@nic.in

7. **Mukherjee , Subhash Chandra, Dr.**
   Department of Neurology Medical College, Kolkata.

8. **Nath, K. J., Prof.**
   Ex. Director, All India Institute of Public Health & Hygiene & Chairman, Arsenic Task Force, West Belgal.
   Email : kumarjyoti@rediffmail.com

9. **Pati, Shyamapada, Dr.**
   Department of Obstetrics and Gynaecology,
   IPGMER, SSKM Hospital, Kolkata.

10. **Roy, Abhijit , Mr.**
    Superintending Hydrogeologist
    Central Ground Water Board,
    Eastern Region, Kolkata.

11. **Saha, Dipankar, Dr.**
    Scientist-D
    Central Ground Water Board
    Mid Eastern Region, Patna.
    Email : dsaha002@yahoo.com

12. **Saha, Khitish Chandra, Dr.**
    Professor(Retd.), Deptt. of Dermatology
    School of Tropical Medicine, Kolkata.

13. **Sharma, S. K. Dr.**
    Consultant (GW)
    Ministry of Water Resources,
    Govt. of India,
    New Delhi.

14. **Sinha Ray, S. P., Dr.**
    Ex-Member, Central Ground Water Board & Chairman,
    Fluoride Task Force, West Bengal.
    Email : cgws@rediffmail.com

15. **Srivastava, S. K., Dr.**
    Scientist-B
    Central Ground Water Board, Lucknow.
    Email : sudhir63@yahoo.co.in

Annexure

A. Sustainability of Arsenic Removal Technology

Based on the working principles, the Arsenic removal methods can be classified into three categories: (i) Chemical precipitation method, (ii) Adsorption method, and (iii) Membrane separation method. An appraisal of different treatment technologies and their effectiveness reported from laboratory testing conducted by researchers has been given through **pages 105-108 (Chapter-6).** Among these categories, Membrane separation method by Reserve osmosis has been reported the most promising one with removal efficiency of 99% followed by the Chemical precipitation method using Lime softening with removal efficiency of about 95%. The Chemical precipitation method by Oxidation/iron co-precipitation, has been reported to have removal efficiency ranges between 90 and 99 % under the controlled pH-Eh conditions and an optimized Fe dosage. The efficiency of adsorption methods by Activated alumina or by Ion exchange have been reported ranges above 45%. The Reverse osmosis technology although does not produce toxic solid waste but requires high tech operation and maintenance, and relatively costlier than other two methods. The oxidation/iron co-precipitation method is simple in operation and less costly, but produces toxic solid waste and requires daily dosing of chemicals; while the adsorption method, which is less efficient and relatively costlier than the oxidation/iron co-precipitation method, also produces toxic solid waste and requires periodic replacement/ regeneration of filtering media. Apparently, Lime softening and Iron co-precipitation techniques sound to be the most effective removal technologies, barring the Membrane separation method, however, the adsorption technique showed successful field performances and implications.

Performances of 10 arsenic removal devices developed by different agencies, and applied in West Bengal to treat for removing arsenic from arsenic contaminated groundwater with some degree of success have been given in Table 5.1 **(pages 76 -77) and Fig 5.1 (pages 101-102).** Very few plants could show satisfactory performance at the field level, both in terms of arsenic removal efficiency and in sustainable running. The devises which have shown relatively good performances at the field level are: Granular Ferric Hydroxide (GFH) of Pal Trockner (P) Ltd., Kolkata - a German Technology; Arsenic Removal Plant by Oxide India (Catalysts) Pvt. Ltd, Durgapur; and Apyron Arsenic Treatment Units by Apyron Technologies (P) Ltd. representing Apyron Technologies. The working principles of these technologies are based on adsorption technique. The major setbacks, with other devices remain with the operation, maintenance, replacement and removal of used filters. The systems in which O & M have been linked to the responsibility of suppliers have shown satisfactory performance. It was reported that majority of the operation and maintenance issues were related to tube wells, that have nothing to do with the ARP or its chemical media.

It indicates that sustainability of arsenic removal devices largely relies on the operation and maintenance of the devices, the consistency of the source water quality, and the acceptability of the devices by the users and beneficiaries. A technology having simple operation and cared maintenance as well as cost effective, users and eco-friendly has the potential of sustainability. There is, therefore, need arises for R & Ds to improve upon the existing devices and/or develop new technologies to satisfy the conditions of eco-friendliness (less sludge producing/sludge free), cost effectiveness and user friendliness. 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 meet the demand of potable water supply.

B. Sludge management

The arsenic removal devices, which have been implemented in the field particularly in West Bengal, are based on the working principles of Chemical precipitation and Adsorption. Both the arsenic treatment techniques produce several different types of waste, including sludges, brine streams, backwash slurries and spent media. 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. Arsenic sludge management has been reported as one of the major concerns (pages 94-95, and 112-113). Even the treatment devices, which have shown relatively good performances at the field level, namely; Granular Ferric Hydroxide (GFH) of Pal Trockner (P) Ltd., Kolkata - a German Technology; Arsenic Removal Plant by Oxide India (Catalysts) Pvt. Ltd, Durgapur; and Apyron Arsenic Treatment Units by Apyron Technologies (P) Ltd., are also not devoid of sludge management problem. How the sludge produced and/ or being produced from different arsenic removal filters in the schemes implemented in West Bengal is disposed and managed, has not been clearly spelt out in any document, rather remained an unanswered question. The All India Institute of Hygiene and Public Health (AIIH&PH), Kolkata has suggested the following methods for arsenic rich sludge management:

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

A number of studies (Rouf and Hossain, 2003; Mahzuz et al., 2009) showed that use of arsenic contaminated sludge in proportion in making bricks nearly at 1000oC neither reduces the compressive strength of bricks nor cause any negative effects. The studies clearly suggested that arsenic and iron sludge can be used as brick material. Banerjee and Chakraborty (2005) reported that stabilization process by briquette, cement-sand mortar and concrete mixing with other common ingredient do not produce toxicity Characteristic leachate beyond permissible limit. It was suggested that 25% (by volume) of cement can be replaced by the fly ash to stabilize arsenic-laden to the tune of 11% (by volume of cement-mortar. It indicates that arsenic sludge can also be used/managed effectively for our demand management.

C. Potentials of deeper aquifers and surface water as alternate source of drinking water

(i) Potential of surface water sources

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 in West Bengal. Eight such surface water based schemes have been operationalized by the West Bengal Government in different places, covering population of 3.85 million in 1266 mouzas. All the surface water based schemes are successfully running to provide potable water supply to masses covered under the schemes. In Bihar also, a number of surface water based pipe water supply schemes with their intake from the Ganga River to meet demand of multi-village supply are under construction. Surface water based schemes are constrained by number of factors, namely; (i) technical feasibility, (ii) water availability, (iii) cost factors, etc

Surface water sources are not omnipresent, and, therefore, cannot be located and extended everywhere. Moreover, water in some of the flowing/ stationary bodies remains only for a specific period of a year and cannot form the regular source for public water supply system. In addition to that, due to changes in the river discharges and its flow course, it is difficult to keep a sustainable intake point of water for the whole year. Most of the arsenic affected areas in the Ganges are along linear track of the river Ganga in U.P., Bihar, and Jharkhand state and along the river Bhagirathi in West Bengal, supply of potable water from the surface water sources, wherever feasible, can be the most promising alternative. In areas, where surface water supplies are available or can be made available by any water conservation method, surface water based scheme after suitable purification could be the suitable proposition for potable water supply.

(ii) Potentials of Deeper Aquifers

The arsenic contaminated zones in the Ganga-Brahmaputra fluvial plains mostly lie within the shallow aquifer (<100m bgl). The deep aquifers (>100 m bgl) underneath the contaminated shallow aquifer, in many places of Bengal Delta Plains, are normally seen arsenic free. The deeper aquifer is separated by a thick clay layer of appropriate composition from the shallow aquifer. From the isotopic studies carried out in West Bengal, it was observed that there was no hydraulic connection between the shallow and deep aquifers as they belong to different age groups. Those deep arsenic free aquifers have the potential to yield nearly 5 to 20 lps of water, which is largely adequate to meet demand of water in the domestic sector. Field studies indicated 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 **(pages 61-63)**. Similar is the experience from Bihar; deeper aquifers occur under semi-confined to confined conditions are arsenic free and hold groundwater of about ~3000 yrs, The deeper arsenic-safe aquifer has potential to yield about 150-200 m3 /hr, which can be taped through heavy duty deep tube wells.

A properly designed well with screen length tapping the desired aquifer, along with cement sealing of interface of shallow arseniferous aquifer and deep aquifer, is proficient in safe withdrawal of water from the deep aquifer having no risk of arsenic rich water. 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 an alternate option of dependability on groundwater resources.

References

Banerjee, Goutam and Ranjan Chakraborty, (2005). Management of arsenic-laden water plant sludge by stabilization, Jour. Clean Technologies and Environmental Policies. 7(4), pp. 270-278, Springer Berlin / Heidelberg .

Mahzuz, H. M. A., R. Alam, M. N. Alam, R. Basak, and M. S. Islam, (2009). Use of arsenic contaminated sludge in making ornamental bricks. Intl. J. Environ. Sci. Tech., 6(2), pp. 291-298.

Rouf, Abdur Md., and Md. Delwar Hossain, (2003). Effects of using arsenic-iron sludge in brick. A compilation of papers presented at the International Symposium on Fate of Arsenic in the Environment, *Published by*, ITN Centre, BUET on behalf of the Bangladesh University of Engineering and Technology and The United Nations University, Tokyo, Japan.. ISBN 984-32-0507-3.