

# Chapter 10

## Evaluating Hydrogeological and Topographic Controls on Groundwater Arsenic Contamination in the Middle-Ganga Plain in India: Towards Developing Sustainable Arsenic Mitigation Models

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**Abstract** We investigated the spatial distribution and severity of groundwater arsenic contamination in three previously un-studied villages located near the confluence of the Rivers Ganges and Sone, within the Maner block of Patna district in the Bihar State, India. We also gathered information on the demographic, socioeconomic and health issues of local residents in order to identify at-risk populations due to the exposure to elevated concentrations of arsenic. Arsenic concentrations were measured in 157 drinking water sources, which were tested using field-tests kits. Spatial patterns in arsenic distribution were compared with local physiographic and hydrogeologic parameters. Arsenic levels exceeding the WHO and the BIS standards (10 µg/L and 50 µg/L respectively) were found in all three villages, with a maximum of 300 µg/L. The shallow aquifers ( $\leq 50$  m below ground surface) and older hand pumps were found to be arsenic contaminated. The deeper aquifers ( $>50$  m) exhibited arsenic levels within permissible limits. Elevated arsenic levels are observed close to the River Ganges. However, a moderate ( $r=0.240$ ,  $p=0.031$ ) positive correlation with the surface water flow direction indicates that arsenic migrates from south to north and from west to east in the study area. This suggests that River Sone alluvium is a potential source of arsenic contamination in Bihar.

### Highlights

- Arsenic concentrations exceeding WHO and BIS standards are documented in three villages in the Maner Block of Patna district, Bihar, India.
- Arsenic contaminated hand pumps in Suarmarwa, Rampur Diara, and Bhawani Tola are 10–15 years older than the arsenic-free hand pumps.

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- Arsenic concentration correlates with the depth of tube wells, flow direction of surface water, distance to the rivers, and distance to the drainage point.
- The River Sone is a potential source of arsenic contamination in the Middle-Ganga Plain in India.
- The National Chemical Laboratory-Arsenic Field Test Kits (NCL-FTK) is a reliable and quick field method to analyze arsenic levels in water.

## 1 Introduction

Geogenic groundwater arsenic contamination is referred to as “the biggest global mass poisoning in human history,” with the maximum incidence in South Asia (Nordstrom 2002; Rahman et al. 2014; Singh and Vedwan 2015). Arsenic is a group ‘A’ carcinogen (IARC-WHO 1999, 2001). It occurs in five valence states, among which arsenic *III* (arsenite, the most toxic form) and arsenic *V* (arsenate) are the most abundant species in groundwater (Ravenscroft et al. 2009). Exposure to arsenic through drinking and food induces carcinogenic and non-carcinogenic health effects (Phan et al. 2010; Singh 2011; Singh et al. 2014). Children are particularly susceptible to arsenic-induced health problems such as reduction in IQ levels, among other ailments (Nahar et al. 2014; Wasserman et al. 2014). The impacts of arsenic hazards on human health are exacerbated by poor socioeconomic conditions, which make impoverished people especially vulnerable to elevated arsenic level in drinking water (Curry et al. 2000; Singh and Vedwan 2015).

Alleviating arsenic contamination presents a major challenge to researchers, communities, and policy makers. India continues to follow the World Health Organization’s (WHO) old standard, set in 1963, of 50 µg/L of arsenic as the maximum concentration for “safe” drinking water (Yamamura 2001; Singh and Vedwan 2015), even though the Bureau of Indian Standards (BIS) later set a lower acceptable limit of 10 µg/L (BIS 2012). Approximately three decades ago, millions of hand pumps were installed in Bangladesh and India to extract groundwater for domestic use (Opar et al. 2007). At that time, groundwater was viewed as a safer alternative to unhygienic surface water sources and considered a means to protect millions of people from a variety of water-borne diseases (Opar et al. 2007; Singh and Vedwan 2015). However, in the Middle-Ganga Plain (*MGP*), approximately 87 % of the tested groundwater sources were found to be contaminated with arsenite (Mukherjee et al. 2012). Previous studies have addressed health impacts related to consumption of arsenic-contaminated groundwater and food (Chakraborti et al. 2003; Singh 2011; Singh and Ghosh 2011, 2012; Singh et al. 2014). However, the total exposed population to groundwater arsenic and the consequences of exposure are still unknown in the Bihar State in the *MGP*.

Groundwater and surface water arsenic contamination have been linked to both natural geochemical processes (geogenic) and anthropogenic activities. The latter includes mining and application of arsenic-bearing fertilizers and pesticides (Mukherjee et al. 2006; Ravenscroft et al. 2009). Natural geogenic arsenic is

common in India, Bangladesh, Nepal, and Pakistan (Smedley and Kinniburgh 2002; Singh and Vedwan 2015). Recent studies suggest that microbially-driven or chemically-driven reductive dissolution of arsenic-bearing Fe oxyhydroxides in organic-rich sediment is the main source of arsenic in shallow aquifers (Nickson et al. 1998, 2000; Dowling et al. 2002; Mahanta et al. 2015; Stuckey et al. 2015).

The use of physiographic, hydrogeologic and soil properties have been explored as predictors of heavy metal contamination in shallow aquifers using probability models (Twarakavi and Kaluarachchi 2005; Winkel et al. 2008; Yang et al. 2014). The heterogeneous natures of these properties, both at the surface and at depth, make aquifer-specific investigations vital to understanding arsenic mobility at the local scale. Winkel et al. (2008) found a positive correlation between organic-rich Holocene fluvial and deltaic sediments and groundwater arsenic levels above 10 µg/L. Similarly, Yang et al. (2014), found that deltaic, organic rich sediments were the strongest predictors of elevated arsenic. In both the studies the data sets were restricted to areas of flat topography, and neither the well depth nor the surface elevation was included in the model.

Additional parameters need to be incorporated into the next generation of predictive models. These include flow direction, flow accumulation, and distance to drainage point. These parameters are derived from Digital Elevation Models (DEM). “Flow direction” gives the cardinal direction of the surface water flow. “Flow accumulation” is a dimensionless parameter that represents the cumulative flow into each cell from all upstream cells in the DEM. “Drainage points” are cells with the highest flow accumulation. These parameters and methods utilize Geographic Information Science (GIS) and remote sensing (RS) techniques, which are well suited to identifying spatial and temporal patterns. These new parameters can be used to investigate whether arsenic transport is a contributing factor to elevated arsenic concentrations in groundwater.

Moreover, easily interpretable presentation of results for decision-makers in the form of statistical models or GIS maps is lacking in Bihar (Singh and Vedwan 2015). A recent study presented a composite vulnerability index and GIS-based vulnerability map for the arsenic contaminated areas and the communities living in those areas (Singh and Vedwan 2015). This map, combined with predictive models, would be helpful for decision-makers to prioritize areas for arsenic-mitigation programs and predict the probability of success of an arsenic-mitigation policy in a given area.

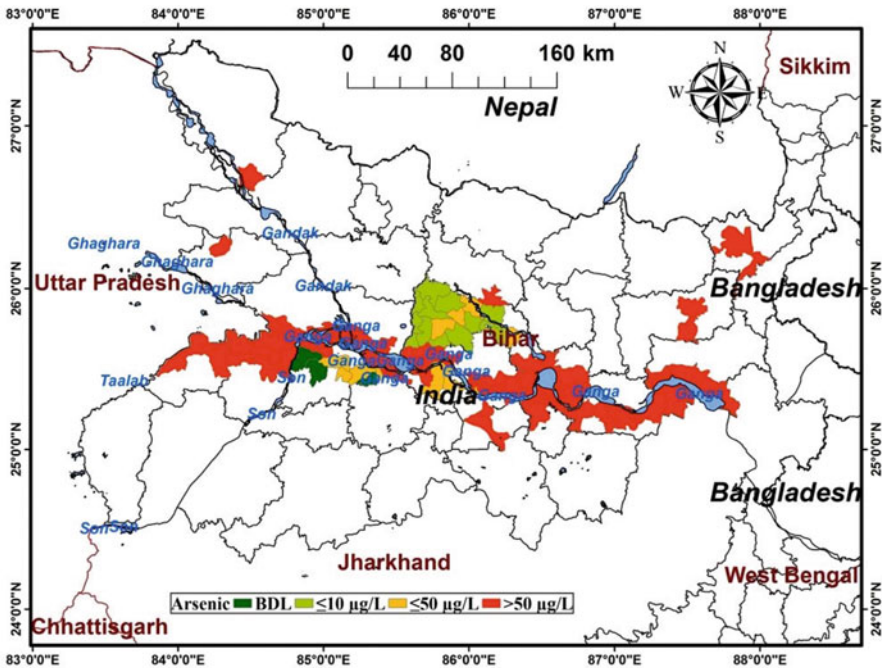
The objectives of this study are to: (a) evaluate the arsenic contamination levels in drinking water sources in three (two previously unstudied) villages in the Bihar; (b) assess the population size at risk due to exposure to arsenic contamination; and (c) assess the hydrogeologic and topographic relationships with arsenic concentrations in groundwater.

## 2 Study Area

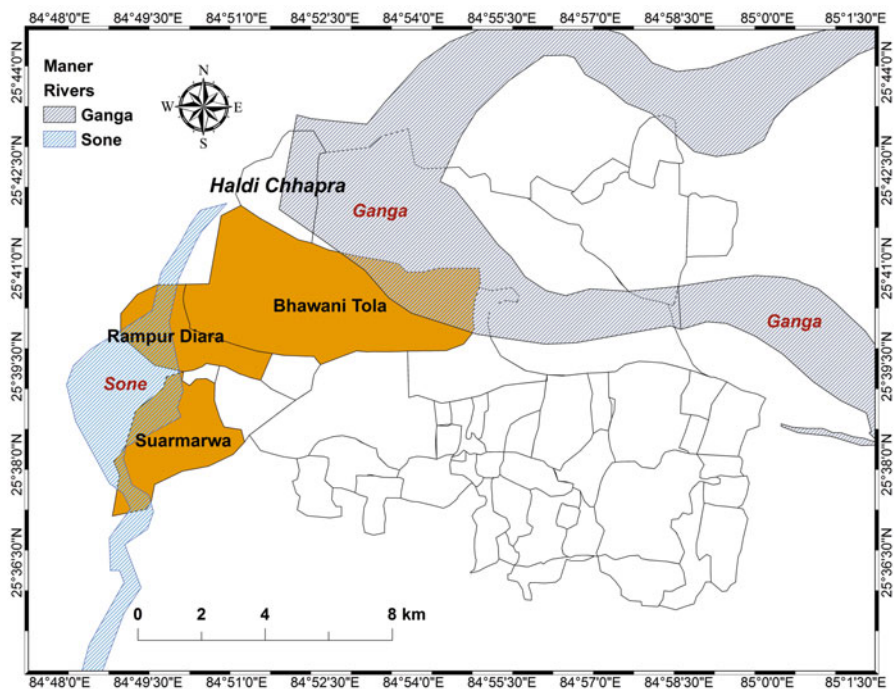
The Bihar State is located in the *MGP* of India (Fig. 10.1). Approximately 12 million inhabitants have been reported as at-risk in the state (Singh et al. 2014; Singh 2015a, b; Singh and Vedwan 2015). Groundwater arsenic contamination in Bihar was first detected a decade ago in the Bhojpur district (Chakraborti et al. 2003). As of 2014, groundwater arsenic contamination has been documented in 22 of 38 districts (Singh et al. 2014). The remaining 16 districts have either not been investigated or results not yet reported in mainstream scientific literature.

Multiple research groups and agencies have investigated the origin and distribution pattern of arsenic in the *MGP* (Ghosh et al. 2009; Saha et al. 2011; Mukherjee et al. 2012; Saha and Shukla 2013). There exists a wide spatial distribution of groundwater arsenic levels in the region. The levels frequently exceed 1000  $\mu\text{g/L}$  (100 times higher than the WHO standard) in several districts located within 10 km of the River Ganges including Buxar, Bhojpur, Patna, Samastipur, and Bhagalpur (Ghosh et al. 2009; Saha 2009; Saha et al. 2009; Singh and Vedwan 2015).

This study investigated three villages covering 70 acres; Suarmarwa (30 acres), Rampur Diara (25 acres), and Bhawani Tola (15 acres) in the Maner block of Patna



**Fig. 10.1** Arsenic contaminated community blocks of Bihar and neighboring regions (Singh 2015a)



**Fig. 10.2** The study area showing the three villages in Maner block of Patna district, Bihar. Bhawani Tola is bordered by the River Ganges to the north. Rampur Diara and Suarwarwa are situated on the bank of the River Sone. Haldi Chhapra is a highly arsenic contaminated village located immediately north of the study area. Neither Suarwarwa or Bhawani Tola has been investigated for arsenic contamination

district of Bihar State (Fig. 10.2). The block is one of the worst arsenic affected blocks in the state (SOES 2004; Singh 2011; Singh and Ghosh 2012). The groundwater based drinking sources in most of the villages of this block, which are within 10 km of the River Ganges, have elevated levels of arsenic (SOES 2004; Ghosh et al. 2009; Singh 2011; Singh and Ghosh 2012).

### 3 Materials and Methods

#### 3.1 Arsenic Testing

To sample over a large area and investigate the maximum number of drinking sources possible, we used reliable and pre-tested field test-kits (FTK) for arsenic analysis. FTKs have been widely used for initial screening of arsenic contamination in drinking water (Nickson et al. 2007; Ghosh et al. 2009; George et al. 2014; van Geen et al. 2014). We used an arsenic FTK developed by the National Chemical

**Table 10.1** Comparison of NCL-FTK and AAS arsenic concentrations

Sample	NCL-FTK ( $\mu\text{g/L}$ )	AAS ( $\mu\text{g/L}$ )
1	BDL ( $<10 \mu\text{g/L}$ )	BDL ( $<5 \mu\text{g/L}$ )
2	60	70
3	50	70
4	40	40
5	50	60
6	BDL ( $<10 \mu\text{g/L}$ )	BDL ( $<5 \mu\text{g/L}$ )
7	40	40
8	50	50
9	70	80
10	40	10

*BDL* below detection limit; for FTK:  $<10 \mu\text{g/L}$  and for AAS  $<5 \mu\text{g/L}$

Laboratory (NCL), Pune, India, which is a constituent laboratory of the Council of Scientific and Industrial Research (CSIR), Government of India. The NCL-FTK protocols for field-based arsenic measurements have been approved by the Government of Bihar, the Government of Uttar Pradesh, and the United Nations Children's Fund (UNICEF) (Nickson et al. 2007; Ghosh et al. 2009). The NCL-FTK detects arsenic levels between 10 and 110  $\mu\text{g/L}$ , with an approximate 15 min reaction period and a cost of \$0.83 per sample (based on 2013 USD rate) (NCL 2002). Arsenic concentrations exceeding 110  $\mu\text{g/L}$  must be analyzed by Atomic Absorption Spectrophotometry (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS). We selected 22 samples at random for AAS analysis in order to assess the range of arsenic concentrations in the study area (Tables 10.1 and 10.2). Samples were handled according to the protocols of Nickson et al. 2007. AAS analyses were conducted by the Sriram Institute for Industrial Research (An ISO-9001:2008 certified Institute in Delhi, India).

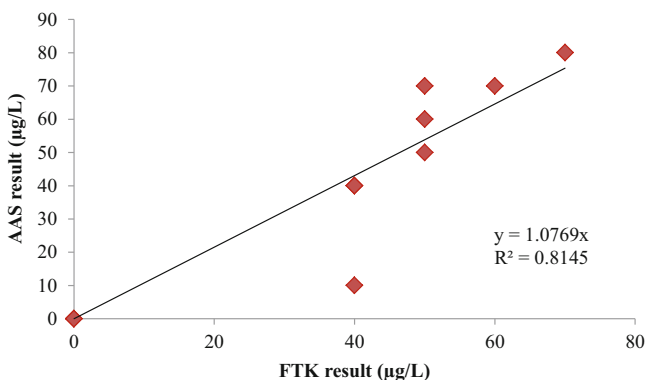
The FTK uses a cotton plug saturated with lead (Pb)-acetate to filter impurities. The color of the plug was monitored after every analysis. High arsenic levels ( $>50 \mu\text{g/L}$ ) caused the plug to turn black, in which case the plug was immediately replaced. A fresh plug was used after every ten analyses, and an arsenic standard of 50  $\mu\text{g/L}$  was measured after every 20 analyses.

The accuracy of the NCL-FTK was previously reported at 67 %, i.e., an  $R^2$  of 0.67 was determined for a set of ten samples analyzed using both the NCL-FTK and AAS (Ghosh et al. 2009). In this study, we obtained an  $R^2$  value of 0.82 for a set of ten samples analyzed by NCL-FTK and AAS (Tables 10.1 and 10.2; Fig. 10.3). Although some samples are off the trend line, the NCL-FTK can be utilized to identify low contamination (arsenic levels  $<10 \mu\text{g/L}$ ), moderately contaminated water (10–50  $\mu\text{g/L}$ ), and highly contaminated ( $>50 \mu\text{g/L}$ ) water.

A total of 157 water samples (Suarmarwa = 57, Rampur Diara = 50, Bhawani Tola = 50) were collected from hand pumps and tested immediately using the NCL-FTK. One hundred and fifty-four samples were taken from shallow aquifers ( $<50 \text{ m}$ ) and three from deep tube wells ( $>50 \text{ m}$ ). We also tested open wells/dug wells (Fig. 10.4), which were abandoned by the communities. Though open well results

**Table 10.2** Arsenic concentration in groundwater samples from Atomic Absorption Spectrophotometry

Sample no.	Village name	[Arsenic] µg/L
1	Rampur Diara	5<
2	Rampur Diara	70
3	Rampur Diara	80
4	Rampur Diara	80
5	Rampur Diara	70
6	Rampur Diara	40
7	Rampur Diara	70
8	Rampur Diara	20
9	Rampur Diara	60
10	Rampur Diara	<5
11	Rampur Diara	300
12	Rampur Diara	40
13	Rampur Diara	40
14	Rampur Diara	<5
15	Rampur Diara	5<
16	Bhawani Tola	80
17	Rampur Diara	40
18	Rampur Diara	40
19	Rampur Diara	50
20	Bhawani Tola	250
21	Rampur Diara	10
22	Rampur Diara	30
Min		<5
Max		300
Mean		62
Std. dev.		75



**Fig. 10.3** Comparison of NCL-FTK and AAS arsenic concentrations in water samples. Values that were below detection were plotted as 0 µg/L

are not presented here, they exhibited arsenic levels well within the WHO limit (BDL). Open wells have been reported as arsenic-free sources of drinking water and could be a cost-effective arsenic-mitigation option (Saha 2009; Singh 2015a, b).

**Fig. 10.4** An open dug-well in Rampur Diara potentially targeted for renovation (Photograph by Sunil Kumar Singh 2014)



### 3.2 Population At-Risk and Population Exposed to Arsenic

We define an “at risk” population as one whose members consume arsenic contaminated drinking water. The “population exposed” describes individuals who have access to drinking water sources with arsenic levels exceeding safe levels. This can be calculated with either the WHO (10 µg/L) or the BIS (50 µg/L) standard (Nickson et al. 2007). At-risk population size is calculated as:

$$\begin{aligned} \text{Population at risk} &= \text{Total population covered}_{A_s} \\ &\quad \times \% \text{ of sources contaminated with arsenic} \end{aligned}$$

where  $\text{total population covered}_{A_s}$  is the total population that uses the tested water sources (Singh 2015a). Total population covered is calculated as the number of households surveyed multiplied by 6, which is the average household size in the three villages (Singh 2015a). Population exposed was calculated as follows:

$$\begin{aligned} \text{Population exposed} &= \text{Total population of the village} \\ &\quad \times \% \text{ of sources contaminated with arsenic} \end{aligned}$$

### 3.3 GIS Mapping and Data Analysis

Arc Geographic Information System (ArcGIS) Desktop version 10.2 (ESRI 2012) was used to create all the maps. Block level shape files were obtained from the Central Ground Water Board, Mid-Eastern Region, Patna, Bihar, India. River shape files for the Bihar State were downloaded from the diva-GIS web-portal (<http://www.diva-gis.org/datadown>). A hardcopy of the village map of the Maner block was obtained from the Bihar Census Bureau, India. The village map was



georeferenced to generate village layers. A RICOH GPS Enabled Camera was used to take photographs of water sources and enter their geographical coordinates into shape files using the GPS Photo-Link program. Only 88 of 157 water sources were processed in this manner due to weak satellite signals or failure of the GPS Photo-Link program to process the coordinates. Other information such as arsenic concentration and elevation of the water source was entered into the attribute table.

Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 2 (2011), a product of the Ministry of Economy, Trade, and Industry (METI) of Japan and the U.S. National Aeronautics and Space Administration (NASA), was used for hydrological and topographic analysis (<http://earthexplorer.usgs.gov/>). The surface elevation, slope, flow direction, and flow accumulation were extracted at the coordinates of each water source using the Spatial Analyst tool. ASTER GDEM and Arc Hydro Tools 10.2 were used to analyze elevation, slope, flow direction, flow accumulation, stream network geometry, drainage catchment area, and drainage points. All possible sinks in the GDEM were filled by applying the fill-sink option available within the Arc Hydro Tool. The flow direction tool was applied to determine the direction of steepest downward slope, where each of the eight possible flow directions out from the center of a  $3 \times 3$  grid of cells is represented by an integer that increases in a clockwise manner in increments of 16 from 1 (East) to 128 (Northeast). The flow accumulation tool was used to determine the cumulative flow into each cell from all upstream cells. Drainage points were defined as the cells of highest flow accumulation. The probable effect of the any nearby drainage (such as the Ganges and the Sone) on the contamination level in the tested sources was analyzed. In addition, distance between tested water sources and drainage points, and the distance between arsenic contaminated and arsenic-free drinking water sources were calculated.

### **3.4 Statistical Analysis**

The water quality analysis data and the DEM-derived spatial data were transferred into SPSS for statistical analysis (IBM 2012). A crosstabs analysis was performed between arsenic concentration and the villages surveyed to assess the independence. Bivariate analysis was performed to examine associations between water quality and hydrological and topographical data.

## **4 Results**

### **4.1 Groundwater Arsenic Contamination in the Surveyed Villages**

The AAS analysis results of 22 groundwater samples are given in Table 10.2. Rampur Diara had a maximum arsenic concentration of 300  $\mu\text{g/L}$ . This is substantially higher than the maximum of 103  $\mu\text{g/L}$  observed in a previous study in this

village (Singh 2011; Singh and Ghosh 2012). The next highest level of 250  $\mu\text{g/L}$  was measured in Bhawani Tola (Table 10.2).

Of the 157 groundwater sources tested by the NCL-FTK, 39 of 57 sources in Suarwarwa (68 %), 31 of 50 sources in Rampur Diara (62 %), and 18 of 50 sources in Bhawani Tola (36 %) were below the detection limit (BDL) of 10  $\mu\text{g/L}$  (Table 10.3). Two sources (4 %) in Rampur Diara and two sources in Bhawani Tola (4 %) had arsenic concentrations near the WHO standard of 10  $\mu\text{g/L}$ . Thirteen samples (22.8 %) in Suarwarwa, 11 (22 %) in Rampur Diara, and 10 (20 %) in Bhawani Tola, had arsenic levels between the WHO standard of 10  $\mu\text{g/L}$  and the BIS standard of 50  $\mu\text{g/L}$  (Table 10.3). In Bhawani Tola, 20 samples (40 %) have arsenic concentrations exceeding 50  $\mu\text{g/L}$  (Table 10.3). The average arsenic concentration was 14  $\mu\text{g/L}$  in Suarwarwa, 17  $\mu\text{g/L}$  in Rampur Diara, and 38  $\mu\text{g/L}$  in Bhawani Tola. The arsenic levels in all the three villages were significantly different from each other ( $p = 0.001$ ) (Table 10.3).

The depths of the drinking water sources were similar ( $p = 0.322$ ) in the three villages (Table 10.3, Fig. 10.5). Only 5 % of the water sources in Suarwarwa and 6 % each in Rampur Diara and Bhawani Tola drew from depths shallower than 20 m below the ground surface (Table 10.3). The majority of the water samples (Suarwarwa = 95 %, Rampur Diara = 90 %, and Bhawani Tola = 94 %) were drawn from depths between 20 and 50 m below ground surface (Table 10.3). Only two drinking water wells in Rampur Diara drew water from depths below 50 m below ground surface. Both the sources (one boring and one hand pump) were arsenic-free. The crosstabs analysis between the three arsenic contamination groups (Table 10.4) and the three depth groups indicates that of 90 % of the water sources (79 of 88) in the BDL group were located between 20 and 50 m.

Four water sources with 10  $\mu\text{g/L}$  of arsenic were observed (Table 10.3). Two of these came from 0 to 20 m depth and two from 20 to 50 m depth. One hundred percent (100 %) of the sources ( $n = 34$ ) with arsenic levels between 11 and 50  $\mu\text{g/L}$  were collected from wells in the depth range of 20–50 m below ground. Approximately 97 % ( $n = 30$ ) of the sources with arsenic levels  $>51$   $\mu\text{g/L}$  were collected in the same depth range of 20–50 m below ground surface. Only one sample with an

**Table 10.3** Distribution of arsenic concentration and well depths ( $p =$  significance level)

Village	Arsenic ( $p = 0.001$ )				Depth ( $p = 0.322$ )		
	BDL	10 $\mu\text{g/L}$	11–50 $\mu\text{g/L}$	$>51$ $\mu\text{g/L}$	0–20 m	20–50 m	$>50$ m
Suarwarwa	39 (68 %)	0 (0 %)	13 (23 %)	5 (9 %)	3 (5 %)	54 (95 %)	0 (0 %)
Rampur Diara	31 (62 %)	2 (4 %)	11 (22 %)	6 (12 %)	3 (6 %)	45 (90 %)	2 (4 %)
Bhawani Tola	18 (36 %)	2 (4 %)	10 (20 %)	20 (40 %)	3 (6 %)	47 (94 %)	0 (0 %)
N	88	4	34	31	9	146	2

*BDL* below detection limit

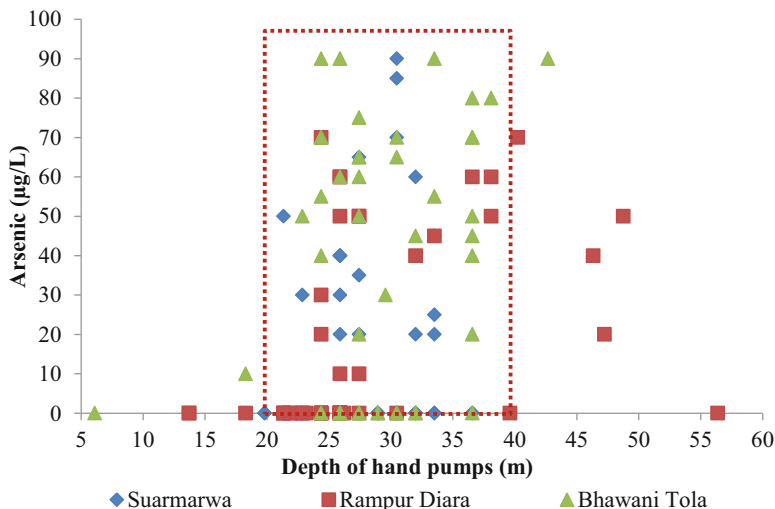


Fig. 10.5 Arsenic concentrations vs. depths of hand pumps

Table 10.4 Arsenic concentrations by depth of hand pumps

		Depths of hand pumps (m) (p = 0.007)		
		0–20 (%)	20–50 (%)	>50 (%)
Arsenic concentration (µg/L)	BDL (n = 88 of 157)	8	90	2
	10 (n = 4 of 157)	50	50	0
	11 to 50 (n = 34 of 157)	0	100	0
	>51 (n = 31 of 157)	3	97	0

BDL below detection limit

arsenic level of 85 µg/L came from a shallow well in the depth range of 0–20 m below ground. Based on the Chi-square test, the distribution of arsenic was significantly different at different depths (p = 0.007), which showed a wide spatial distribution.

### 4.2 Populations At-Risk and Exposed

Approximately 10% (n = 204) of individuals were found to be at-risk due to exposure to >10 µg/L of arsenic in drinking water. The highest population at-risk is in Suarmarwa 12% (n = 78), followed by Rampur Diara (9%, n = 66), and Bhawani Tola (8%, n = 60) (Table 10.5). The total population at-risk due to the exposure to >50 µg/L of arsenic in drinking water is 9% (n = 186), with the highest population at-risk in Bhawani Tola 17% (n = 120), followed by Rampur Diara

**Table 10.5** Populations at-risk and exposed to drinking arsenic contaminated water

Village	TPC	TP	PR >10 µg/L	PR >50 µg/L	PE >10 µg/L	PE >50 µg/L
Suarmarwa	667	4696	78	30	1071	413
Rampur Diara	769	3437	66	36	756	412
Bhawani Tola	712	3000	60	120	600	1200
Total	2148	11,133	204	186	2427	2026

*TPC* Total population covered, *TP* Total population, *PR* Population at risk, *PE* Population exposed

(5 %, n = 36), and Suarmarwa (4 %, n = 30) (Table 10.5). Population at risk and exposed population at >10 and >50 µg/L are completely separate populations.

A total of 22 % (n = 2427) and 18 % (n = 2026) of the inhabitants were found to be exposed to >10 µg/L and >50 µg/L of arsenic in drinking water, respectively (Table 10.5). The highest exposed population was in Suarmarwa at >10 µg/L (WHO standard) and in Bhawani Tola at >50 µg/L (BIS standard) (Table 10.5).

## 5 Discussion

### 5.1 Spatial and Temporal Patterns of Arsenic Contamination

We compared our arsenic concentration data with previously reported results from Maner block (Table 10.6). High concentrations of arsenic have previously been observed in Rampur Diara (Singh 2011; Singh and Ghosh 2012). However, this is the first time that we have observed arsenic concentrations above the WHO and the BIS standards in Suarmarwa and Bhawani Tola.

All of the arsenic contaminated sources draw water from the depth range of 20–50 m below the ground surface, with the exception of one 10 µg/L sample in Bhawani Tola. The findings are consistent with previous studies. It suggests that shallow aquifers are contaminated to a depth of 50 m, the maximum depth of the hand pump sources tested in this study (Saha 2009; Saha et al. 2009). We found a positive correlation between the hand pump depths (up to 50 m) and arsenic concentration ( $R^2 = 0.217$ ,  $p = 0.007$ ). In previous studies, no significant correlation between arsenic concentration and hand pump depths was reported, possibly due to limited sample size and smaller geographical area of study (Singh and Vedwan 2015). However, defining a clear relationship between arsenic contamination and depth requires a large number of samples at each depth horizon.

The age of the majority of the hand pumps tested was between 4 and 13 years. Twenty one percent (21 %) of the arsenic-free water sources were installed between 1950 and 2000. A slight majority (51 %) of the arsenic-free hand pumps were installed between 2001 and 2010, followed by 28 % installed in 2011 or later. A majority (59 %) of water sources with arsenic levels between 11 µg/L and 50 µg/L were installed between 2001 and 2010, followed by 35 % in 2011 or later, and only 6 % before the year 2000. Likewise, a majority (57 %) of drinking water sources with arsenic levels greater than 50 µg/L was installed between 2001 and 2010,

**Table 10.6** Arsenic concentrations reported in villages of Maner Block of Patna District

Village	# samples analyzed	10–50 µg/L	>51 µg/L (%)	References
Puranka Tola	54	2 %	98	(SOES 2004)
Nayka Tola	41	0	100	(SOES 2004)
Badal Tola	74	9 %	91	(SOES 2004)
DihalRike Tola	16	0	100	(SOES 2004)
Haldichhapra	10	0	100	(Singh and Ghosh 2012)
Rampur Diara	10	40 %	60	(Singh and Ghosh 2012)
Suarmarwa	57	23 %	9	This study
Rampur Diara	50	26 %	12	This study
Bhawani Tola	50	24 %	40	This study

**Table 10.7** Distance between arsenic contaminated and arsenic safe<sup>a</sup> sources

	Suarmarwa	Rampur Diara	Bhawani Tola
Mean (m)	49.7	50.3	203.1
Std. deviation (m)	30.9	28.9	75.9
Minimum (m)	9.0	20.0	24.0
Maximum (m)	98.0	112.0	303.0

<sup>a</sup>Safe represents sources with arsenic concentration of 10 µg/L or below the detection limit (BDL)

followed by 37 % sources in 2011 or later, and 6 % before the year 2000. We did not find any significant correlation between the arsenic contamination groups and the age groups (year of installation) of the hand pumps ( $p = 0.254$ ).

A distance analysis was performed between arsenic contaminated drinking water sources ( $>10$  µg/L) and arsenic safe drinking water sources ( $\leq 10$  µg/L). The purpose was to investigate the distance that villagers would be required to travel to obtain arsenic-free water. The mean distance between the contaminated and safe sources is approximately 50 m in Suarmarwa and Rampur Diara (Table 10.7). The mean distance for Bhawani Tola is 203 m (Table 10.7). However, there may be other sources in between, which were not tested in this study.

## 5.2 Hydrogeological and Topographic Assessment

The three villages are located at elevations between 46 and 64 m above mean sea level (mamsl) (Fig. 10.6). The tested water sources have surface elevations between 52 and 62 mamsl. The slope (mean =  $2.76^\circ$ ) of the ground surface is towards the north and east (Table 10.8). Suarmarwa (50–64 mamsl) and Rampur Diara (49–64 mamsl) have similar elevation profiles, with a mean elevation of approximately 56 mamsl and a standard deviation of 3 m. There is no relationship between elevation and arsenic concentration in Suarmarwa and Rampur Diara. Bhawani

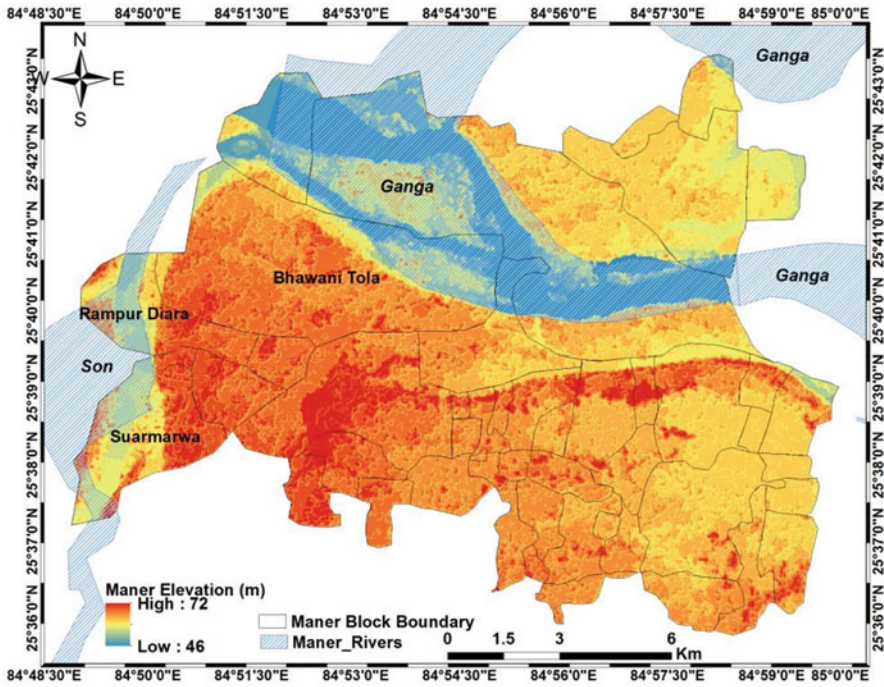


Fig. 10.6 Digital Elevation Model (DEM) of Maner Block of Patna District, Bihar, India. Data from ASTER Global Digital Elevation Model (GDEM) Version 2 (2011)

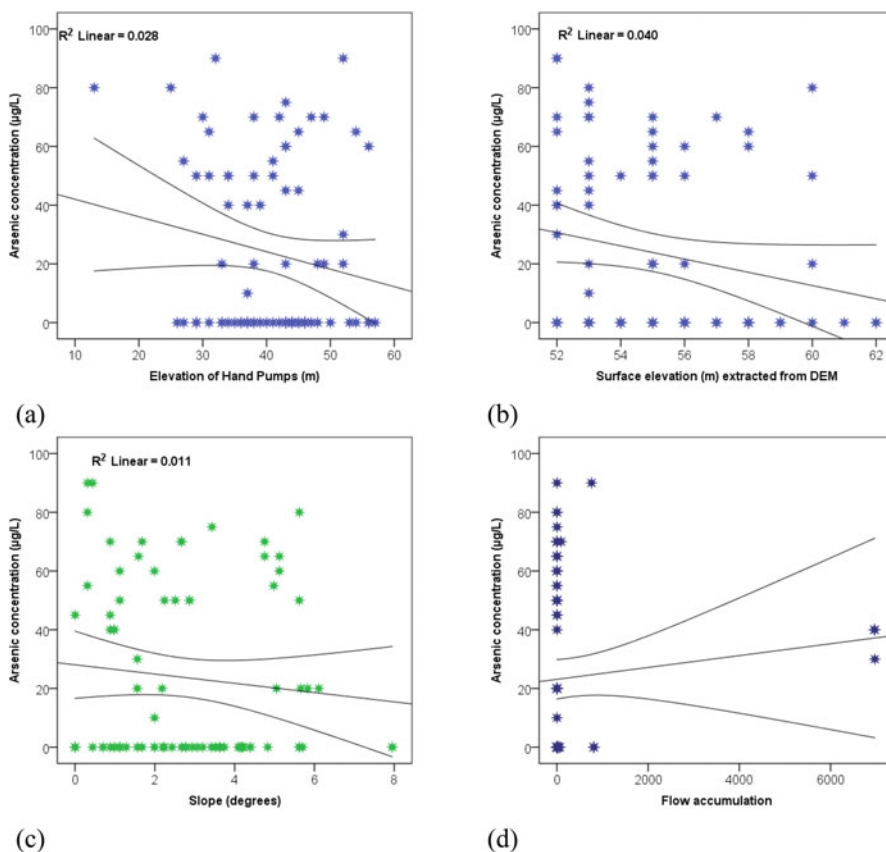
Tola is located at elevations of 46–64 mamsl with a mean value of 54.2 mamsl and a standard deviation of 3.9 m. In Bhawani Tola, higher arsenic concentrations were found at higher elevations.

The average distance between the tested sources and the River Sone was 1172 m, with a maximum distance of 1854 m (Table 10.8). The distance between the tested sources and the River Sone was less than half of the distance to the River Ganges (5209 m; Table 10.8). The average distance between the tested sources and the nearest drainage point was 636 m and average samples fall on the geographical coordinates between 25.65864° N and 84.84340° E (Table 10.8).

We observe no correlation between arsenic concentrations and elevation of the hand pumps, topographic slope, or flow accumulation (Fig. 10.7a, d). This may be due to the relatively constant topography in our study area, with only 20 m of vertical change over approximately 20 km. We note that Twarakavi and Kaluarachchi, 2005, found elevation, along with land use and soil hydrologic group, to be a statistically significant variable for arsenic prediction in the Sumas-Blaine Aquifer in Washington State. Elevation may play a more significant role in areas with a greater elevation range and steeper slopes, which influences soil texture.

**Table 10.8** Descriptive statistics of hydrogeological and topographic attributes of tested drinking water sources

	Minimum	Maximum	Mean		Std. deviation
	Statistic	Statistic	Statistic	Std. error	Statistic
Surface elevation (m) extracted from DEM	52	62	55.07	0.29	2.62
Slope (degrees)	0.00	7.95	2.76	0.22	1.94
Flow direction	1	128	37.99	4.93	44.41
Flow accumulation	0	6971	290.79	147.33	1325.96
Distance to the River Sone (m)	530.3	1854.8	1171.63	42.05	378.45
Distance to the River Ganges (m)	3955.4	6980.8	5209.33	114.07	1026.62
Distance to the drainage point (m)	67.4	981.8	636.48	26.89	242.10



**Fig. 10.7** Arsenic concentrations vs. (a) elevations of the tested hand pumps (b) surface elevations extracted from DEM (c) slope, and (d) flow accumulation, with regression line and 95% confidence lines

A moderate positive correlation ( $r=0.240$ ,  $p=0.031$ ) was observed between arsenic concentration and flow direction (Table 10.9, Fig. 10.8a–c), i.e., arsenic concentration tends to increase in the direction of surface water flow.

Near Analysis results shows a weak but significant negative correlation ( $R^2=0.090$ ,  $p=0.006$ ) between the arsenic concentration and the distance to the River Ganges (Fig. 10.9 and 10.10), i.e., arsenic concentrations are highest closer to the Ganges. This supports the hypothesis that the River Ganges and/or its levees and alluvium are sources of arsenic to groundwater.

A moderate positive correlation ( $R^2=0.176$ ,  $p<0.001$ ) was observed between arsenic concentration and the distance to the River Sone (Fig. 10.9b), i.e., arsenic concentrations are lowest close to the River Sone, and increase with distance away from the River Sone. Explaining this observation requires geologic and hydro-geochemical study of River Sone water and alluvium.

A negative correlation ( $r=-0.456$ ,  $p<0.001$ ) was observed between arsenic concentration and distance to the drainage points, i.e., high concentrations of arsenic occur close to the drainage points in the study area (Fig. 10.10, Table 10.9). This suggests that arsenic is concentrated along drainage lines and at drainage points (Fig. 10.11), and these are potential transport paths of arsenic to drinking water sources in their vicinity.

This finding also suggests that areas far from the drainage points are potential arsenic free sources of drinking water.

Two drainage points associated with high concentrations of arsenic are located adjacent to the River Ganges, and situated at the confluence of multiple drainage line networks that pass through the three villages and through the River Sone (Fig. 10.11). This suggests that arsenic carried by the River Sone, from alluvium and/or surface run-off, is transported towards the River Ganges. This would amplify the Ganges floodwaters as a source of arsenic contamination in the surrounding floodplain.

Arsenic concentrations are weakly but positively associated with the latitude ( $r=0.264$ ,  $p=0.017$ ) (Fig. 10.12a, Table 10.9) and moderately positively associated with the longitude ( $r=0.449$ ,  $p<0.001$ ) (Fig. 10.12b, Table 10.9). This is consistent with the flow direction results (Fig. 10.8a–c), suggesting that groundwater flows towards the northeast, from 25.64 N to 25.67 N (South to North) and 84.84 E to 84.85 E (West to East). In addition, high arsenic concentrations are prevalent in the villages situated in the North and Northeast of the study area, such as Haldi Chhapra (Fig. 10.2). There are more than 40 villages and habitations in Maner block that are located further to the North and East of our study area. If the observations reported here extend over a larger spatial scale, these villages to the northeast are predicted to have elevated levels of arsenic in their drinking water, and their water sources should be tested.



**Table 10.9** Correlation matrix of arsenic concentrations and hydrogeological and topographic attributes

	Arsenic concentration (µg/L)	Distance to the River Some (m)	Depth of hand pumps (m)	Elevation of hand pumps (m)	Surface elevation (m) extracted from DEM	Slope (degrees)	Flow direction	Flow accumulation	Distance to the River Ganges (m)	Distance to the drainage point (m)	Latitude (degree decimal)	Longitude (degree decimal)
Arsenic concentration (µg/L)	1	0.420 <sup>a</sup>	0.375 <sup>a</sup>	-0.168	-0.199	-0.104	0.240 <sup>b</sup>	0.090	-0.301 <sup>a</sup>	-0.456 <sup>b</sup>	0.264 <sup>b</sup>	0.449 <sup>a</sup>
Distance to the River Some (m)		1	0.009	-0.182	-0.127	-0.057	0.274 <sup>b</sup>	-0.206	-0.923 <sup>a</sup>	-0.819 <sup>a</sup>	0.883 <sup>a</sup>	0.991 <sup>a</sup>
Depth of hand pumps (m)			1	0.085	0.051	0.109	0.139	-0.028	0.017	-0.017	-0.023	0.015
Elevation of hand pumps (m)				1	0.146	0.134	0.144	0.015	0.115	0.301 <sup>a</sup>	-0.100	-0.182
Surface elevation (m) extracted from DEM					1	0.640 <sup>a</sup>	0.010	-0.260 <sup>b</sup>	0.088	0.172	-0.077	-0.130
Slope (degrees)						1	0.084	-0.193	0.052	0.052	-0.049	-0.059
Flow direction							1	-0.094	-0.195	-0.359 <sup>a</sup>	0.173	0.280 <sup>b</sup>
Flow accumulation								1	0.278 <sup>b</sup>	0.126	-0.290 <sup>a</sup>	-0.172
Distance to the River Ganges (m)									1	0.580 <sup>a</sup>	-0.996 <sup>a</sup>	-0.869 <sup>a</sup>

(continued)

Table 10.9 (continued)

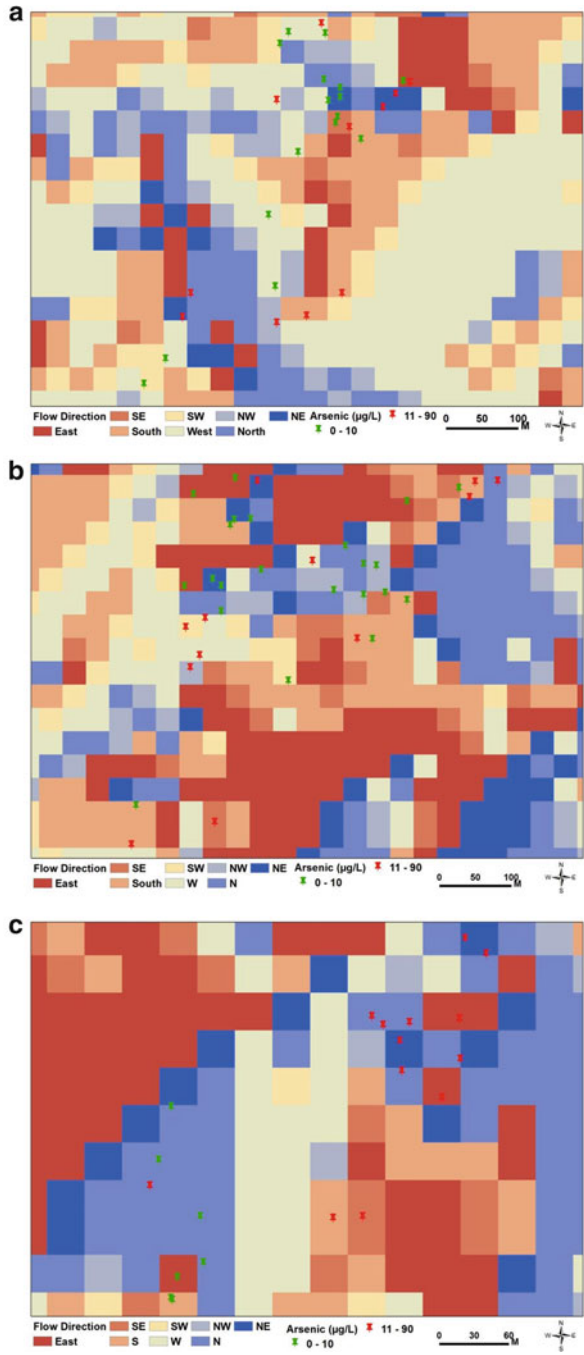
	Arsenic concentration ( $\mu\text{g/L}$ )	Distance to the River Sone (m)	Depth of hand pumps (m)	Elevation of hand pumps (m)	Surface elevation (m) extracted from DEM	Slope (degrees)	Flow direction	Flow accumulation	Distance to the River Ganges (m)	Distance to the drainage point (m)	Latitude (degree decimal)	Longitude (degree decimal)
Distance to the drainage point (m)										1	<b>-0.511<sup>a</sup></b>	<b>-0.855<sup>a</sup></b>
Latitude (degree decimal)											1	<b>0.819<sup>a</sup></b>
Longitude (degree decimal)												1

<sup>a</sup>Correlation is significant at the 0.01 level (2-tailed)

<sup>b</sup>Correlation is significant at the 0.05 level (2-tailed)

Pearson Product Moment Correlation Coefficients ( $r$ ) between arsenic concentrations and the hydrogeological and topographic parameters. The significance level was set at  $\alpha = 0.05$ . Bolded values are significant at  $\alpha = 0.05$  (marked<sup>b</sup>) and at  $\alpha = 0.01$  (marked<sup>a</sup>)

**Fig. 10.8** Arsenic concentration (*red* and *green* symbols) superimposed on the flow direction map in (a) Suarmarwa, (b) Rampur Diara, and (c) Bhawani Tola. Each grid cell is color coded to indicate the flow direction in that cell



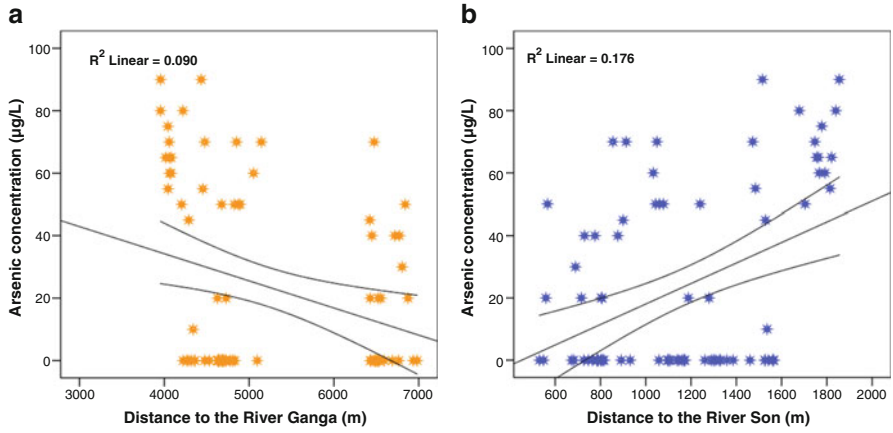


Fig. 10.9 Arsenic concentrations vs. distance to the (a) River Ganges and (b) River Sone with 95 % confidence lines

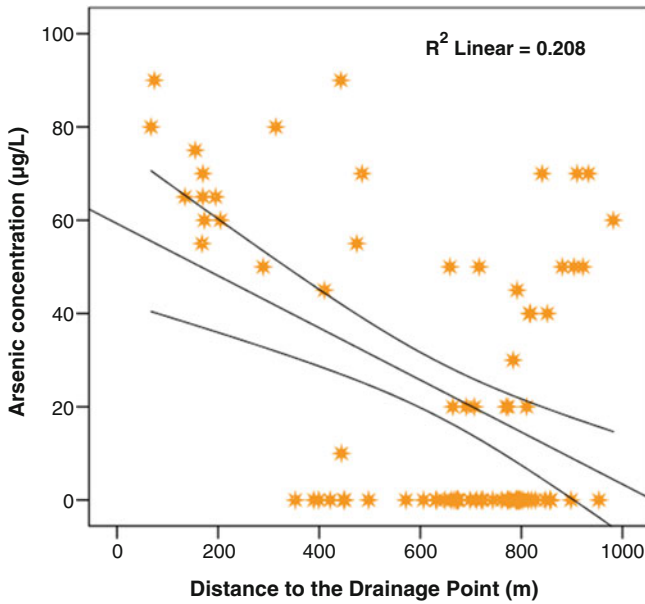
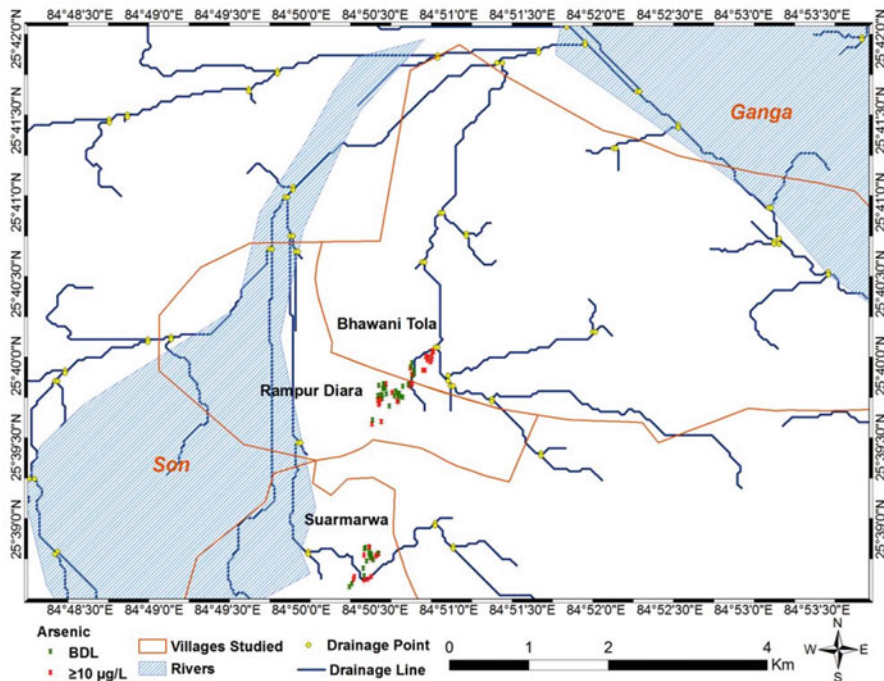
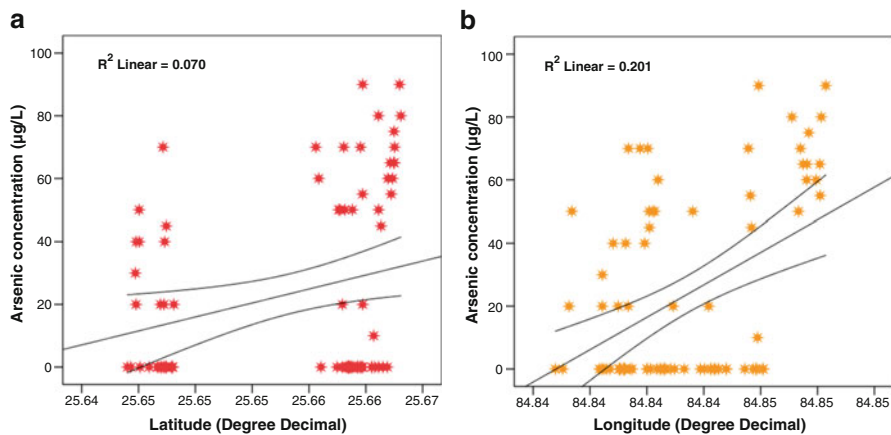


Fig. 10.10 Arsenic concentrations vs. distance from the drainage point with 95 % confidence lines



**Fig. 10.11** Distribution of arsenic along drainage point and drainage line networks. *Note:* The orange circle at the north of the study area encloses two drainage points associated with high arsenic levels, and which sit at the confluence of drainage lines passing through all three villages and through the River Sone



**Fig. 10.12** Arsenic concentrations vs. (a) latitude and (b) longitude with 95 % confidence lines

## 6 Conclusions

The NCL-FTK was found to be a rapid and reliable method to identify low ( $<10 \mu\text{g/L}$ ), moderate ( $10\text{--}50 \mu\text{g/L}$ ), and high ( $>50 \mu\text{g/L}$ ) levels of arsenic contamination in drinking water. Our results document arsenic contamination in aquifers that supply drinking water to Suarmarwa and Bhawani Tola, two previously unstudied villages. Arsenic levels of  $250\text{--}300 \mu\text{g/L}$  were observed in Bhawani Tola and Rampur Diara. We observed correlations between arsenic levels and depth of hand pumps, land surface elevation, surface water flow direction, distance to the River Ganges, and distance to drainage points. While the River Ganges has previously been identified as a source of arsenic, our results suggest that the River Sone and/or its alluvial deposits are also potential sources of arsenic. The highest population at-risk due to drinking arsenic contaminated water found in Bhawani Tola, followed by Rampur Diara and Suarmarwa. Low cost arsenic mitigation strategies are likely to be the most attractive and feasible options for these rural villages.

## 7 Initiatives Taken

Two open dug-wells in Rampur Diara (Fig. 10.3) were identified for further renovation and installation of hand pumps. Homeowners living adjacent to water wells were approached and verbal consent obtained for operation and maintenance of the wells after renovation. Homeowners were willing to renovate the existing open wells to access arsenic-free water, and agreed to share the water with their community. The lack of funds to renovate wells is an obstacle, but can be surmounted with community contributions along with external funding and logistical and technical support from agencies such as UNICEF, WHO, the “Group for the Protection, Study, and Monitoring of the Environment (GPSME),” a US-based non-profit organization, and the Indian Institute of Sustainable Development (IISD), of New Delhi, India.

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