

# Risk assessment for arsenic-contaminated groundwater along River Indus in Pakistan

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**Abstract** The study determined the risk zone and estimated the population at risk of adverse health effects for arsenic exposure along the bank of River Indus in Pakistan. A cross-sectional survey was conducted in 216 randomly selected villages of one of the districts along River Indus. Wells of ten households from each village were selected to measure arsenic levels. The location of wells was identified using global positioning system device, and spatial variations of the groundwater contamination were assessed using geographical information system tools. Using layers of contaminated drinking water wells according to arsenic levels and population with major landmarks, a risk zone and estimated population at risk were determined, which were exposed to

arsenic level  $\geq 10$   $\mu\text{g/L}$ . Drinking wells with arsenic levels of  $\geq 10$   $\mu\text{g/L}$  were concentrated within 18 km near the river bank. Based on these estimates, a total of 13 million people were exposed to  $\geq 10$   $\mu\text{g/L}$  arsenic concentration along the course of River Indus traversing through 27 districts in Pakistan. This information would help the researchers in designing health effect studies on arsenic and policy makers in allocating resources for designing focused interventions for arsenic mitigation in Pakistan. The study methods have implication on similar populations which are affected along rivers due to arsenic contamination.

**Keywords** Arsenic · Risk assessment · Drinking groundwater · Global positioning system · Pakistan

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## Introduction

Arsenic is widespread in the environment, and its adverse health effects are a global concern (WHO 2010). Though exposure to arsenic also occurs through food, beverages and burning of coal, the contaminated groundwater is the main source of exposure for majority of the population around the world (Gilbert-Diamond et al. 2011; WHO 2012). High levels of arsenic in underground water mainly result from natural contamination. Natural sources of arsenic contamination include spring from volcanic terrains, solubilization resulting from reduction of ferric iron arsenate or arsenite and geothermal processes (Reid et al. 2003).

Arsenic exposure leads to arsenicosis—characterized by hyperpigmentation and symmetric (involving both sides, i.e., left and right equally) hardening of skin of palms and soles. Some of these lesions may culminate into skin cancers. Non-skin health effects due to arsenic exposure include cardiovascular diseases, hypertension, diabetes mellitus, decreased lung functions, gastrointestinal disturbances and liver disorders including enlargement, tenderness, jaundice, ascites and elevated liver enzymes, and internal cancers including liver and bladder (Brown and Ross 2002; Ahsan et al. 2006; Chen et al. 2013; Smith et al. 1992; Khan et al. 2003). Extent and severity of these disorders depend on the exposure dose, i.e., concentration in the media and duration of exposure (Yoshida et al. 2004; Nafees et al. 2011).

Arsenic commonly contaminates underground water and affects population along the rivers. Arsenic contamination of groundwater is a well-recognized problem in Southeast Asia (Rahman et al. 2009). About 40.3 % of water sources in the river plains of Ganga–Meghna–Brahmaputra in Bangladesh had arsenic levels above 10 µg/L. Along this river, 48.0 %, 32.7 % and 32.3 % drinking water sources in West Bengal, Bihar and Jharkhand states in India were affected, respectively (Chakraborti et al. 2013). Overall, estimated 500 million populations were at risk of arsenic toxicity along Ganga–Meghna–Brahmaputra plains (Sengupta et al. 2003).

Among the factors that increases the concentration of arsenic in groundwater along rivers include the presence of clay in the sediment, iron ( $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$ ) contents (Sharif et al. 2008) and total organic carbon. (Reza et al. 2010). Studies have shown that wells located near the rivers have high arsenic levels. A study from Vietnam and Cambodia found wells located within 10 km distance from the river had mean arsenic levels of 64 µg/L compared to wells at a distance of more than 10 km which had levels of 8 µg/L (Berg et al. 2007). Another study from Vietnam found that wells within 2 km distance from the river had ten times higher levels of arsenic than wells at a distance of more than 2 km (Hoang et al. 2010). Depth of wells inversely relate to arsenic levels (Datta et al. 2009; Fendorf et al. 2010; Berg et al. 2007; Hoang et al. 2010). However, depths at which arsenic levels were below the guideline value of <10 µg/L vary from place to place (Fendorf et al. 2010; Hoang et al. 2010).

United Nations Children’s Emergency Fund (UNICEF) with the help of government conducted a national survey in 2001 on arsenic levels in groundwater in Pakistan (Ahmed et al. 2004). The survey found that 9 % of the drinking water sources had arsenic concentrations above 10 µg/L, using field arsenic test kits, whereas 30 % of the samples had arsenic concentrations above 10 µg/L using laboratory methods, i.e., atomic absorption spectroscopy. Also, few studies have estimated the burden of arsenic toxicity in Pakistan, determining health effects related to skin and lung function (Fatmi et al. 2009, 2012; Nafees et al. 2011).

To date, there have been random efforts to mitigate and develop arsenic interventions in Pakistan, which has led to minimal or no effect and has wasted resources. In 2007, Government of Pakistan formulated National Action Plan for Arsenic Mitigation (NAPAM—2007 to 2011) (Government of Pakistan 2007). Major components of this plan were: screening of water sources for arsenic contamination; alternate supply of safe water; use of appropriate arsenic removal methods; and social mobilization and monitoring and evaluation of impact. However, no progress on implementation of plan was made. In order to have better understanding of the potential health impact of arsenic contamination of groundwater, the population at risk needs to be estimated as a first step. This will help develop better intervention plans. Population exposed to higher arsenic concentration through groundwater contamination has not been estimated along River Indus. River Indus is the largest river of Pakistan and is one of the largest rivers in the world. It extends to a length of more than 3000 km and serves as the main source of water for large part of the country for domestic as well as agricultural use, as it irrigates 80 % of agricultural land in Pakistan (Fig. 1). There is higher population density as millions of people live along the River Indus. We, therefore, aimed to identify the risk zone and estimated the population at risk of contaminated groundwater with arsenic along River Indus, estimating it through conducting an in-depth study in the district of Khairpur, province of Sindh.

## Methods

A cross-sectional survey was conducted in district Khairpur between January and June 2006, details of



**Fig. 1** River Indus in Pakistan [reproduced with permission from Pakistan Geographic (2014)]

which were published earlier (Fatmi et al. 2009). In brief, 216 villages were selected randomly from 1850 villages of seven *Talukas* (subdistrict) where more than 95 % population of the district Khairpur lives. From each selected village, drinking water samples were collected from wells of ten households. Additional samples were also collected if the household used more than one drinking water source. Water samples were obtained in 500-ml arsenic-free (pre-acid-washed and rinsed with deionized water) polyethylene containers. The Pakistan Council for Research in Water Resources (PCRWR) laboratory, Islamabad, conducted arsenic level testing. The total

arsenic in water was measured by mercury/hydride system atomic absorption spectrophotometer (HG-AAS) with an arsenic detection limit of 0.1 µg/L. Duplicates of 10 % samples were also sent for laboratory testing, which gave 99 % reliability.

Global positioning system (GPS) coordinates were taken using handheld device for each drinking water source. In order to get the results in the form of spatial variations of the groundwater contamination in the district of Khairpur, GIS tool was employed for spatial analysis. Layout map of the study area (District Khairpur) was generated using district boundary, Indus River, Aror Mountain and *Deh* (village) level

map of District Khairpur. These layers were generated with the help of the 1-m resolution online satellite image, courtesy of Esri Incorporation. Each layer generated was given a projection of Universal Transverse Mercator and datum of WGS-1984. Satellite image was also projected on the same datum. A total of 2517 samples of the groundwater were collected from the wells of the villages in the study area to evaluate the concentration of arsenic in water. About 450 location points were removed due to the repetition of locations mainly due to closely located wells, located in the same households. The data were generated and compiled in EXCEL containing arsenic results with X, Y coordinates. These compiled data of arsenic contamination in water were exported in Arc Map in the form of spatial data with the same projection of UTM and datum of WGS-1984. In this way, the data were plotted as point locations with exact locations on map. Geospatial technique was applied, using the statistical properties of the collected data. This technique produced the prediction surfaces and uncertainty surfaces. With the help of the arsenic point data plotted on Arc Map, the interpolation was applied using the Kriging technique. An interpolated color-shaded map of arsenic data was generated with this technique. Color-shaded-interpolated map has been divided into low-risk and high-risk zone using 10 µg/L as cutoff. This map helped to spatially analyze the result and approximated the arsenic value of the location for which sampling was not done. Using the same technique, well depth distribution map was also generated to get the relationship of well depths with arsenic levels.

Population data of District Khairpur were taken from district census report of Khairpur. *Deh* level data of the Khairpur District were generated and compiled in EXCEL. These data were linked with the *Deh* level map (layer) to generate the thematic map of population. These generated layers were then merged to produce the spatial variation of arsenic contamination in relation to the distance of River Indus and population.

## Results

District Khairpur is located in northern Sindh on east bank of River Indus, Pakistan. It lies between 26°–11' and 27°–44' north latitudes and 68°–12' and 7°–11' east longitudes. Annual average rainfall in this area is

139 mm (iMMAP Pakistan 2014). According to 1998 population census, the estimated population was 1,298,364, with a growth rate of 2.71 % per year (PCO 2000). With the given growth rate, projected population for 2013 was 2.3 million (iMMAP Pakistan 2014). It comprises eight *Talukas* (subdistrict) with evenly distributed population over the entire district except for few urban areas such as Gambat where there is high population density and a large desert area (Nara *Taluka*) where there is sparse population. This study was conducted in seven *Talukas* except Nara (Figs. 2, 3). River Indus traverses along four *Talukas* of District Khairpur, namely Khairpur, Kingri, Gambat and Sobho Dero (see Figs. 2, 3), and has a length of approximately 140 km. Its width ranges from 450 to 1500 m in the district.

A total of 2517 water samples were analyzed for arsenic concentrations. Mean arsenic level was 14.98 µg/L (SD ± 29.6 µg/L). Maximum concentration level was 350 µg/L. Variations in the arsenic levels were observed at *Taluka* levels. Distribution of average *Taluka*-wise arsenic levels is given in Table 1. As shown in Fig. 2, proportion of wells with arsenic levels ≥ 10 µg/L was higher in the *Talukas* located near the River Indus.

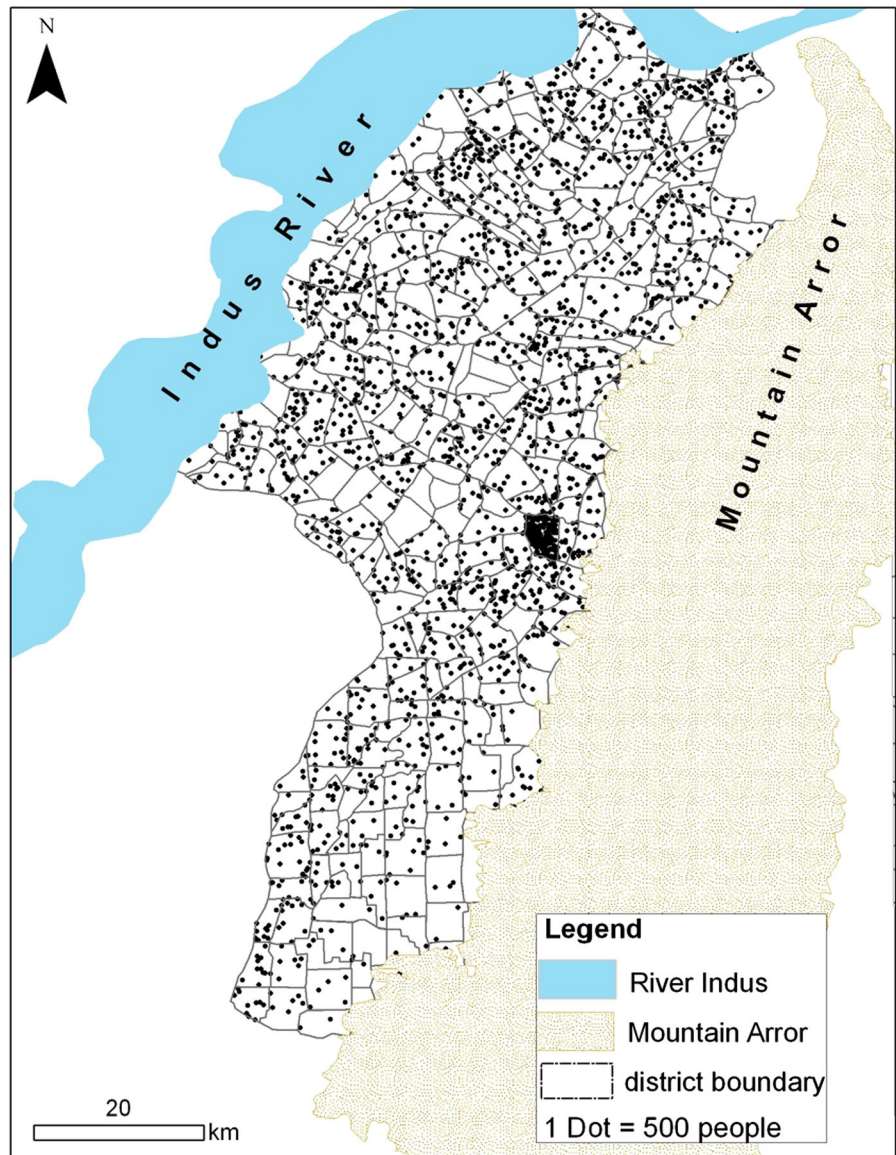
Spatial analysis showed that well with higher concentrations of arsenic was concentrated near the river bank. As the distance from River Indus increased, the concentration of arsenic in groundwater decreased (Fig. 4). Red dots showed water sources with arsenic levels above the World Health Organization's guideline value limits, i.e., 10 µg/L. A zone of high-risk population was identified which is extended 18 km from the River Indus bank (Fig. 5). Population in these villages should be considered at risk of arsenic and developing the adverse health consequences. Black dots on the map show the spatial distribution of population and its density in the area. A single black dot depicts a population of 500, which gives an estimated population of 410,379 in 127 out of 421 *Dehs* exposed to higher arsenic concentrations in the high-risk zone.

Wells with depth between 20 and 40 feet were concentrated near the river bank, which is the high-risk depth (Fig. 6).

## Discussion

A 66-km-long and 18-km-wide area along the River Indus was a high-risk zone, where arsenic levels in the

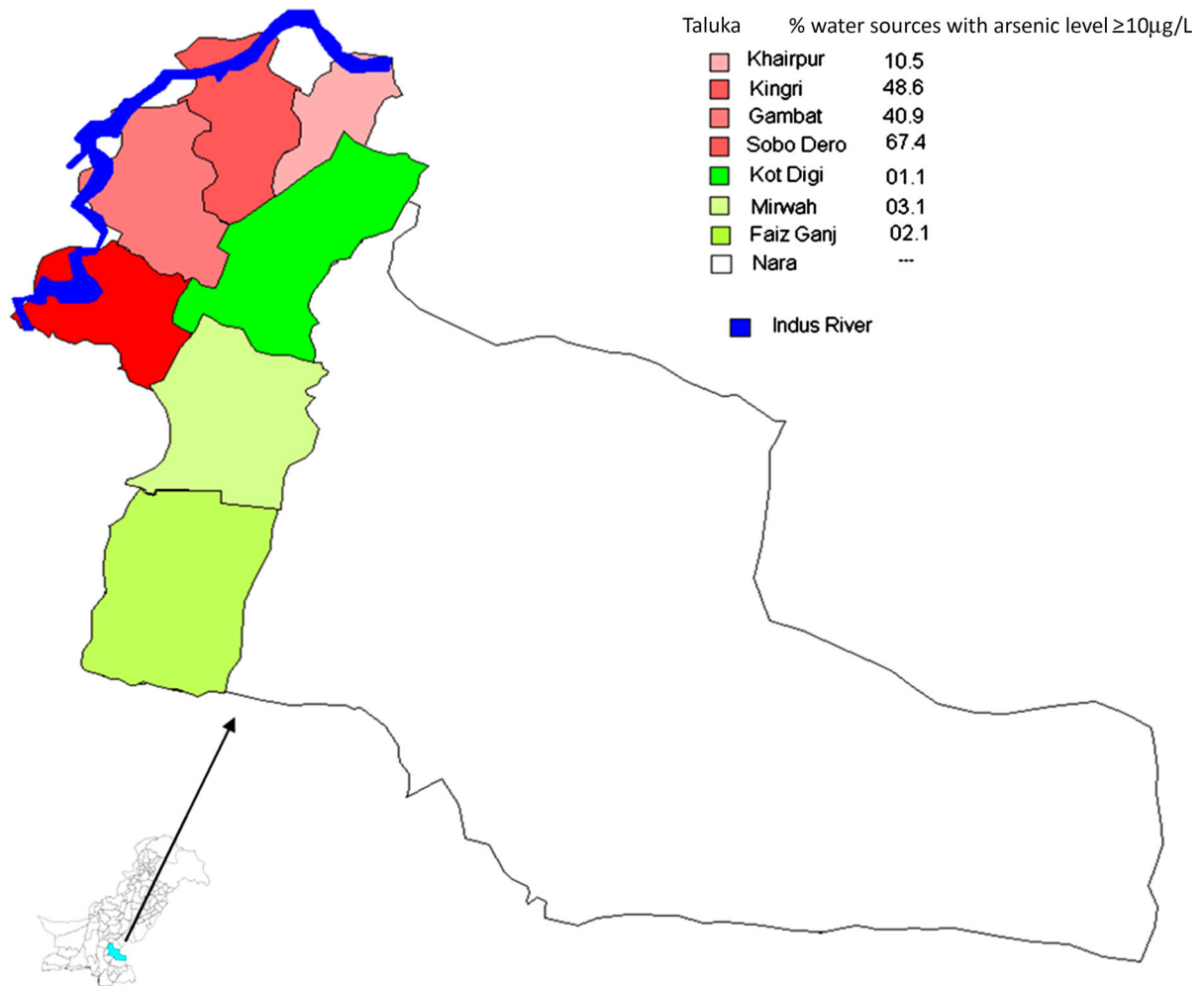
**Fig. 2** Population distribution in District Khairpur, Sindh



groundwater was higher than the guideline value limits in district Khairpur, Sindh. An estimated 0.76 million people, approximately one-third of total population of the district (according to 2013 estimate of population), were living in the high-risk zone and were exposed to adverse effects of arsenic in the district of Khairpur alone.

Indus River is the largest river of Pakistan with an approximate length of about 3180 km. A large population resides along the river banks and therefore may be exposed to similar toxic concentrations of arsenic as in district Khairpur. According to national survey,

proportion of contaminated samples was 12.2 % in Punjab and 11 % in Sindh (Government of Pakistan 2007). This indicates the levels of arsenic in water were comparable in both the provinces where River Indus passes. Based on these figures, we assume that equal proportions of population in the other districts were affected by arsenic-contaminated water as in district Khairpur. There are 27 districts, including Khairpur, where the river is either flowing through or population are living alongside the river. The estimated total population living in these 27 districts is about 40 million. Applying assumption that one-third

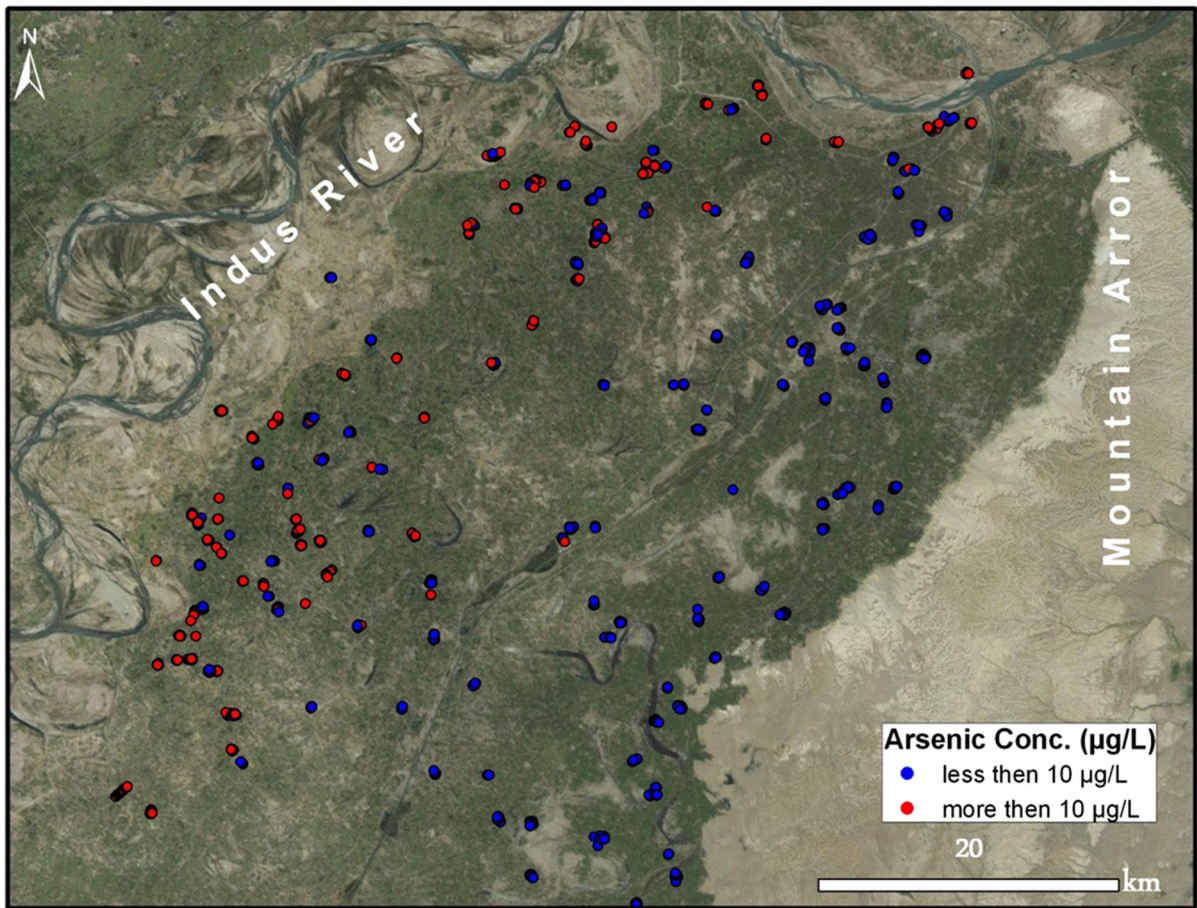


**Fig. 3** Spatial distribution of groundwater sources in study Talukas (subdistricts) in Khairpur, Sindh [reproduced with permission from Fatmi et al. (2009)]

**Table 1** Average arsenic levels in Talukas (subdistricts) of Khairpur, Sindh

Taluka	Arsenic concentration mean (SD) [ $\mu\text{g/L}$ ]
Kingri	27.6 (34.2)
Sobho Dero	24.4 (29.7)
Gambat	24.0 (36.5)
Khairpur	8.8 (18.1)
Thari Mirwah	6.56 (13.8)
Faiz Ganj	2.70 (5.5)
Kotdiji	1.09 (1.86)

population in these districts were also exposed to high levels of arsenic, an estimate was made for all the districts along the River Indus. This gives an estimated 13 million out of total 40 million populations in 27 districts along River Indus, who were exposed to arsenic  $\geq 10 \mu\text{g/L}$  in drinking groundwater in Pakistan. According to National Arsenic Survey, 9 % of water sources in Pakistan had arsenic levels  $\geq 10 \mu\text{g/L}$  (Government of Pakistan 2007). Estimated population of Pakistan in 2013 was 182 million. Based on this figure, people using arsenic-contaminated water are approximately 16 million. According to census 1998,



**Fig. 4** Distribution of well contaminated with arsenic

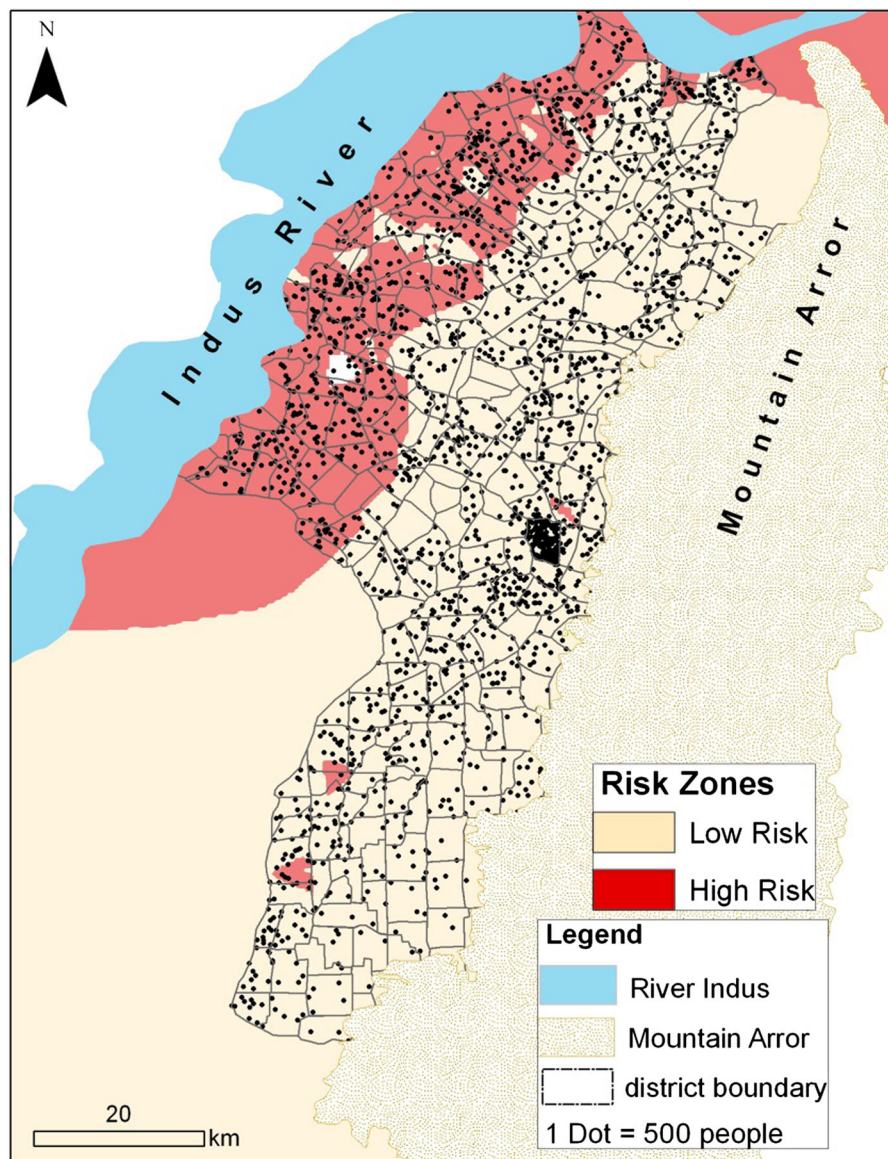
female constitutes about 48 % of the total population and about 43 % are children under 15 years of age. Based on these proportions, out of 13 million who are exposed to arsenic-contaminated water, about 6.24 million are women and 5.6 million are children under 15 years of age.

Correlation between distance of groundwater source from river bank and arsenic levels has been well documented (Berg et al. 2007; Hoang et al. 2010; Buschmann et al. 2007; Polya et al. 2005). Buschmann et al. (2007) reported arsenic concentration ranged from 1 to 1340 µg/L (average 163 µg/L), with 48 % exceeding 10 µg/L limit. Polya et al. (2005) found mean arsenic levels to be  $210 \pm 310$  µg/L in groundwater immediately near the major channels of the Mekong and Bassac rivers. The current study also showed clear spatial variation in the arsenic contamination with reference to River Indus as indicated by

higher number of arsenic-contaminated wells located near the river.

Various factors control the variability of arsenic level in groundwater, and these include: sediment geochemistry, recharge potential, thickness of surface aquitard, local flow dynamics and degree of reducing properties of aquifers (Sharif et al. 2008). This variation in the arsenic concentration with distance from the river bank is due to contamination of local aquifers by the river. The concentration of arsenic in Mekong River in Vietnam was much lower than in the groundwater. It is hypothesized that river water may contain a considerable amount of allochthonous or dissolved organic carbon (DOC). These come from recent degradation of plants in the soils or waste water and transported to different locations together with autochthonous carbon coming from co-deposition of plants in the sediment over the geologic time. This

**Fig. 5** High-risk zone and population exposed to arsenic-contaminated water in the district Khairpur, Sindh



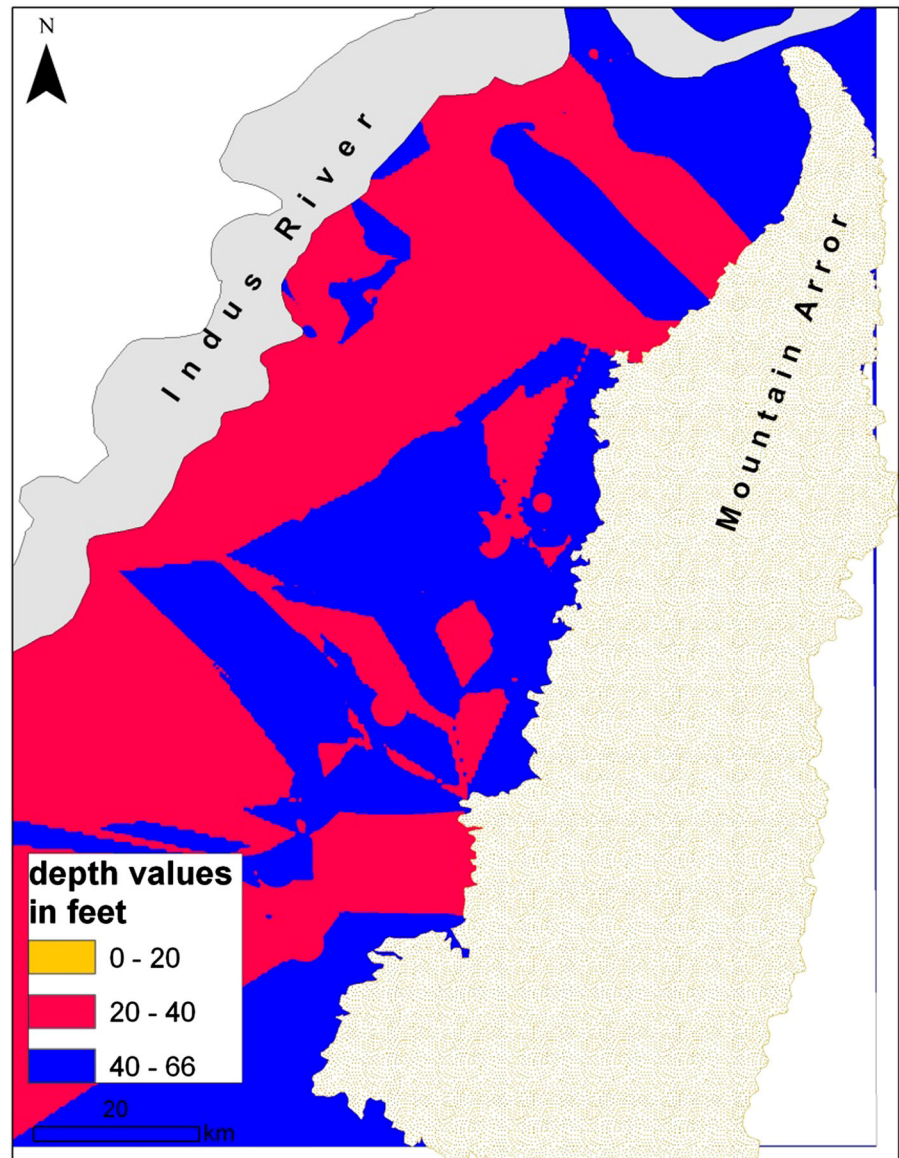
may enhance the reduction of iron oxides, resulting in arsenic mobilization (Harvey et al. 2002). Another possible explanation for this phenomenon is the intrusion of river water into local aquifer system. Higher concentration of dissolved oxygen in river water may change the oxidation/reduction potential (ORP) in the local aquifer system, from strong reduction potential to moderate reduction potential. Change in ORP may increase the release of arsenic from the deposits (Lap Nguyen et al. 2000). Possible anthropogenic sources of arsenic in the groundwater near River Indus could be industrial (pharmaceuticals,

pesticide, mining and metallurgy industries) and agricultural effluent discharged without treatment. Natural sources include thermal volcanism, oxidation of arsenical sulfide minerals, reduction of FeOOH while releasing its sorbed load to groundwater, desorption of arsenic (As) from mineral sorption sites in response to increase in pH and evaporative concentration (Nickson et al. 2005; Rubab et al. 2014; Shafiq et al. 2011).

Association between well depth and arsenic levels has also been reported. Polya et al. (2005) reported substantial differences in arsenic concentrations with



**Fig. 6** Distribution of well depth along the River Indus in district Khairpur, Sindh



depth of wells: Shallower wells (<16 m) had less hazardous arsenic concentration than the deeper wells (>16 m). However, no dependency of arsenic levels with well depth was found in groundwater adjacent to Bassac River in Vietnam (Rowland et al. 2008). Sharif et al. (2008) found that amount of arsenic in sediment decreased with increasing depth. Similarly, they observed a high arsenic concentration in deep monitoring wells compared to shallow wells, while at the other site, results were reverse (Sharif et al. 2008). Our study also showed that wells <40 m deep were concentrated near the river bank which is high-risk

zone. However, this should also be noted that the wells are usually shallower near the river.

Arsenic has a short half-life in human body and excreted in urine in 1–3 days (Calderon et al. 1999; Chen et al. 2002). However, chronic exposure (>15 years) of arsenic concentration at >10 µg/L will have adverse health effects related to various body systems (Mazumder 2008). People living in the high-risk areas of arsenic contamination are therefore vulnerable to chronic arsenic exposure and develop manifestations of arsenicosis on skin including cancers (Kadono et al. 2002), cardiovascular diseases

(CVDs) (Chen et al. 1996), hypertension (Lee et al. 2005), diabetes (Tseng et al. 2000; Rahman et al. 1998), decreased respiratory functions (Parvez et al. 2008), adverse reproductive and pregnancy outcome (Ihrig et al. 1998; Cherry et al. 2008), and internal cancers (Michaud et al. 2004; Morales et al. 2000).

This study identified the priorities of further research. Studies on health effects identifying arsenic skin lesions and other systemic health effects need to be conducted along River Indus, preferably within 18 km. This will further strengthen the evidence for intervention. The main policy option for mitigation of arsenic in Pakistan should be switching of wells. Switching of wells has been demonstrated to be effective means of mitigation in similar situations (Chen et al. 2007; Flanagan et al. 2012; Van Geen et al. 2002). It is cheap and cost-effective intervention for low-income countries such as Pakistan. However, cultural barriers such as population coherence need to be considered while planning these interventions. In order to implement this policy, blanket survey should be done and wells need to be marked (painted with colors of red and green for unsafe and safe levels). Behavior change messages need to be delivered through health and other relevant department responsible for provision of water and sanitation (George et al. 2012, 2013). Switching policy would work for about 95 % of the affected villages. However, <5 % of the villages where almost all of the sources of water were arsenic-contaminated, a separate intervention needs to be adapted. For those few villages, digging of deep wells and provision of piped water supply need to be explored.

This study is first of its kind from Pakistan to estimate the population at risk of arsenic toxicity along the bank of River Indus. We used atomic absorption spectrometry for the measurement of arsenic in the drinking water which is gold-standard test for arsenic measurement. GIS tool was applied to show the geographical distribution of the contaminated wells, and for this purpose, Kriging method was used which is the best estimation method for producing output surfaces.

Since this was a cross-sectional survey, seasonal variation in the arsenic levels with changes in the groundwater level could not be assessed. Arsenic levels change with changes in the groundwater level, concentration decreasing during rainy and increasing during dry season. However, the rainfall in this area is

not substantial to have any major influence on the concentration of arsenic in groundwater. In some of the areas, depth of wells could not be inquired as people were not aware; however, we applied geospatial techniques to produce the prediction and uncertainty surfaces.

## Conclusion

This paper has identified vulnerable population due to arsenic exposure along River Indus. This study has implication on similar populations which are affected along rivers due to arsenic contamination. Higher levels were observed in a zone extending about 18 km from the bank of River Indus. Population of around 13 million were exposed to  $\geq 10$   $\mu\text{g/L}$  of arsenic in groundwater. These populations were at risk of developing health effects from chronic arsenic exposure. Identification of high-risk zone for arsenic will save resources and lead to focused interventions. Further research to assess the health impact of arsenic exposure among people living close to the river should be prioritized. Policy makers in collaboration with other concerned department should provide alternate water sources by switching wells, digging deep wells and piped water.

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