# Geogenic Contamination and Technologies for Safe Drinking Water Supply

**8**

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## 8.1 Introduction

Geogenic contaminants in groundwater are those which originate from the rock material by weathering and deposit in the aquifer and enter into aqueous phase by the processes of natural soil/rock-water interaction. Among the geogenic contaminants, arsenic and fluoride are the most widespread affecting health of millions of people the world over by the intake of excessive amounts beyond the permissible limit. The guideline values of the World Health Organization (WHO) for drinking water are 10 μg/l for arsenic and 1.5 mg/l for fluoride, and presently India also follows the same guidelines. These geogenic substances are mobilized from aquifer under certain geochemical and geological conditions. Despite these facts, arsenic- and fluoride-contaminated aquifers are continued to have tapped for drinking and irrigation water supplies because of the growing scarcity of water resources, and groundwater is mostly preferred in India as reliable source for drinking and irrigation water in rural areas.

Exposure to arsenic can cause variety of disorders, ranging from changes in skin pigmentation, hyperkeratosis and cardiovascular problems to cancer [10]. While small amounts of fluoride provide protection against caries and strengthening of bones, elevated concentration in water can lead to irreversible fluorosis [3].

India is one of the large-scale victimized countries of arsenic and fluoride contamination in groundwater. A number of district covering approximately 88,688 km² and 50 million people in seven states, namely, West Bengal, Bihar, Uttar Pradesh, Jharkhand, Assam, Manipur and Chhattisgarh, have been reported exposed to groundwater arsenic contamination above 50 μg/l [16], while about 66.62 million people, out of which are 6 million children below the age of 14 years from 19 states, namely, Andhra Pradesh, Assam, Chhattisgarh, Delhi, Gujarat, Haryana, J & K,

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Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal, have been reported exposed to fluoride contamination in groundwater above 1.5 mg/l [26]. With every additional survey, new arsenic- and fluoride-affected villages and people suffering from arsenic- and fluoride-related diseases are being reported [16].

Although the exact sources and geochemical processes are yet to be established, however, the cause has been recognized to be of geogenic origin, and the contaminants are released from soil under conditions conducive to dissolution from solid phase on soil grains to liquid phase in water. Whether the understanding and technological options available are adequate to resolve the issues or there are further needs to undertake, more investigations to strengthen understanding of geochemical processes to mitigate and remediate geogenic contaminants in groundwater are some of the concerns that need to be addressed for attaining sustainability in supply of safe groundwater in the affected areas.

It is in those contexts, the chapter is focused to give an insight on sources of geogenic contaminants, probable causes of attribution, geochemical processes that dominate mobilization in the aquifer systems, etc. to help suggest some possible conservation and remedial measures to restore back dependability of using groundwater resources with less health risks.

The detailed illustrations on clinical health risks, social aspects, scope of removal technologies developed, scale-up of the problem in different areas, geochemistry part and behaviours of the contaminants that coexist with other chemical constituents, which are available in many literatures, are kept beyond the purview of this paper.

## 8.2    Arsenic Menace in India

Arsenic contamination 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. Almost all the identified arsenic-affected areas, in the Gangetic plains, are in a linear track on both sides of the River Ganga in UP, Bihar, and Jharkhand or the River Bhagirathi in West Bengal (Fig. 8.1), except areas in Chhattisgarh and three districts of Bihar, namely, Darbhanga, Purnea and Kishanganj. The areas in Assam and Manipur are in the flood plains of the Brahmaputra and Barak, respectively [16]. Ironically, all the arsenic-affected areas have the river routes originated from the Himalayan region. Whether the source material has any bearing to the outcrops or not is a matter of research, however, over the years, continued exploitation of groundwater has made the problem of arsenic contamination more complicated, to a large extent at both local and regional scale, by a number of unknown factors.

Arsenic in groundwater in the Holocene aquifers, which are of Quaternary age and comprise of micaceous sand, silt and clay derived from the Himalayas, 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 clay [4, 12].
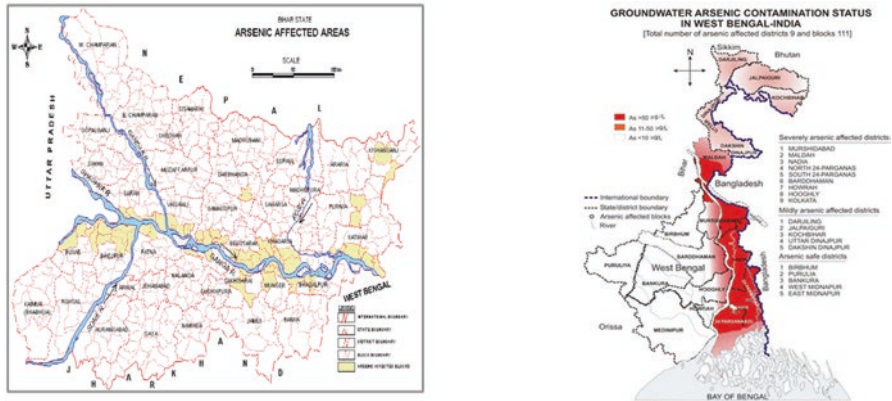
**Fig. 8.1** Arsenic-contaminated areas along the River Ganga in Uttar Pradesh, Bihar and along the river Bhagirathi in West Bengal [16]

### 8.2.1   Hypothesis on Origin of Arsenic

A numerous speculations about the primary source of arsenic in the Bengal basin are available in literature. Several investigators have given varied opinions on origin of arsenic; however, commonality of those opinions is natural phenomena attributed by anthropogenic interferences [1, 2, 17]. The prominent hypotheses are:

 (i)  Arsenic has been 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 [19].
 (ii)  Arsenic has been transported by the North Bengal tributaries of Bhagirathi and Padma near the Gorubathan base-metal deposits in the Eastern Himalayas [17].
(iii)  Arsenic has been transported with the fluvial sediments from the Himalayas [12] and deposited in the Holocene aquifer. This is the most accepted hypothesis at present.

The physical processes associated with the most commonly accepted hypothesis as explained by many investigators [15, 23, 24] are:

The attribution of arsenic in groundwater is from the subsurface sediments. These subsurface sediments originated from the mountains in the upstream river catchment had been deposited thousands of years back, and the deposited material formed the aquifer. Mountain erosion led to a release of rock-forming minerals and arsenic into the hydrosphere. Eroded iron turned to rust, iron (hydroxide) [(FeO(OH)] and formed particles as well as coatings on the surface of particles as such silt and sand. The FeO(OH) was capable to scavenge dissolved arsenic from water and bound it to its surface. Suspended particles with FeO(OH) coatings and adsorbed arsenic were washed into rivers and transported downstream. Arsenic bound to

suspended solids was thus brought to rivers' deltas and deposited in the soils with the settling sediments. For thousands of years, deposits of river sediments have created the soil layers (sediments) that formed the delta as it is known today.

### 8.2.1.1 Hypothesis on Occurrence and Mobilization of Arsenic in Groundwater

Numerous literatures [13, 15, 20, 23] explaining occurrence of arsenic in groundwater, particularly in the alluvial aquifers of the Ganges delta, are available. 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 [5]. 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, releasing soluble $As^{3+}$, sulphate ($SO_4^{2-}$) 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 sulphide. The released $As^{3+}$ is partially oxidized to $As^{5+}$ by microbial-mediated reactions. The chemical reaction is given by:

$$FeAsS + 13\,Fe^{3+} + 8\,H_2O \rightarrow 14\,Fe^{2+} + SO_4^{2} + 13\,H^+ + H_3AsO_4\ \left(aq.\right)$$
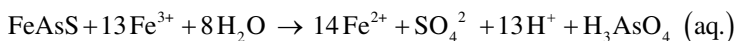
(ii) Dissolution of **As**-rich iron oxyhydroxides (FeOOH) due to the onset of reducing conditions in the subsurface: Under oxidizing conditions and in the presence of **Fe**, inorganic species of **As** are predominantly retained in the solid phase through interaction with FeO(OH) coatings on soil particles. The onset of reducing conditions in such environments can lead to the dissolution of FeO(OH) coatings. Fermentation of peat in the subsurface releases organic molecules (e.g. acetate) to drive reducing dissolution of FeO(OH), resulting in release of $Fe^{2+}$, $As^{3+}$ and $As^{5+}$ present on such coatings. The chemical reaction is given by:

$$8\,FeOOH - As_{(s)} + CH_3COOH + 14\,H_2CO_3 \rightarrow 8\,Fe^{2+} + As_{(d)} + 16\,HCO_3^{-} + 12\,H_2O$$
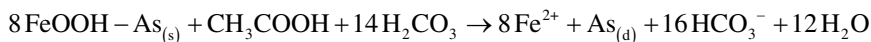
where $As_{(s)}$ is sorbed As, and $As_{(d)}$ is dissolved As**.**

(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 FeO(OH) under reducing conditions is considered to be the most probable reason for excessive accumulation of **As**

in groundwater. Elaborating further to this hypothesis linking it to the most commonly accepted theory of origin of arsenic, the cause of As in groundwater has been explained as follows:

The accepted geochemical theory is anxious dissolution of FeO(OH) and release of previously absorbed arsenic. The arsenic remains fixed in the sediments as long as groundwater contains sufficient dissolved oxygen. Arsenic is released when these come in contact with the oxygen-depleted groundwater [12, 14, 15, 23]. During the inundation periods, high loads of river sediments (suspended particles) are frequently covering the topsoil layers including vegetation. This process results in the entrapment and subsequent burial of natural organic matter (rotten plant, peat) in the sediment structure. Organic matter can serve as substrate (food) for microorganism to thrive on. These microorganisms consume dissolved oxygen to degrade organic material, thereby leading to oxygen depletion in the groundwater (anoxic conditions). Under anoxic condition, some microorganisms can use FeO(OH) as a source of energy instead of oxygen. Degradation of solid FeO(OH) particles releases arsenic formerly attached firmly to the particle surface.

## 8.2.2   Present Status of Arsenic Problem

It is now generally accepted that the source is of geological origin and percolation of fertilizer residues might have played a modifying role in its further exaggeration. Identification of parental rocks or outcrops including their sources, routes, transport, speciation and occurrence in Holocene aquifers along fluvial tracks of the Ganga-Brahmaputra-Barak valley and in scattered places, adjoining to it, in their basins is yet to be studied comprehensively. The question of the possible role of excessive withdrawal of groundwater for its triggering, however, has continued to have divided opinions. Whether the processes of physicochemical transformation were influenced by excessive groundwater exploitation or there were other coupled actions of a number of hydrogeological and geo-environmental disturbances over the periods is yet to be established.

Since arsenic menace was first surfaced in year 1984, substantial works have been carried out mostly towards enrichment of knowledge and understanding, which can be categorized as follows:

  (i) The source and cause of arsenic contamination in groundwater
 (ii) Extent and magnitude of scale-up
(iii) Mechanism of dissolution of arsenic from soil phase to aqueous phase
 (iv) Impact on people health: diagnosis of sickness and symptoms
  (v) Development of technologies for removal of arsenic from extracted groundwater
 (vi) Analytical techniques for detecting arsenic in groundwater

The understanding and knowledge base accomplished from R & D activities are not adequate to resolve the problem completely. The counteractive and

precautionary measures initiated by the government are not 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 vary from identification of shortfalls to success stories. In this context, a detailed compilation made by NIH and CGWB [16] is referred. The present state of affairs of the problem in many states of India demands a systematic translation of success stories of one place/region to another, overcoming the shortfalls by conceiving R & D studies in areas wherever they are deemed fit.

Although the calamity of groundwater arsenic contamination in the other states is not as old as and as serious as it is in West Bengal, however, scaling up and surfacing of groundwater arsenic with every additional survey in a number of districts pose a serious threat towards further exploitation and uses of those contaminated aquifers and also to the people using the contaminated groundwater in different forms. Studies carried out and action taken so far in other states to understand the problem-resolving issues, counteractive measures, etc. are meagre in comparison to West Bengal, while characteristics and features of the problem, geological formations and causes of the problem are largely similar. Thus, the experiences and knowledge base acquired so far from the West Bengal could help evolve a framework of activities and sustainable mitigation strategies for other states as well.

## 8.3    Fluoride Menace in India

Fluoride contamination in groundwater in 19 out of 35 states and UTs in India and its intake with drinking water in excess to the permissible limit of 1.5 mg/l has emerged as more serious problem than arsenic from an endemic disease known as 'fluorosis' [7]. Its occurrence is quite widespread that varies from one hydrogeological and geological setting to another. About 70–100% districts in Andhra Pradesh, Gujarat and Rajasthan; 40–70% districts in Bihar, Delhi, Haryana, Jharkhand, Karnataka, Maharashtra, Madhya Pradesh, Orrisa, Tamil Nadu and Uttar Pradesh; and 10–40% districts in Assam, Jammu and Kashmir, Kerela, Chattisgarh and West Bengal have been reported affected by fluoride contamination in groundwater, while the endemicity for the rest of the states is not known. The fluoride level in the affected states ranges from 0.1 mg/l up to a maximum of 29 mg/l. Fig. 8.2 [26] depicts percentage districts and range of fluoride concentration detected in different states of India. The occurrence mainly in top aquifer system, i.e. in shallow groundwater zone, has been reported due to the result of the geochemical processes of the source rock material. Unlike arsenic occurrence in groundwater in a linear track represented by fluvial alluvium sediments, fluoride contamination is widespread in different states represented by varied hydrogeological formations. The only commonality with arsenic problem is that both have geogenic source and are attributed by the geochemical processes of the source rock-water interaction. The hydrogeological formations of the fluoride-contaminated aquifer are mainly basalt; crystalline rocks, viz. granites, gneisses and schists; and Precambrian sedimentary, viz. consolidated sandstones, shales, limestones, Gondwana sedimentary, etc.
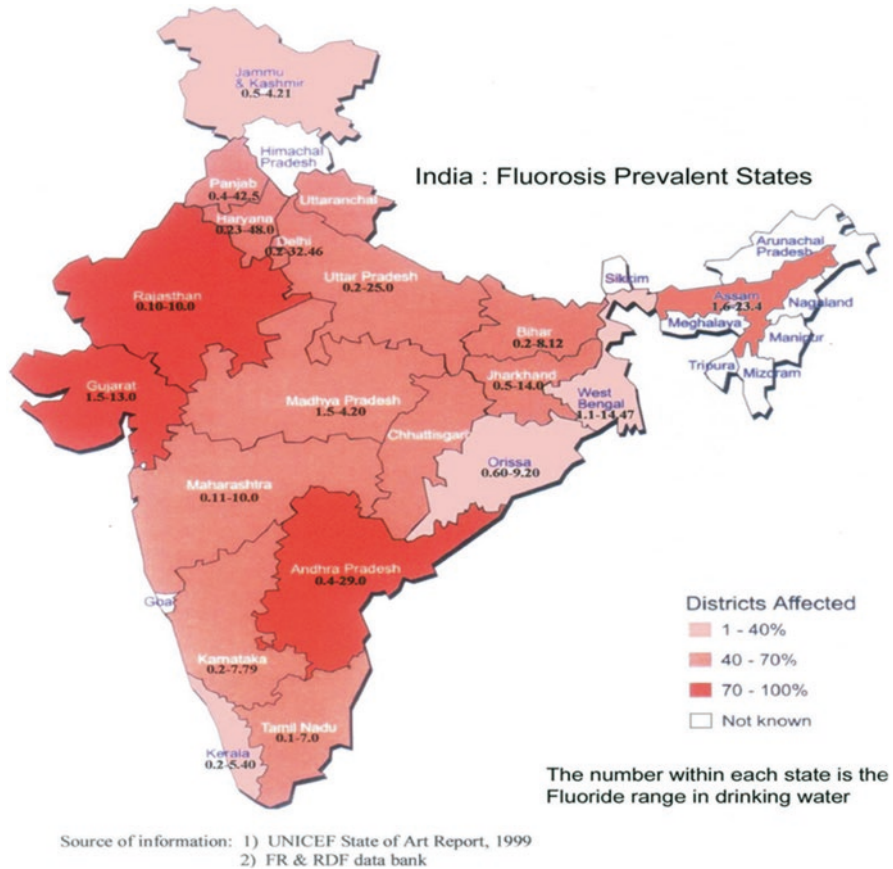
**Fig. 8.2** Fluoride-contaminated states in India and percent districts affected in each state and fluoride range detected in drinking water [26]

## 8.3.1 Fluoride-Containing Rocks

The fluoride content of groundwater varies greatly depending on the geological settings and rock types. The most common fluorine-bearing minerals are fluorite, apatite and micas. Fluoride problems are predominant in places where these minerals are most abundant in host rocks. Groundwater from crystalline rocks, especially granites (deficient in calcium), are particularly sensitive to relative high fluoride concentrations. Such rocks are found especially in Precambrian basement areas. Fluorine transport in the aqueous solutions is mainly controlled by the solubility of $CaF_2$ [6]. Sedimentary rocks also contain fluorine concentration. In carbonate sedimentary rocks, the fluorine is present as fluorite. Metamorphic rocks also contain fluorine concentration.

The geological formations represented by the states affected by fluoride contamination in groundwater possess similar rock types. The occurrence of fluoride in

groundwater is not a phenomenal but a continued geochemical process of rock-water interaction whose triggering effect could notice through large-scale laboratory and clinical detection.

### 8.3.2 Factors Affecting Natural Fluoride Concentration

The ultimate fluoride concentration in groundwater largely depends on its reaction time with aquifer materials. Groundwater can have high fluoride concentration if it has longer residence time in the aquifers. Such groundwaters are associated with deep aquifer systems and a slow groundwater movement. Shallow aquifers which contain recently infiltrated rainwater usually have low fluoride concentration.

Arid regions are prone to high fluoride concentrations because of slow groundwater movement and thereby long residence time with rock materials. The fluoride contents in water may increase during high evaporation if solution remains in equilibrium condition with calcite and alkalinity. Fluoride increase is less pronounced in humid tropics because of high rainfall and their diluting effect on groundwater chemical composition.

### 8.3.3 Fluoride Removal Technologies

Defluoridation techniques, currently in practices, can broadly be divided in three categories according to the main removal mechanism:

- Chemical additive methods
- Contact precipitation
- Adsorption/ion exchange methods

Based on the above defluoridation mechanisms, a number of devices have been developed in which the Nalgonda technique (named after the village in Andhra Pradesh where the method was pioneered) which follows the mechanism of chemical additive method and uses alum (hydrate aluminium salts) as coagulant has acquired popularity. The other devices, which are based on adsorbent/ion exchange, such as activated alumina ($Al_2O_3$), activated charcoal, or ion exchange resins, are used for defluoridation of contaminated groundwater for both community and household uses.

## 8.4 Groundwater Usages Scenarios in India

In India, groundwater meets nearly 85% of rural domestic water needs, 50% of urban and industrial water needs and about 60% of irrigation requirements [8, 25]. Usages of groundwater in India have increased at a very rapid pace by the advent of tube wells as the groundwater extraction structure. The data of the Minor Irrigation
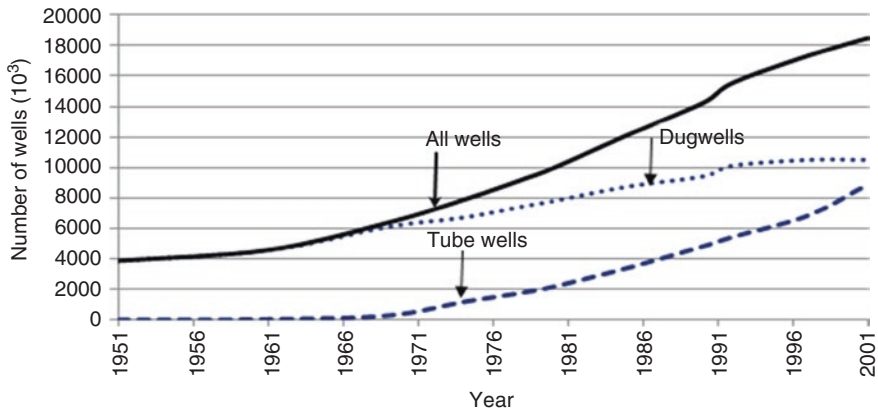
**Fig. 8.3** Growth of groundwater irrigation structures in India (1951–2001) (Source: Graph prepared using data of Minor Irrigation Census, 2001 & data compiled by Singh & Singh, 2002)

Census conducted in 2001 together with the data compiled by Singh & Singh [22] shows (Fig. 8.3) enormous growth of groundwater structures. The number was around 18.5 million in 2001. Many people predicted [21] that by 2009, the number of groundwater irrigation structures might have gone up to 27 million. With such a huge number of groundwater abstraction structures and nearly 61% of status of groundwater development [8], India is placed now the largest groundwater user in the world [21].

Groundwater is mostly preferred because (1) rural people have a common notation that groundwater is less risk-free from pollution than surface sources of water, and (2) it is ubiquitous and can be drawn on demand wherever and whenever required. These general beliefs together with poor public irrigation and drinking water delivery system, new pump technologies, flexibility and timeliness of groundwater supply, government subsidy on electricity in the rural areas and lack of groundwater regulation legislation have given rise to preferential growth of groundwater uses in India. There is no rationale to believe that the growth of groundwater withdrawal structures and uses of groundwater in India are going to slow down in the future, unless otherwise controlled by enforcing legislation; rather, it will continue to rise because of growing concern on water quality, socio-economic improvement and sociocultural dimensions of the rural sector.

The rise of tube well extraction structures and their uses to large exploration depth, in many situations, have led to excessive withdrawal and overexploitation of aquifer than the annual groundwater recharge to it. Consequential effects of which have emerged in the form of persistent groundwater level depletion in many areas and triggering of contaminants earlier attached to the soil and rock formations to the water by the natural geochemical processes of soil-water interaction. Depletion of groundwater levels, on the one hand, provoking private players to dig tube wells at larger depth, and water in the deep aquifers, on the other hand, because of large contact times with the source materials, poses a serious threat of fluoridation.

In the case of arsenic, the intermediate aquifer depth that ranges between 20 m and 80 m has been reported contaminated, and its mobilization to the deep aquifer depends on its exploitation and movement direction of groundwater flow. In areas where deep aquifer is separated by an impervious layer from the overlain arsenic-contaminated zone, the impervious layer acts as barrier between the two layers.

## 8.5 Conservation, Mitigation and Remedy to Fluoride and Arsenic Contamination

The foremost task towards combating geogenic source of groundwater contamination should be to prepare risk maps delineating areas with elevated arsenic and fluoride concentrations in groundwater together with aquifer map. Most of the maps published represent detected limit of point measurement without referring to the spatial variation of the concentration. These resulted into a misinterpretation and varied opinions on the physical processes of attribution. Aquifer mapping representing geological formations together with the risk maps of contaminants can help understand and develop aquifer management plan to combat geogenic source of groundwater contamination.

### 8.5.1 Conservation of Arsenic Contamination

Arsenic contamination in groundwater has far-reaching consequences including its ingestion through food chain. Food is the second largest contributor to arsenic intake by people after direct ingestion of arsenic-contaminated water [16]. The concern, therefore, cannot be directed towards not only supply of arsenic safe drinking water but also supply of irrigation water. Arsenic removal technologies, which only consider ex situ treatment, cannot be an affordable task for supplying irrigation water. It is necessary to devise alternate methods for supply of both drinking and irrigation water. Ex situ arsenic treatment device can be employed where scale-up of the problem is less. For large-scale attribution, it should be the last resort and can be used as a stopgap arrangement till sustainable alternate solutions are devised.

#### 8.5.1.1 Exploring Possibility of in Situ Treatment of Aquifer

Arsenic contamination is largely along the fluvial tracks in the Ganga-Brahmaputra plains, and its release is due to the result of reductive dissolution of source materials triggered by the microbial activities under the anoxic condition. As long as groundwater contains sufficient dissolved oxygen, arsenic remains fixed in the sediments. These connotations underline the possibility of in situ remedial measure by supply of oxygenated water to the arsenic-contaminated aquifer. In that direction, the Queen's University claim on the development of an eco-friendly in situ treatment of arsenic-contaminated aquifer by injecting oxygenated water into it – which can ensure safe irrigation and potable water supply at an affordable cost – is mentionable.

### 8.5.1.2 Surface Water as an Alternate Source

Definitely surface water source is the best option instead of exploiting contaminated aquifers if it is available sufficiently both for drinking and irrigation water supply. Surface waters are generally risk-free from arsenic contamination. Few states, namely, West Bengal and Bihar, have adopted some schemes to supply drinking water to the people living in arsenic-affected areas from surface water sources. The question about agricultural water supply still remains.

Rainwater harvesting and groundwater recharge are provoked by many experts as a method for dilution of concentration in the aquifers. Indeed, this innovative approach coupled with rejuvenation of traditional tanks/ponds in the affected areas would not only help in diluting the contaminated water but also to the infiltration of oxygenated water to the contaminated aquifer. A properly conceived 'managed aquifer recharge (MAR)' scheme, which has similar connotation as that of artificial recharge in India with only difference in consideration of water quality and environmental conditions, based on the geomorphology and hydrogeological characteristics of the area, can help reduce concentration level of arsenic in groundwater. MAR is a technique defined as intentional storage and treatment of water in aquifers for subsequent recovery or environmental benefits [9].

### 8.5.1.3 Possibility of Exploiting Deep Aquifers

In the Gangetic plains, the deep aquifer below 100 m has arsenic safe groundwater, and the deep aquifer is overlain either by clay or impervious formations. CGWB [16] has reported that with proper sealing of the tube well to stop connectivity between the contaminated and non-contaminated aquifer, the deep aquifer can safely be tapped. This approach invokes requirement of aquifer mapping and groundwater modelling study.

### 8.5.1.4 Bank Filtration (BF) for Sustainable Drinking Water Supply

Riverbank or simply bank filtration (RBF/BF) [18] is a low-cost (pre)treatment technology in which water is withdrawn from wells located close to a river (typically, 20–200 m away). By pumping a bank filtrate well, river water is induced to flow through porous riverbank and bed sediments to the production well. During soil and aquifer passage, chemical, biological and particulate contaminants are removed due to microbial and physical processes and by mixing with groundwater. A schematic diagram of RBF processes is shown in Fig. 8.4.

River water-based supply schemes in India are normally designed for posttreatment of water drawn by intake wells constructed on the riverbed. In such situation, the intake wells only draw water from the river, and considerable amount of money is spent on posttreatment. In the RBF technique, production well draws water both from river and aquifer, and riverbank and bed act as filtering media and thereby reduce drastically the posttreatment cost. The perennial stream/river in and around the arsenic-affected areas can be used for supply of drinking water by employing RBF technique. Riverbank hydraulically connects top aquifer and river. As most of the aquifers up to 20 m depth are free from arsenic contamination, therefore, RBF technique may not have the risk of withdrawing arsenic-contaminated groundwater.
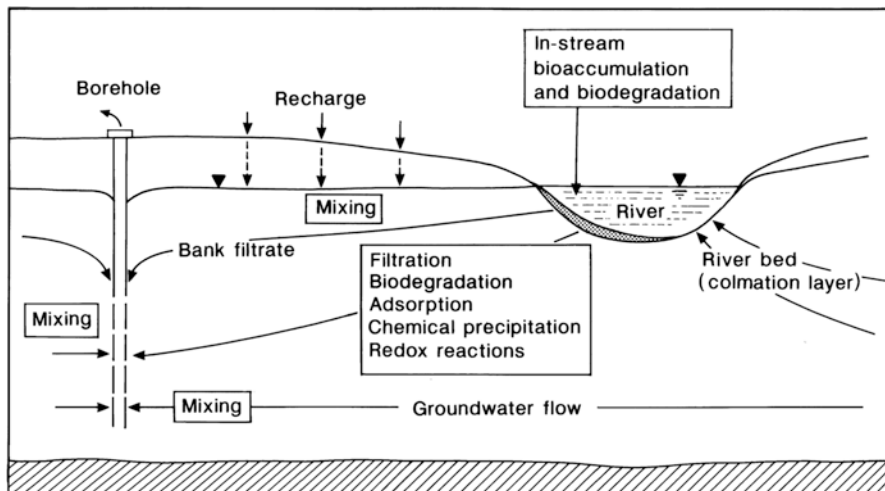
**Fig. 8.4** Schematic diagram of processes affecting water quality during bank filtration [11]

Feasibility of implementing a RBF scheme depends on the hydrogeological setup of the area and the physical processes of river-aquifer interaction.

### 8.5.2 Conservation of Fluoride Contamination

Fluoride problem can be prevented or minimized by using alternate water sources. The preventive measure can be removal of excessive fluoride from drinking water and improvement of the nutritional status of populations at risk. The removal and improvement of the nutritional status can be recognized as living with the problem by care without bothering its mitigation.

It is now well recognized that the source is the fluorine-bearing materials, and their attribution and concentration level depend on the contact time of source material with groundwater. Further, recent aged groundwater (top aquifer) is free from fluoridation, and the risk of fluoridation increases with increasing depth of groundwater because of longer residence time of water with the source material. These connotations underscore the use of surface water, rainwater and low-fluoride groundwater.

#### 8.5.2.1 Surface Water and Rainwater as an Alternate

The use of surface water as drinking water source is the best option in fluoride-contaminated areas. In arid and hyperarid areas, scope may not exist for maintaining perennial condition of surface water sources. Rainwater harvesting can provide a possible alternative. Particular caution is required when opting for surface water, since it is often heavily contaminated with biological and chemical pollutants. Surface water should not be used for drinking without treatment and disinfection.

Rainwater is usually a much cleaner water source and may provide a low-cost simple solution. The problem, however, is limited storage capacity in communities or households. Large storage reservoirs are needed because annual rainfall is extremely uneven in tropical and subtropical regions. Such reservoirs are expensive to build and require large amounts of space.

### 8.5.2.2 Managed Aquifer Recharge (MAR)

The 'young-aged' groundwater (top aquifer) has less risk of fluoridation because of minimum residence time with the source aquifer materials. An appropriately designed MAR scheme by conserving monsoon surface runoff and groundwater recharge with provision of tapping top aquifer either by the radial collector wells or by open dug wells can help resolve water scarcity problem in fluoride-contaminated aquifer.

### 8.5.2.3 Bank Filtration (BF) for Sustainable Drinking Water Supply

In areas where perennial stream/river water sources are available, RBF technique can be employed. The same concept as explained in the case of arsenic-contaminated area will apply because top aquifer and river water are risk-free from fluoride contamination.

## 8.6 Conclusions

Arsenic and fluoride contamination in groundwater are due to the resulting effects of geochemical characteristics of the aquifer materials. The attribution of arsenic in a fluvial track from subsurface sediments containing arsenic-rich iron oxyhydroxides is by the process of reductive dissolution of source materials triggered by the microbial activities under anoxic condition. The attribution of fluoride in groundwater is due to the geochemical characteristics of fluorine-bearing rock-water interaction.

In case of arsenic, oxygen depletion in the groundwater is said to be the cause of activation, and arsenic remains fixed in the sediments as long as groundwater contains sufficient dissolved oxygen. While fluoride concentration in groundwater depends on the reaction time with aquifer materials, i.e. longer residence time of water in the aquifer can lead high fluoride concentration.

Based on the hypotheses given by researchers on origin, occurrence and attributing characteristics of the contaminants in the aquifer being tapped for groundwater withdrawal, possible hydrological and hydrogeological scope for management of contaminated aquifers to help conservation of aquifer from attribution of geogenic contaminants and continuance with withdrawal of groundwater have been suggested; these include:

(i) Preparation of contaminant risk maps including aquifer mapping.
(ii) Adopting innovative techniques for supply of oxygenated water to the arsenic-contaminated aquifer as in situ remediation technique.

(iii) Exploring scope to tap deep aquifer below the arsenic-contaminated aquifer. This can be corroborated by aquifer mapping and groundwater modelling studies.

(iv) Exploring possibility to adopt managed aquifer recharge (MAR) technique by rainwater harvesting with emphasis on tapping top aquifer (young-aged water) as groundwater withdrawal.

(v) In areas where perennial surface water sources, such as river and lake, are available, implementation of riverbank filtration (RBF) or bank filtration (BF) technique can provide a sustainable solution to supply arsenic safe drinking water.

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