

National threat of Arsenic in Groundwater

Review, Critical Analysis and Vision for the Future



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National Threat of Arsenic in Groundwater

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Pakistan Council of Research in Water Resources (PCRWR)

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Executive Summary

Groundwater has been reported to be the largest source of arsenic exposure worldwide. Globally 108 countries are affected by groundwater arsenic contamination beyond the World Health Organization's drinking water guideline value of 10 µg/L. Southeast Asian belt is considered as the arsenic contaminated areas including countries such as Bangladesh, India, Pakistan, China, Nepal, Vietnam, Myanmar, Thailand and Cambodia.

Pakistan is located in the same region of subcontinent in which India and Bangladesh stretch out and share the common heritage of water resources and similar geological conditions. Pakistan Council of Research in Water Resources (PCRWR) discovered higher levels of arsenic in Pakistan's groundwater in 1999. Following initial discovery of arsenic presence, PCRWR had undertaken various studies during 1999-2021 to assess the spectrum of groundwater arsenic contamination. Acquiring groundwater arsenic data from these studies, an in-depth analysis has been performed to present true picture of arsenic contamination and associated human health risks and to assess needs for mitigation and policy measures.

The analysis shows that arsenic is a serious issue mainly in two provinces Punjab and Sindh where, about 2% and 5% of water sources were found contaminated above the Pakistan's permissible limits of 50 µg/L, respectively. About 14% and 10% of the water sources were found above the WHO level of 10 µg/L in Punjab and Sindh, respectively. Altogether, 13% of 45,920 water sources including few sources of KP exceeded the WHO guideline value of As (10 µg/L) and 3% beyond the Pakistan's limit of 50 µg/L. Highly contaminated districts are Multan, Bahawalpur, Rahim Yar Khan in Punjab, Khairpur and Dadu in Sindh province.

Groundwater arsenic data shows a non-uniform pattern of geogenic arsenic distribution and indicated that both the shallow and deep-water sources were contaminated. All these field-based evidence suggest that the process of arsenic release from alluvial deposits lying near to Indus river system is faster than those lying away from the river zone. Assessment of Pakistan's rice varieties indicates arsenic range of 0.084 to 0.356 mg/kg and only 12 samples slightly exceeded the WHO's maximum limit of 0.2 mg/kg.

Health Risk assessment model has quantified an overall arsenic exposure, cancer and non-cancer risks for an age group of 3 to 67 years. Consumption of water by this age group with a total inorganic arsenic above the WHO value (10 µg/L) has indicated a maximum average daily dose (ADD) of 0.1290 mg/kg/day; higher than the WHO's provisional tolerable daily intake (PTDI) of 0.0021 mg/kg/day body weight.

Probabilistic cancer risks for an exposure of 3 to 67 years age group was also found to be above the acceptable US EPA cancer risk criteria of 1.0×10^{-4} (i.e. 1 case of cancer per 10,000). This study shows that an early life arsenic exposure may result in 26

chances in a population of 10,000 children of age 3 to 16 years to develop cancer. If these children remained on prolonged arsenic exposure with life expectancy of 67 years, there is cancer risk probability of 19 adults in a population of 10,000 in later ages. Similarly, a higher risk level for non-cancer impacts quantified as Hazard Quotient (HQ) also exceeded the threshold of 1. The simulated results also shows coincidence with higher arsenic levels reported previously in human biomarkers of arsenic affected districts of Punjab and Sindh.

These findings remind us to integrate arsenic monitoring and mitigation approaches with provincial water, health and climate policies frameworks, action plans and strategies both in urban and rural settings. Hospitals and basic health units should establish an Arsenicosis Patient Facility (APF) to enable early identification and treatment of arsenic affected patients in Sindh and Punjab. Moreover, the best possible option of curtailing the arsenic effects is by reducing human activities that release arsenic into the environment such as disposal of untreated wastewater to the water bodies.

1 Introduction

Arsenic (As) contamination in groundwater continues to increase in many countries, especially in developing nations. This is considered a worldwide public-health crisis due to its wide range of health implications. The World Health Organization guidelines (1993) for arsenic in drinking water is 10 µg/L having been reduced from 50 µg/L, hence many regions around the world exceeded the levels established for safe drinking water supplies (World Health Organization, 2008). Following this, about 108 countries are reported to be affected by groundwater arsenic contamination beyond the WHO maximum permissible limit of 10 µg/L. The highest number of countries are from Asia (32) and Europe (31), followed by regions like Africa (20), North America (11), South America (9) and Australia (4) (Shaji et al., 2021). Consequently, more than 230 million people globally including 180 million from Asia are at risk of arsenic poisoning. Southeast Asian Belt is considered as the most arsenic contaminated areas including countries such as Bangladesh, India, Pakistan, China, Nepal, Vietnam, Myanmar, Thailand and Cambodia (Ghosh et al., 2021).

Pakistan is located in the same region of subcontinent in which India and Bangladesh stretch out and share the common heritage of water resources and similar geological conditions. Thus, higher levels of arsenic in Pakistan's groundwater have been discovered in 1999 by Pakistan Council of Research in Water Resources (PCRWR). Following this, PCRWR undertook various arsenic monitoring studies during the last two decades to elucidate the spectrum of arsenic contamination in the groundwater aquifers of the country. As a result, a huge data sets were produced taking into account an integrated approach. In this report, a comprehensive review and analysis of the arsenic contamination in water, soil, environment, biomarkers and human health is also presented along with identifying needs for mitigation and policy measures. Moreover, data gaps are identified, possible causes of arsenic contamination, associated health risks are highlighted, and mitigation strategies are suggested. The outcomes of this review are expected to assist water, food and health related organizations as well as community groups for safe guarding public health.

1.1 Occurrence, Types and Sources of Arsenic

Arsenic (As) is a metalloid and its compounds exist in crystalline, powder, amorphous or vitreous forms. It is a natural component of the Earth's crust, present at an average concentration of 2 mg/kg (Swain et al., 2021). The primary source of As in the environment (hydrosphere, pedosphere, biosphere and atmosphere) is its geogenic release from As-enriched minerals. Volcanic eruptions and other natural processes cause dissolution of As compounds, adsorbed onto pyrite ores, into the water. Apart from the natural geological occurrence, arsenic contamination of water and soil may result from human activities due to disposal of industrial wastes, smelting of arsenic

bearing minerals, burning of fossil fuels and application of arsenic compounds in many products especially in the past few hundred years through use of insecticides, herbicides, phosphate fertilizers, semi-conductor industries and timber.

Arsenic exists in nature in the oxidation states +V (arsenate), +III (arsenite), 0 (arsenic) and -III (arsine). Arsenic compounds can be categorized as inorganic compounds without an arsenic-carbon bond, and organic compounds with an arsenic-carbon bond. In the aqueous environment, inorganic arsenic appears commonly in the oxidation states +V and +III as arsenous acid (As(III)), arsenic acid (As(V)), and their salts. Bacteria, fungi, and yeasts can methylate inorganic arsenic compounds to the organic compounds such as monomethyl arsonic acid (MMA), dimethylarsinic acid (DMA), and gaseous derivatives of arsine. The toxicity of arsenic depends on its binding form. Organic arsenic compounds have been reported to be less toxic than inorganic arsenic compounds (Byeon et al., 2021). Inorganic forms of arsenic dissolved in drinking water are the most significant forms of natural exposure.

1.2 Impact of Arsenic on Human Health

The main sources of human exposure to arsenic are through arsenic contaminated water or food. Inorganic arsenic compounds (such as those found in water) are highly toxic while organic arsenic compounds (such as those found in seafood) are less harmful to health. Arsenic exposure has been reported to be associated with an increased risk of cancer and non-cancer health effects depending on the duration of exposure (Jack et al., 2003).

1.3 Non-Cancer Health Effects

The immediate symptoms of acute arsenic poisoning include vomiting, abdominal pain and diarrhoea. These are followed by numbness and tingling of the extremities, muscle cramping and in extreme cases death.

The first symptoms of long-term exposure to high levels of inorganic arsenic are usually observed in the skin, and include pigmentation changes, skin lesions and hard patches on the palms and soles of the feet (hyperkeratosis). These occur after a minimum exposure of approximately five years and may be a precursor to skin cancer. There are specific dermal effects that have been attributed to chronic arsenic resulting in lesions and formation of hard patches on the soles of the feet and hands. This condition is named as melanosis (pigmentation) followed by keratosis and hyperkeratosis (Chakraborti et al., 2017).

Other adverse health effects that may be associated with long-term ingestion of inorganic arsenic include developmental effects, diabetes, pulmonary disease, and cardiovascular disease. High concentrations of arsenic can also cause several disorders of respiratory system, cardiovascular system, digestive system, reproductive

system, endocrine system, neurological system, hematopoietic system and renal system (Jomova et al., 2011). According to a study conducted by Mazumder et al. (2000), where they examined 7683 participants in arsenic contaminated areas of West Bengal, India, persistent exposure and consumption of arsenic through drinking water caused many respiratory complications amongst humans such as shortness of breath, cough, bronchitis and wheezing.

Likewise, Ramsey et al. (2013) found that prolonged exposure of arsenic amongst children resulted in inflammation of airways and alteration of liver function. Moreover, studies have found that arsenic exposure can induce hypertension and increase the risk of diabetes (Mazumder et al., 2012).

Arsenic is also associated with adverse pregnancy outcomes and infant mortality, with impacts on child health in utero and in early childhood resulting in mortality in young adults due to multiple cancers, lung disease, heart attacks, and kidney failure (Rahman et al., 2018). Ahamed et al. (2006) also found spontaneous abortions, stillbirths and premature births in women living in high arsenic affected areas in Bangladesh, where the range of arsenic was between 201 and 1200 µg/L.

1.4 Carcinogenic Health Effects

The International Agency for Research on Cancer (IARC) has classified arsenic and arsenic compounds as carcinogenic to humans (Group 1) (IARC, 2012). On the basis of a number of studies in various countries such as Taiwan, Bangladesh, India, the USA, Chile and others, the IARC concluded that chronic exposure to arsenic mainly through water and other exposure sources (Figure 1) can cause cancer in skin, urinary bladder and lungs. Saha (2003) found 5.14% incident rates for malignancy, wherein 4.34% of the cases were regarding skin malignancy and 0.78% about internal malignancy in the West Bengal, India.

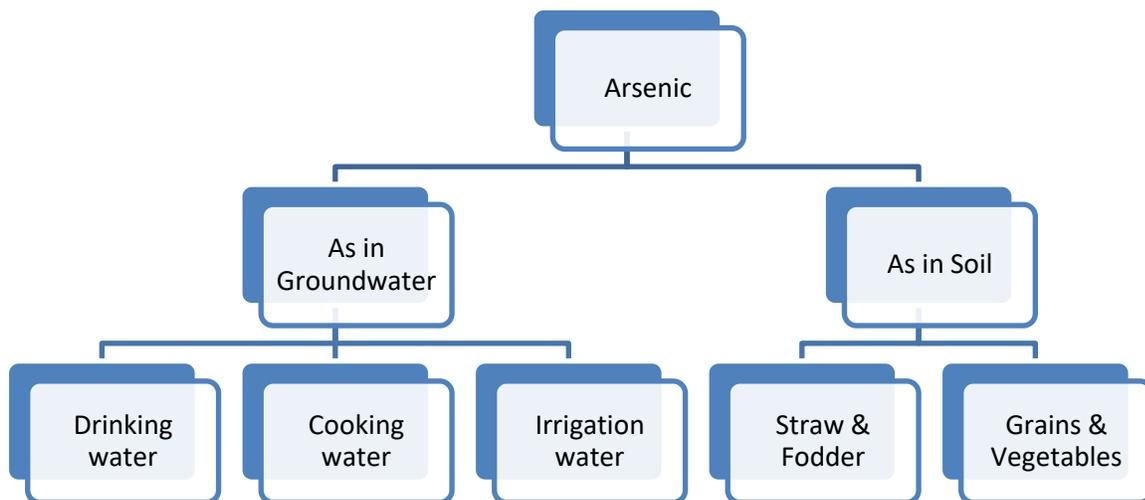


Figure 1: Pathway of human exposure to arsenic

2 Methodology

2.1 Literature Exploration and Selection Approach

Pakistan Council of Research in Water Resources has conducted arsenic monitoring through its various research studies from 1999 to 2021. The data produced in these studies, having uniform sampling and testing methodologies, have been taken into account for this review to investigate the scale of groundwater arsenic contamination in the country. Under these studies, all groundwater samples were collected, preserved and tested following the standard methods for examination of water and wastewater (American Public Health Association, 2017). These studies are listed in Table 1:

Table 1: Arsenic monitoring studies undertaken by PCRWR (1999-2021)

Sr No.	Study report Title	Monitoring year	Cities/Districts covered	No. of groundwater samples*
1	Preliminary Investigations	1999-2000	6 districts	308 followed by 96 samples**
2	National Survey undertaken by PCRWR collaboration with UNICEF	2001	35 districts	8,712**
4	Arsenic Monitoring and Mitigation Program	2005-2010	63 districts	33,388
5	Rural Water Quality Monitoring Program (Phase I)	2005-2014	24 districts	10,440
6	Rural Water Quality Monitoring Program (Phase II)	2010-14	4 districts	2140
7	National Water Quality Monitoring Program (2020)	2020-21	29 cities	435
8	Assessment of Arsenic in Rice Grown in Pakistan	2014	10 districts	200
	Total Samples	-	-	55,719

*Data of 45,920 water sources was available.

**Data not available for analysis. However, available summaries of data are included in the situation analysis.

2.2 Sampling and Arsenic Testing

Water samples were collected in ½ liter polyethylene bottles according to standard methods. A distance of half kilometer was maintained between the two sampling points. The preservative (1% concentrated HCl) was used in the samples collected for arsenic analysis. Field and laboratory test methods such as arsenic testing kit developed by PCRWR and Atomic Absorption Spectrometer (Hydride Generation mode) were used for testing of samples for arsenic.

For the analysis of arsenic, the Atomic Absorption Spectrophotometer (AAS Vario 6 Analytik Jena AG), Mercury/Hydride System HS55 (Analytik Jena AG), and Argon Gas with 99.99% purity were used. In the Hydride technique, hydrogen liberated in the reaction of the weakly acidic sample solutions reacts with sodium boro-hydride which combines with metal ions to form gaseous hydrides. These are carried to the hot quartz cell by the carrier gas such as Argon (99.99% purity) and decomposed by collision processes in a series of steps, until free As atoms were obtained.



Figure 2: Sample induction in the reaction cell of Mercury Hydride system of AAS

2.3 Quality Control Measures

The quality of analytical work was checked by the analysis of NIST (National Institute of Standards and Technology) traceable standard reference materials (SRMs-1640A, trace elements in natural water), blanks and duplicates. Data quality in terms of accuracy, method detection limits (MDLs) met the criteria established in the PCRWR NWQL's quality assurance manual (QAPP), i.e., relative percent difference (RPD) of 25%, percent recovery of 75 to 125%. All the glassware used for preparation of standard solution were acid washed with 1:1 HCl and rinsed three times with deionized water prior to use. Deionized water used for analytical work was freshly prepared having EC of $>0.2 \mu\text{S}/\text{cm}$.

2.4 Data Analysis

The groundwater arsenic data used in this study, originated from above listed studies, was pooled to form a single database ($n = 45,920$) which was further analyzed for descriptive analysis. The test data was evaluated by comparing with the public health standards and guidelines for arsenic in drinking water. Moreover, hazard maps were prepared for the occurrence of arsenic concentrations in groundwater exceeding the WHO As guideline of $10 \mu\text{g}/\text{liter}$ and Pakistan's National Drinking Water Quality Standard (NDWQS) for As in drinking water $50 \mu\text{g}/\text{L}$.

2.5 Review of External Publications

A number of scientific publications databases: (Medline; PubMed), Environmental Sciences & Pollution Management (ESPM) and the National Center for Biotechnology Information (NCBI) were searched to ascertain peer-reviewed papers relating arsenic sources, exposure and risk in Pakistan, published between 2000 and 2022. The following criteria was used for selection of studies to analyze the spectrum of arsenic exposure:

- a. Concentrations reported for arsenic in surface and ground water, food items, soil, and biomarkers.
- b. Peer reviewed studies with methodological approach.
- c. Potential health risks identified and associated to reported levels.

Based on this, 167 peer-reviewed articles have been used in this review analysis of arsenic in water, soil, food and human biomarkers.

2.6 Exposure and Risk Assessment

Taking into account the pooled data of 64 districts of 45,920 water sources, human health risk assessment, model of the US Environmental Protection Agency (2005) was used for province wise and overall risk calculations (Equations 1 to 4). The average daily dose (Equation 1) and the life-time average daily dose (Equation-2) was calculated

for As for population of arsenic monitored region based on inputs given in Table 2 and assuming 100% bioavailability of inorganic arsenic (As).

$$ADD = \frac{C \times IR \times EF \times ED}{AT \times BW} \quad \text{Equation (1)}$$

$$LADD = \frac{C \times IR \times EF \times ED}{AT_e \times BW} \quad \text{Equation (2)}$$

Where:

- ADD Average daily dose (mg kg⁻¹ day)
- LADD Lifetime average daily dose (mg kg⁻¹ day)
- C Arsenic concentration: water (µg L⁻¹)
- IR_x Ingestion rate: water (L day⁻¹)
- EF Exposure frequency (days year⁻¹) 365
- ED Exposure duration (years)
- AT Averaging time is the period of time over which the exposure is relevant for health risk characterization (days/year).
- AT_e Average life expectancy (days) = (365 days/year × 67 years)
- BW body weight (kg)
- ADAF Age dependent adjustment factor.

Non-cancer risk as the "hazard quotient" (HQ) is quantified using Equation 3

$$HQ = \frac{ADD}{RfD} \quad \text{Equation (3)}$$

Cumulative cancer risk (CR) was quantified as a probability of developing cancer by using the exposure and cancer slope factor (CSF) for skin cancer in Equation (4).

$$CR = LADD \times CSF \times ADAF \quad \text{Equation (4)}$$

To calculate lifetime risk for a population with an average life expectancy, the risk calculated for each of the age groups was summed after applying recommended Age Dependent Adjustment Factors (ADAFs). Thus, the life time cancer risk was calculated for a total period of 67 years (Pakistan's average life expectancy), starting at the minimum age 3 years.

For non-cancer effects, HQ>1 shows that there may be health concern (U.S. Environmental Protection Agency, 2016), whilst the USEPA acceptable cancer risk is 10^{-4} to 10^{-6} depending on the size of the target population (U.S. Environmental Protection Agency, 2017). In this case, an acceptable cancer risk of 1.0×10^{-4} (one case per 10,000 populations) was considered.

Table 2: The input parameters used in probabilistic risk estimation

Input variable		Descriptive statistics	Probabilistic estimates	Data source
Concentrations in water ($\mu\text{g L}^{-1}$)	tAs as As (n=45,920)	Min-max: 0.08-100	Log-Normal Distribution	PCRWR studies listed in Table 1
Estimated daily intake (IR) for Pakistani population	Water (L/day)	Male: 3.9 Female: 3.2 Overall mean: 3.5	constant	(Hifza et al., 2017b)
Body weight (Pakistani population)	kg	Male: 68 Female: 55 Mean >16: 63	constant	(Hifza et al., 2017b)
Exposure duration (ED) (years)	years	Adults >16 Year: 67 Age (picked by Monte Carlo)	constant	Pakistan's average life expectancy: The World Bank, (2020)
		Overall ED: 67 years		
Average Life expectancy	years	67 (for Pakistan)	constant	The World Bank, (2020)
Age range of Pakistani population	years	Min-max: 3-67		Hifza et al. (2017)
Averaging Time (AT)	days/ year	365	constant	-
Reference dose (RfD) (mg kg^{-1} day)	As	0.0003 (based on skin lesions/ Hyperpigmentation, keratosis and possible vascular complications)	constant	USEPA (2011)
Oral slope factor for non-melanoma skin cancer (CSF) ($\text{mg kg}^{-1}\text{day}^{-1}$)	As	1.5	constant	USEPA (2011)
Age dependent adjustment factor (ADAF)		For age 16-67 years = 1		USEPA (2011)

The health risk was modeled using Equations 1 to 4 in “@RISK” software (Version 7.5, Palisade Corp. USA). Running the model for 100,000 iterations, the life time cancer and non-cancer risk was calculated based on Pakistan’s average life expectancy of 67 years. Risk plots were acquired as “@RISK” output of Monte Carlo simulations indicating cumulative density functions (CDFs) of the mean risk estimates with 95% confidence interval.

3 Results and Discussion

The results and discussion comprise position of arsenic in water sources, soil, food and human biomarkers followed by a correlated analysis based on PCRWR data and critical review of studies from external sources. Thus, status of arsenic contamination, its exposure and health risks are presented as three main sections.

Section-I: Arsenic Contamination in Water

3.1 Arsenic in Water

Various arsenic monitoring studies (1999-2021) taken up by PCRWR reveal the distribution of arsenic in groundwater of many areas of Pakistan (Table 1). Following the risk analysis, a synthesis is given to discuss the probable intensity of arsenic exposure in the affected districts, possible risks and required strategies to address the arsenic challenge.

3.1.1 Preliminary investigations (1999-2000)

The initial study on arsenic monitoring was conducted in six districts of Northern Punjab i.e. Jhelum, Chakwal, Attock, Rawalpindi, Sargodha and Gujrat. This geographical region was selected on the basis of criteria given below:

- a) Areas draining coal and/or iron mining;
- b) Areas where geothermal waters are known to occur naturally;
- c) Areas with reducing groundwater, where compounds like dissolved iron, hydrogen sulphide, or methane are found; and
- d) Areas draining crystalline igneous rocks such as granites or basalts.

Following the above criteria, 308 samples were collected from six districts taking one sample each from a grid size of 100 km² based on district maps prepared by Geological Survey of Pakistan. The minimum distance between the sampling points in the adjacent grid was above 2 km. Analysis of 308 samples reveals that 14% of samples had arsenic level exceeding the WHO guideline value in drinking water (10 µg/L) and 3% (6 samples/sites) above Pakistan's permissible limit (50 µg/L) in Gujrat, Jhelum and Sargodha (Figure 3). Specific results of the six sites where contamination level was found above 50 µg/L are shown in Figure 4.

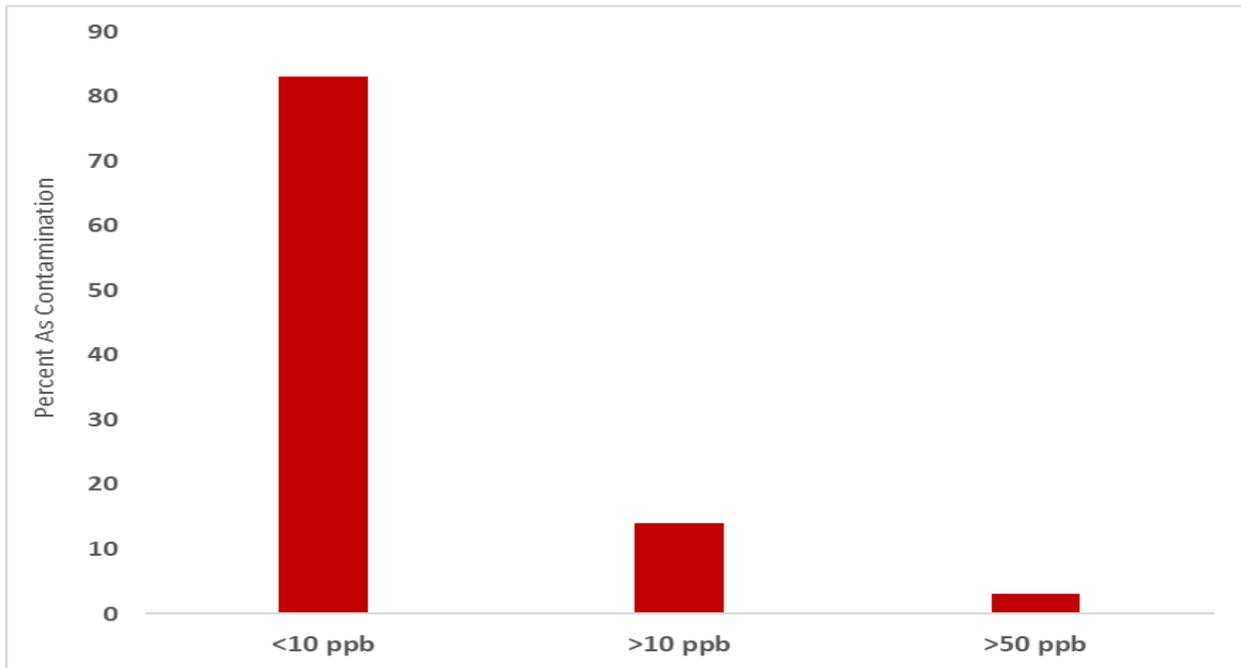


Figure 3: Groundwater arsenic contamination in six districts (1999)

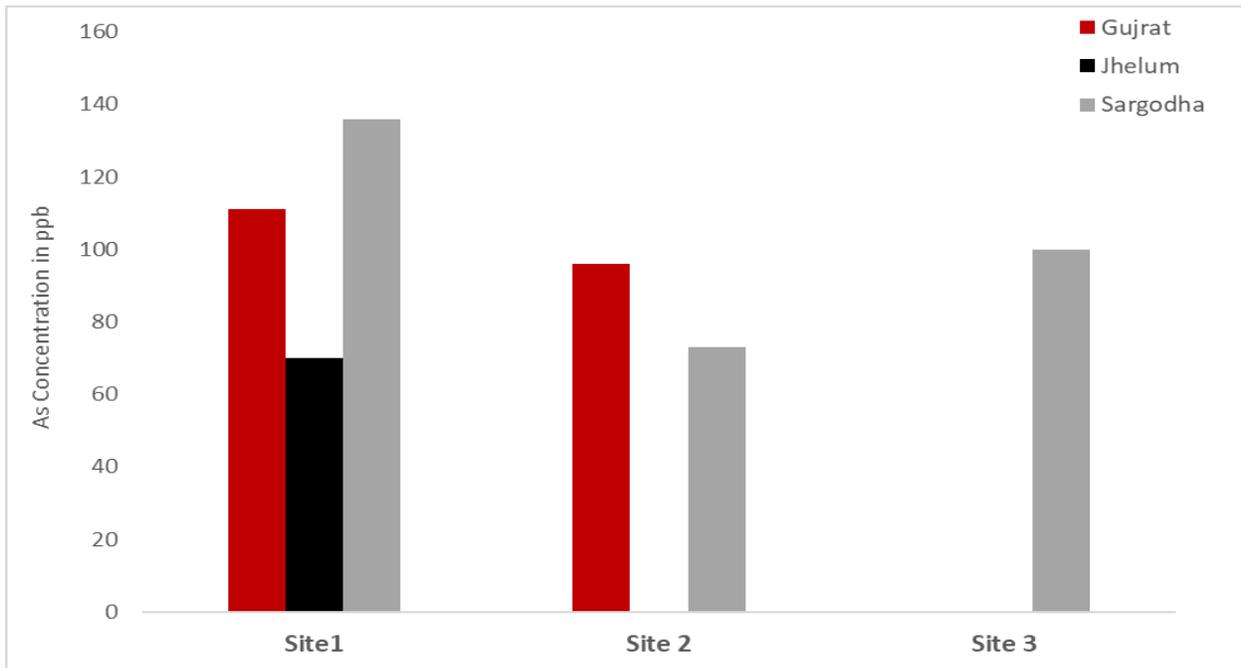


Figure 4: Six contaminated sites with As above 50 $\mu\text{g/L}$

A 2nd round of this preliminary investigation was undertaken to validate the arsenic contamination of six sites in in Gujrat, Jhelum and Sargodha (Ahmad et al., 2004). During this round, 96 samples (16 each from a grid of 100 km²) were collected selecting

a grid size of 6.25 km² (1 sample each from a grid of 2.5 km x 2.5 km) from all the 6 sites where arsenic contamination was found above 50 µg/L. Two replicate samples were taken from each site where previous results were above 50 µg/L. Out of 96 samples, 26% and 11.5% were found contaminated over 10 µg/L and 50 µg/L, respectively. These results were 2 to 4 times higher than those obtained in the 1st round (Ahmad et al., 2004).

3.1.2 National Survey (2001) in Collaboration with UNICEF

A national level arsenic monitoring survey was undertaken by PCRWR, Public Health Engineering Department (PHED) and Local Government and Rural Development (LG&RD) covering one-third of all districts of the country existing in 2001 (35 of 104 districts). The sampling strategy was set to collect five samples from different water sources at Union Council (UC) level covering all the UCs in the selected districts. A total of 8,712 samples were analyzed in the field using Merck field testing kit, while 848 samples were tested on AAS. Out of 8,712 samples, 9% exceeded the WHO guidelines 10 µg/L and 0.70% of samples had arsenic concentration beyond the Pakistan's permissible limit of 50 µg/L (Table 3).

Table 3: Arsenic contamination profile of National Survey (2001)

District	Total Samples (No.)		>10 µg/L (%age)		>50 µg/L (%age)	
	Field	Lab	Field	Lab	Field	Lab
Balochistan	619	71	1.30	1.40	0	0
KP	1560	156	0.30	22	0	0.6
Punjab	4315	428	12.2	36	0.60	9
Sindh	2218	193	11	26	1.40	10
Total	8712	848	9	28	0.70	7

Validation of 10% of total samples (848 samples) was conducted by analyzing samples at PCRWR's Water Quality Laboratory Islamabad. Test results revealed that 28% of samples had arsenic concentration over 10 µg/L and 7% above 50 µg/L (Ahmad et al., 2004). Table 3 and Figure 5 indicate arsenic prevalence mainly in Punjab and Sindh provinces where over 11% of field samples exceeded arsenic level above 10 µg/L and 0.6 to 1.4% samples above 50 µg/L. Khyber Pakhtunkhwa and Balochistan relatively had no arsenic contamination except one district in KP (Mardan) for which lab results indicated presence of arsenic over 50 µg/L.

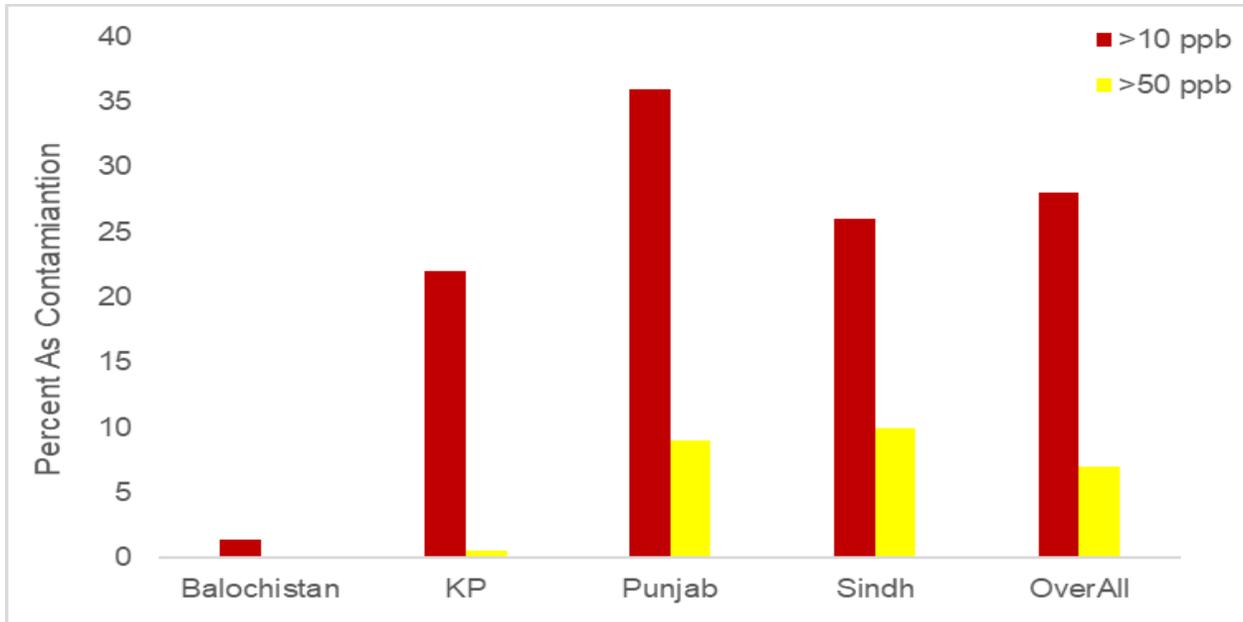


Figure 5: Status of groundwater arsenic contamination in 35 districts (2001)

In Punjab, three districts viz., Multan, Rahim Yar Khan, and Bahawalpur (located in Southern Punjab) showed the highest level of arsenic contamination where 35%, 14%, and 9% had arsenic concentration over 10 $\mu\text{g/L}$ and 1%, 2.3%, and 0.6% over 50 $\mu\text{g/L}$, respectively (Figure 6). Similarly, in Sindh, 4 of 9 districts had arsenic contamination of 1% over 50 $\mu\text{g/L}$ with a maximum of about 5% in district Dadu followed by 3% in district Khairpur (Figure 6). In Dadu and Khairpur 18% and 21% of samples had arsenic contamination over 10 $\mu\text{g/L}$, respectively (Ahmad et al. 2004).

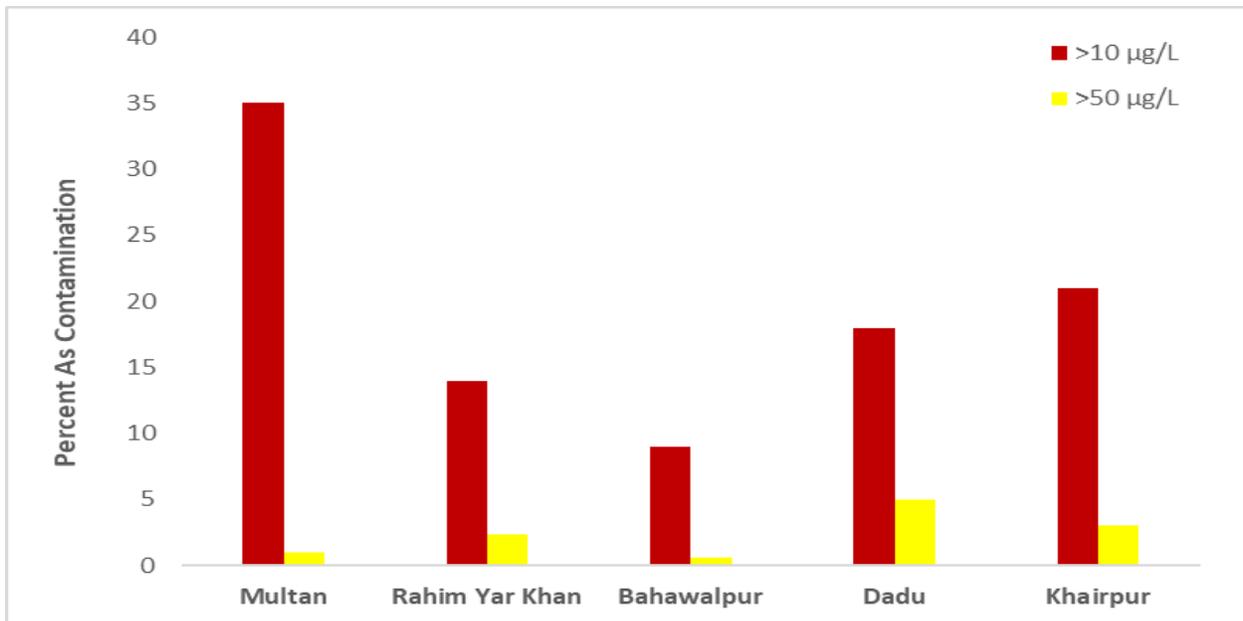


Figure 6: Districts with higher arsenic contamination (2001)

The overall findings of the National Survey in 2001 led to the conclusion that some of the areas in Pakistan have arsenic contamination requiring to further investigation and taking remedial measures.

3.1.3 Arsenic Monitoring and Mitigation Program (2005-10)

Following the above discussed preliminary studies, PCRWR initiated a countrywide arsenic monitoring program in all the districts of Punjab and Sindh in 2005. A uniform criterion for site selection was adopted and a grid size of 2 km² was selected and drawn on topographical district maps. A minimum distance of 1 km was maintained between the two monitoring points. Thirtythree thousand three hundred and eighty eight (33,388) water sources were selected for arsenic monitoring in 64 districts of Pakistan including 36 districts of Punjab and 28 districts of Sindh (Figures 7 & 8). Analysis of this large data sets revealed that in total, 15% of the monitored water sources were unsafe due to excessive arsenic concentration in Punjab and Sindh when compared with WHO Guideline value for arsenic. Comparing the findings with Pakistan's National Standards for Drinking Water Quality for arsenic, the prevalence of arsenic was found in 3% of the total monitored water sources in both the provinces.

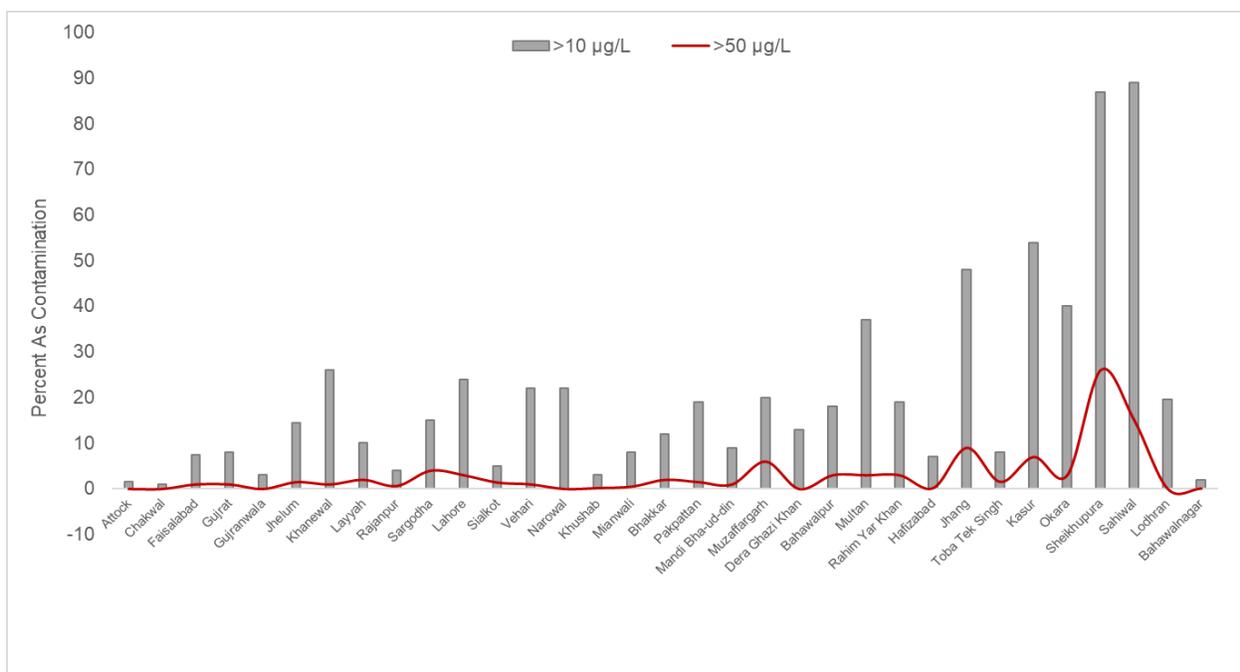


Figure 7: Arsenic contamination in districts of Punjab (2004-10)

The highly contaminated areas in Punjab included Sahiwal, Sheikhupura, Kasur, Jhang, Multan, and Khanewal (Figure 7). In Sindh province, highly contaminated areas included Matiari, Tando Muhammad Khan, Tando Allahyar, Kashmore, Dadu, Khairpur, Thatta East, Hyderabad, Nawab Shah, and Ghotki (Figure 8).

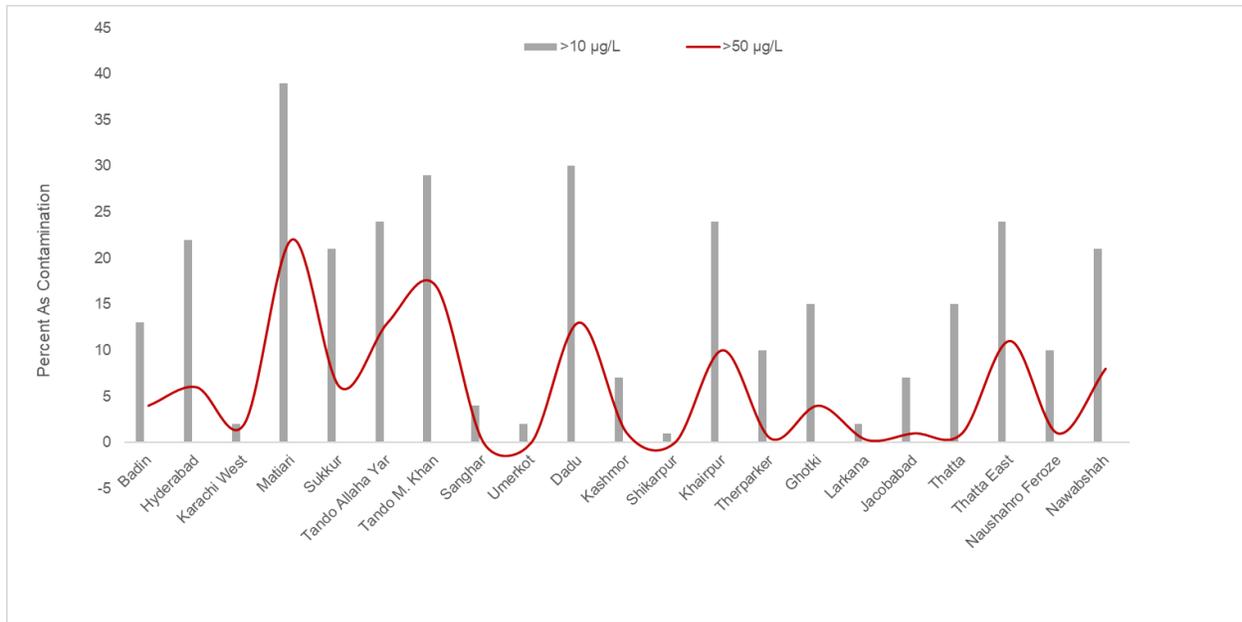


Figure 8: Arsenic Contamination in districts of Sindh (2004-10)

Arsenic data of this study comprising 19,874 sources of Punjab and 13,514 sources of Sindh are pooled in the main data base and further analysed to determine the groundwater arsenic situation at national level.

3.1.4 Rural Water Quality Monitoring Program (Phase I)

The Rural Water Quality Monitoring Program (RWQMP-I) was undertaken in 24 districts of Punjab. This included 49 tehsils, 1227 union councils and 2090 villages, from where 10,440 water samples were collected and evaluated by conducting field and laboratory analysis. Findings revealed that 14% of the sources were above WHO Guideline value for arsenic, while 1% (n = 92) of water sources in six districts were unsafe when compared with Pakistan’s National Drinking Water Quality Standards for Arsenic. This study showed higher level of As contamination in rural areas of Lahore followed by Kasur and Multan (Figure 9).

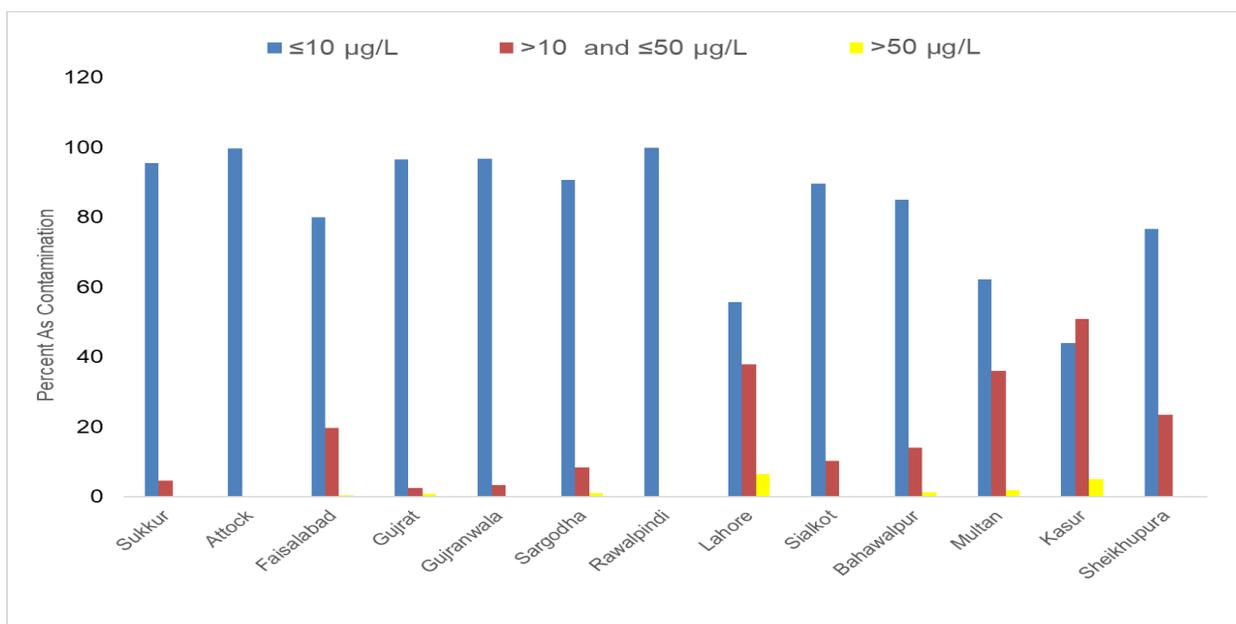


Figure 9: Arsenic contamination in rural areas of Pakistan under RWQMP (Phase I)

3.1.5 Rural Water Quality Monitoring Program (Phase II)

Water quality monitoring under this program was initiated in the rural areas of four districts in 2009. This included Badin, Nawabshah, Vehari and Khanewal. From these 20% villages of each district were selected by covering all rural union councils. The villages from each union council were selected on the basis of Population Census Report, 1998 i.e. villages with large population size were selected on priority basis in each union council. Approximately five water samples have been collected from each village depending upon the availability of water source within a village. Public places like schools, basic health units, dispensary etc. were given preference during the sampling. In addition to other physico-chemical and microbial test parameters, Arsenic testing of 2140 water sources revealed that 23% of the sources were beyond the WHO Guideline alue for arsenic (10 µg/L), while 1% of the sources were unsafe exceeding the limit of 50 µg/L (Figure 10).

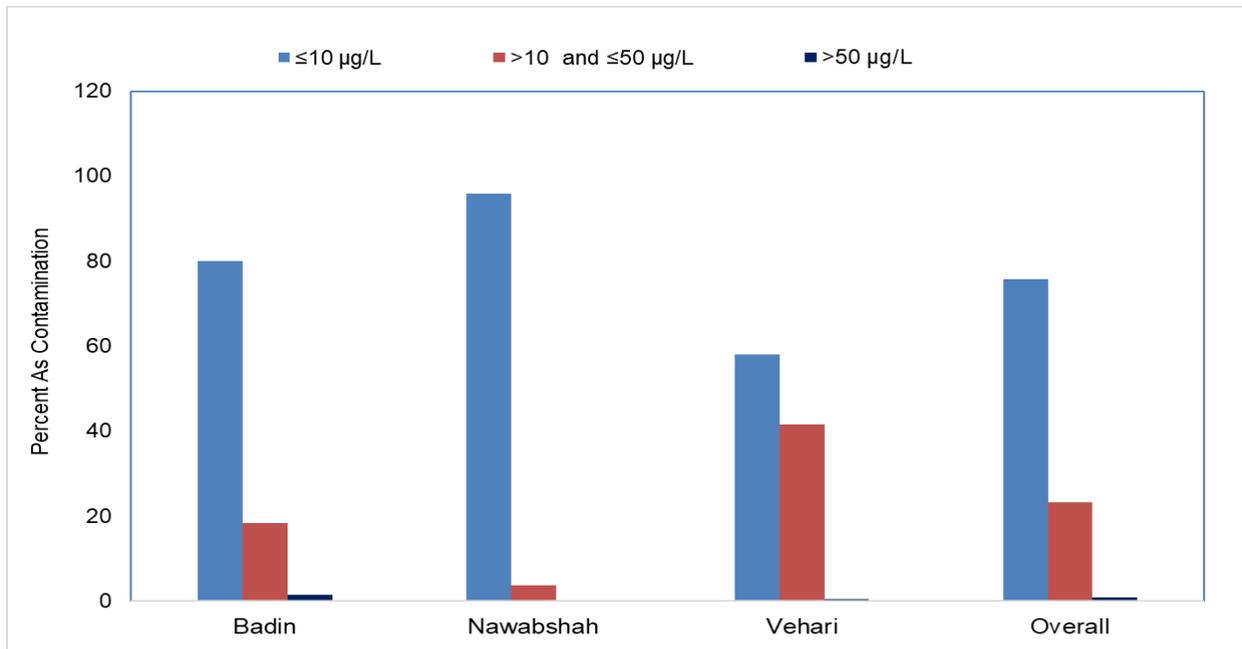


Figure 10: Arsenic contamination in rural areas of Pakistan under RWQMP (Phase II)

3.1.6 National Water Quality Monitoring Program (2020-21)

The National Water Quality Monitoring Programme (NWQMP) was initiated by PCRWR in 2001. It was the premier project which generated the first detailed water quality profile of 23 major cities of the country. The NWQMP continued for five years (2001-2006). During this phase, 357 water samples were collected adopting the uniform sampling criteria and analyzed for 79 physico-chemical parameters, including trace, ultra-trace elements and bacterial indicators. The water quality analysis of 357 water sources also confirmed the presence of arsenic in 24% of the sites as 2nd major water quality problem in the country. This monitoring program became the regular activity over two decades. Despite some improvement measures undertaken by the water supply agencies to combat arsenic, the recent segment of this program undertaken in the year 2020 still confirmed the presence of arsenic in urban water supplies. An overall analysis of 29 cities in 2020-21 monitoring phase indicated the excessive level of arsenic in 5% of the total 435 sources (Figure 11).

A trend over the time of this monitoring program (2001-2020) shows an improvement in water quality for arsenic in Punjab. The Council has been regularly disseminating the findings of this program and sensitized the stakeholders specifically the water supply agencies about this issue. As a result, water supply service providers took remedial measures for arsenic contamination in some cities, which improved the quality of water supply for the consumers (Figure 12).

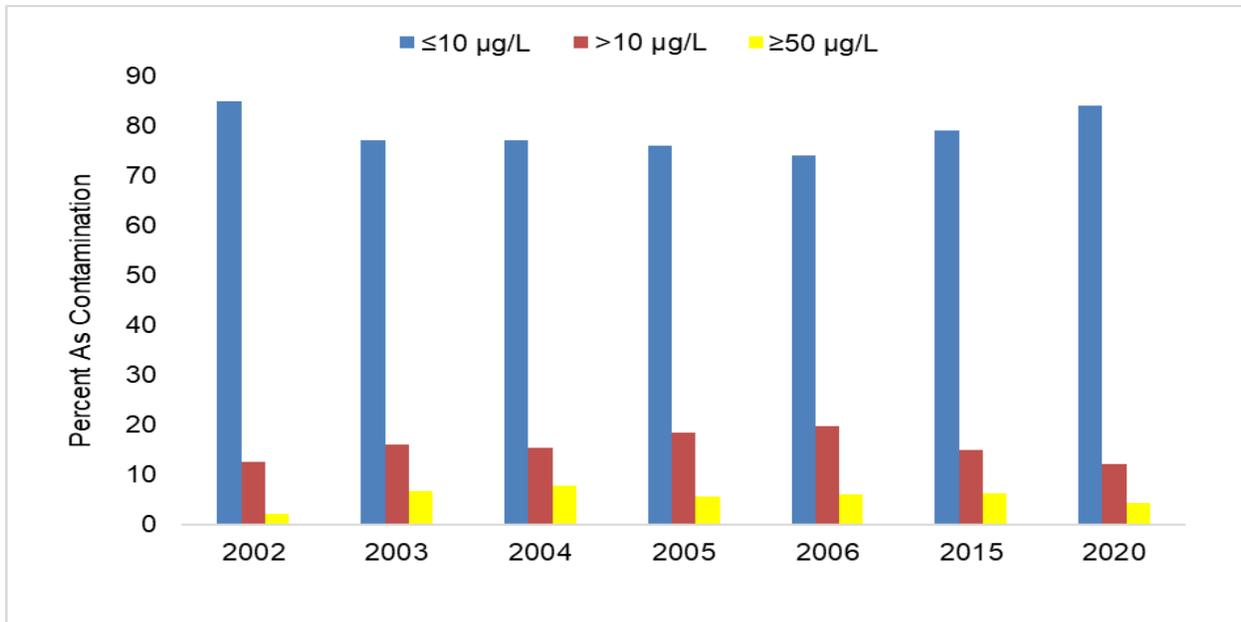


Figure 11: Trend of groundwater arsenic contamination in Punjab under NWQMP

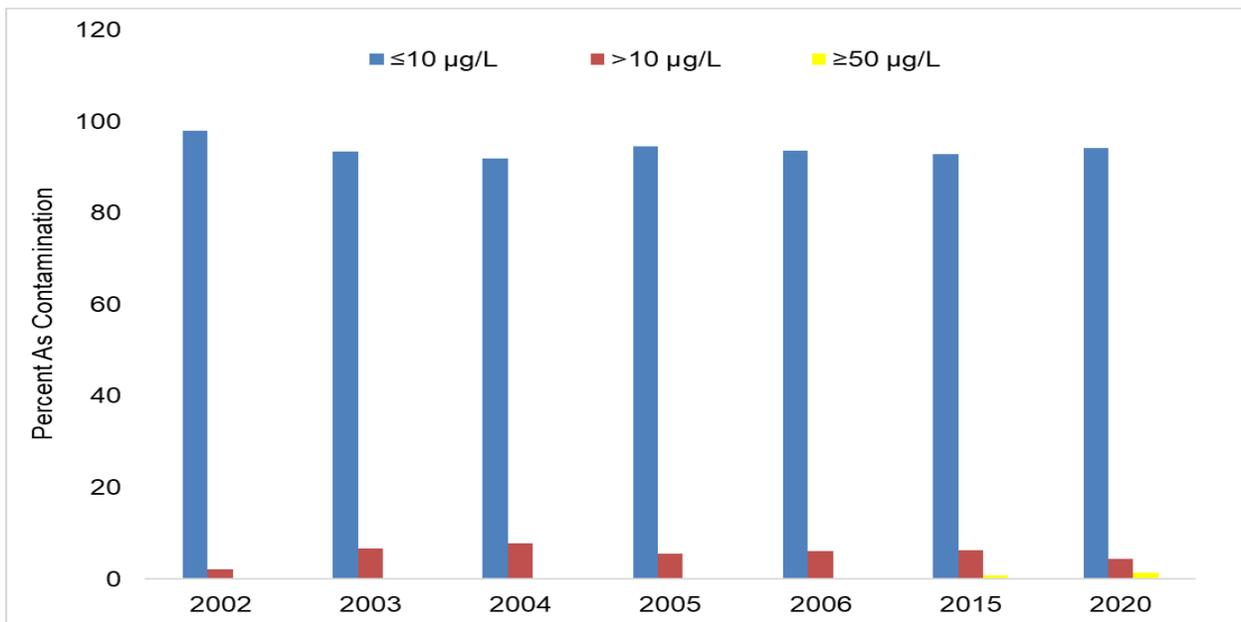


Figure 12: Trend of groundwater arsenic contamination in Sindh under NWQMP

3.2 Analysis of Pooled Arsenic Data (1999-2021)

Arsenic contamination was found to be the most prevalent in Punjab and Sindh districts, thus extensive blanket monitoring had been undertaken in these provinces. A few evidence of presence of lower levels arsenic in other areas of the country (i.e KP) were

also found. Arsenic profiles of all monitoring studies undertaken by PCRWR were pooled to form a single database. Thus pooled data resulted to have arsenic values of 45,920 water sources. Analysis of this large data sets reveals the spectrum of groundwater arsenic contamination at tehsil, district, provincial and national level.

3.2.1 Arsenic Contamination in Punjab Province

Descriptive statistics of arsenic concentration of 30,110 samples collected from 36 districts of Punjab (existing at project inception). Table 4 shows an overall mean arsenic concentration of 24.63 µg/L and maximum level of 2046 µg/L.

- In total, 85% of the samples (n = 25503) were found below the WHO guideline value for Arsenic in drinking water (10 µg/L) and were safe.
- 14% of the total samples (n = 4138) were found beyond the safe limit of 10 µg/L (>10 to ≤50 µg/L).
- Comparing the data with the safe level of National Drinking Water Quality Standard for Pakistan (NDWQSP) for arsenic i.e 50 µg/L shows that 2% of the total samples (n = 469) were exceeding this safe level (Table 4 and Figure 13).

Table 4: Descriptive statistics of arsenic contamination in Punjab

Sr #	District	Population (2017)	Total Samples	Mean	Min	Max	SD	≤10 µg/L		>10 to ≤50 µg/L		>50 µg/L	
								No.	% age	No.	%age	No.	% age
1	Attock	1,886,378	1111	1	0	41	2	1100	99	11	1	0	0
2	Chakwal	1,495,463	357	1	0	19	2	354	99	3	1	0	0
3	Faisalabad	7,882,444	2179	6	0	200	12	1905	87	259	12	15	1
4	Gujrat	2,756,289	1526	3	0	140	9	1457	95	56	4	13	1
5	Gujranwala	5,011,066	1572	3	0	50	5	1512	96	60	4	0	0
6	Jhelum	1,222,403	255	5	0	126	14	218	85	33	13	4	2
7	Khanewal	2,920,233	820	11	0	251	17	603	74	209	25	8	1
8	Layyah	1,823,995	666	7	0	150	16	597	90	57	9	12	2
9	Rajanpur	1,996,039	758	3	0	250	15	729	96	24	3	5	1
10	Sargodha	3,696,212	2046	8	0	437	31	1788	87	205	10	53	3
11	Rawalpindi	5,402,380	1769	1	0	32	1	1768	100	1	0	0	0
12	Lahore	11,119,985	586	16	0	251	27	381	65	177	30	28	5
13	Sialkot	3,894,938	1062	4	0	250	21	990	93	62	6	10	1
14	Vehari	2,902,081	1850	11	0	200	16	1287	70	547	30	16	1
15	Norawal	1,707,575	142	9	0	50	12	111	78	31	22	0	0
16	Khushab	1,280,372	870	3	0	150	9	843	97	25	3	2	0
17	Mianwali	1,542,601	627	4	0	250	15	579	92	45	7	3	0
18	Bhakkar	1,647,852	1101	7	0	250	22	971	88	111	10	19	2
19	Pakpattan	1,824,228	537	9	0	152	18	435	81	94	18	8	1
20	Mandi Bahauddin	1,594,039	592	3	0	85	9	539	91	49	8	4	1
21	Muzaffargarh	4,328,549	533	11	0	244	27	428	80	75	14	30	6

22	Dera Ghazi Khan	2,872,631	456	4	0	49	6	396	87	60	13	0	0
23	Bahwalpur	3,669,176	2003	7	0	465	18	1664	83	298	15	41	2
24	Multan	4,746,166	1062	13	0	327	21	653	61	374	35	35	3
25	Rahim Yar Khan	4,807,762	1116	8	0	178	16	907	81	177	16	32	3
26	Hafizabad	1,156,957	484	4	0	100	9	449	93	34	7	1	0
27	Jhang	2,744,085	62	14	0	79	19	34	55	24	39	4	6
28	Chaniot	1,369,740	34	12	0	39	12	16	47	18	53	0	0
29	Toba Tek Singh	2,191,495	385	5	0	67	9	354	92	25	6	6	2
30	Kasur	3,454,881	946	15	0	2046	19	417	44	477	50	52	5
31	Okara	3,040,826	179	13	0	85	15	108	60	65	36	6	3
32	Sheikhupura	3,460,004	967	13	0	92	18	603	62	311	32	53	5
33	Nankana-Sahib	79,540	320	6	0	37	7	252	79	68	21	0	0
34	Sahiwal	2,513,011	53	31	0	93	23	6	11	39	74	8	15
35	Lodhran	1,699,693	82	13	0	50	16	66	80	16	20	0	0
36	Bahawalnagar	2,975,656	1002	2	0	250	10	983	98	18	2	1	0
Total		108,716,745	30110	8	0	2046	7	25503	85	4138	14	469	2

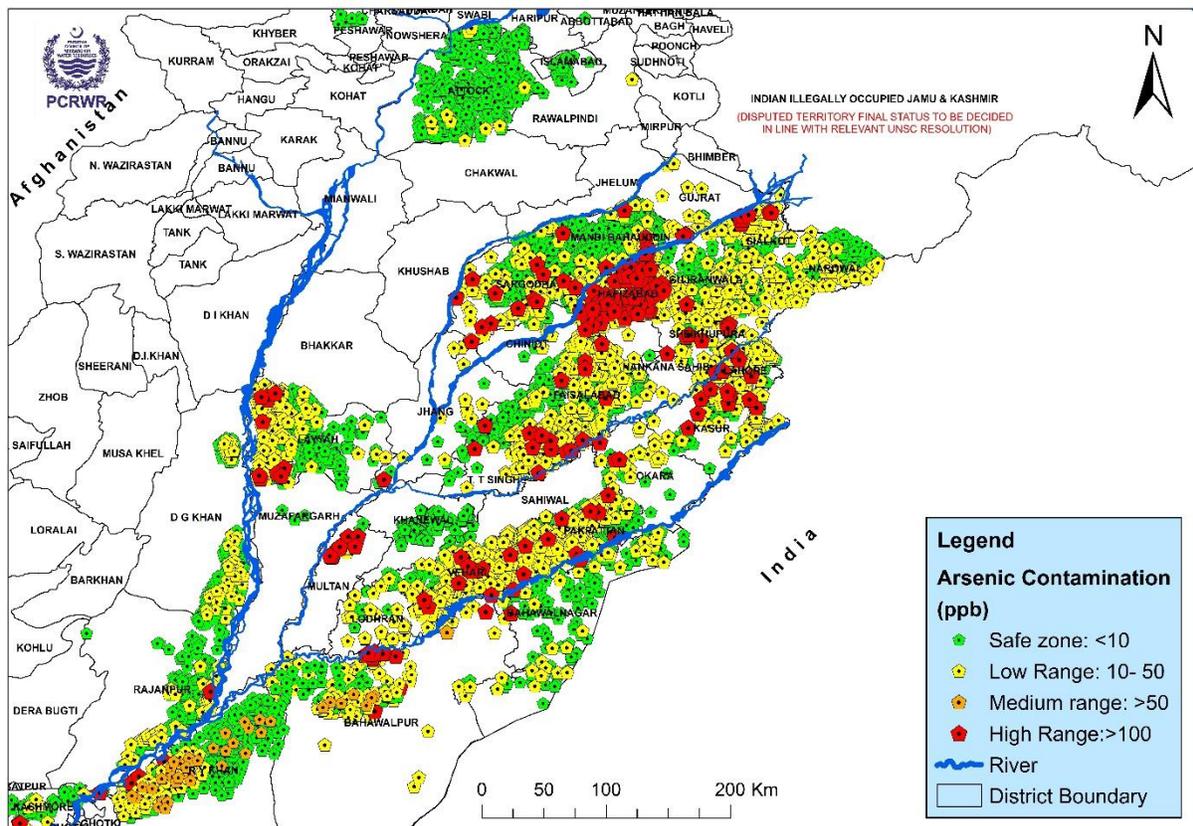


Figure 13: Arsenic distribution in groundwater of Punjab

Figure 14 shows that the highest arsenic contamination above the 10 µg/L was found in district Sahiwal (74%) followed by district Kasur (50%), Jhang (44%), Sheikhupura (37%), Okara (36%), Multan (35%), Vehari and Lahore (30%).

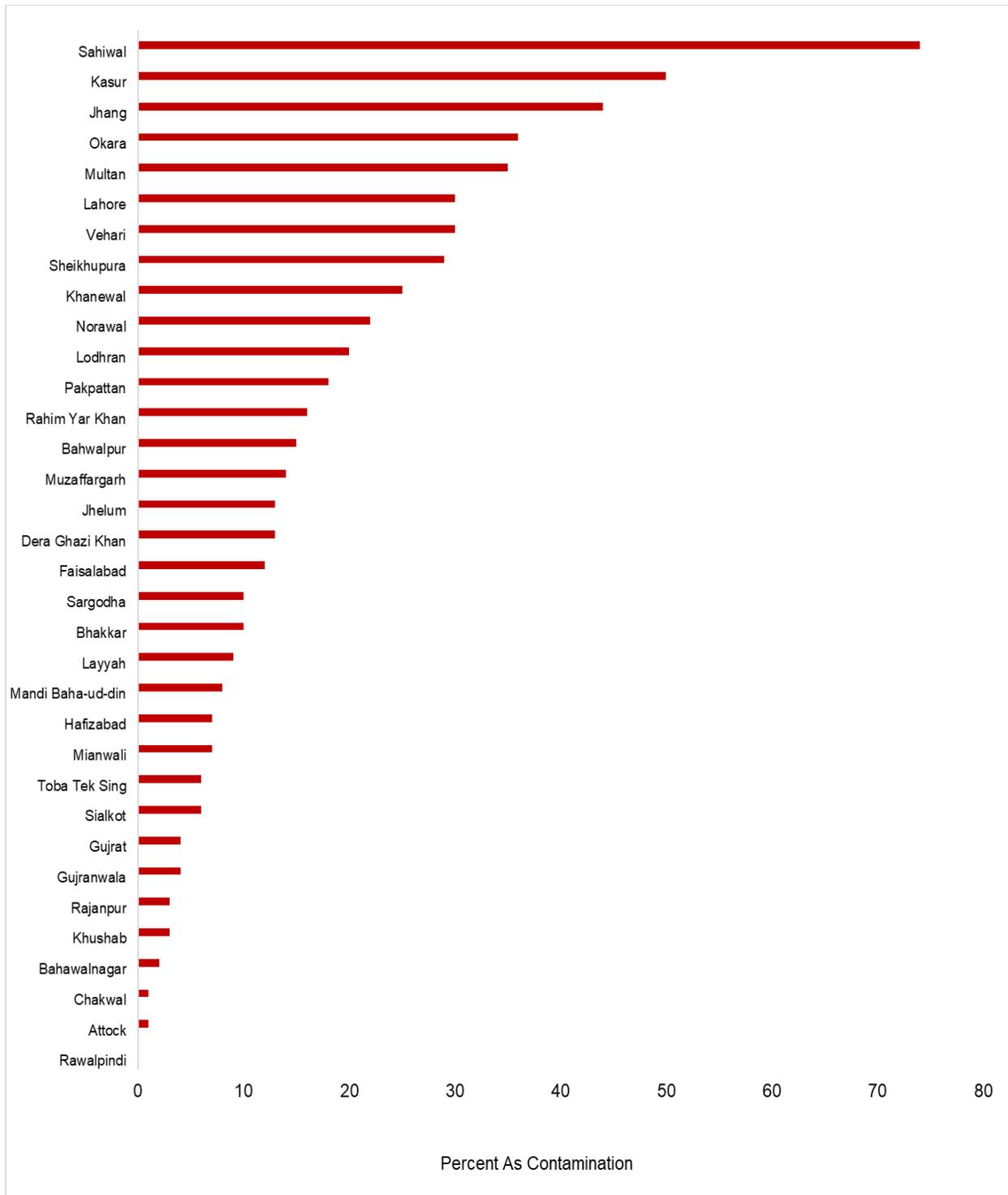


Figure 14: Ranking of cities for groundwater arsenic contamination in Punjab

Comparing the data with the limit of 50 µg/L shows that districts Sahiwal (15%), Sheikhpura (8%), Muzaffargarh (6%), Kasur and Lahore (5%) have considerable exceedance than Pakistan's standard for arsenic in drinking water. Out of all the samples, the maximum concentrations detected was 2046 µg/L in district Kasur followed by 465 µg/L in district Bahawalpur, 327.70 µg/L in Multan and 250 µg/L in Bahawalnagar (Table 4).

3.2.2 Arsenic Contamination in Sindh

Descriptive statistics of pooled data of groundwater arsenic (n = 15,727) in Sindh is given in Table 5. A comparison of the data with the safe permissible limits shows that 85% (13348) of the total water sources were within the WHO Guideline value of arsenic in drinking water (≤ 10 µg/L). About 10% of the total sources (1587) were found above 10 µg/L. Whereas, 5% of the total samples (792) were found exceeding the National Drinking Water Quality Standard for Pakistan (NDWQS) for arsenic.

In Sindh the maximum arsenic level was found as 972 µg/L in district Khairpur, followed by 500 µg/L in five districts i.e Larkana, Jacobabad, Thatta, Thatta East and Nowsheroferoz (Table 5).

Table 5: Descriptive statistics of arsenic contamination in Sindh

Sr #	District	Population	Total No. of samples	Mean	Min	Max	SD	≤ 10 µg/L		>10 to ≤ 50 µg/L		>50 µg/L	
								No.	age	No.	age	No.	age
1	Badin	1,804,958	1429	11	0	250	26	1184	83	212	15	33	2
2	Dadu	1,550,390	2104	21	0	495	45	1474	70	355	17	275	13
3	Ghotki	1,648,708	857	12	0	250	34	731	85	95	11	31	4
4	Hyderabad	2,199,928	476	3	0	250	20	465	98	8	2	3	1
5	Jacobabad	1,007,009	941	6	0	500	30	878	93	51	5	12	1
6	Jamshoro	993,908	162	0	0	0	0	162	100	0	0	0	0
7	Karachi Center	2,971,382	142	2	0	10	2	142	100	0	0	0	0
8	Karachi East	2,875,315	54	2	0	10	2	54	100	0	0	0	0
9	Karachi South	1,769,230	43	2	0	5	2	43	100	0	0	0	0
10	Karachi West	3,907,065	126	5	0	250	31	124	98	0	0	2	2
11	Kashmur	1,090,336	113	9	0	250	24	105	93	7	6	1	1
12	Khairpur	2,405,190	2748	18	0	972	53	2085	76	385	14	278	10
13	Larkana	1,521,786	1100	3	0	500	17	1073	98	24	2	3	0
14	Malir	1,924,346	138	1	0	25	2	137	99	1	1	0	0
15	Matiari	770,040	72	46	0	250	71	44	61	12	17	16	22
16	Mirpur Khas	1,504,440	248	0	0	2	0	248	100	0	0	0	0
17	Nausheroferoz	1,612,047	1284	8	0	500	26	1155	90	113	9	16	1

Sr #	District	Population	Total No. of samples	Mean	Min	Max	SD	≤10 µg/L		>10 to ≤50 µg/L		>50 µg/L	
								No.	age	No.	age	No.	age
18	Shaeed Benazirabad	1,613,506	590	5	0	100	13	554	94	29	5	7	1
19	Qambar	1,338,035	102	1	0	10	2	102	100	0	0	0	0
20	Sanghar	2,049,873	431	5	0	40	5	412	96	19	4	0	0
21	Shikarpur	1,233,760	130	1	0	20	3	129	99	1	1	0	0
22	Sukkur	1,488,372	532	10	0	250	29	462	87	53	10	17	3
23	Tando Allahyar	838,527	89	31	0	250	70	67	75	12	13	10	11
24	Tando Md-Khan	677,098	65	38	0	250	72	46	71	8	12	11	17
25	Tharparker	1,647,036	227	4	0	84	8	205	90	21	9	1	0
26	Thatta	982,138	656	11	0	500	30	557	85	90	14	9	1
27	Thatta East	Included in Thatta district	631	29	0	500	72	478	76	86	14	67	11
28	Umerkot	1,073,469	237	2	0	25	4	232	98	5	2	0	0
Total		44,497,892	15727	10	0	972	24	13348	85	1587	10	792	5

The district wise comparison shows that the maximum arsenic contamination was found in the district Matiari and district Dadu (17%), followed by district Badin (15%), districts Thatta, Thatta East & Khairpur (14%), Tando Allahyar (13%) (Figures 15 & 16). Comparing with the limit of 50 µg/L reveals that higher number of water sources of district Matiari (22%) were contaminated followed by Tando Muhammad Khan (17%), Dadu (13%) and Tando Allahyar (11%) as shown in Figure 15.

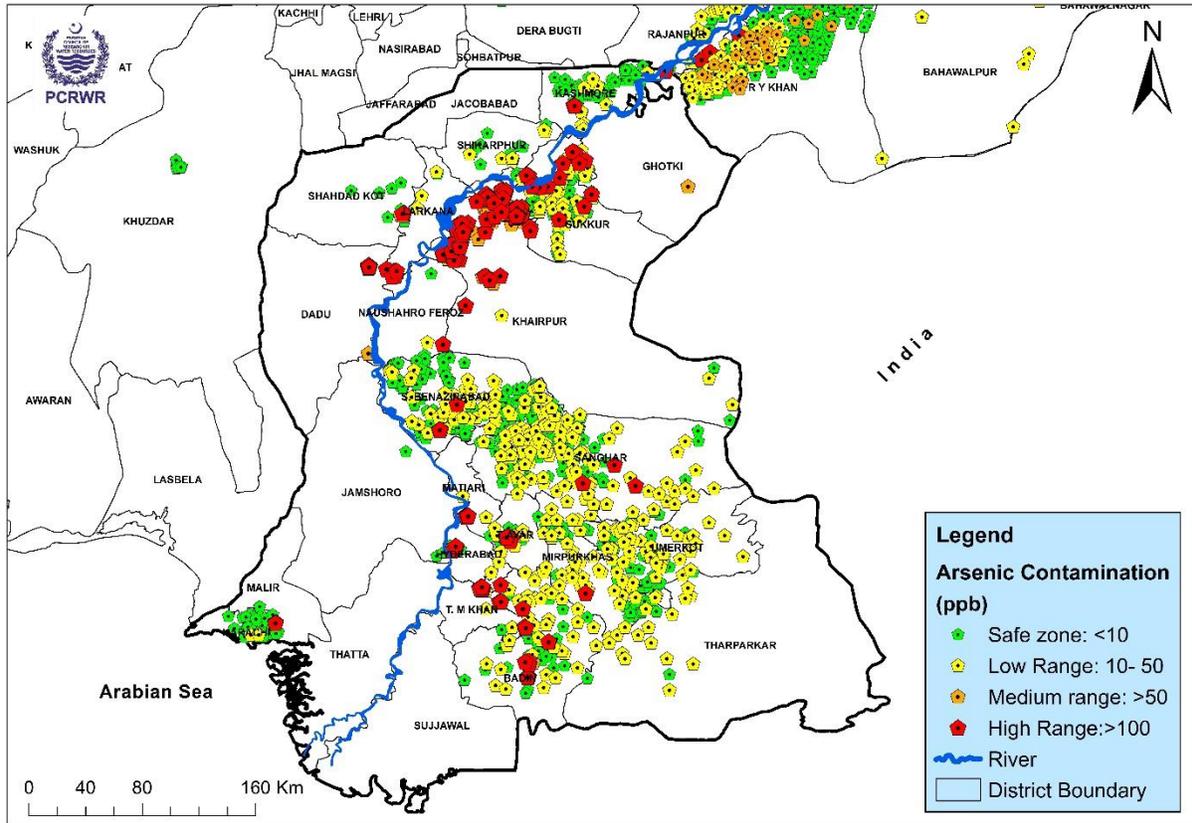


Figure 15: Arsenic distribution in groundwater of Sindh

District wise ranking with respect of arsenic contamination status in Sindh is shown in Figure 16.

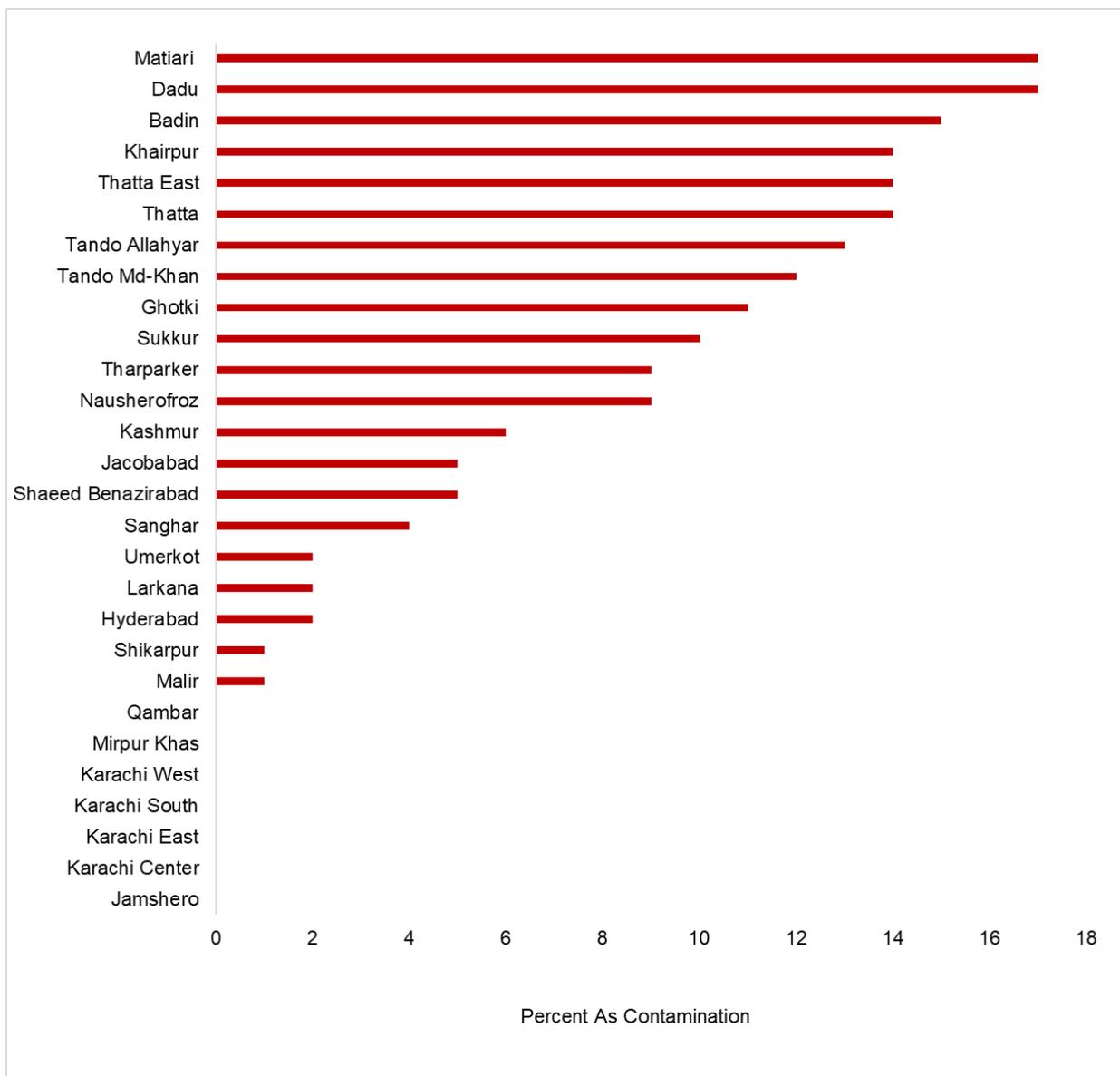


Figure 16: Ranking of cities for groundwater arsenic contamination in Sindh province

3.2.3 Arsenic Contamination in Khyber Pakhtunkhwa (KP)

Water quality monitoring studies undertaken by PCRWR in KP has revealed arsenic mainly in the groundwater of Dera Ismail (DI) Khan district. DI Khan is the main district of KP and situated along the Indus river at north-east to south-west direction. This region is mainly considered as the bone-dry alluvial plain. Arsenic monitoring of 85 water sources showed 44% of the unsafe sources due to arsenic concentration higher than the WHO Guideline value and 2% sources exceeding the NDWQS's limit. A tehsil wise comparison shows that the higher arsenic contamination is found in tehsil Parova, where 86% of water samples have arsenic above 10 µg/L (Table 6 and Figure 17).

Table 6: Scale of Arsenic Contamination in KP

Sr.#	Tehsil (s)	No. of samples	≤10 µg/L		>10 to ≤50 µg/L		>50 µg/L	
			No.	%age	No.	%age	No.	%age
1	D.I. Khan	41	19	46	22	54	0	0
2	Darband	6	5	83	0	0	1	17
3	Kulachi	6	6	100	0	0	0	0
4	Parova	14	2	14	12	86	0	0
5	Pharapur	18	14	78	3	17	1	6
Grand Total		85	46	54	37	44	2	2

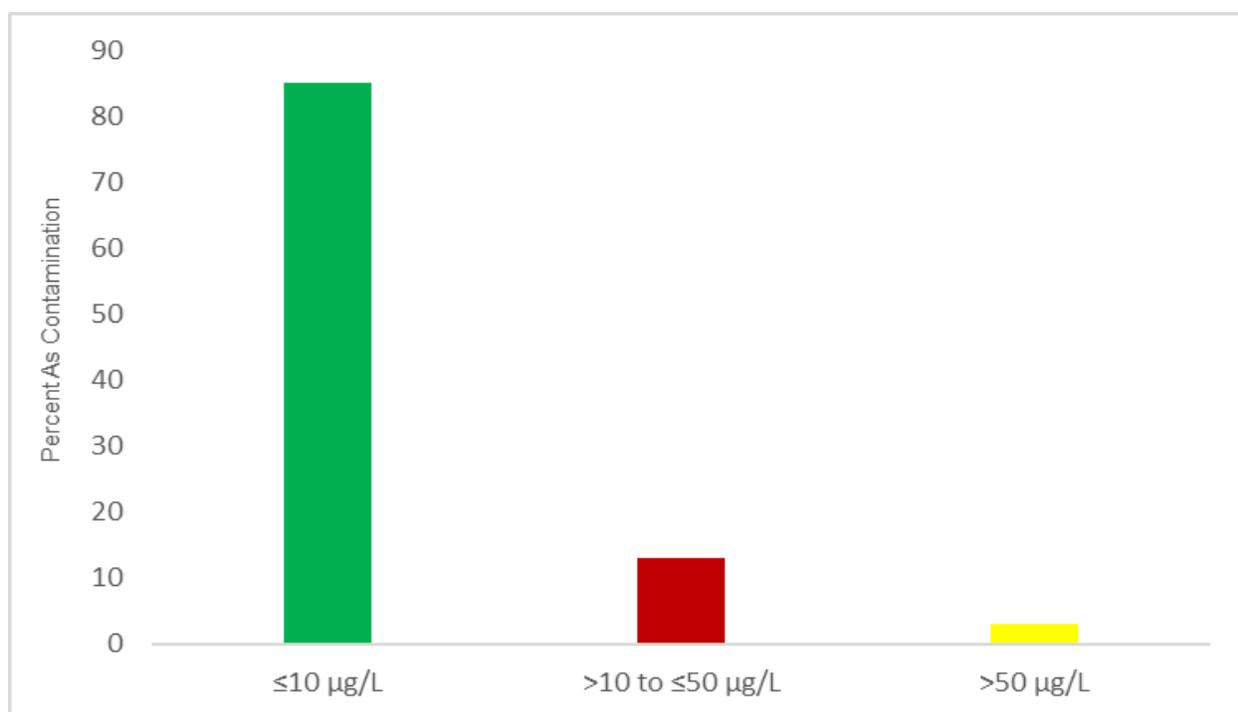


Figure 17: Distribution of Arsenic in Water Sources of DI Khan District

3.2.4 Overall Situation of Arsenic Contamination in Pakistan

An analysis of 45,920 samples from the country reveals the following situation:

- In total, 85% of the samples (n = 38,897) were below the WHO guideline value for Arsenic in drinking water (10 µg/L) and were safe.
- 13% of the total samples (n = 5,762) were found beyond the safe limit of 10 µg/L (>10 to ≤50 µg/L).
- Comparing the data with the safe level of National Drinking Water Quality Standard for Pakistan (NDWQS) for arsenic (50 µg/L) shows that 3% of the total samples (n = 1,263) were found exceeding this safe level (Table 7, Figure 18).

Table 7: Scale of arsenic contamination in Punjab, Sindh & KP

Sr.#	Province	No. of samples	≤10 µg/L		>10 to ≤50 µg/L		>50 µg/L	
			No.	%age	No.	%age	No.	%age
1	Punjab	30,110	25,503	85	4,138	14	469	2
2	Sindh	15,725	13,348	85	1,587	10	792	5
3	KPK (DI Khan)	85	46	54	37	44	2	2
Grand Total		45,920	38,897	85	5,762	13	1,263	3

Table 7 shows that the percent arsenic contamination beyond 10 µg/L is comparatively higher in Punjab (14%) than the Sindh (10%). However, percent arsenic contamination beyond 50 µg/L is comparatively higher in Sindh (5%) than Punjab (2%). Maximum arsenic level in Sindh (972 µg/L) was found comparatively lower than that detected in the Punjab (2046 µg/L).

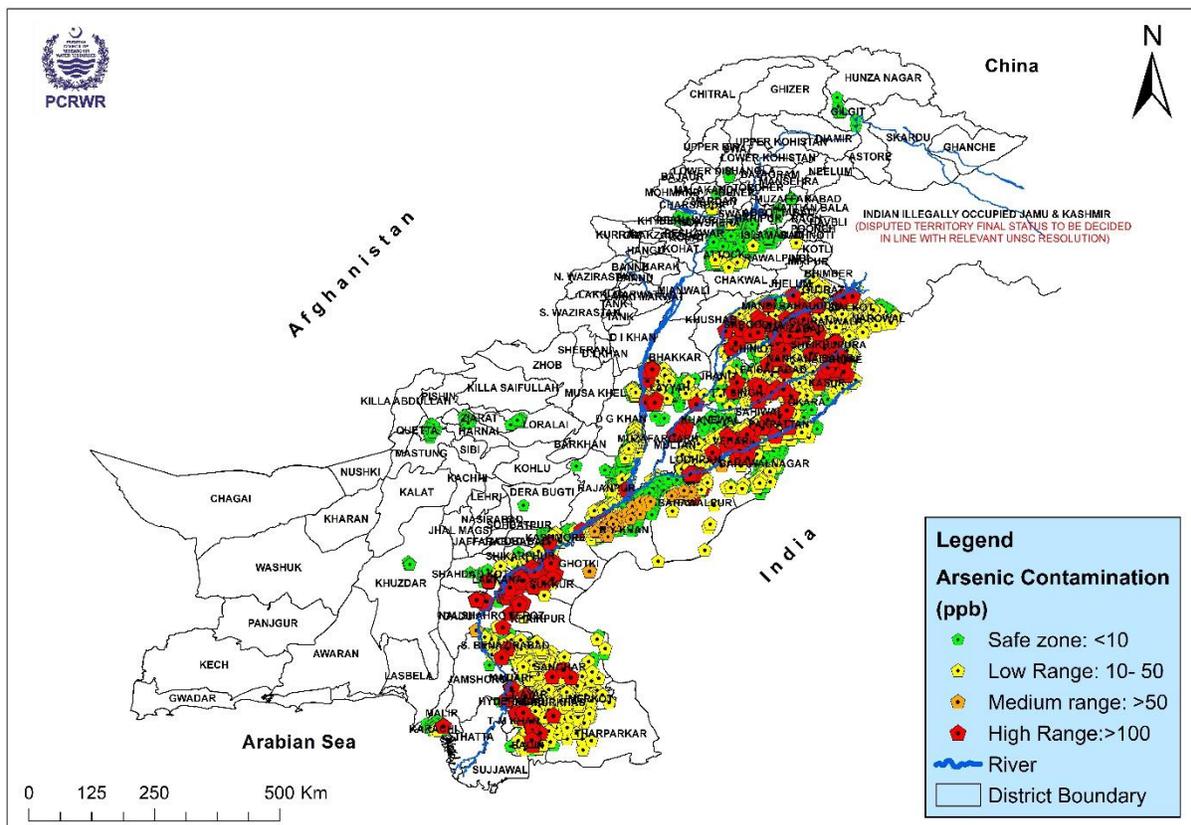


Figure 18: Arsenic affected areas in Pakistan

3.2.5 Arsenic in Surface Water of Pakistan

As such no arsenic has been detected by the PCRWR or reported by other studies in the surface water bodies. However, maximum As concentration in groundwater of the adjacent locations of Manchar lakes falling in the range of 23.3 to 96.3 µg/L had been reported (Arain et al. 2009). Arsenic contaminated groundwater used for domestic, industrial and irrigation purposes is ultimately disposed as untreated wastewater into the surface water bodies (drains, streams, rivers, lakes etc), contaminating the surface water with arsenic in addition to various other chemical and biological contaminants. In this regard, clear evidence had been shown in a past study undertaken by the PCRWR to assess impact of sewerage and industrial effluents on water resources, soil, crops and human health in Faisalabad (Kahlowan et al., 2006). The study also revealed the presence of excess arsenic in groundwater sources. .

Mean As level in fish farm water was found to be in the range of 7-65 µg/L which at few sites exceeded the Pakistan's limit of 50 µg/L and could be a source of arsenic exposure from intake of fish grown in such water. However, aquaculture water quality standards for arsenic and other parameters are yet to be established.

3.2.6 Distribution of Arsenic with respect to Water Table Depth

Table 8 shows PCRWR arsenic monitoring data (2001-2021) of Punjab. Both shallow and deep water sources (i.e less than 46 m and above 46 m) have arsenic contamination. In addition, data gathered by the UNICEF in 1999, for 6 wells (3 shallow and 3 deep) in Muzaffargarh (Punjab) located at lateral distance of 20 m to 50 m apart from each other revealed that arsenic in shallow well (6-11 m deep) ranged from 2.2 µg/L to 9 µg/L while in deep wells (30 m to 107 m deep) it was from 61 to 170 µg/L showing an increase of arsenic with depth in this specific locality (Ahmad et al., 2004).

Following above, we cannot generalize presence or absence of arsenic for given sources and thus every source needs to be tested for arsenic for determining its degree of fitness for drinking. Subject to the geological variations in different areas, every arsenic affected district needs in-depth investigation both horizontally and vertically to identify the arsenic free zones.

Table 8: Distribution of As with respect to depth in Punjab

Depth (Meter)	Total Samples	≤10 µg/L		>10 to ≤50 µg/L		>50 µg/L	
	No.	No.	%age	No.	%age	No.	%age
3-15	13,475	11,684	87	1,580	12	211	2
15-30	10,668	8,819	83	1,733	16	116	1
30-45	1,935	1,688	87	229	12	18	1
Above 45	1,439	1,216	85	183	13	40	3

Data from Sindh (Table 9) also shows more or less similar results as that of Punjab. Both water sources from less than 46 m and above 46 m have arsenic contamination. For Sindh, arsenic distribution at 3-46 m follows almost similar pattern. However, for over 46 m deep water sources, only 9 sources showed presence of arsenic. Table 9 shows a non-uniform pattern of geogenic arsenic distribution in Sindh.

Table 9: Distribution of As with respect to depth in Sindh

Depth (Meter)	Total Samples	≤10 µg/L		>10 to ≤50 µg/L		>50 µg/L	
	No.	No.	%age	No.	%age	No.	%age
3-15	5,799	5,104	88	554	10	141	2
15-30	2,546	2,365	93	135	5	46	2
30-45	115	76	66	29	25	10	9
Above 45	44	35	80	3	7	6	14

Though most studies have reported association of arsenic contamination with shallow wells, however other studies have provided evidence of its presence in deep wells. The Stanford School of Earth Sciences discovered arsenic in numerous deep wells drilled in the Mekong Delta region of southern Vietnam (Erban et al., 2013). According to the study, the contamination occurs as arsenic is squeezed from ancient clay sediments surrounding the wells. Tables 8 and 10 suggest that the impacts of arsenic contamination from deep groundwater extraction may be reduced by quantifying the extent of deep groundwater arsenic, restricting uncontrolled pumping and treating abstracted groundwater to comply with the public health standards.

3.3 Causative Analysis for Arsenic Mobilization in the Indus Plain

Various research studies undertaken in arsenic-affected regions of the world reveal that arsenic can strongly influence groundwater quality through natural geogenic leaching processes from host rocks and sediments (Shaji et al., 2021, Raju, 2022). These studies have reported various geochemical process as responsible for arsenic mobilization in groundwater. These include, reducing environments, arid oxidizing environments with elevated pH, geothermal activity and/or oxidative weathering of sulfide minerals.

Indus River with a length of 3180 km flows through the Indus Plain in Pakistan. The morphology and age of flat-lying, Holocene fluvial sediments along the Indus River and its tributaries are similar to those of the well-known arsenic-affected areas of the Ganges and Brahmaputra Rivers in India and Bangladesh, the Red River in Vietnam, and the Mekong River in Cambodia and Vietnam (Guo et al., 2014, Berg et al., 2001) . Aquifers within Holocene sediments are particularly susceptible to arsenic enrichment due to the sediments' limited time of exposure to groundwater flushing such that the sediments continue to hold a relative abundance of mobilizable arsenic within its grains (Postma et al., 2012, McArthur et al., 2001).

A chemically reducing environment generally dominates in the aquifers along these rivers. Generally due to an abundance of organic material along with a limited supply of oxygen, results in the desorption of arsenic from iron oxy hydroxides. Depleted oxygen levels can come about, for example, due to an impermeable near-surface silt and/or clay layer that prevents contact of the aquifer with the atmosphere.

Pakistan is the third-largest user of groundwater, consuming about 9% of the global groundwater abstraction and occupying 4.6% of the total groundwater-irrigated area of the world (Qureshi, 2020). The groundwater aquifers in the Indus Plain of Pakistan were reported to be composed of up to 300 m of Quaternary alluvial deposits and permeable soils low in organic content (Greenman et al., 1967).

A critical analysis of available data revealed that arsenic contamination is predominant in Indus plain. For example, all those districts identified as high in arsenic contamination (Multan, Bahawalpur, Rahim Yar Khan in Punjab and Khairpur, and Dadu in Sindh) are lying in alluvial deposits along the Indus river. Interestingly, within a given district, areas lying closer to Indus river system were found to have relatively higher arsenic concentration than those away from the river system. For example, in district Dadu, data available for three Talukas/Tehsils (sub-district units) clearly provide evidence for this hypothesis. Table 40 shows that Johi and Sehwan Talukas located very near to the Indus river have several water sources beyond the contamination level above 50 µg/L. The same pattern is prevalent in district Khairpur where Gambat taluka is located very near to Indus river, Khairpur taluka in mid way while Kot Diji is farthest from the Indus

river. The respective arsenic levels above 50 µg/L for Gambat, Khairpur, and Kot Diji are 26%, 2%, and 1% (Table 5). In Tharparkar district (one of southern districts in Sindh bordering with sea), areas closer to sea were found to have high arsenic level than those away from sea.

Contrary to the other As contaminated regions in Asia, the principal contributing factors in the release of As in Indus plain includes the extensive irrigation from unconfined aquifers and elevated pH dissolution resulting from basic topsoil. Due to oxidizing conditions and the presence of unconfined aquifers that cause much lower concentration of As in groundwater as compared with India and Bangladesh (Smedley, 2003). Moreover, pockets of reductive dissolution, human and animal organic waste, and intensive agricultural activities are also causing the release of As into the environment. In Tharparkar, arid environment and complex geology promote reductive dissolution of As minerals leading to higher release of arsenic in groundwater in the range of 100–2580 µg/L (Brahman et al., 2013). In Khairpur district (Tharimirwah, Kot Digi, Sobo Dero, and Kingri) alluvial deposit of Indus river is the primary source of As contamination (Rabbani et al., 2017). Arsenic distribution at depths of 3-46 m showing groundwater contamination both in shallow and deep wells (Nafees et al., 2011). Low hydrological gradient may also result in sluggish groundwater flow and hence the increased arsenic level (Smedley and Kinniburgh, 2002).

The abundant water resources and fertile soils in the Indus plain of Pakistan hosts extensive agricultural production. The demonstration of the government-funded Salinity Control and Reclamation Projects (SCARPs) model in 1960's motivated farmers to install their own tubewells, resulting in the massive development of private tubewells, from merely 30,000 in 1960 to around 1.5 million in 2022. Out of these, more than 90% are only working in the Punjab 4.4% are in Sindh, 1.8% are in Khyber Pakhtunkhwa (KP), and 3.8% are in Balochistan. During this period, the irrigated area in Punjab was almost doubled (from 8.6 to 16 Mha), and the groundwater contribution to the overall irrigation water supply at the farmgate increased from 8 to 75% (Qureshi, 2018, Asghar et al., 2018).

In Pakistan, groundwater is providing over 90% of the drinking water for humans and animals in the rural and desert areas of the country, In addition to higher-volume pumping tube wells, shallow small-scale and family-based hand and motorized pumps have long been a major source of drinking water in the Indus plain. The growing population, agriculture, and periods of drought have forced more reliance on groundwater that has resulted in water level declines of up to 1 meter annually. Following extensive groundwater abstraction and pumping in these areas has likely increased the contribution of younger, more toxic groundwater in wells with decreasing arsenic or, less frequently, increased the contribution of higher pH or reduced groundwater in wells with increasing arsenic (Haugen et al., 2021).

All these field based evidence suggest that the process of arsenic release from alluvial deposits lying near to Indus river system is faster than those lying away from the river zone. However, a detailed scientific investigation needs to be done to get more insight on spatial and temporal variations of arsenic.

Section-II: Arsenic in Soil and Food

3.4 Review of Arsenic Contamination in Soil

Arsenic is distributed uniformly in major types of rocks, soils and its common concentrations in most rocks range from 0.5 to 2.5 mg/kg and in contaminated soils from 10 to 2470 mg/kg (Colbourn et al., 1975). Arsenic contamination of soil by irrigation water and subsequent uptake by crops poses a potentially significant public health risk. There are relatively few studies that have identified a positive correlation between arsenic concentrations in soil and irrigation water and between arsenic uptake by rice and arsenic in soil water (Meharg and Rahman, 2003, Das et al., 2004, Duxbury and Zavala, 2005).

In Pakistan, a few studies have reported an overall range of 0.5 to 54 mg/kg of arsenic in the soil profile (Table 10). Soil arsenic level exceeding the European Union's recommended maximum acceptable limit for agricultural soil (20 mg/kg) has been associated with mining activities, contaminated groundwater used for irrigation and use of arsenical pesticides (Zhu et al., 2008). Table 10 shows that soil in the vicinity of Manchar Lake irrigated with lake water had arsenic (8.7– 47 mg/kg) above the EU limit of 20 mg/kg. Likewise, agricultural soil in Lahore (6-20 mg/kg), Khairpur Mir's (20.5-36.3 mg/kg) and Kot Diji (15.2-54.0 mg/kg) have been reported to have arsenic beyond the EU's limit and probably showing its relation with groundwater arsenic. In district Nagarparkar the reported soil arsenic is also found beyond the EU's limit (21.38-30.92 mg/kg).

Table 10: Summary of arsenic distribution in soil

Region	Sample type and location	Possible Source	Reported Arsenic levels (mg/kg)	References
Punjab	Lahore	Agricultural land, pesticides and fertilizers which enhance the process of soil alkalinization	6-19	Abida et al. (2009)
		-do-	1-19	Abida et al. (2009)
Sindh	Manchar Lake (Soil Irrigated with lake water)	Not defined	8.7-47	Arain et al. (2009)
	Manchar Lake (Soil Irrigated fresh canal water)	Not defined	2-6.8	

	Soil amended with untreated industrial sewage sludge, Hyderabad	Not defined	0.941- 4.71	Jamali et al.(2007)
	Khairpur Mir's	Alluvial deposits	20.5-36.3	Baig et al. (2009)
	Kot Diji	Not defined	15.2-54.0	
	Nagarparkar,	Anthropogenic	8.58-9.61	Naseem et al.(2010)
	Rock, Nagarparkar,		11.31-13.96	
	Clay, Nagarparkar		21.38-30.92	
KPK	Bannu	Not defined	0.6-10.1	
	DI Khan	Not defined	1.53-6.64	Zahir Ur Rehman et al. (2016)
	Kohat	Not defined	0.05-3.7	
	Hangu	Not defined	0.50-1.85	
	Lakki Marwat	Not defined	0.70-1.75	
	Chitral	As present in form of sulphide and carbonate ores	2.8-18.50	Shandana et al. (2019)

Regions with lower level of groundwater arsenic also shows lower arsenic in soil of that region such as Bannu, DI Khan, Kohat, Hangu and Lakki Marwat and Chitral (Jehan et al., 2019). A low level arsenic (0.94 - 4.71 mg/kg) has also been reported in Hyderabad soil amended with untreated industrial sewage sludge (Jamali et al., 2007).

The mobility of arsenic compounds in soils depends on the type and amount of adsorbing soil constituents, the pH value, and the redox potential. It is influenced by compounds of Iron, Manganese, Aluminium, Calcium and Magnesium, natural organic matter, and clay minerals. Other anions compete with arsenic anions for adsorption sites on soil constituents and influence the mobility of arsenic compounds.

The higher concentrations tended to occur in areas with higher soil pH and near sand and clay younger than 10,000 years. The major sources of high As in soils include weathering of arsenic-rich minerals in country rocks, as well as various anthropogenic sources. Anthropogenic As contamination of soil may result from mining, milling, and smelting of copper, lead, and zinc sulfide ores, hide tanning waste, dyes, chemical weapons, electroplating, gas exhaust, municipal sludge of land, combustion of fossil fuels, As additives to livestock feed, coal fly ash, and agricultural use of arsenical pesticides.

Uptake of arsenic from soil and irrigation water keep considerable importance from public health standpoint. Thus, it is important to quantify the arsenic in soil and irrigation water to understand the relationship between water–soil–plant system, and risks of arsenic contaminated irrigation water for crop and human health.

3.5 Arsenic in Rice

Rice is an efficient scavenger of arsenic and takes up 10 times as much as other cereal crops probably due to growth in flooded fields (Zavala et al., 2008). Pakistan is the world's largest producer of rice. Each year, it produces an average of 6 million tonnes and together with the rest of the South Asia; the country is responsible for supplying 25 of the world's paddy rice output (Memon, 2013). In 2020, rice, paddy production for Pakistan was 8.42 million tonnes. Though Pakistan rice, paddy production fluctuated substantially in the recent years, it tended to increase through 1971 - 2020 period ending at 8.42 million tonnes in 2020 (Akhter and Haider, 2020). Most of the rice crop is grown in the fertile Punjab and in some areas of Sindh and thus millions of farmers rely on rice cultivation as their major source of income and employment (Figure 19).

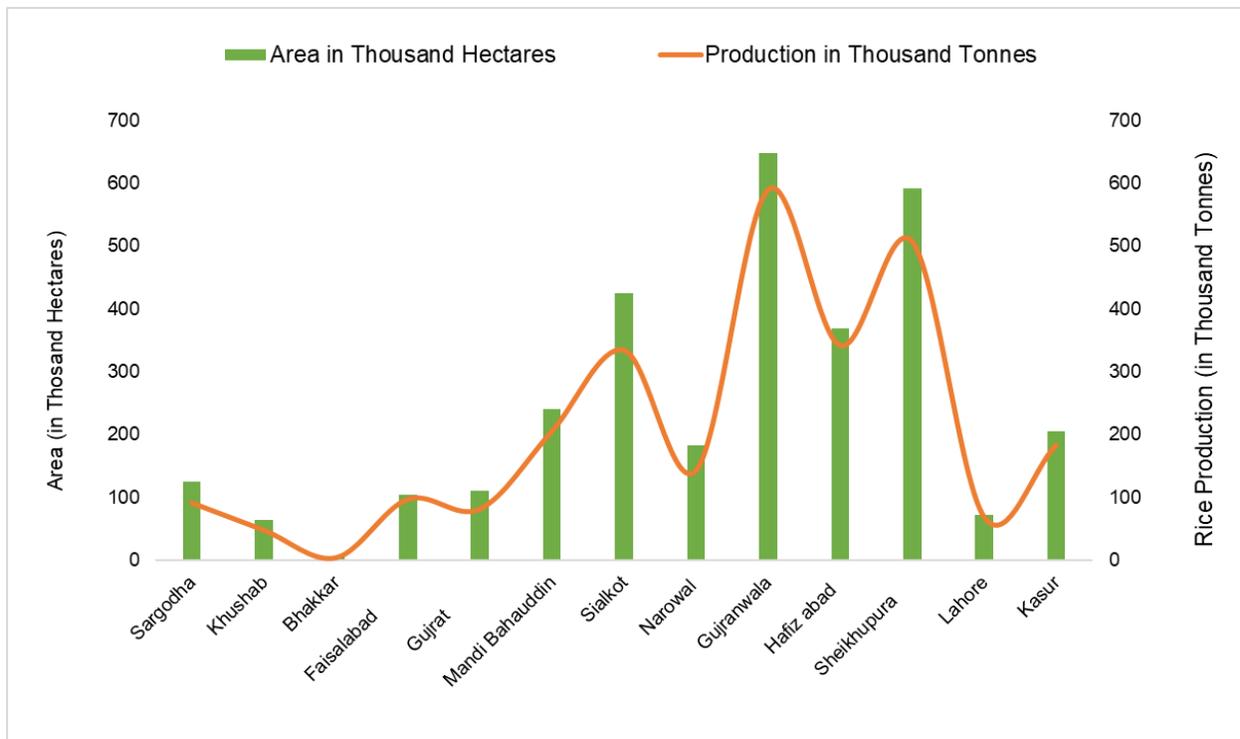


Figure 19: Rice production in the rice growing region of Punjab, Pakistan (2020-21)¹

¹ Data source: Agriculture Department Lahore 2021

Arsenic exposure is likely to be greater for people who eat large amounts of rice every day and for infants, whose first solid meals are mainly rice-based baby food. Considering the rising concerns of international community regarding arsenic in rice, PCRWR in 2014 quantified arsenic in various rice brands grown in primary rice growing areas of Pakistan to elucidate the impact of use of arsenic contaminated groundwater for irrigation. The study was focused primary on the rice growing region including 10 districts such as Gujranwala, Gujrat, Hafizabad, Kasur, Lahore, Mandi Bahauddin, Narowal, Okara, Sheikhupura and Sialkot (Hifza, 2014).

In total, 250 samples of different rice varieties grown or available in the selected districts were collected, preserved and processed for the determination of concentrations of total and inorganic arsenic in polished and brown rice. A descriptive statistical analysis of arsenic in rice is presented in Figure 20 indicating arsenic in the range of 0.084 to 0.356 mg/kg.

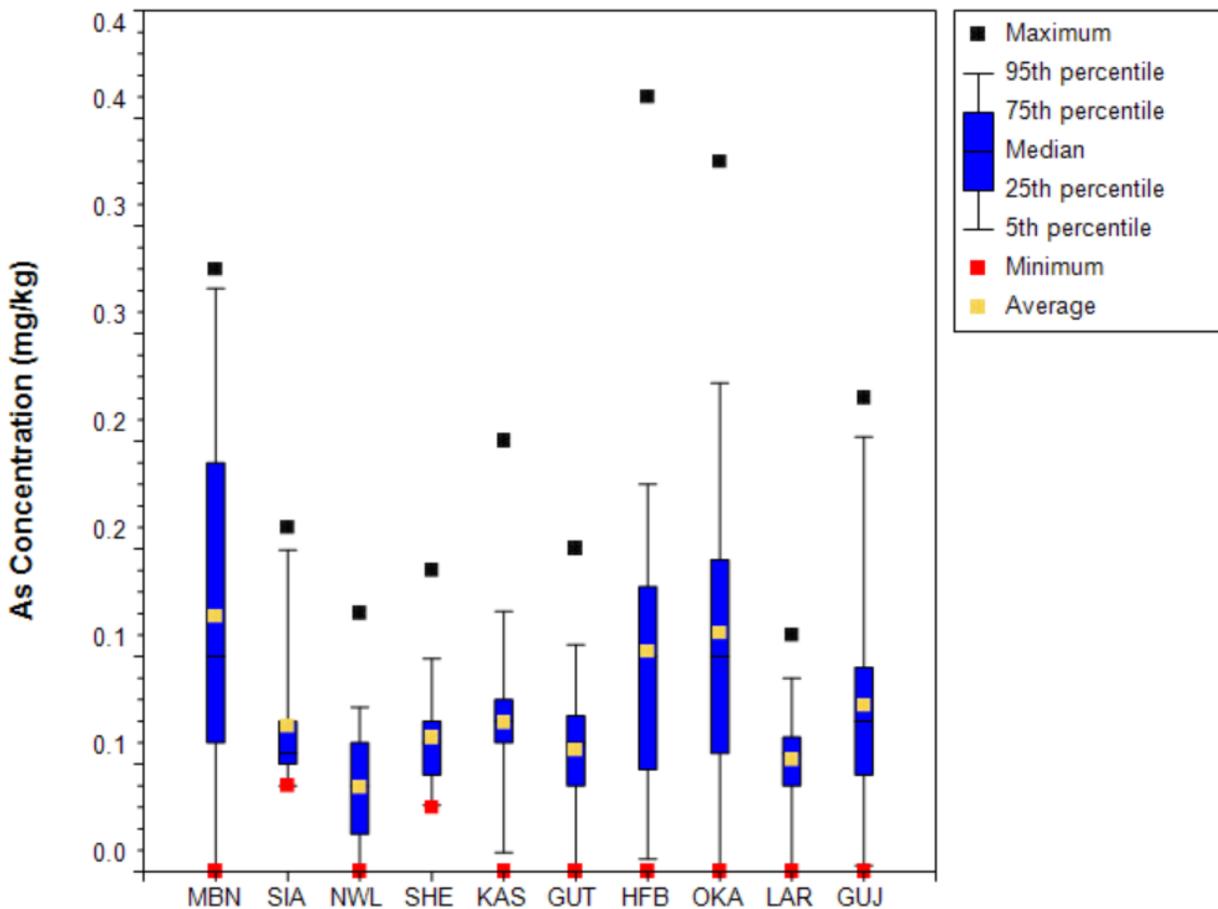


Figure 20: Descriptive statistics of Arsenic in Rice Grown in the Rice Growing Region

These findings were compared with the WHO recommended permissible limit for arsenic in food (1.00 mg/kg and with limit of 0.2 mg/kg revised later in 2014). None of

the samples was found exceeding the 1.00 mg/kg, whereas 12 samples were found beyond the revised Maximum Limit (ML) of 0.2 mg/Kg.

To assess the distribution of arsenic in groundwater used directly or indirectly for the irrigation of paddy fields, 200 water samples from above mentioned 10 districts were also collected and tested for total arsenic. Higher groundwater arsenic in the rice growing areas as shown in Figure 21 is a concern.

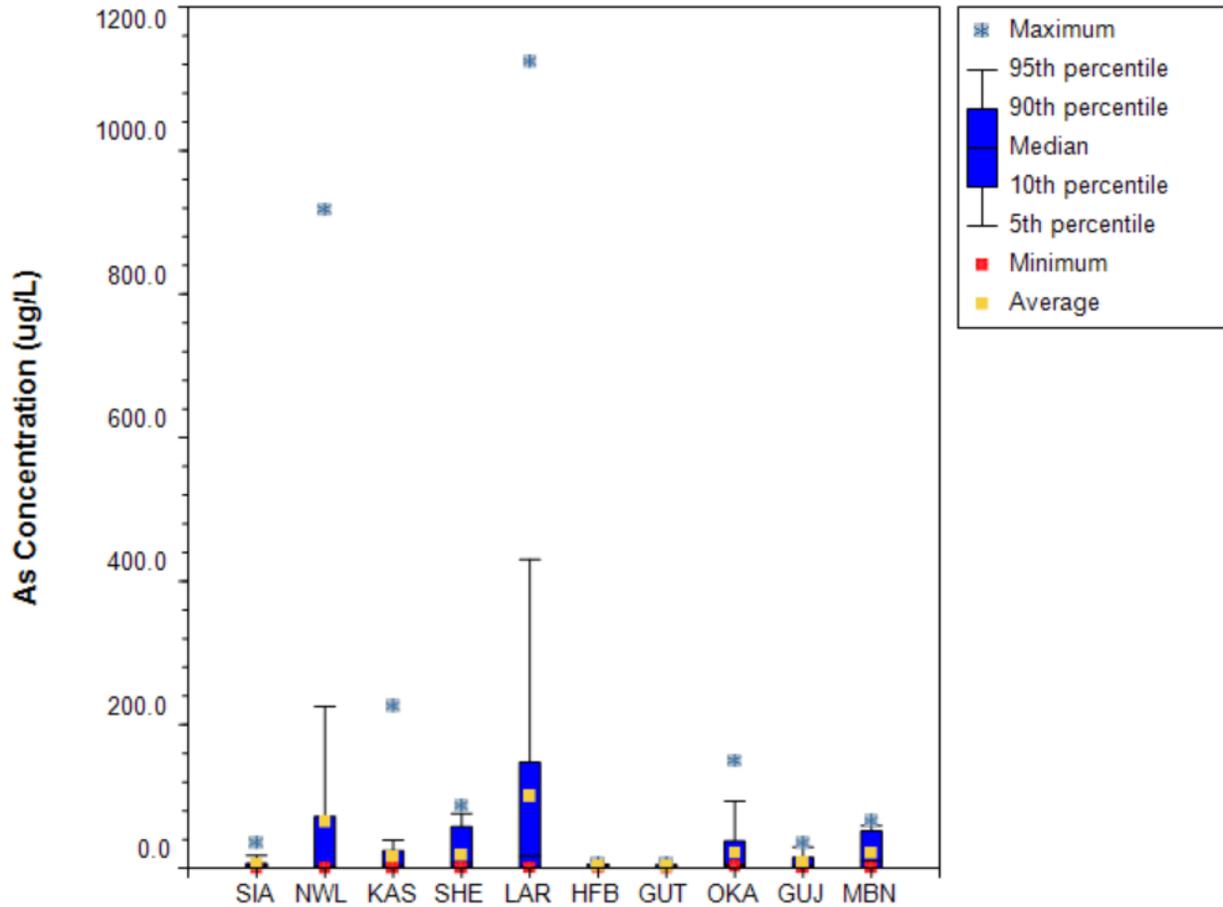


Figure 21: Descriptive statistics of Arsenic in Groundwater of the Rice Growing Region

A comparison of arsenic distribution in groundwater of these districts with the WHO Drinking Water Guideline for arsenic (10 µg/L), NDWQS drinking water standards (50 µg/L) and FAO permissible limit of arsenic in irrigation water (100 µg/L) has concluded that 51 sources were identified with the arsenic level exceeding the WHO drinking water guideline and out of these 13 were found exceeding the limit of 50 µg/L and 06 samples were found beyond 100 µg/L (Figure 22). Pakistan needs to establish the arsenic standards for its irrigation water quality.

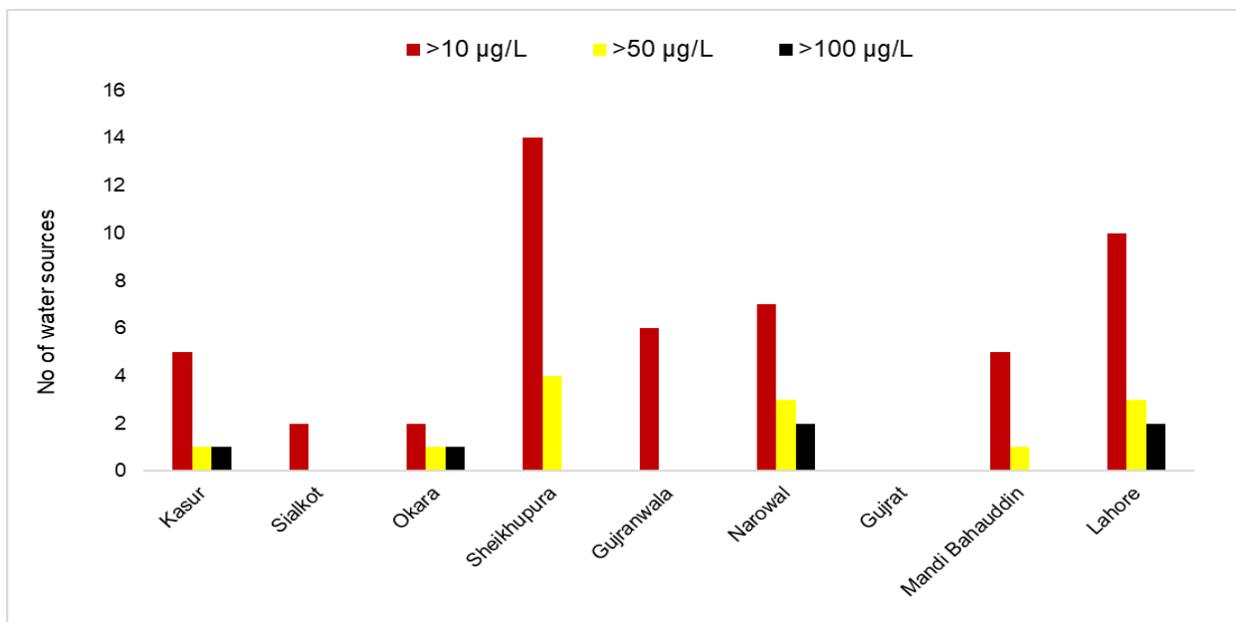


Figure 22: Water sources in rice growing areas with arsenic above WHO Drinking Water Guideline for arsenic ($10 \mu\text{g/L}$), NDWQS drinking water standard for arsenic ($50 \mu\text{g/L}$) and FAO permissible Limit of Irrigation Water for arsenic ($100 \mu\text{g/L}$)

The samples of rice and groundwater in this study were treated as two independent variables mainly due to random sampling and hence; cannot be directly associated to each other. Linkage between arsenic in different rice varieties and its uptake from soil and irrigation water need a well-designed study in different rice growing areas of the country.

The distribution and levels of arsenic in the investigated rice varieties does not seem to be a risk. However, to avoid the future risks related to health impacts on the local or international communities and its impact on rice export in international market, there is need to take appropriate steps, such as the development of new irrigation strategies, adoption of irrigation system modernization with due consideration of irrigation water quality, preference to surface water irrigation systems (as surface water is almost arsenic free), research on developing/introducing arsenic resistant rice varieties, continuous arsenic monitoring of irrigation water and rice grains.

Section-III: Exposure and Health Risk Analysis

4 Health Risk Assessment Need

The International Agency for Research on Cancer (IARC) has categorized arsenic as a “Group 1 Carcinogen,” meaning there is sufficient evidence of carcinogenicity in humans (International Agency for Research on Cancer, 2012). However, majority of epidemiologic studies focused on the carcinogenicity of arsenic have been limited to skin, urinary bladder, and lung cancers (Smith et al., 1992). Various scientific studies have reported that any arsenic exposure, no matter how small that is could boost risks for diabetes, heart disease, immunological problems and cancer (Navas-Acien et al., 2008). The diseases caused by chronic arsenic ingestion are called arsenicosis and develop when arsenic contaminated water is consumed for years. The progression of skin disease in response to As exposure is shown in Figure 23.

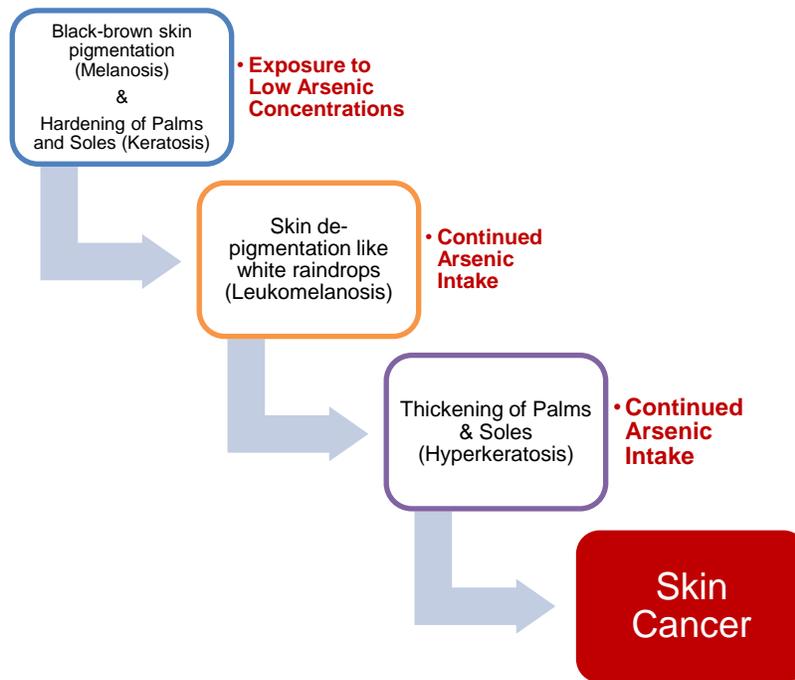


Figure 23: Development of skin disease in response to Arsenic exposure

Long-term ingestion of arsenic in water may also lead to problems with kidney and liver function (Shrivastava, 2016). Nachman et al (2013) revealed that urinary arsenic concentrations reflecting low and moderate drinking water exposures were associated with lung, prostate and pancreatic cancer, as well as with cardiovascular disease, among Native Americans living in Arizona, Oklahoma, and the Dakotas (Mateen et al., 2017, Saint-Jacques et al., 2018). Following these scientific evidence, an exposure and risk assessment in the present study is carried out for our dataset exceeding WHO provisional drinking water guideline value of 10 µg/L to predict the health challenges

with prolonged arsenic exposure. In this context, the principal factors that have been taken into account have been presented earlier in Table 2.

4.1 Results of Probability distributions for input variables

Body weight and age of Pakistani population were described as probability density functions in @RISK (Version 7.5, Palisade Corp. USA) to identify the most appropriate probabilistic density functions based on Akaike information criterion (AIC), whilst other variables were kept as constant (Table 2). Arsenic concentration levels of Sindh, Punjab and overall data were best represented by the Pareto distribution (Annexure I). Inter-dependency between a range of age and body weight of Pakistani population (Hifza et al., 2018) was done by copula fitting as given in Figure 24.

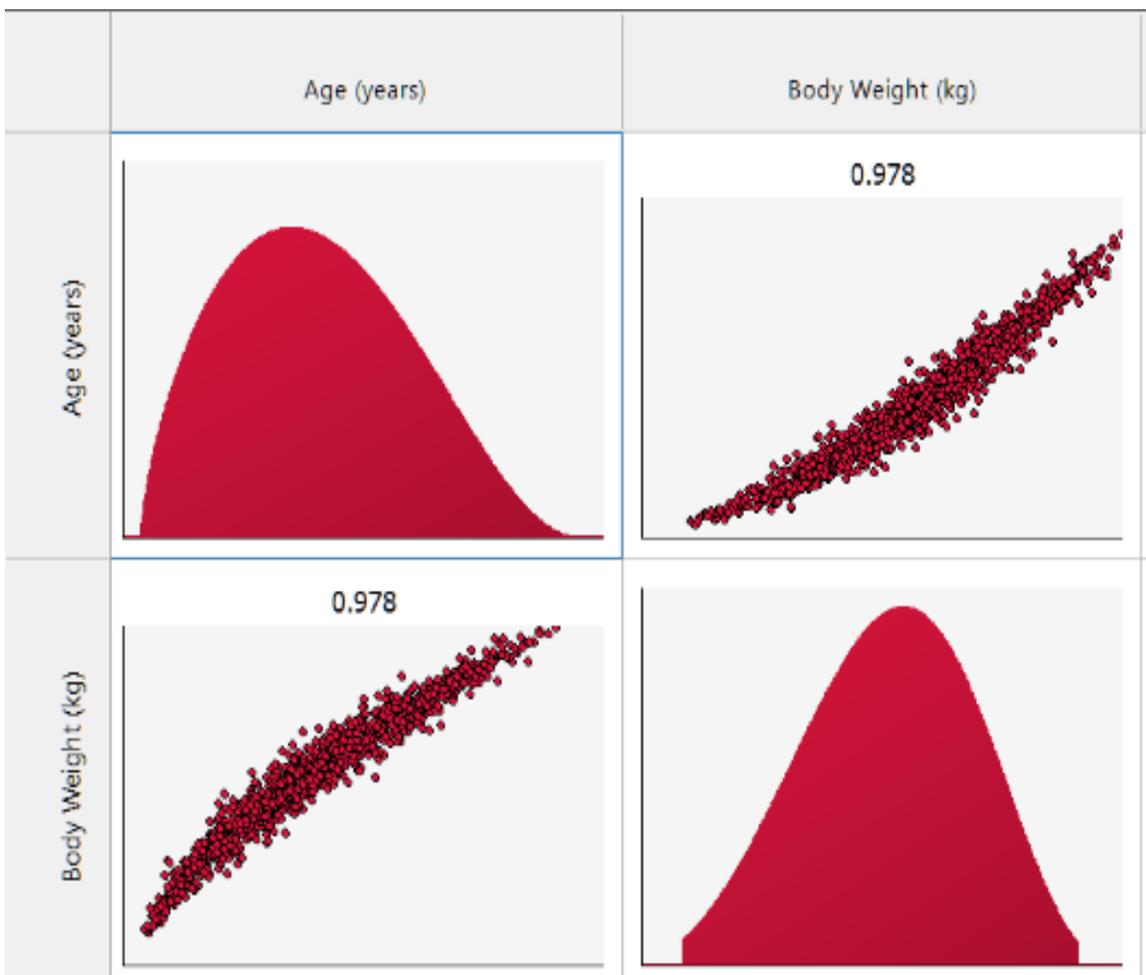


Figure 24: Copula (Elliptical t-type) output for modelling dependence of age and body weight of a Pakistani population

4.2 Exposure and Risk in Punjab

Exposure Level: The probabilistic mean daily intake of total arsenic as an average daily dose (ADD) for population with arsenic exposure above 10 µg/L is estimated to be 0.002 ± 0.003 mg/kg/day. The ADD values were compared with the WHO provisional tolerable daily intake (PTDI) of 0.0021 mg/kg/day body weight (WHO, 2010). Consumption of water with a total inorganic arsenic level above the WHO value (10 µg/L) indicated a total daily intake for total arsenic equivalent to the PTDI of 0.0021 mg/kg/day body weight in Punjab. However, at a concentration level of above 50 µg/L, the ADD exceeded up to the maximum level of 0.088 mg/kg/day. Probabilistic estimates of ADD (95th percentiles) for Population of Punjab was estimated to be 0.006 mg/kg/day (Figure 25).

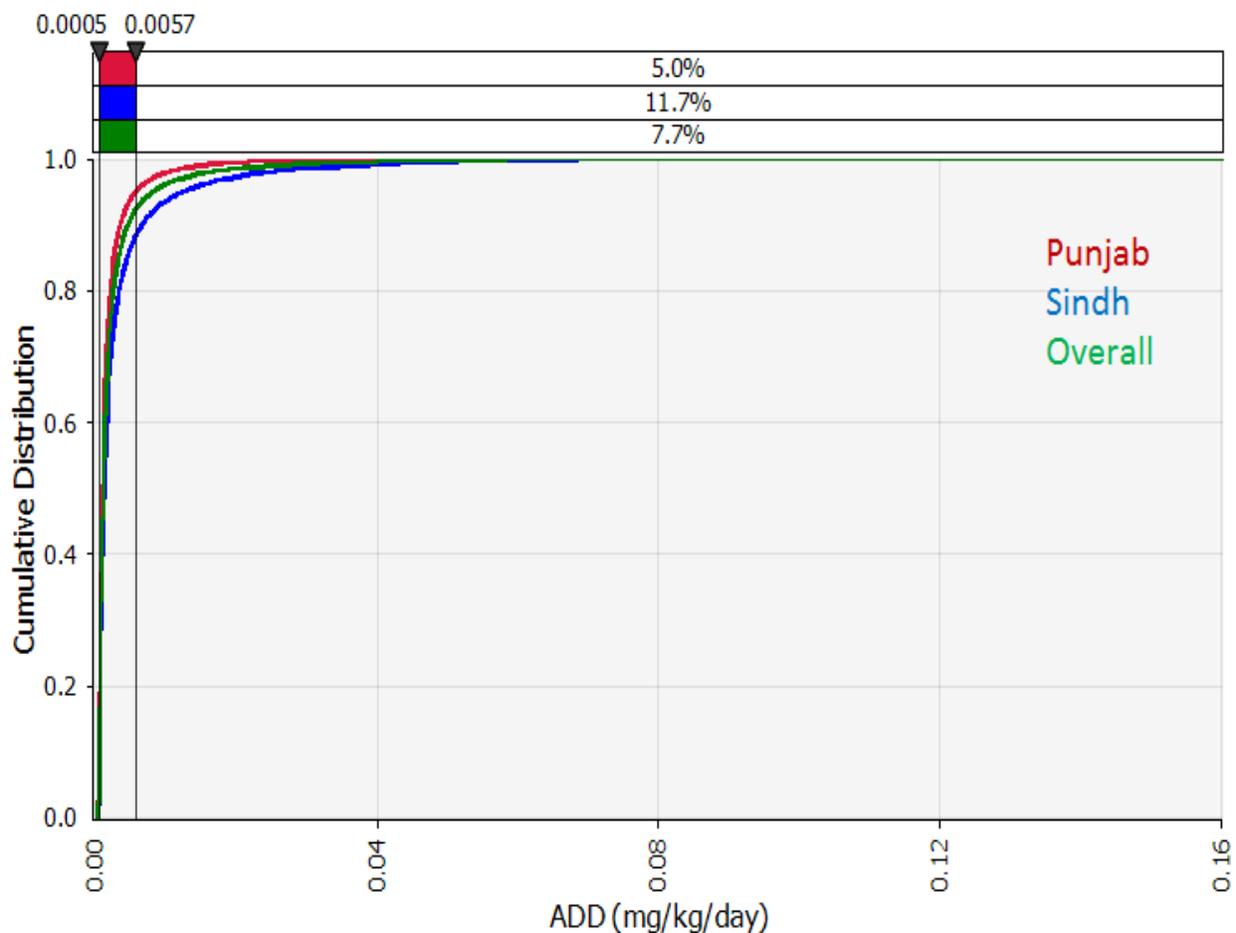


Figure 25: 95th percentile of average daily dose (ADD) of Arsenic in Punjab, Sindh and overall

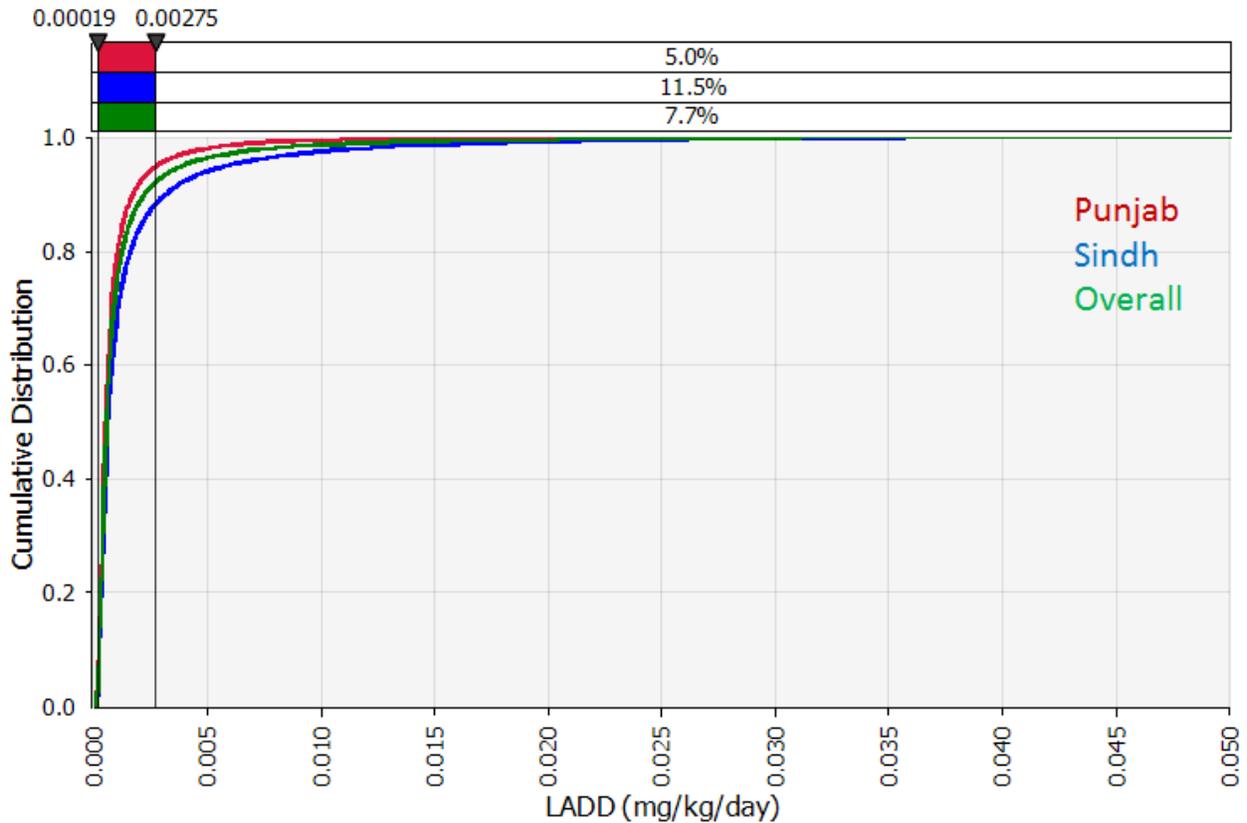


Figure 26: 95th percentile of Lifetime Average Daily Dose (LADD) of Arsenic in Punjab, Sindh and Overall

With Pakistan’s life expectancy of 67 years (The World Bank, 2020), the mean and maximum Life Time Average Daily Dose (LADD) in Punjab was estimated to be 0.001 mg/kg/day and 0.033 mg/kg/day respectively (Figure 26, Table 11).

Table 11: Probabilistic estimates of lifetime exposure and risk of skin cancer and non-cancer skin lesions (as hazard quotients, HQ) due to As intake in Punjab

Name	As (µg/L) - Punjab	ADD (mg/kg/day) Punjab	LADD (mg/kg/day) Punjab	Cancer Risk (CR) Punjab	HQ Punjab skin lesions as the point of departure
Minimum	10.000	0.000	0.000	0.000	0.885
Maximum	2460.01	0.088	0.033	0.071	291.967
Mean	28.499	0.002	0.001	0.002	6.281
SD	38.447	0.003	0.001	0.002	9.177
5 th Percentile	10.383	0.001	0.000	0.000	1.798
50 th Percentile	16.595	0.001	0.001	0.001	3.621

Name	As ($\mu\text{g/L}$) - Punjab	ADD (mg/kg/day) Punjab	LADD (mg/kg/day) Punjab	Cancer Risk (CR) Punjab	HQ Punjab skin lesions as the point of departure
75 th Percentile	27.431	0.002	0.001	0.002	6.171
90 th Percentile	52.629	0.004	0.002	0.003	11.888
95 th Percentile	84.477	0.006	0.003	0.005	19.096

Health Risk Estimates: Probabilistic estimates of ADD of As from water in the studied area resulted in a simulated mean HQ (non-cancer risk) of 6.281 ± 9.177 (Table 11). If the HQ is equal to or <1 , human health effect is assumed to be negligible, while a HQ >1 suggests that there may be health concerns (USEPA, 2011).

A 5th to 95th percentiles of probabilistic HQ in Punjab indicate levels above the value of 1 and points out the possibility of various non-cancer health implications such as kidney and liver diseases (Figure 27). Fatoki et al. (2013) have indicated that arsenic may attack internal organs without causing any visible external symptoms, making arsenic poisoning difficult to recognize.

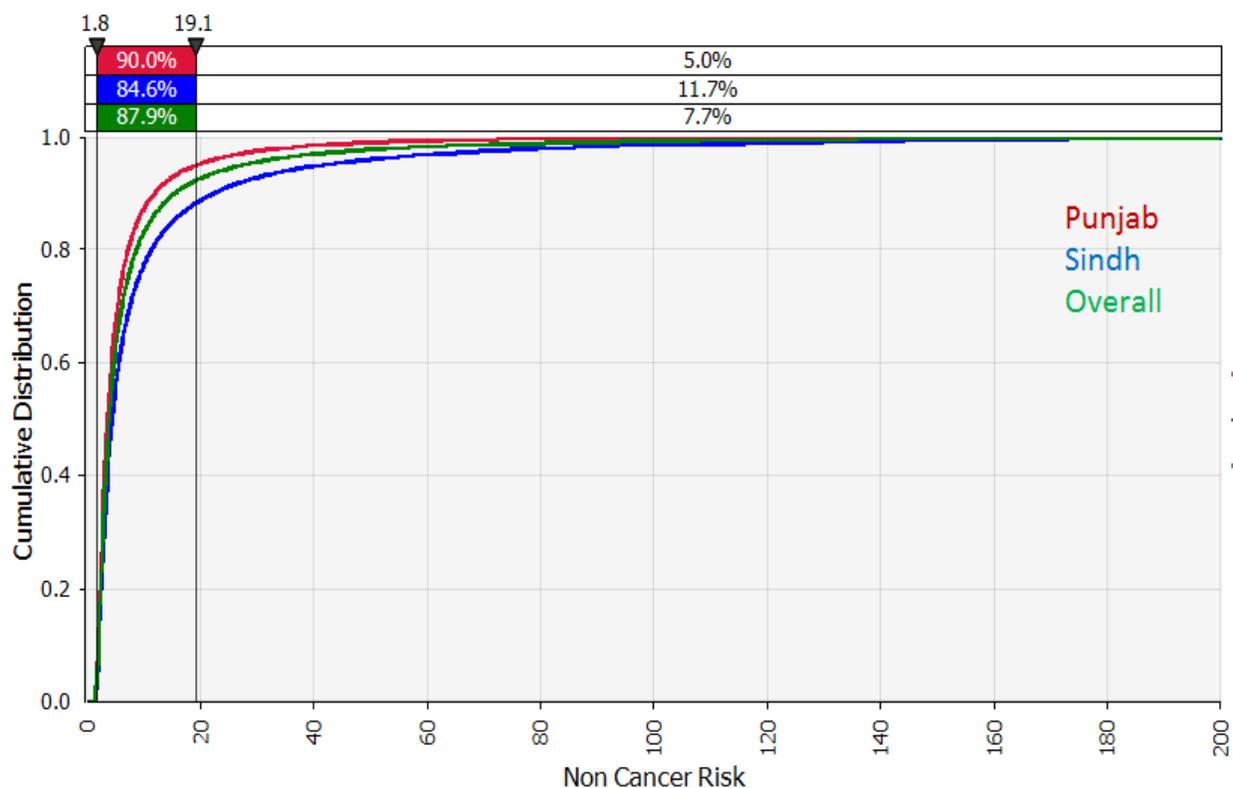


Figure 27: 95th percentile of cumulative probability distributions of As induced lifetime non-cancer risk (HQ) in Punjab, Sindh and Overall

Probabilistic estimates of total daily intake of As from water resulted in a simulated mean skin cancer risk of 0.002 (20 persons in every 10,000 persons) in Punjab as given in Table 11. A 95th percentiles of the intake from arsenic sources (Figure 28) shows estimated cancer risk of 0.005 (50 persons in 10,000 population). Nevertheless, all of these estimates are above the USEPA acceptable cancer risk criteria of 1×10^{-6} to 1×10^{-4} (1 in 1,000,000 to 1 in 10,000).

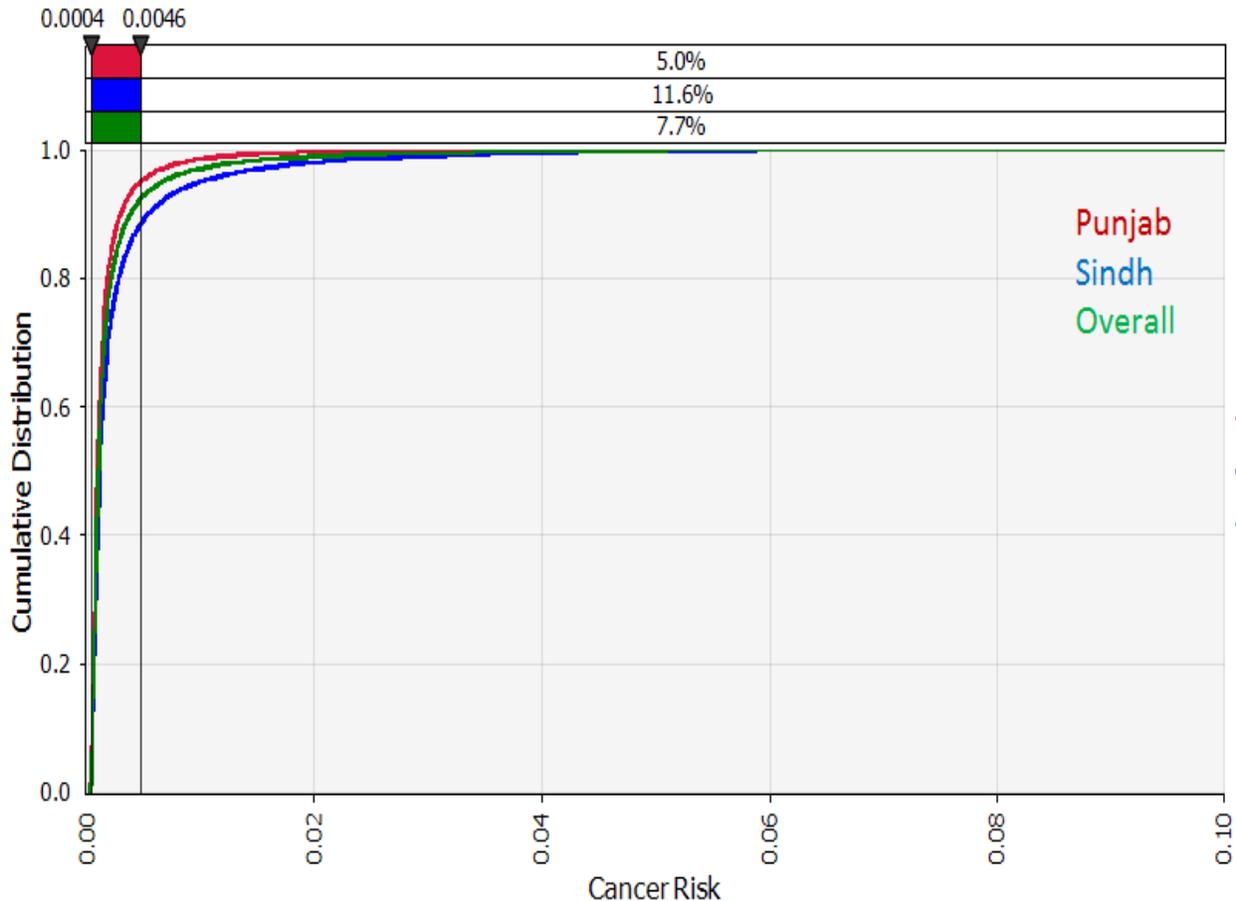


Figure 28: 95th percentile of As induced excess lifetime cancer risk in Punjab, Sindh and Overall

4.3 Exposure and Risk in Sindh

Exposure Level: The mean daily intake of total arsenic as an average daily dose (ADD) for population with arsenic exposure above 10 $\mu\text{g/L}$ is estimated to be 0.003 ± 0.007 mg/kg/day. Comparing ADD value with the PTDI of 0.0021 mg/kg/day body weight (WHO, 2010) shows an exceedance for mean ADD outcome (Figure 25, Table 11).

For Pakistan's life expectancy of 67 years, the mean and maximum Life Time Average Daily Dose (LADD) was estimated to be 0.002 mg/kg/day and 0.062 mg/kg/day respectively (Table 11).

Health Risk Estimates: Probabilistic estimates of total daily intake of As from water in Sindh resulted in a simulated HQ (non-cancer risk) of 10.889 ± 21.721 (Table 12). Comparing with the USEPA limit of HQ reveals that 5th to 95th percentiles of HQ in the study area (Figure 134) showed risk levels above 1 which warns about possibility of various non-cancer health implications such as problems related to skin, digestion, kidney, liver etc.

Probabilistic estimates of total daily intake of As from water resulted in a simulated mean skin cancer risk of 0.003 (30 persons in every 1000 persons and maximum up to 0.125 i. e 1250 persons in 10,000 population) as given in Table 12. A 5th to 95th percentile of the probabilistic cancer risk ranges up to 0.010 (up to 100 persons in 10,000 population) as shown in Figure 28.

Table 12: Probabilistic estimates of lifetime exposure and risk of skin cancer and non-cancer skin lesions (as hazard quotients, HQ) due to As intake in Sindh

Name	As ($\mu\text{g/L}$)	ADD (mg/kg/day)	LADD (mg/kg/day)	Cancer Risk (CR)	HQ
Minimum	10.000	0.000	0.000	0.000	0.801
Maximum	971.572	0.142	0.062	0.125	473.272
Mean	49.441	0.003	0.002	0.003	10.889
Std Deviation	92.954	0.007	0.003	0.005	21.721
5% Perc	10.547	0.001	0.000	0.000	1.878
50% Perc	20.453	0.001	0.001	0.001	4.458
75% Perc	41.293	0.003	0.001	0.002	9.096
90% Perc	100.366	0.007	0.003	0.005	22.222
95% Perc	185.452	0.012	0.006	0.010	40.786

Overall Exposure and Risk (Age & Projected Population at Risk)

Since the overall cancer risk in Sindh and Punjab (Table 13) was found to be above the USEPA (2001) acceptable cancer risk range of 1×10^{-6} to 1×10^{-4} (1 in 1,000,000 to 1 in 10,000) and if arsenic exposure from water used for drinking and food preparation remained un-addressed, this would pose increased risk to the native population.

Table 13: Overall Probabilistic estimates of lifetime exposure and risk of skin cancer and non-cancer skin lesions (as hazard quotients, HQ) due to As intake

Name	As (µg/L)- Overall	ADD (mg/kg/day) Overall	LADD (mg/kg/day) Overall	Cancer Risk Combined	HQ Overall
Minimum	0.05	0.00	0.00	0.00	0.03
Maximum	968.20	0.12	0.05	0.08	402.86
Mean	8.30	0.00	0.00	0.00	1.83
Std Deviation	38.03	0.00	0.00	0.00	8.89

This will also help us determine lifetime risks based on exposure beginning very early compared with those that begin later in life. Following this, the probabilistic cancer risks for an exposure duration of 3 to 67 years (min age 3 to Pakistan's life expectancy of 67 years) was found to be above acceptable US EPA cancer risk criteria of 1.0×10^{-4} (1 case of cancer per every 10,000) (Figure 29). An early life As exposure showed 26 chances in a population of 10,000 children of age 3 -16 years and if these children remained on prolonged arsenic exposure; there is cancer risk probability (in later age) of 19 adults in a population of 10,000 (Figure 29).

The age adjusted risk models revealed higher lifetime cancer (Punjab: 20 children, Sindh: 34 children in a population of 10,000) and non-cancer risk with $HQ > 1$ for children (Figures 29 & 30). These findings also suggest that higher childhood exposure to As may result in increased cancer risk in adulthood. Children being more sensitive to toxic elements and identified at higher exposure levels were also expected to be vulnerable to low dose exposure (Rasheed et al. 2017) as also proved in this case (Figures 29 & 30). Studies have also shown that there is a strong connection between arsenic exposure and infant mortality (Rahman et al., 2018). Numerous studies have demonstrated negative impacts of arsenic exposure on cognitive development, intelligence, and memory (Tolins et al., 2014).

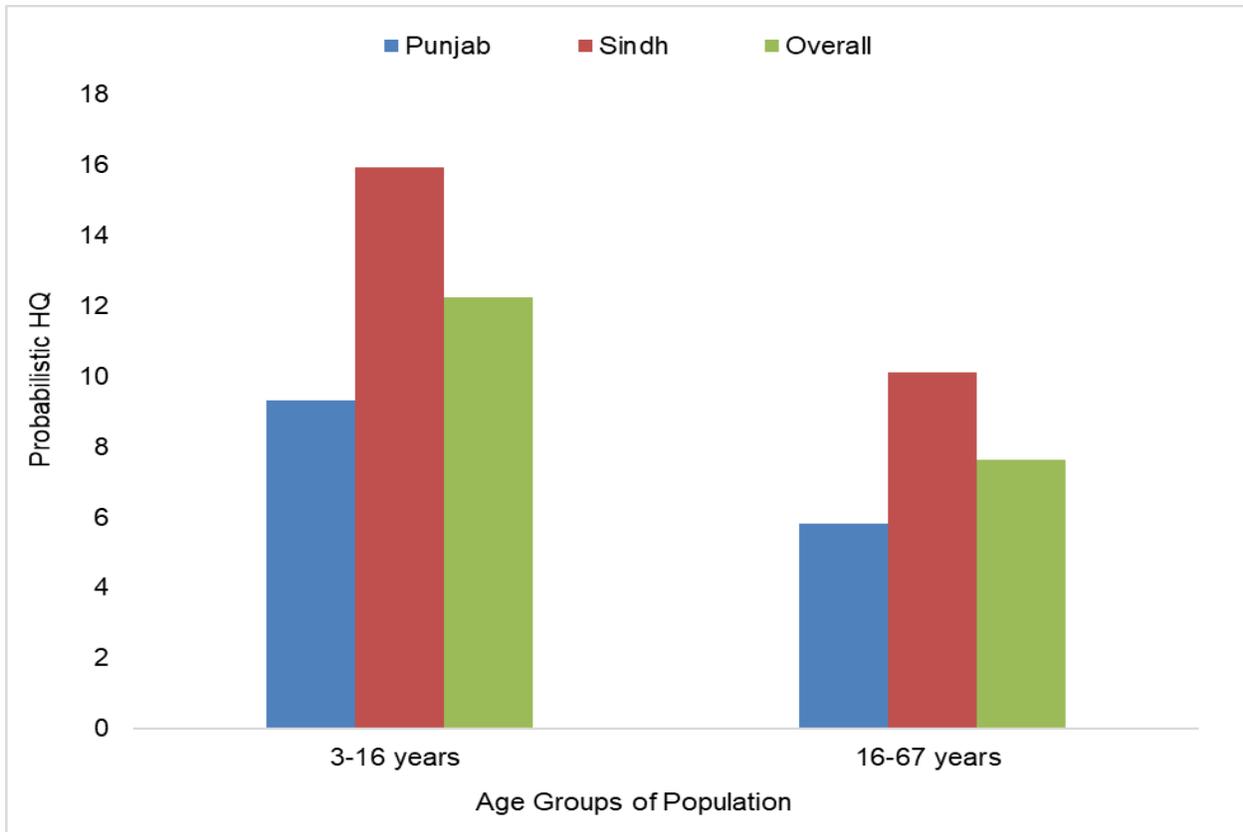


Figure 29: Age adjusted arsenic induced non-cancer risk in Punjab, Sindh and Overall

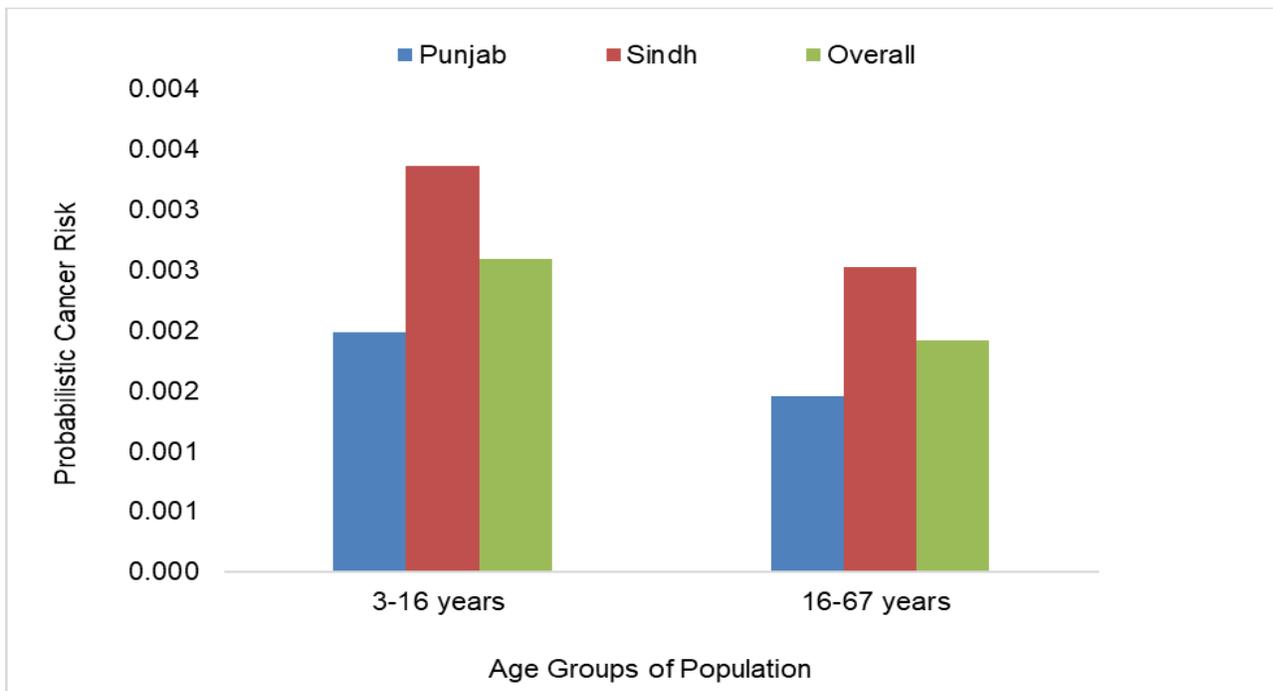


Figure 30: Age adjusted As induced lifetime age adjusted cancer risk in Punjab, Sindh and Overall

Prevalence of arsenic induced health implications (skin problems) as reflected in Figures 31 and 32 make us to believe that the simulated non-cancer risks is a reality and if not taken seriously by undertaking remedial actions may result in carcinogenic implications with prolonged arsenic exposure.



Figure 31: Arsenic induced health problems prevailing in arsenic affected districts of Punjab and Sindh



Figure 32: Arsenic induced health problems prevailing in arsenic affected districts of Punjab and Sindh

Arsenic exposure with influence of other factors such as nutritional inadequacy, genetic polymorphisms, second-hand smoke and above all the limited access to advance health care facilities may exert synergistic effect. This have been reported to enhance the arsenic induced disease progression (Hifza et al., 2016).

Groundwater arsenic contamination and earlier described risk estimates demand the risk management initiatives such as establishing the Public Health Goals (PHG) for arsenic in public and private water sources and compliance to the public health standards for arsenic. Similar to water, setting the food safety limits and strict monitoring, and establishing the consumption allowance of high impact food should also be set and enforced. Based on the current study results, current exposure to arsenic via water used for drinking/cooking through use of shallow domestic hand pumps or dug wells, crop irrigation with arsenic contaminated tube well water or possible application of arsenical pesticides are some of the important concerns requiring attention specifically in the rural settings of Punjab and Sindh.

Further, the findings of the current study show the presence of arsenic along the Indus river and it is presumed that population in such areas is on higher exposure of arsenic through groundwater used for drinking and food preparation. Altogether 7,025 of the total monitored groundwater sources (n = 45,920) of all districts of Sindh and Punjab were found to be arsenic contaminated. Projecting the overall percent As contamination on the total Pakistani population of 229 million revealed that:

- a. An overall 13% of arsenic contamination above 10 µg/L poses risk on 9% of Pakistani population (15 million in Punjab and 5 million in Sindh) (Figure 33).
- b. An overall 3% arsenic contamination above 50 µg/L poses risk on 2% of Pakistani population (2 million in Punjab and 2 million in Sindh) (Figure 33).
- c. The combined population of Punjab and Sindh (153 million) projected to indicate that 20 million (13%) is at risk above 10 µg/L, while comparing with 50 µg/L revealed 5 million (3%) at risk of arsenic exposure and thus of developing cancer and non-cancer health problems (Figure 33).

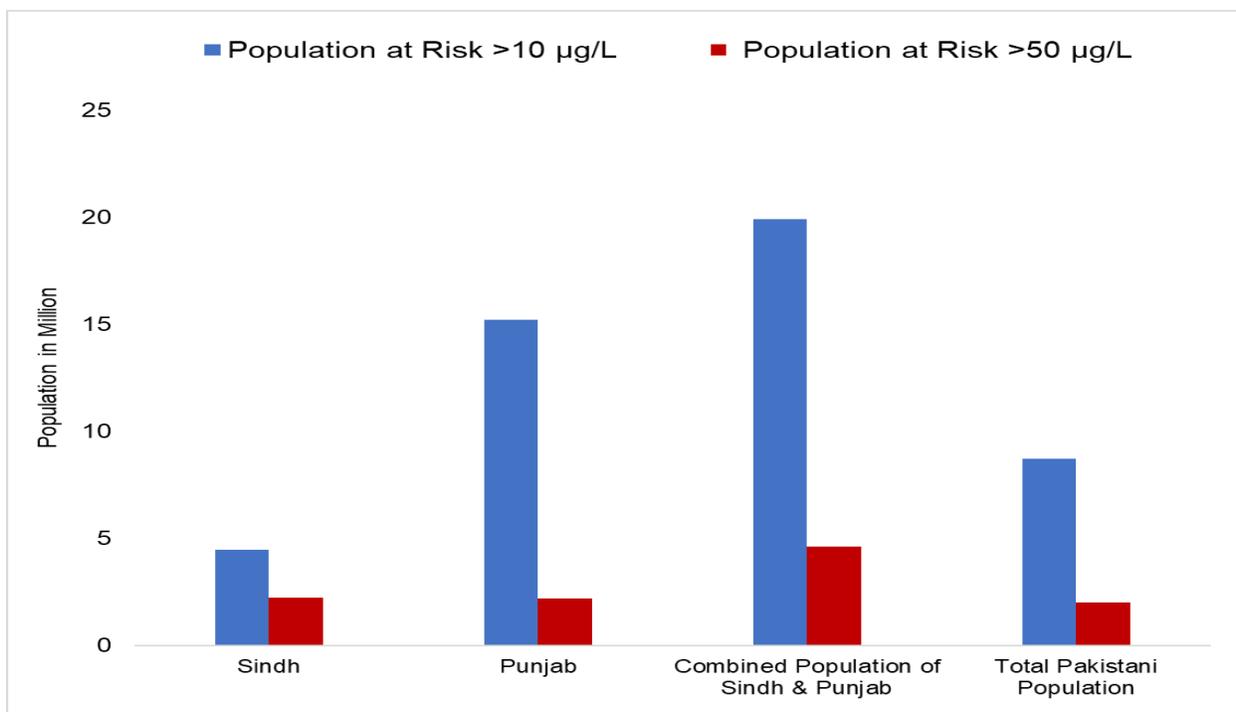


Figure 33: Population at risk of Groundwater Arsenic exposure

According to Global Cancer Observatory of IARC (2020), the prevalent cases of cancer based on 5 years data were 329,547 in Pakistan. IARC has also reported 178,388 new cases in Pakistan in 2020. Likewise, number of registered cancer patients have increased in 2021 than previous years (Figure 34). In addition to various other causes of cancer, exposure to chemicals including arsenic may also be one of the major risk factors. Arsenic exposure and its possible contribution in increased cancer rates in Pakistan and other arsenic affected countries cannot be ignored and required to be scientifically elucidated.

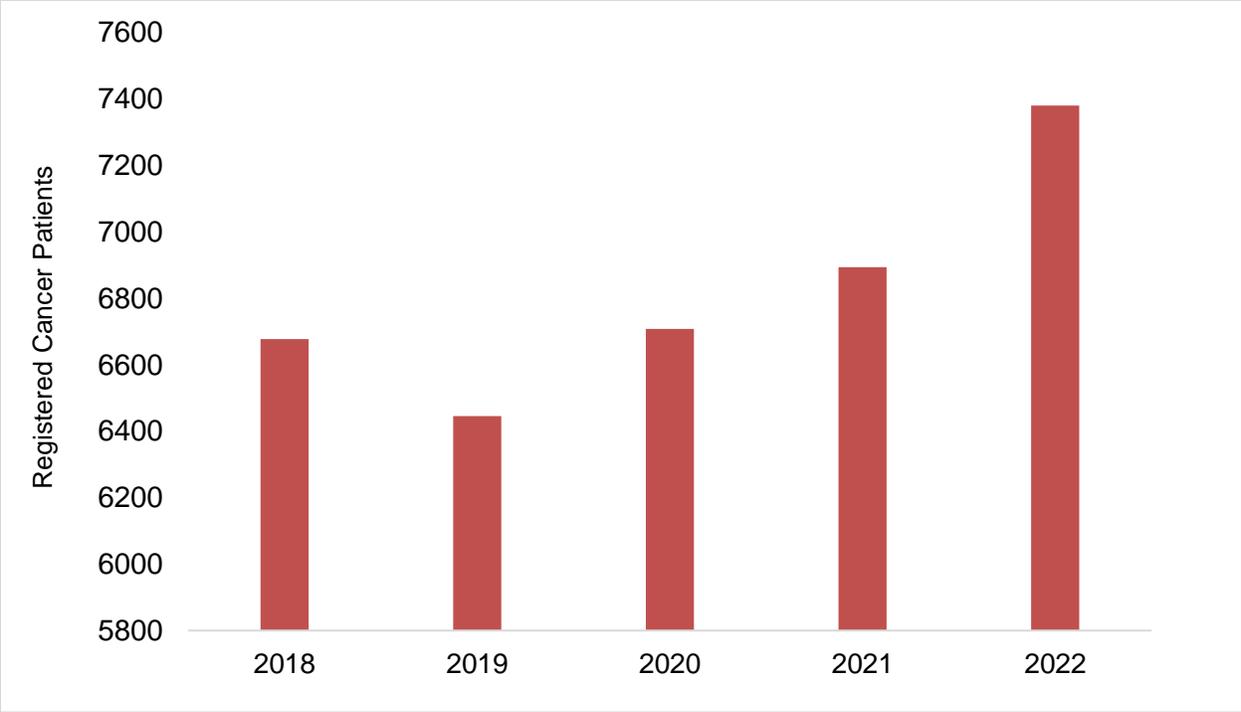


Figure 34: No. of registered cancer patients (2018-2022)

Date source: Shaukat Khanum cancer registry data (Different cancers such as Prostate, stomach, Esophagus, Colon, rectum, anal canal, and anus, Liver and bile duct, Lip and Oral Cavity, Urinary Bladder, Trachea and lungs and Skin)

5 Conclusions

This report provided an overview of the arsenic contamination in water supplies of Pakistan followed by the risk assessment. Arsenic contamination of groundwater and its devastating impact on human health seems to be one of a biggest water-related challenges.

- a. Arsenic is an emerging serious issue mainly in two provinces Punjab and Sindh where about 2% and 5% of water sources are found contaminated over 50 µg/L. The percentage of water sources contaminated above WHO level of 10 µg/L is 14% and 10%, respectively in Punjab and Sindh. The DI Khan district of KP showed 44% and 2% water sources exceeding the limits of 10 µg/L and 50 µg/L, respectively. Altogether, 13% of 45,920 water sources exceeded the WHO guideline value of As 10 µg/L and 3% beyond the Pakistan's limit of 50 µg/L. The data showed a non-uniform pattern of geogenic arsenic distribution and indicated that both the shallow and deep water sources were found to be contaminated and therefore, testing of every water sources is essential.
- b. Arsenic contamination is predominant in the Indus plain. All those districts identified as high in arsenic contamination (Multan, Bahawalpur, Rahim Yar Khan in Punjab , and Khairpur, and Dadu in Sindh) are lying in alluvial deposits along the Indus river. Interestingly, within a given district, areas lying closer to river Indus were found to have relatively higher arsenic concentration than those away from the river. All these field based evidence suggest that the process of arsenic release from alluvial deposits lying near to Indus river is faster than those lying away from the river zone. However, a well designed and detailed scientific investigation needs to be done to get more insight in every district affected with arsenic.
- c. Pakistan's rice varieties had As in the range of 0.084 to 0.356 mg/kg with no samples exceeding the WHO recommended permissible limit of 1.00 mg/kg for arsenic, whereas; 12 samples were found beyond the revised Maximum Limit (ML) of 0.2 mg/Kg. The distribution and levels of arsenic in the investigated rice varieties does not seem to be a risk.
- d. Risk assessment of groundwater used for drinking and food preparation has also revealed the higher level of arsenic exposure, cancer and non-cancer health risks for all age groups. The 95th percentile of HQ exceeded 1 and CR was above the safe value of threshold value of 10^{-4} .The CR estimation results implies that groundwater use for drinking and food preparation purpose places people at risk of As exposure. The simulated results also show coincidence with higher As levels in human biomarkers of As affected districts of Punjab and Sindh.

- e. About 9% of 229 million population of Pakistan (15 million in Punjab and 5 million in Sindh) is projected to be living with As exposure. This is a serious concern especially from child health stand point and its mitigation requires a national program uniformly implementable up to the village level. Moreover, the increasing cases of different cancers in Pakistan need to be studied under the influence of As exposure.

6 The Way Forward

Arsenic mitigation without any government policy lacks directions and vision. Policy initiatives to mitigate the groundwater arsenic contamination are required to be implemented in a systematic way. To achieve these, following recommendations are suggested to reduce arsenic exposure from drinking water and food in areas with a high level of arsenic:

1. **National Arsenic Monitoring and Surveillance Program** may be designed, launched and implemented. The success of such a wide-scale program would depend primarily upon planning at national, provincial, district and local level both in urban and rural areas with the involvement of all stakeholders. The proposed components of the program may be:
 - a. **Alternate water sources:** Arrangements for alternate safe water sources in the arsenic affected areas should be made. Moreover use of rainwater harvesting should be considered after assurance that preventative measures are in place to avoid microbial contamination and breeding of mosquitoes. Likewise, provision of surface water supply after proper treatment is also an option.
 - b. **Arsenic Removal Technologies:** Installation of domestic or centralized arsenic removal systems with implementation of effective O&M protocol and arrangements for appropriate disposal of arsenic waste.
 - c. **Identification of Arsenic contaminated groundwater sources:** A strong arsenic monitoring system should be established and maintained at the town and village level. This should be done by registering all water sources in the area and painting the status of whether the water source has been checked or not e.g. unpainted for unchecked, red for arsenic contaminated and green for safe. Based on this strategy, determine the areas of safe water for the people and in this process create more public awareness on this issue.
 - d. **Controlled groundwater abstraction:** This requires discouraging the installation of hand pumps and giving more focus on an increased access of piped water supply and household tap connections to ensure safe drinking water in rural areas. For the agriculture sector, combined usage of surface water and groundwater in arsenic affected areas should be considered to minimize the exposure of the crops to arsenic.
 - e. **Establishing arsenicosis patient registry:** Hospitals and basic health units should establish an Arsenicosis Patient Registry to enable early identification of such patients. This should be supported through a robust arsenicosis surveillance program managed by the local authorities. The district hospitals should have the required resources and expertise to manage arsenicosis patients in most affected. Capacity building of health department on case diagnosis and treatment of patients is also required.

- f. **Behavioral change communication and Schools awareness program:** School-based arsenic awareness program should be launched to keep children aware of arsenic issue and ensure that all required measures are disseminated to the future generation. In addition, development of communication support materials would also be helpful.
- g. **National Arsenic Portal** A national program may be developed for fast and effective sharing of vital data and information on arsenic with users/communities. It would build confidence making the mitigation measures successful.
- h. **Reconsideration of Safe Permissible limit:** Subject to the reported health issues at lower level of exposure, an in-depth risk evaluation study should be undertaken in the diversity of arsenic affected areas followed by consultation with stakeholders to reconsider the arsenic standard of National Drinking Water Quality Standards (NDWQS) of Pakistan (50 µg/L). Following this, compliance to the permissible limits set in the National Drinking Water Quality Standards (NDWQS) of Pakistan must be ensured by the Federal, Provincial and local water and rural supply agencies at source and at the consumer end.

In lieu of above, continuing actions are required to decrease arsenic exposure from natural geogenic sources as well as from anthropogenic activities. Institutional arrangement, coordination mechanism, and resource mobilization need to be made in Pakistan for ensuring sustainable and effective arsenic mitigation efforts.

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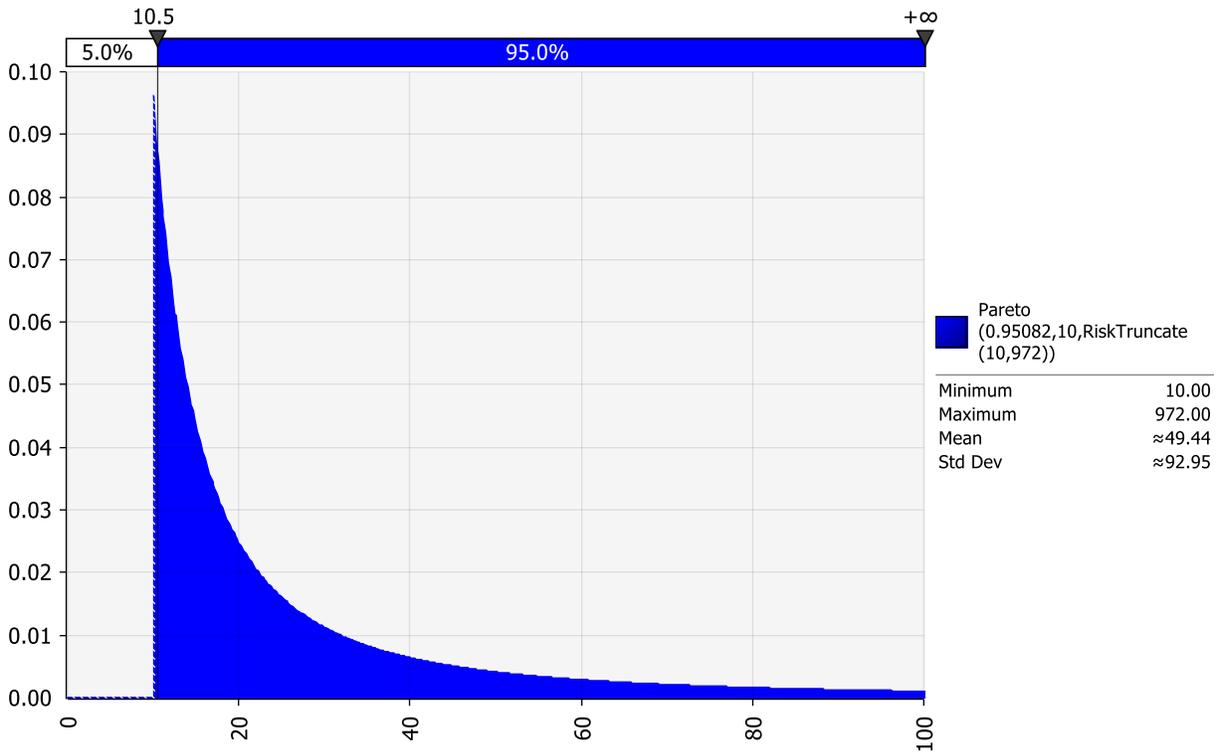
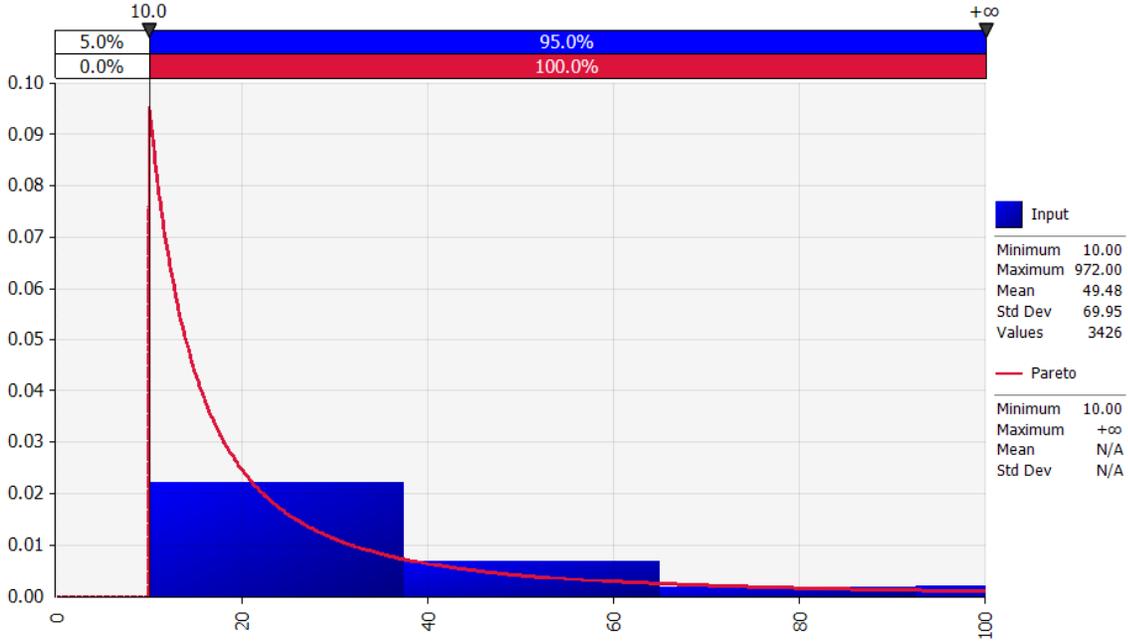
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Annexures

Annexure-I

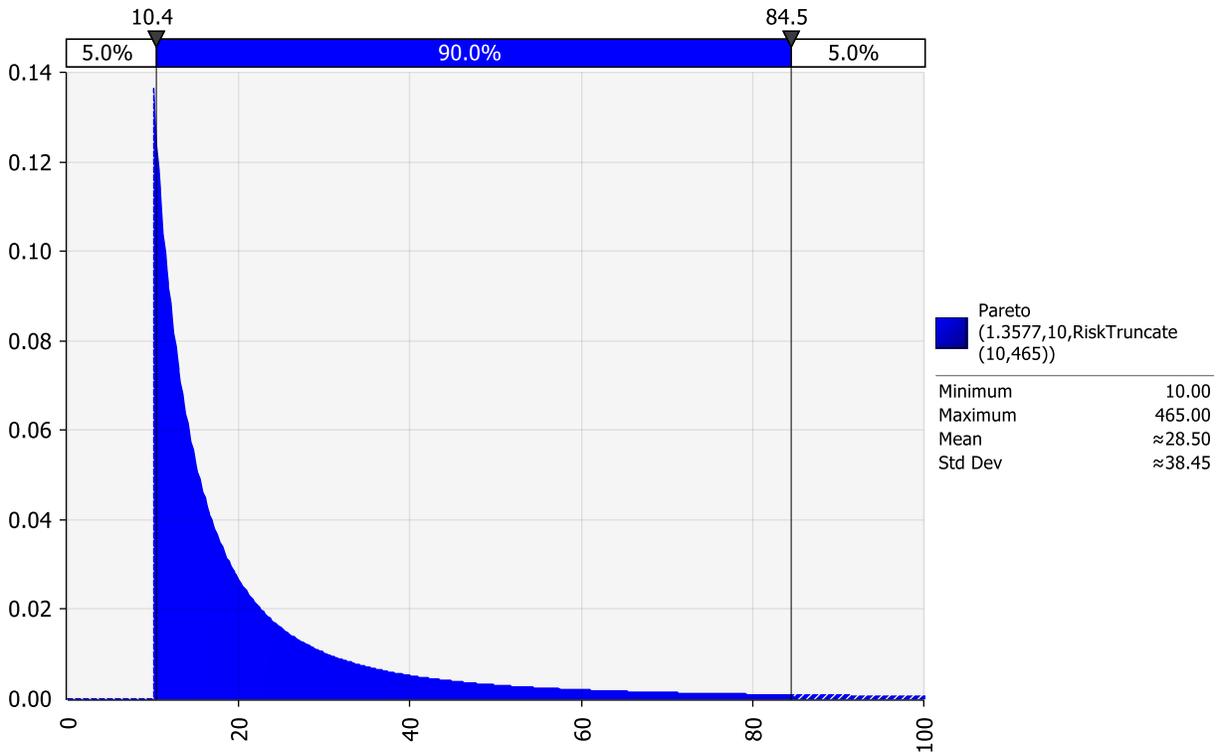
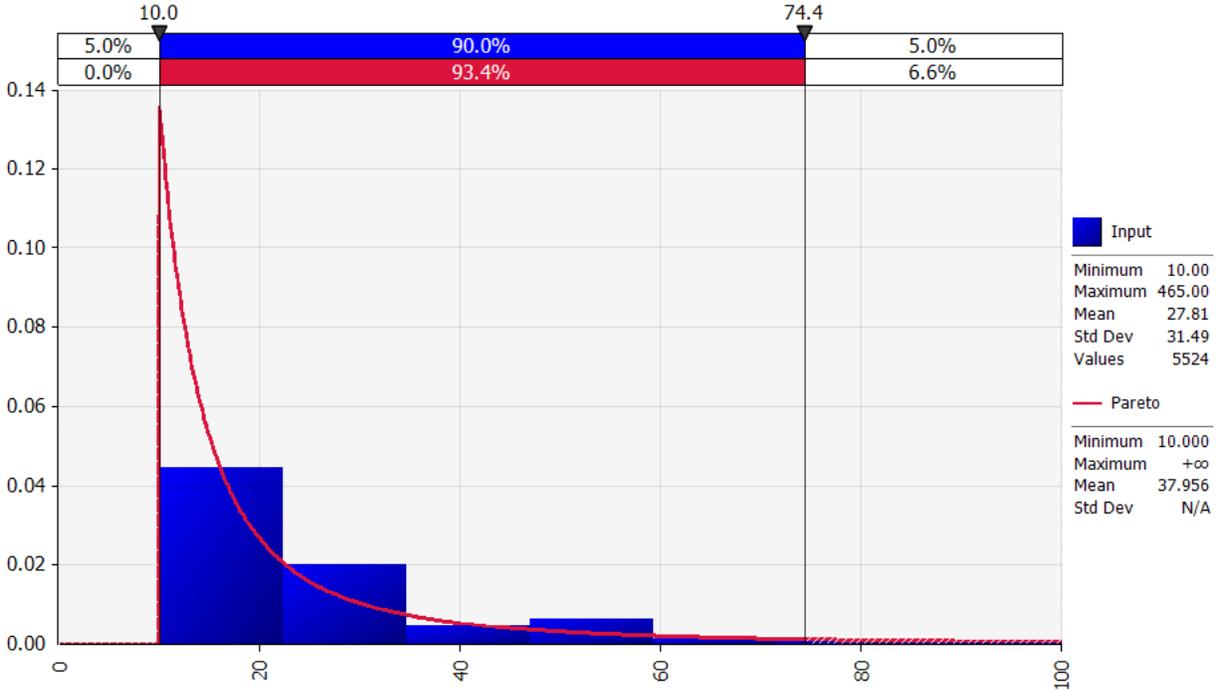
Fit Comparison for As (ug/L) - Sindh

RiskPareto(0.95082,10)

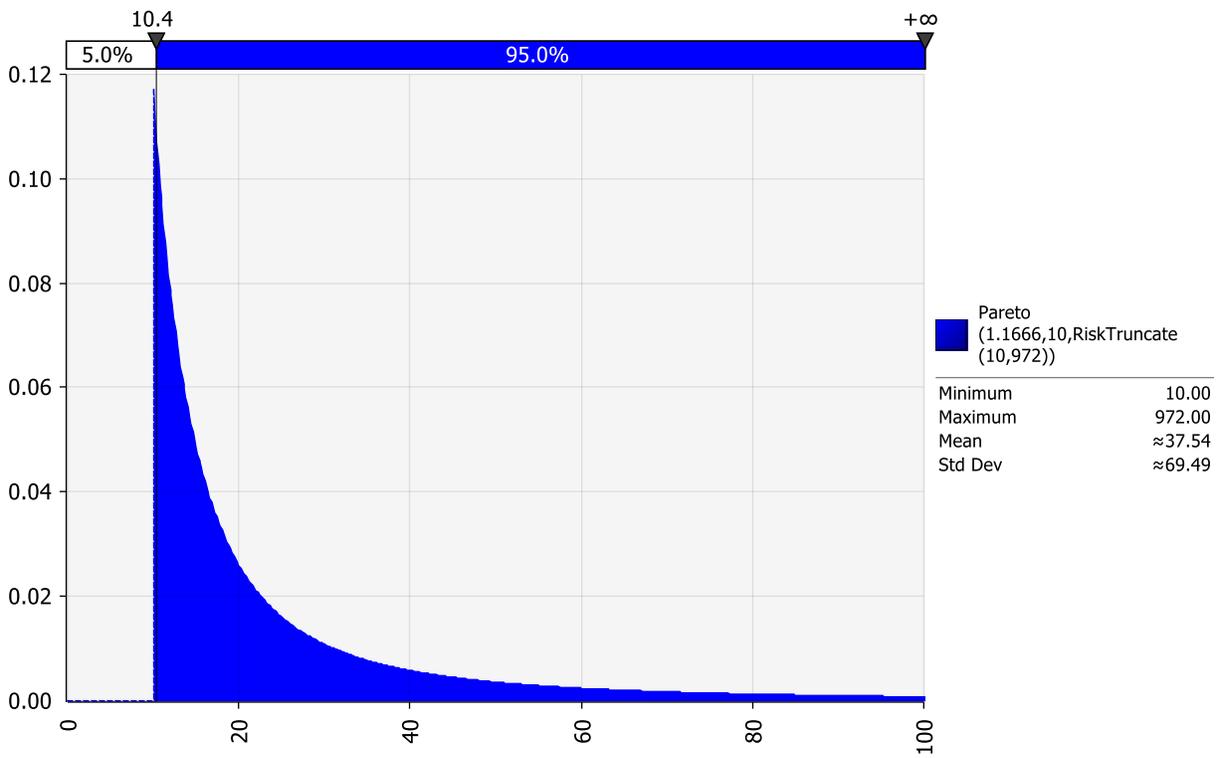
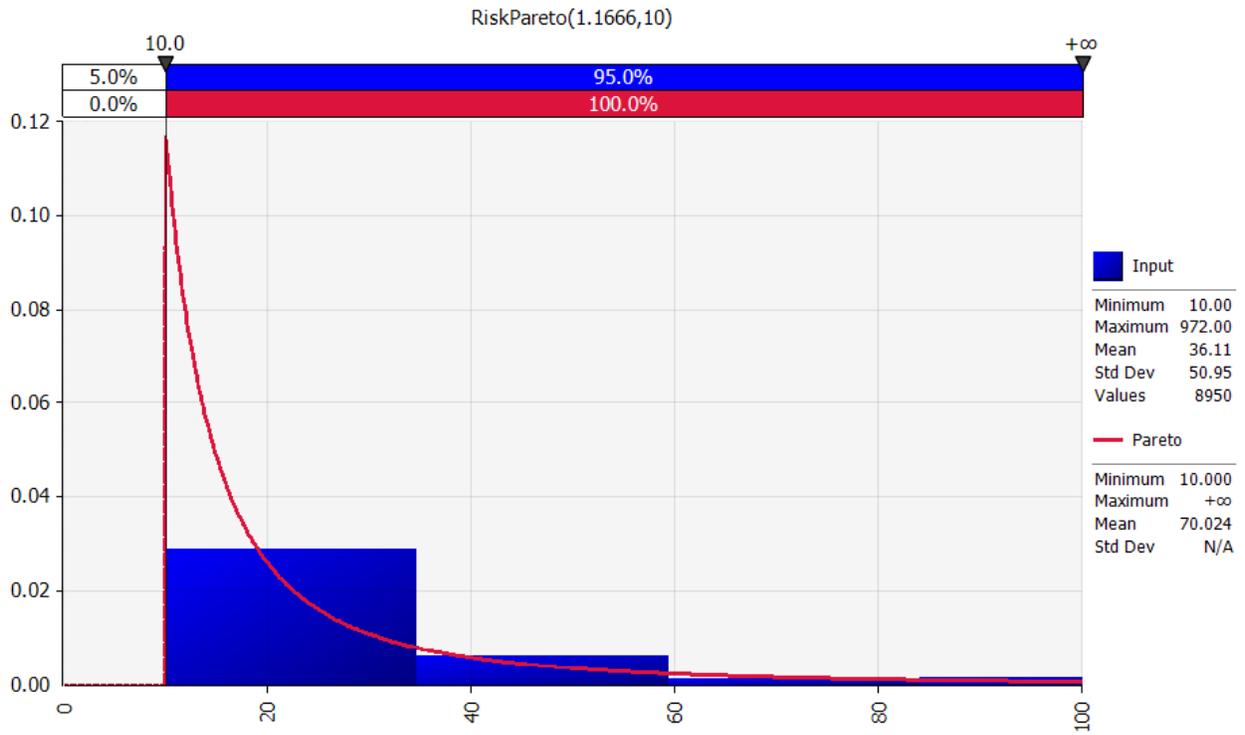


Fit Comparison for As (ug/L) - Punjab

RiskPareto(1.3577,10)



Fit Comparison for As (ug/L) - Overall



About PCRWR

PCRWR is an apex body of the Ministry of Water Resources and is mandated to conduct, organize, coordinate and promote research on all aspects of water resources including irrigation (surface and groundwater), drainage, soil reclamation, drinking water and wastewater. It has eight regional offices located at different agro-ecological zones and each centre conducts research on water-related issues of the respective zones. These Regional Offices are located at Lahore, Bahawalpur, Tandojam, Quetta, Peshawar, Karachi, Gilgit and Muzaffarabad. Besides these eight Regional Offices, PCRWR has a setup of 24 water quality testing and research laboratories in major cities of the country. This includes ISO-17025 accredited National Water Quality Laboratory having its own Laboratory Information Management System (LIMS). PCRWR has all types of infrastructure such as soil and water testing laboratories, groundwater assessment equipment, research farms to conduct and disseminate the research. It is the only organization in Pakistan that owns drainage type lysimeters in Lahore, Tandojam, Quetta and Peshawar. PCRWR has done considerable work on crop water requirements, tile drainage, soil reclamation, on-farm water management technologies, rainwater harvesting, artificial recharge, groundwater assessment and management, skimming wells, drinking water, and indigenous development of water testing and treatment tools, salinity and moisture sensors. To help in developing the capacity of in-service professionals and fresh graduates, PCRWR has also a well-equipped National Capacity Building Institute in Islamabad to provide short and long term trainings on all aspects of water.