Chapter 3
Social Vulnerability of Arsenic Contaminated Groundwater in the Context of Ganga-Brahmaputra-Meghna Basin: A Critical Review

Satabdi Biswas, Satiprasad Sahoo, and Anupam Debsarkar

Abstract The most alarming part of inorganic arsenic contamination is its silent killing ability which has an adverse impact on human society. Anthropogenic activities trigger threat from bio-physical to social vulnerability. The Ganga-Meghna-Brahmaputra (GMB) basin has been the worst sufferer for the last four decades. This review paper tries to focus on the impacts and consequences of arsenic calamity, assessment of the risk through Geographical Information System (GIS) and a feasible way-out involving rain water harvesting (RWH) with special reference to India. Arsenic poisoning creates a huge burden for rural people. Identification of various dimensions of arsenic coverage has been a difficult task which made GIS an important tool for the assessment of social vulnerability. However, the rural Indian mass is yet to become fully aware of the severity of the arsenic-related risk. They are still consuming the poison through drinking water for the last four decades without even knowing the treatment protocols. RWH is one of the easy way-outs to combat the situation of the arsenic risk, especially for the poor socio-economic rural households. Thus, to prevent further damages, awareness creation, proper medical care with due endeavours from national and international levels are required.

Keywords Arsenic contamination · Risk assessment · GIS · RWH

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P. K. Shit et al. (eds.), *Geospatial Technology for Environmental Hazards*, Advances in Geographic Information Science, https://doi.org/10.1007/978-3-030-75197-5_3

3.1 Introduction

The most significant and alarming aspect of inorganic arsenic (As) toxicity is its silent but for the extensive impact on society. As per WHO (2001), 140 million people in 50 countries have been consuming arsenic-contaminated water above the WHO safe limit of 0.01 ppm. As, the 'king of poison', is a highly toxic element and is naturally found in air, weathering of rocks, soil and groundwater of shallow aquifers (Aurora, 2005; Brinkel et al., 2009). More than 2.5 billion global populations rely on groundwater for drinking purposes. Nearly 108 countries with more than 230 million people have been suffering from As disaster (Shaji et al., 2020). The arsenic-contaminated aquifers are generally found in parts of younger orogenic belts and deltaic plains of the world, such as the western USA, central Mexico, Argentina, the Pannonian Basin, Inner Mongolia, the Indus Valley, the Ganges-Brahmaputra delta and the Mekong River and Red River deltas (Podgorski & Berg, 2020; Ghosh et al., 2020). There is a wide difference between developed and developing countries in terms of the impact of arsenic toxicity. For instance, developed countries like the USA have the same problem in alluvial areas, but the impact of it is not the same compared to the developing countries (Acharyya, 2002). In developing countries like India, Pakistan, Nepal and Bangladesh, unrestrained irrigation with shallow tube-well has been responsible for lowering the water table with arsenic contamination (Alcamo et al., 2000; CGWB, 2013). Under such a complex bio-physical arsenic-contaminated situation, the most vulnerable section, i.e. poor people of Southeast Asia are exposed to high-level risk (Hoque et al., 2019). However, the Ganga-Meghna-Brahmaputra (GBM) basin, i.e. in Bangladesh and India, are the worst cases of recent times (Levien, 2011; Chakraborty et al., 2020). For instance, more than 70 million people in Bangladesh are exposed to the toxicity of arsenic through drinking water (Ghosh et al., 2020). Simultaneously, in India, 20 states (West Bengal, Jharkhand, Bihar, Uttar Pradesh, Assam, Gujarat, Haryana, Madhya Pradesh, Punjab, Arunachal Pradesh, Karnataka, Tamil Nadu, Himachal Pradesh, Telangana, Andhra Pradesh, Orissa, Nagaland, Tripura, Manipur, Chhattisgarh) and 4 union territories (Delhi, Daman and Diu, Puducherry and Jammu and Kashmir) have the largest mass poisoning happened due to arsenic contamination in shallow groundwater (Sharma et al., 2014; CGWB, 2013; Shaji et al., 2020). West Bengal, Jharkhand, Chhattisgarh, Bihar, Uttar Pradesh, Assam, Arunachal Pradesh and Manipur are the major states in India having As contamination at a higher level (>10 μg/L) (Puri et al., 2014). As per BIS (2012), half of the Indian people have been affected by excessive iron and As contamination. However, West Bengal is the worst affected state, which has recently turned into an issue of global concern as a high concentration of arsenic patches are found in 79 blocks of eight districts (CGWB, 2013). It has been estimated that nearly 16.26 million people out of 91.28 million are at high risk in West Bengal (Chatterjee et al., 2009). However, to date, 85% of Indian rural domestic water requirements are fulfilled by groundwater (Suhag, 2016). Arsenic is not a new thing; rather hydro-geochemical evolution revealed that it occurred in the entire Ganga Basin with a spatial variation since the historical past. Unfortunately, the severity increased in such a way that it gradually became a global concern in the last four decades.

Most of the recent studies on As contamination were based on the assessment of groundwater quality or character of the sediment. For example, a study by Shaji et al. (2020) established a correlation between aquifer types with arsenic intoxication based on geological analysis of peninsular India. The result revealed that 90% and 10% of As contamination was found in the unconsolidated alluvial terrain and hard rock terrain, respectively. In the hard rock aquifer states (e.g. Karnataka and Chhattisgarh), As contamination happened due to sulphide mineralization and acid volcanic association. Singh et al. (2020) tried to assess the anthropogenic effect of arsenic and its probable vulnerability based on 171 seasonal groundwater samples collected for 2015–2016 in Darbhanga district, Bihar in the Ganga Flood plain. The result showed that agrochemicals, viz. calcium nitrate, calcium phosphate, As-bearing compounds and bleaching powder, applied over the surface get diluted and mobilized into groundwater by potential monsoon recharge. The pre-monsoon drafting should be regulated to restrict the high As concentration in the groundwater. Another hydrochemical study on STW water in Bangladesh conducted by Edmunds et al. (2015) established that the excessive tapping of groundwater for potable and irrigation purposes is a matter of serious concern and is yet to be understood well by the stakeholders. Richards et al. (2020) collected 273 samples of pre- and post-monsoonal groundwater from 5 to 180 m depth in38 districts of Bihar, India, to assess the harmful effect of geogenic contamination of As, uranium (U), and other elements on human health. The result showed that As, iron (Fe) and manganese (Mn) were positively correlated with each other, and As was inversely correlated with the depth of the aquifer. Saha and Sahu (2016) studied the similarities and differences between the Middle Ganga Plain (MGP) and the Bengal Basin based on the hydrogeological and geochemical assessment of shallow aquifers (8.0 m below the ground). The As contamination was noticed along the River Ganga and other Himalayan tributaries and sub-tributaries, i.e. the Ghaghra, the Gandak, the Kosi and the Mahananda. The rainwater carried organic carbon in the form of clay plugs, increased microbial processes, spread the anoxic front and released As in groundwater through infiltration and percolation by natural recharge in monsoon. They found that the newer alluvium areas of MBP having Pleistocene brownish yellow sediment had low concentration of As in groundwater after assessing the transmissivity of the aquifer. They recommended cement sealing for the wells of middle clay layers to stop downward leakage of As from the top aquifer. Patel et al. (2019) studied sediment samples of monsoon and post-monsoon seasons of the Subarnsiri-Dikrong-Ranganadi River system, Upper Brahmaputra floodplain, India, to assess the effect of leaching of As and fluoride (F^-) by annual flooding events. The results showed that the highest As and Fe were found in the raw sediments of the Ranganadi river that fell sharply in the post-monsoon season. They concluded that the total level of As is not only the prime determiner of groundwater contamination but the local anthropogenic influence also disturbed the fluvial environment. Almost similar observations were made by Das et al. (2018), who assessed the hydrochemical quality of groundwater and sediment samples in the Brahmaputra floodplains (BFP), India. The result found the strongest relationship between As and Fe in the upper BFP followed by the lower and middle BFP. They observed a definite trend of gradual increase in As and Fe due to easier access to shallow aquifer. This is responsible for the increase in non-cancer health risks among the 835 children in the BFP. Chen et al. (2020) also establish a geochemical analysis based on 23 soil samples in Suzhou University, China. After the spatial analysis of the samples, the results found that the Cu and As were slightly contaminated due to the use of chemical fertilizer in agricultural activities. Janardhana Raju (2012) assessed 68 borehole sediment and groundwater samples of the Ganga in Varanasi, India. However, borehole samples of the eastern side of Ganga showed high As and Fe concentration in newer alluvium sediments of the Holocene period. Thus, without knowing the quality of the shallow tube wells (40–70 m) water, the rural people had been using arsenic-contaminated water for drinking and irrigation purposes in the affected nine villages. Though no arsenical skin lesions were noticed in their survey, they concluded that continuous consumption of arsenic contaminated water without necessary precaution would increase the cases of arsenic victims in these villages in the near future.

Majorities of the recent approaches involved an assessment of groundwater quality or lithology-based analysis for assessment of the severity of As. Most of the researchers recommended structural management or government initiatives, alternative water sources, i.e. RWH for restricting As position but yet to emphasize generating awareness of potable water quality, the role of the governance, sharing the threat of As and its probable impact over the poor rural households. In this perspective, a critical review has been presented in this paper on arsenic-related social hazards to clarify a few important key aspects. The aspects of the paper are organized as (1) impact and consequence of arsenic as a bio-physical social hazard, (2) application of GIS techniques for arsenic assessment and (3) significance of water governance with RWH as a mitigation measure for arsenic. This paper also helps to address one of the most widely asked questions, i.e. whether RWH could be a feasible solution to arsenic contamination, especially for Asian countries.

3.2 Materials and Methods

Generally, mixed methods were adopted for the representation of the arsenic risk in the GIS environment. The ultimate goal was to detect the vulnerability of its effects on the population. In some cases, researchers combined quantitative data (spatial and attribute data) with qualitative data (questionnaire survey) for designing the problem formulation, data manipulation, analysis and interpretation (Hassan et al., 2003; Bhatia et al., 2014; Singh & Vedwan, 2015). The quantitative data (primary or published tube-well water data) were combined with another set of quantitative medical data (data about arsenicosis-affected persons). Then other sets of local or regional geostatistics data were transferred into the GIS platform to generate arsenic hazard-related thematic maps for spatial analysis (Hassan et al., 2003). The geostatistical method helped to detect the accuracy of the present status of the calamity and also predicted future needs. This further helped to take certain measures by the local authorities to manage the present groundwater scenario. Numerous researches used field variables (hydro-geochemical analysis of laboratory tested tube-well water samples, sediments samples, soil samples, lithology characters data) and secondary data (climate data, published groundwater data) to develop models by assigning weightage and ratings to correlate and assess the arsenic vulnerability by GIS overlay analysis (Hassan et al., 2003; Puri et al., 2014; Ghosh et al., 2020; Podgorski & Berg, 2020). Qualitative analysis was done based on hydrochemical properties of groundwater, and the results obtained were used to develop statistical model, viz. kriging, Thiessen polygon, DRASTIC Model, Random Forest model, Logistic Regression model and Hydrostratigraphic model for prediction of the sensitivity of the coverage (Puri et al., 2014; Mehrotra et al., 2016; Ghosh et al., 2020). Statistical modeling was carried out based on satellite data along with climate and arsenic data to highlight the As risk (Podgorski & Berg, 2020; Chakraborty et al., 2020).

3.3 Results and Discussion

Impact and Consequences of Arsenic as Bio-physical Social Hazard

More than 90% of arsenic pollution is geogenic (Ghosh et al., 2020). In the GMB plain, the alluvial soil has high agricultural potentiality. The uncontrolled increase in population and associated demands, i.e. food grains, irrigation, industrial and drinking purpose implied heavy drafting which worsens the condition. Easy drafting of groundwater, subsidized electricity, less expense of boring of tube wells (TWs), availability of loans from a bank and dependency of ‘Boro paddy’ (winter rice) along with other crops are responsible for unethical major share drafting of groundwater common in West Bengal and Bangladesh (Banerjee & Jatav, 2017; Hoque et al., 2019). Being agrarian-based countries, most of the poor farmers are forced to cultivate throughout the year. Hence, intensive use of groundwater is required for cultivation. Wealthy farmers are drafting groundwater 24 h a day (UNDP, 2006). However, the farmers are engaged in a race of drilling deeper and deeper with bore wells and fall into money owing traps (Banerjee & Jatav, 2017). In this way, the atmospheric oxygen enters into groundwater while drafting the same. As a result, the groundwater level declines continuously with increasing As contamination (Acharyya, 2002). Further, the application of chemical fertilizers and insecticides throughout the year especially the increase of winter rice cultivation is causing qualitative and quantitative degradation of water. Glendenning (2009) mentioned that in India, water extraction by shallow tube-wells benefited farmers in the short term, but this practice makes their land barren in the long run. The unplanned urbanization influenced the significant changes in land use/land cover (LULC). These LULC changes decreased the natural phenomena, i.e. water bodies, vegetation and wetland largely with a consequent increase of impervious area. On the other side, it is responsible for less infiltration capacity of water (Patra et al., 2018). Thus faster urbanization deteriorates groundwater recharge (DDWS, 2011). However, the groundwater has been still treated as an individual property. Thus, over-exploitation with contamination has taken place in several areas (DDWS, 2011). About 85% of the supply of drinking water in India is based on groundwater (DDWS, 2011). The unethical easy electrified pumps in shallow tube-well (STW) tap the groundwater for drinking purposes (Puri et al., 2014). A huge number of private shallow hand pump tube-wells were installed by individual households on their premises recently, the main source of rural drinking water with an excess of As and iron. Rural households tap this contaminated drinking water, and millions of people have been suffering from qualitative water stress varying from health to social (Chatterjee et al., 2009; Bhatia et al., 2014; Hoque et al., 2019). Since 2004, villages of West Bengal had experienced the huge growth of STW with the coming up of the National Policy of As Mitigation (NPAM) (Banerjee & Jatav, 2017). This further increased the gravity of the arsenic problem (CGWB, 2007). However, various Government Departments monitor observatory wells and do acknowledge these issues. In this monitoring process, they often identify and put a red cross on those contaminated tube-wells. Despite knowing the fact, local people are compelled to consume this contaminated water as they do not have any other alternative. Thus the situation was turned into a major socio-ecological risk (Hoque et al., 2019; Biswas et al., 2020). For instance, in coastal Bangladesh, the privately funded tube wells increased four times, compared to 78% in 2018, whereas the population grew by 4% during the past decade (Hoque et al., 2019). The groundwater is safe in terms of waterborne diseases, but at the same time, it gradually lifted the As to the top layer of the surface (Hassan et al., 2003). These hand-pumps covered millions of rural people at risk of arsenic contamination, which was one of the key health problems of the twenty-first century (Bhatia et al., 2014). Two major additional risks were there. One of which was the dietary habit of dependence on rice, both in India and Bangladesh. Gilbert-Diamond et al. (2011) indicated that rice consumption had been one of the main reasons for harmful arsenic exposures to the human body, based on a study of 229 pregnant women. Women in this sample survey had exposures to arsenic via their home tap water concentration ranging from ≤ 0.07 μg/L to nearly 100 μg/L and rice-based food habit (Gilbert-Diamond et al., 2011). They documented a positive relationship between rice consumption and urinary arsenic excretion. Secondly, the mushrooming of private bottled mineral water industries resulted in significant investment and exposure in shallow tube wells in countries like India and Bangladesh. The market entrepreneurship of bottled water industries packaged water over the last few decades without maintaining the WHO standard. Rural innocent people trust private bottled water without any concern and consume the same blindly. This is the recent hazards for an increase in arsenic vulnerability (Dave, 2016). This made a tremendous impact on groundwater particularly in peri-urban villages (Banerjee & Jatav, 2017). Thus, the quality of drinking water did matter a lot for several serious public health problems. The arsenic from underground shallow aquifer silently enters into an ecosystem and responsible for the increase of various diseases (Dave, 2016; Sharma et al., 2014; Bhattacharya et al., 2019; Sinha & Prasad, 2020). The high level of As exposure for a prolonged time has been associated with serious public health hazards, e.g. skin disorders; cardiovascular diseases; respiratory problems; complications of gastrointestinal tract; liver, kidney and bladder disorders reproductive failure neurotoxicity; and even cancer. Thus arsenic contaminated groundwater is grabbing our society slowly. WHO (2018) also noted that 1 in every 100 additional cancer deaths could be caused when people are exposed to contaminated drinking water. However, the rural households are the worst sufferers for the geogenicarsenic poisoning due to lack of proper diet (Mukherjee et al., 2009; Bartram et al., 2015). Arsenicosis cases are worsened by malnutrition, poor socio-economic status, illiteracy, food habit and prolong consumption of arsenic-contaminated water (PCI, 2007). Having no other option, poor people became silent victim of this hardship, and they were forced to enter into a vicious circle,where people further dip into acute poverty generation after generation. However, As contamination in groundwater was first reported in Chandigarh, India (Datta, 2015), and the second case was reported in West Bengal (Garat et al., 1984). Arsenic contamination of drinking water has also several indirect effects apart from the clinical symptom such as economic and social impacts, i.e. human productivity loss, treatment cost, human capital loss and many more (Bhattacharya et al., 2019). Another study by Brinkel et al. (2009) stated that arsenicosis patients face dual problems. Firstly, they face serious social impact such as marriage-related problems, problems of unemployment, social instability, social discrimination and rejection by community and sometimes from own families. Secondly, the patients suffer from mental retardation and disabilities like physical, cognitive, psychological and speech impairments. An arsenic-affected person is still being treated as a social stigma. It had a cascading effect that involved the entire family of the victims (Bhattacharya et al., 2019). Unaffected people were generally scared about arsenic victims. They usually avoided and isolate arsenic patients from the society (Hassan et al., 2003). Thus the mental health condition of arsenicosis sufferers resulted in deep depression where consequences might end up with social loss (Ghosh et al., 2020) (Fig. 3.1).

Application of GIS Techniques for Arsenic Assessment

In absence of any immediate mitigation action or awareness campaign, the people of the study area will be affected by mass poisoning and exposure to fatal diseases (Hassan et al., 2003). Thus, the assessment of arsenic vulnerability is necessary for understanding the risk. The extension of risks may be multidimensional such as economic loss, health loss, loss of opportunities or decline in the socio-economic status of their livelihood (Singh & Vedwan, 2015). Assessment of these risks along with the toxicity of human is a complicated task, not possible to measure directly. Thus various proxy data were used to capture the magnitude of this harm (Hassan et al., 2003). The general trend is to develop various thematic layers of maps of local aquifers to know the severity (DDWS, 2011). The groundwater is available, but it is often the case that it is contaminated by As and Fe pollutants. To make mass awareness about this social risk, need to depend on low-cost and timeless technology. Normally, the spatial study of arsenic-related groundwater needs thousands of water samples with time-series data, and that is also a time-consuming and expensive process. Due to the lack of adequate testing facilities, it is nearly impossible to

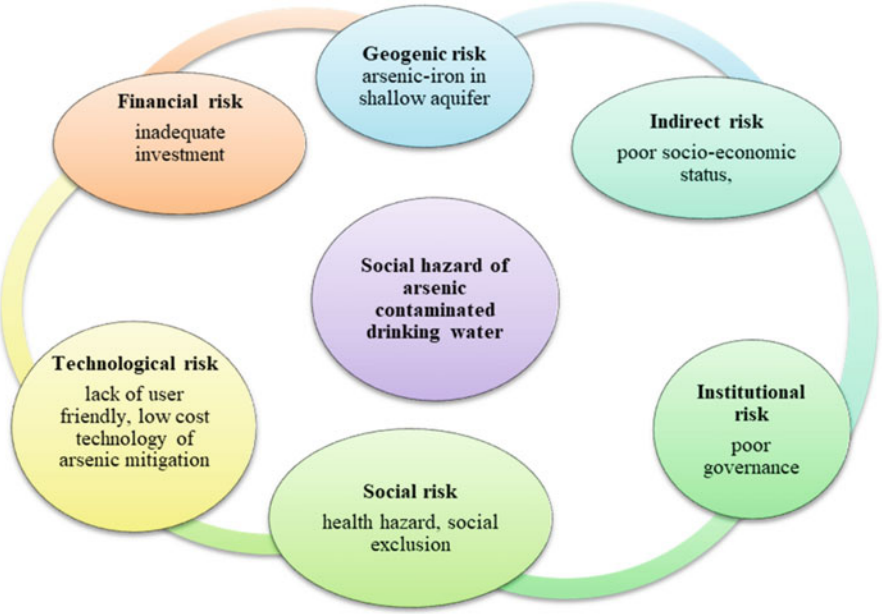

Fig. 3.1 Risks associated with arsenic-contaminated groundwater

collect huge data from vast rural regions. Here comes the importance of GIS for spatial mapping (Ghosh et al., 2020). GIS can be done by the limited sample points, thus easy to develop an As concentration zoning map, which ultimately helps to identify the risk zones exposed to As contamination and then quantify the magnitude of contamination (Ghosh et al., 2020). Thus, GIS is used to identify arsenic risk, an extension of exposures, and spatial zoning of risk, and it further helps to assess the vulnerability, find out the weakness of adaptive capacities and, overall, helps to resolve the issues. The GIS as a tool helps to clarify the situations and plan accordingly to the benefit of the common people (Mehrotra et al., 2016). Thus, like the absence of the As detection sensors, GIS-based techniques can be used for assessment at the block or ward level (Puri et al., 2014). Such GIS techniques help mark out the magnitude of vulnerability based on various proxies, i.e. environmental, bio-physical, natural, lithologies, aquifer characters, hydrology, water samples and other samples (rice, urine, water, soil, diseases even anthropological factors, etc.) (Chakraborty et al., 2020). Ultimately the GIS could easily enable to estimate the visual representation of the population at risk over any specified area. GIS is also helpful to give an alert of groundwater by producing the groundwater vulnerability mapping. Thus it helps to frame out planning by the government or authorities to take decisions to manage safe drinking water supply (Puri et al., 2014). Prediction-based vulnerability maps could be developed in a faster way by GIS tool which is invaluable for the planning of the highly arsenic severity areas (Singh & Vedwan, 2015). The recent trend of using GIS mapping in arsenic contamination usually adopted a regional scale-based assessment and highlighted the spatial heterogeneity. Charlet et al. (2007) found a high level of As presence in wells and that caused the widespread poisoning through drinking water in Chakdaha, West Bengal. They developed a spatial distribution map of arsenic with a depth of the aquifer. Results showed vertical transfer of (As) arsenic happened from shallow to deep wells (150 m) during the dry season. However, those deep wells were marked as high quality of drinking water free from arsenic previously. That was a real threat to the local population. Different methods have been used to evaluate the arsenic-related groundwater mishap. Such the random forest machine-learning model was analysed based on geospatial environmental parameters including 50,000 global data points of groundwater arsenic concentration and household groundwater usages data. The arsenic prediction model estimated that 94–220 million people were exposed to high concentrations. Among them, the majority (94%) of the people were residents in Asian countries (Podgorski & Berg, 2020), whereas Puri et al. (2014) used the DRASTIC model to access the groundwater vulnerability in Bardhaman district, West Bengal, India. The results showed that the study area was severely affected by As. A mixed approach was taken by Chakraborti et al. (2018). They include people's perceptional data on the risk of As, i.e. the opinion of the presence and functionality of government, interpersonal trust, and trust in institutional working along with As water data. Based on the above-mentioned data, they developed a GIS thematic map to capture the underlining adaptive capacity of the exposed communities. Another block-level mixed study was done by Chakraborty et al. (2020), who adopted a 'hybrid multi-modeling approach' based on both hydro-stratigraphic parameters (aquifer characters, geology, geomorphology) and anthropogenic parameters in 25 districts of the transboundary area of the Ganges River delta shared between India and Bangladesh. A high-resolution regional-scale hydro-stratigraphic model of the aquifer system was developed with the help of 2883 geo-referenced borehole lithologies. The result showed that 19 districts were fallen under the category of more than 25% of high As-hazard zones, while 7 districts (28%) were exposed to more than 75% extent of severity. Total 30.3 million people of the Ganges River delta were exposed to a high level of As-concentration (>10 μg/L) through drinking water. Another study by Bhatia et al. (2014) was conducted on 21children having age group of 5–10 years in a marginalized village community of Khaptolain Bihar, India. They assessed the geo-chemical analysis with health impacts using GIS over lay thematic maps. A contour map for arsenic was developed on the basis of drinking water samples from 20 private shallow (15–35 m) hand pump. The result showed that 57% and 25% of the tapping aquifers were responsible for more than 200 and 397 ppb arsenic concentrations, respectively. The children of the study village were under high risk of getting cancer with continued exposure. A study by Ghosh et al. (2020) was based on empirical methodology with interpolation approach ('Thiessen polygon and Kriging'). They also developed blockwise arsenic contamination map based on seasonal well data from the period 2006–2008 through GIS platform in North 24 Parganas, West Bengal, India. The result revealed that the unaffected blocks of 2006 gradually became significantly affected in the year of 2008. As testing was performed by field test kit (FTK) from 522 villages in Bahraich, India. They developed GIS-based arsenic-contaminated zoning map based on the tested drinking water samples. The zoning map showed 45.71% of high probability of arsenic concentration in Kaisarganj and Jarwal blocks and few newer villages and Gram Panchayats. It also identified to the coverage of the problem (Mehrotra et al., 2016). Another mixed approached was adopted by Singh and Vedwan (2015) in Bihar, India. They used biophysical, socio-economic and demographic factors for identifying the community's arsenic coverage by 'composite vulnerability index' and statistical analysis by PCA. They generated unique set of visual maps like social, bio-physical and environmental vulnerability map based on more than 30,000 published tested results of As concentrations in drinking water of Bihar, India. This helped to mark community vulnerability profiles for drawing of arsenic-contaminated groundwater. This study revealed that nine million population was found to be at risk in five districts of the state including Vaishali, Samastipur, Darbhanga, Purnia and Katihar. The highest As-affected population (63%) was found in Khagaria district, covering a total number of three blocks. The results implied that demographically and socio-economically, poor people were highly vulnerable as poor health would be more sensitive to arsenicosis-related health problems. The literacy rate was found to be a very important component to reduce total vulnerability. The expensive As mitigation plan would network in any of these districts. The literacy rate, female literacy rate, rural population, population growth, population below the poverty line, scheduled caste population, infant mortality rate, incidence of flood and drought, concentration of arsenic, fluoride and nitrate, lithology and the lithology-related geological formation were found to be most important variables by PCA for composite vulnerability of the communities. A geostatistical approach was used by Hassan et al. (2003) for detection of arsenic magnitude in a covering area of 17.26 km^2 in Bangladesh and West Bengal, India. A mixed data of spatial and questionnaire survey was used for development of arsenic spatial distribution maps through Kriging method. They collected data related to the arsenicosis patients, their water-consuming habits and period of exposure to the arsenic-contaminated drinking water. The result showed that about 95.50% (358) of tube wells were contaminated with <0.003 to 0.600 mg/L arsenic concentration out of 375 tube wells after analysis by spatial interpolation method. The west and northeast of the study area were more contaminated than southwest part.

The magnitude of arsenic assessment becomes more visual with GIS whatever the initially adopted methods were showing Table 3.1.

Significance of Water Governance with RWH as a Mitigation Measure for Arsenic

After detecting the arsenic contamination in the 1980s, the West Bengal Government had taken three types of mitigation measures, i.e.:

Table 3.1 Arsenic-contaminated groundwater-related studies using GIS

Author	Study area and sample size	Methods	Remarks
Hassan et al. (2003)	West Bengal (India) and Bangladesh, 11,000 inhabitant	Quantitative mixed approach, i.e. special information, 375 TW water data, households questionnaire survey (HHS), health-related data	GIS-based data processing for identifying the magnitude of As problem regions such as arsenic isoline map, three-dimensional arsenic concentration map, special As magnitude map Found 200 TWs (53.33%) highly affected (<0.003 mg/L), overall, 95.50% TWs were contaminated by As
Puri et al. (2014)	Bardhaman district, West Bengal, India, sample size not mentioned	Qualitative method i.e., DRASTIC model based on giving weightage to hydrogeological parameters (depth of the aquifer, recharge, aquifer media, soil, topography, etc.)	Developed thematic maps, i.e. groundwater vulnerability assessment, results revealed study area severely affected by high As concentration
Bhatia et al. (2014)	Bihar, India, 916 population	A mixed approach, 20 TW water samples, questionnaire survey done with the mothers of affected children	GIS overlay map focused on calculating cancer risk, hazard index Found 1.6 ha of area (57%) under extremely high (<200 ppb) As toxicity, predicted 5–10 years of children would be under highly vulnerable of getting affected with cancer
Singh and Vedwan (2015)	15 districts of Bihar, India. Nine million population	The quantitative approach developed a composite vulnerability index based on biophysical, socio-economic, demographic and perception-based information, also used PCA	Overlay maps for quantifying the arsenic vulnerability maps (i.e. As risk zoning, As a vulnerable population, environmental vulnerability, socio-economic demographic map, health, geological, composite vulnerability maps), the first component of PCA was the adaptive capacity of HHS Found 4.4 million of the population in 5 districts with <1000 μg/L As concentration

(continued)

Table 3.1 (continued)

Author	Study area and sample size	Methods	Remarks
Mehrotra et al. (2016)	Uttar Pradesh, India. Sample size not mentioned	The qualitative approach 30,216 hand pumps water samples were tested by field kits applying a blanket approach	Village-level thematic mapping by GIS arsenic affected villages, As zoning map Found 52.06% and 10.86% samples had 10–40 μg/L and >50 μg/L As contamination respectively in two blocks
Hoque et al. (2019)	Coastal Bangladesh, population 58,000.	Mixed method qualitative, i.e. TW water sample, depth of TW, log data and quantitative, i.e. HHS interview data, used PCA	Various thematic mapping for risk assessment applied, i.e. (aquifer quality, water supply infrastructure, sources of drinking water) Found water risk increased as of salinity, flooding and uncontrolled growth of private shallow TWs
Ghosh et al. (2020)	North 24 Parganas, India, sample size not mentioned	The empirical methodology used was based on water samples of TWs, Thiessen polygon and Kriging; a future trend was assessed by statistical analysis	Developed spatial distribution of As concentration map with the help of Thiessen polygon and Kriging, As zoning map of different seasons, predicted future trend through a regression model Found previously unaffected block significantly affected within 2 years. The regression model predicted after 10 years another 2 or 3 blocks were affected if the same trend would be followed
Podgorski and Berg (2020)	Global scale	The mixed approach used, random forest machine-learning model based on geospatial environmental parameters (including 50,000 groundwater samples, arsenic data, depth data) and country based domestic groundwater users HHS data	Developed a global prediction map of arsenic exceeding 10 μg/L having less than 100 m depth Found 220 million global people were affected, among them 94% were Asian Found high probability of affected zones were in central, south and Southeast Asia including Indus and GMB plains

(continued)

Table 3.1 (continued)

Author	Study area and sample size	Methods	Remarks
Chakraborty et al. (2020)	Shared India and Bangladesh with 110 million people	Used 'hybrid multi-modeling' approach based on hydro-stratigraphic, geomorphology, anthropology, bio-geo-chemical factors, statistical methods and artificial intelligence, Random Forest, Boosted regression tree and Logistic Regression	The transboundary model was developed for the prediction of As hazard map, aquifer connectivity map, aquifer permeability map, silt, and clay thickness map. Found 30.3 million people were exposed to As, predicted probability of As by population (in high hazard zone 76% districts) predicted in high As hazard zones

1. As a short-term measure, the installation of numerous hand pump tube wells and ring wells were made into deeper aquifers.
2. Arsenic treatment units were attached with existing tube wells. Introduction of arsenic removal plants in existing groundwater-based piped water supply schemes were made for the medium-term measures. The large diameter deeper aquifer tube wells were fixed for existing or new groundwater based piped water supply.
3. There was12 mega piped-surface-water-supply schemes (PWSS) from the Ganga and another 338-groundwater based piped water supply schemes (PWSS) for arsenic affected areas were still running.

Modified Sujapur-Sadipur model, Gobordanga Model, community-based arsenic removal plant for multi-village water supply schemes in North 24 Parganas, West Bengal were also functional (DDWS, 2011; Rana, 2013; Bhattacharya et al., 2019). Total 28394.56 km^2 alluvial zone in the Ganga-Brahmaputra-Meghna plain of Indian part was recommended for artificial recharge (CGWB, 2013). People did not understand the 'safe water' issues; thus they did not argue for having safe water as their right (Dave, 2016). Another important reason was that mass awareness regarding arsenic-related health effects was very low (Sinha & Prasad, 2020). As an example in the technological park at Baruipur, West Bengal, most of the arsenic removal plants were found abandoned because of a poor sense of belonging, willingness, awareness, etc. (PCI, 2007). However, the public standpoint on deep tube well schemes did not yield the desired health impacts as households continued drinking contaminated groundwater by private hand pumps or wells situated at their premises (PHED, 2018). In recent past, several studies were dealt with groundwater contamination issues with various arsenic corrective technologies mainly removal of arsenic from groundwater using filters, exploration deeper or alternative aquifers, treatment of the aquifer itself, installation of nano-filter, dilution method by artificial recharge to groundwater and conjunctive use of RWH and groundwater, etc. (CPCB, 2008; Singh et al., 2014; Abhinav et al., 2017; Zakhar et al., 2018; Shaji et al., 2020). However, the quality of the water remained a matter of concern. Sarkar et al. (2010) pointed out that in 1997, Bengal Engineering Science and Technology and Lehigh University in the USA introduced community-level arsenic removal units and fortunately that decreased arsenic contamination in affected villages of south Bengal. The high cost of maintenance and installation were the main reasons for failure after the detection of the calamity of near about 32 years. To date, the government is yet to provide a simple low-cost technology to encounter arsenic, while presently available and widely used arsenic mitigation filter system further damages soil, surface water and the local ecosystem due to unplanned open disposal (Dey et al., 2014). The above-mentioned reasons further indicated a weak policy implementation system of arsenic contamination, and it certainly did not trickle down to the marginalized poor rural people (Bhowmick et al., 2018). The water-related governance issues yet to be addressed adequately (MWR, 2012). Thus it was necessary to reform strict water policy and simplistic user-friendly technology, involving mass in the arsenic mitigation plan, giving the incentive to encourage the community to manage their local aquifers were some effective measures (Ghosh et al., 2020). Effective regulations were required at national and international levels to prevent future arsenic-based health hazards (Sinha & Prasad, 2020). Even with the mapping of local aquifer, water quality information was not shared with the communities which was another big issue (Dave, 2016). It was necessary to change the present habit from tapping groundwater to switching to new sources like RWH to avoid deadly diseases and arrest the declining of ground water levels in over-exploited areas (Dey et al., 2014). RWH also helped to dilute the aquifers (DDWS, 2011). The needs of safe drinking water should be the first priority for any water supply scheme. The main goals of the government were to ensure water security to reduce arsenic related diseases. Thus, the Government of West Bengal fixed a target to supply surface water of 70 liters per capita per day (lpcd) in rural areas through Vision 2020 for giving the priority on the arsenic contaminated areas (PHED, 2018). Conjunctive use of RWH and safe groundwater was recommended to provide safe drinking water. However, the main focus was to move away from high cost arsenic treatment plan towards RWH (DDWS, 2011). The RWH was not so popular even in India and Bangladesh, and a wide gap existed between legislation of the rule/policies and its implementation. Bhattacharya et al. (2019) stated that the government needed to immediately take few measures under different programs of Government of India, viz. MSDP/BaDP, Panchayat Raj, etc., as a part of arsenic mitigation plan. For instance, the Government of West Bengal formed Task Force (2005–2006) as long-term measures. However, the Kolkata and Haldia industrial areas already depleted the piezometric surface. Under such circumstances, arsenic pollution had put a huge burden on rural households. It happened in many ways. First, the unpopular Government programme, lack of proper institutional efforts, ignorance of socio-economic and cultural background of affected communities, lack of integrated approach in water planning and lack of funds were some loopholes. These all posed fundamental questions on the failure of governmental policy about RWH (Banerjee & Jatav, 2017; Patra et al., 2018; PHED, 2018; Ghosh et al., 2020). But the supply of safe water entirely depended on governance, political will, investment, international cooperation awareness and acceptance (Asare, 2004; Fakult, 2013; Wutich & Brewis, 2014).

The concept of RS and GIS had been an effective recent tool for selecting sites and planning suitable artificial recharging structures to get the best result (Sharma et al., 2014; Jha et al., 2014; Mahmood & Hossain, 2017). For instance, Jha et al. (2014) identified 83 sites for artificial recharge by farm pond and percolation tanks after the development of land use/land cover (LULC) map. They used the IRS-P6 LISS-IV image and DEM to assess the potential recharge sites for domestic, livestock, irrigation and groundwater recharge purposes. Verma (2016) also identified artificial recharge sites based on GIS and GPS mapping in the different watershed areas of Chhattisgarh, India. The artificial recharge structures, i.e. percolation tank and check dams, were recommended, and these ultimately helped to reduce the demand for the main water supply (groundwater) and also helped to save water, energy and money. Gomez and Teixeira (2017) found 40% of drinking water demand could be saved by RWH. Mahmood and Hossain (2017) developed model-based GIS maps to determine the feasibility of domestic rainwater harvesting (DRH) in the South Asian region. They recommended DRH for Bangladesh, Sri Lanka, from the Himalayan range to North-Eastern, Central, Eastern and coastal parts of Southern India. It could satisfy yearly 7.5 lpcd for drinking and cooking purposes. A study by Mukherjee et al. (2015) investigated the in-situ groundwater storage for Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal, India, after using RS and GIS from the year 2005–2013. They developed potential groundwater recharge zones using GIS-based hydro-geological databases (trends of precipitation, usable groundwater, groundwater storage with analysis of satellite imagery) with a mathematical model for artificial recharge, whereas CPWD (2002) set up an SPG project at Dwarka, New Delhi, India, having a total area of 47.5 ha mainly to augment groundwater in urban areas. Another scheme for the artificial recharge of groundwater was set up at Faridabad in Hariyana to restrict the decline of groundwater along with awareness generation among the common people for proper management of RWH. A study was performed on the LULC changes with multicriteria analysis (MCA) to identify a potential zone for the construction of water reservoirs for RWH with recharge (Kar et al., 2020). However, UN-Habitat (2015) mentioned that in India, RWH was a part of state policy. In Chennai, Delhi and Bangalore, RWH was made mandatory. In the state of West Bengal, RWH was made mandatory for the construction of new buildings in urban areas under West Bengal Municipal (Building) Rules (GWB, 2007) but not in rural areas. Meanwhile, CGWB (2011) started that the identification of artificial recharge areas with suitable structures in different states including West Bengal in its VIII plan (1992–1997) to handle the contaminated groundwater situation. Further, the central groundwater board started the experiment of artificial recharge of the aquifer in 1970. From the eighth plan, rooftop RWH was introduced in West Bengal and during the tenth plan; a demonstration was implemented through NGOs in 100 rural schools. Various techniques of RWH such as injection well with rooftop RWH was proposed for potential recharge of the confined aquifer areas which indirectly enhanced the quality of groundwater (Sekar & Randhir, 2007; CGWB, 2013). For instance, installation of an arsenic removal plant (ARP) with RWH at the Sujapur, West Bengal, found that the concentration of arsenic and iron was reduced from 0.2 mg/L to 0.03 mg/L and 1.7 mg/L to 0.25 mg/L, respectively (Studer & Liniger, 2013). The central groundwater board (CGWB, 2007) of India already started the RWH with artificial recharge schemes into permeable strata of shallow depth. On average yearly, 5500 to 34.50 lakh cubic meter of runoff was successfully recharged in selected areas of Arunachal Pradesh, Assam, Bihar, Chandigarh, Gujrat, Hariyana, Jharkhand and Uttar Pradesh by RWH. Similarly, in Himachal Pradesh, Karnataka, Punjab, Tamilnadu, Madhya Pradesh, Orissa and Maharashtra, a substantial amount of water was recharged through a combination of percolation tanks, watershed structures along with recharge wells and rooftop rainwater harvesting (RRH). RWH with artificial recharge by a combination of farm pond, Nala bunds, and sub-surface dykes were capable to rise by 0.15 m of water table successfully in the districts of Purulia, Bankura and Birbhum, in the western part of West Bengal, though Rajasthan had a prestigious historical background to practice RWH. Consequently, RWH was predominant in India, Jordan and other parts of Asia, Italy and South Africa since the late 1900s (Debusk & Hunt, 2012). Providing arsenic-free safe drinking water to huge rural masses had been a major challenge to the government, planners and executors (Ghosh et al., 2020). Md Rana (2013) mentioned that the modified Sujapur-Sadipur model, Gobordanga model and community-based arsenic removal plant for multi-village water supply schemes for North 24 Parganas of West Bengal Government were very much time taking and high-cost projects. CGWB (2013) suggested that RRH could supply domestic water requirements, not for water-scarce areas but water excess areas. The RWH had been user-friendly, low cost and an alternative technology for arsenic mitigation. The CGWB estimated up to 70% of groundwater recharge would be possible with 100 m^2 roof in the regions having 780 mm of average monsoon rainfall. Another 55–275m^3 harvested water could be managed to meet the demand of a five-member family for 100 to 500 days. Except for Darjeeling, other districts did not implement RWH successfully in West Bengal (PHED, 2018). However, before the use of harvested water in domestic sector solar technology, rapid sand filters, Filtration Absorption Disinfection (FAD) purification system for turbidity, COD, DOC, *E. coli* and total coliforms were the best options for maintaining the microbiological free harvested water supply (Helmreich & Horn, 2009; Naddeo et al., 2013). RWH was a local solution for proving safe drinking water by a pond and supplying it with piped water after purification. Ponds had been a good source of drinking water provided proper planning and motivation of local people (Adham et al., 2018). One of the main objectives of the National Water Mission of India (Government of India, 2013) was to publish comprehensive water quality-quantity data in the public domain. Other objectives were to publish the area-wise impact assessment of vulnerability and promote the concern of the state's water conservation, augmentation, and preservation policies among citizens. It also highlighted traditional water conservation systems (i.e. RWH), mandatory water audits, incentivizing by giving awards for water conservation, efficient use and efficient irrigation practice (MWR, 2012).

Again Ministry of Drinking Water and Sanitation of India (MDWS, 2013) decided to cover at least 55% of rural households under piped water schemes by 2017. Among them, 35% would have water connections within households thereby decreasing public tap water use by less than 20% and hand pump used by less than 45% to mitigate arsenic calamity. Thus, PHED (2013) suggested RWH and prepared a document namely ‘Master Plan for Artificial Recharge to Ground Water-2013’ to provide information about area-specific artificial recharge techniques. This plan would construct a 1.11 crore artificial recharge structure including rooftop RWH in urban and rural areas. It was estimated that 85.565 MCM of surplus runoff would be harnessed to augment groundwater. Water security was determined by the complex interactions among water resources, governance systems, infrastructure development and user needs (Hoque et al., 2019). Bhowmick et al. (2018) described that there had been still a lack of well-planned effort for the mitigation of arsenic risk. Thus, good governance should introduce transparent information about water resources (quality and quantity), careful water management with RWH, include law enforcement to prevent social isolation, maintain equity and social justice for affected people. Existing Acts might have to be modified accordingly to get a mass response from the affected community to build good institutional coordination for the underprivileged people (Brinkel et al., 2009; DDWS, 2011; Hoque et al., 2019). By sensitizing the local, arranging rehabilitation programs to generate employment opportunities and providing accurate health information and supportive counseling process, it could be possible to overcome the bio-physical socio crisis of arsenic.

3.4 Recommendation for Sustainable Groundwater Management

It is indeed a great challenge ahead of the policymakers and engineers to ensure the supply of arsenic safe water understanding the magnitude of the arsenic poisoning. Many alternatives are safer, but none of them is suitable or affordable compared to shallow tube wells. At the same time, the traditional water sources, i.e. large-diameter dug wells, ponds and lakes, are also getting polluted. Considering the magnitude and extent of the problem, following recommendations are suggested.

- To make people aware of the calamity, the extent of arsenic poisoning is required to be estimated through vulnerability mapping based on GIS technology. This may include the present scenario of the quality as well as quantity wise status of the groundwater. Sharing of these thematic maps and models with the affected community would be the simplest but effective form of regular public awareness campaign.
- The land use/land cover (LULC) maps should be published on the local level to restrict any drastic change of the same and augment the natural recharge.

- The launch of the proper treatment protocols involving locals and ensuring the availability of adequate medical personnel are essential to support the mental and physical health of the affected population. Alternate job opportunities are to be ensured to restrict any excessive drafting of groundwater.
- RRH should be made mandatory even for small rooftops in rural areas with low-cost water treatment technology (slow sand filter). Poor people should be given incentives to install the RRH. Social acceptance of the scheme is essential to make it a success.
- As a long-term resolution, a global strategy is to be formulated to eradicate the hazard of arsenic.

3.5 Conclusions

The outcome of the review emphasizes the careful analysis of arsenic risk identification, causes and consequences. There is still a gap in the awareness of the impact of biophysical aspects of arsenic contamination as affected people have not been taking RWH seriously. It is not even popular among educated people. The project of real investment for RWH depends on the acceptance of common people. RRH may be of much help as an alternative solution to the arsenic calamity in rural areas. To overcome the arsenic-iron risk, the responsible authorities should arrange a water safety plan including an awareness programme. Also, periodical updating of mapping with qualitative data on local aquifers and providing proper know-how of the RWH scheme to the people remains a great challenge. The present study, in that sense, would help the policymakers and concerned authorities to delineate a proper guideline for remediation of the arsenic-related problem.

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