

Investigation of Groundwater Contamination Due to Heavy Metals for Sustainable Development of Agriculture in Punjab State, India

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Abstract

Punjab, an intensive agricultural state, is currently experiencing a problem because of elevated levels of heavy metals and uranium (U) in its groundwater. It is commonly known that the groundwater in every district in Punjab's Malwa region has anomalous levels of uranium, with a U content that exceeds the World Health Organization (WHO) safe limit of 30 parts per billion. There have been reports of arsenic (As) in the Majha belt of Punjab that is over the permissible level. These abnormalities are thought to have originated from geogenic origins. The presence of various heavy elements, including iron, nickel, cadmium, chromium, mercury, and lead, has caused the quality of the groundwater to further decline. According to our research, groundwater uranium concentrations range from 80.6 ppb in the Muktsar district to 366.0 ppb in the Fazilka district. Our study reports on the health hazards associated with uranium and other heavy metals in groundwater. Reductions in uranium and heavy metals have been suggested as mitigating strategies for the State of Punjab's agriculture. The World Bank-funded initiative "Toward Managing Rural Drinking Water Quality in the State of Punjab, India" has addressed the issue of groundwater contamination. Ion exchange and AMRIT technologies are two of the many steps the Punjab government's Department of Water Supply and Sanitation has made to provide drinkable water while reducing the levels of iron and arsenic in the Majha belt. In the Malwa belt, RO plants and canal water supply are the potable sources of drinking water. For agricultural practices, the use of canal water is being promoted.

Keywords: Agriculture, groundwater, heavy metals, mitigation, uranium.

INTRODUCTION

The British annexed Punjab in 1849. Irrigation facilities have been developed to promote agriculture on a commercial scale in Punjab. The Sirhind Canal System was constructed in the year 1874-82 to utilize the water of the Sutlej River from the Ropar Head Works in Eastern Punjab. Canals were dug up in Western Punjab to cultivate arid areas by irrigation. In the irrigated interfluvial areas east of Jhelum

and west of Beas River, nine canal colonies were established between 1885 and 1940 (Table 1). An agricultural revolution resulted in the increased production of wheat, cotton, and sugarcane in Punjab [1, 2]. The new colonies provided potable water from the canal system, which was free of pollutants such as uranium and heavy metals.

After the partition of Punjab, most canal colonies went to Pakistan. To augment irrigation in Indian Punjab, the Bhakra Canal System was constructed during the 1950-60s. The Green Revolution began

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in Punjab during 1965–66 and agricultural production started rising exponentially. The enhanced use of fertilizers, pesticides, and weedicides has brought havoc to the ecology of Punjab. Canal irrigation was not sufficient to meet the irrigation needs of the farmers. Many tube wells were installed to maintain the wheat-paddy rotation pattern in Punjab. The provision of free electricity supply to farmers of Punjab, groundwater was over-exploited, and most of the cultivable area was declared under the red zone by the Central Ground Water Board. This was the crux of the current situation in Punjab. The Punjab environment was destroyed by the aftereffects of the Green Revolution. Heavy metal pollution in groundwater is the result of resource over-exploitation.

High concentrations of heavy metals and uranium (U) in Punjab's subterranean water table have been predicted in the province [4–7]. During the past 20 years, Tribune (www.tribuneindia.com) has published almost two dozen reports on the high toxicity of U in Punjab's waters. It was suggested in the Ruchika M. Khanna report dated May 18, 2016 [8] that canal water is mostly used for drinking and hazardous groundwater for irrigation. This report is based on uranium (U) research findings published by a group of Indian scientists at the Bhabha Atomic Research Center (BARC). The potential of contaminated food grains and vegetables grown in the fields is highlighted in the report as a consequence of the water pumped from these tubewells. Although the cause of the high concentration of U in the groundwater of Punjab is still debated, geology is thought to be the primary source [9].

Based on information gathered by the Punjab Water Supply and Sanitation Department (PWSSD), studies have been conducted on the prevalence of uranium and heavy metals in groundwater drawn from tube wells in Punjab [10–14]. The fact that PWSSD has gathered data from over 50% of Punjab's inhabitants (villages) and analyzed it in its advanced laboratory facility in Mohali, Punjab, using cutting-edge equipment like ICPMS (Inductively Coupled Plasma Mass Spectrometry (ICP-MS)) and Ion Chromatography, will be of interest to the general public. The analysis in this study is also based on PWSSD data gathered in three stages between 2009 and 2016, and it has been updated and amended through March 31, 2021. The majority of these data have been uploaded and are accessible to the Indian government's Ministry of Jal Shakti (Water Resources) [15].

Scientists at PAU (Punjab Agriculture University) have taken many initiatives to study arsenic in groundwater and canal water [16, 17]. Some studies have been conducted to estimate the heavy metal content of vegetables grown in contaminated soil. Plants absorb heavy metals from the soil solution through their roots. The accumulation of heavy metals from soil to plants depends on many factors, such as metal forms, plant species, and soil properties [18, 19].

Table 1. Timeline of canal colonies in Punjab under the British [3].

Colony	Period of colonization	Doab	District	Area in acres
Sidhnai	1886-88	Bari	Multan	250,000
Sohag Para	1886-88	Bari	Montgomery	86,300
Chenab	1892-1905, 1926-30	Rechna	Gujranwala, Jhang, Lyallpur, Lahore, Sheikhpura	1,824,745
Chunian	1896-98 1904-05	Bari	Lahore	102,500
Jhelum	1902-06	Jech	Shapur, Jhang	540,000
Lower Bari Doab	1914-24	Bari	Montgomery, Multan	1,192,000
Upper Chenab	1915-19	Rechna	Gujranwala, Sialkot, Sheikhpura	78,800
Upper Jhelum	1916-21	Jech	Gujrat	42,300
Nili Bar	1916-40	Bari	Montgomery, Multan	1,650,000

MATERIALS AND METHODS

For sample collection, 100 ml bottles of superior-quality plastic were used. The bottles were first washed with the soap solution and then with distilled water. The samples were rinsed with deionized water and then dried. Groundwater from the source was allowed to flow freely in plastic bottles before collection. Approximately 100 ml of water was collected from the running water source. Samples must be filtered through a 0.2-micron (μm) filter at the field site to separate the dissolved metal components. Nitric acid (0.5M HNO_3) solubilization is required before the determination of total recoverable U. The preservation and digestion of U in acid are used to aid the breakdown of complexes and minimize interference by polyatoms.

The U analysis of the collected water samples was performed using a Model 7700 Agilent Series ICP-MS following the standard procedure in the Regional Water Testing Laboratory (RTWL) of the Punjab state set up in Mohali. The instrumental details for heavy metal analysis in groundwater samples and calibration of ICP-MS are available in our earlier publication at JoWPPR [20].

URANIUM IN GROUNDWATER

The PWSSD survey covered 6182 habitations (a village or a group of dwellings) over the course of three phases. Two limits have been established by PWSSD in the data table to identify quality-affected (QA) habitations: the Acceptable Limit (AL) of 30 $\mu\text{g/L}$ (ppb) and the permissible limit (PL) of 60 $\mu\text{g/L}$ (ppb) set by the Atomic Energy Regulatory Board (AERB) of the Bhabha Atomic Research Centre (BARC), Trombay, Mumbai (higher than the limits set by all other countries). The 15 microgram/liter (ppb) World Health Organization (WHO) standard has been revised to 30 ppb. Regarding uranium in water, the Bureau of Indian Standards (BIS) adheres to WHO regulations.

Different QA habitation results were obtained when we analyzed the U data, based on these limitations. In Punjab, 785 habitations had QA groundwater according to the PL criteria; however, when the AL criteria were applied, the number increased to 1141. Using the WHO threshold of 30 parts per billion for safe drinking water, the proportion of QA habitations increased to 18% of all habitations included in the PWSSD survey. It is worrisome to provide Punjab people with clean drinking water after the removal of U from groundwater.

Many variations in U content have been noted [10–14, 21–24] within districts and between habitats, contingent on the characteristics and profile of groundwater, which in turn may be influenced by the geomorphology and geohydrology of the water table. In comparison to the districts of the Majha and Doaba belts, the districts of Mansa, Muktsar, Moga, Barnala, Bathinda, Patiala, Sangrur, Ferozepur, and Fazilka in Punjab's Malwa belt exhibited higher U concentrations in the groundwater (Table 2). However, according to the AL criteria, the greatest U concentration in Punjab's ground waters was found in 15 habitats in the Hoshiarpur district, with values ranging from 2109 to 2277 ppb. This is approximately 20 times higher than the average U content for the entire province (115 ppb). The frightening result of our research is that the increased cancer risk for 2277 ppb U is 6.5 per 1000 persons! The cancer risk for the entire province of Punjab is 3.3 per 10,000 people if we consider the average value of 115 ppb. Research on the epidemiological impacts of high U concentrations in drinking water on public health is urgently required. A district map of the Punjab state is shown in Figure 1.

There is insufficient information available on how U concentration in water affects human health. Overall, the data suggest that below an exposure dose of 30 $\mu\text{g/l}$ (ppb), there is no convincing evidence of its impact. Indeed, until a considerably greater exposure dose is reached, the evidence for impacts on the kidney, which seems to be the most sensitive organ, is ambiguous. When U is ingested (consumed), the human body can experience two different effects: chemical and radioactive. Chemical toxicity risk is always present at all doses, but at higher doses, above roughly 100 $\mu\text{g/l}$ (ppb), radiological danger resulting from U's high radioactivity must be taken into account.



Figure 1. Map of Punjab State showing District boundaries (Courtesy Maps of India).

RADIOLOGICAL AND CHEMICAL RISK ASSESSMENT

Uranium and heavy metals ingested through drinking water can cause both radiological (carcinogenic) and chemical (non-carcinogenic) risks. The theoretical formulation used for the assessment of both types of risks due to uranium contamination in water has been described elsewhere, as given in the Appendix [14].

Table 2 represents the highest cancer risk values of the Malwa belt districts with a variation from 2.28×10^{-4} to 10.37×10^{-4} . In India, the AERB guidelines are followed, which allow an excess cancer risk level of 1.67×10^{-4} . This clearly shows that in the surveyed habitations of the Malwa belt districts, excess cancer risk is higher than the maximum acceptable limit set by the AERB [25]. Following the standard protocol [14], the mean excess cancer risk for the Fazilka district is 5.01×10^{-4} , which is highest for the Malwa belt and may lead to five cancers per 10,000 people. The highest cancer risk for inhabitants of village Kotha in Fazilka district is estimated to be 10.37×10^{-4} , which is 10 cancers per 10,000 people. According to the Cancer Registry of the Government of India, the national average cancer risk is 80 cancers per million population; for Punjab, it is 90 cancers per million, but for the Malwa belt of Punjab, it is much higher, at 136 cancers per million population. Our investigation reveals that the Fazilka district in the Malwa belt of Punjab has assumed alarming proportions of 500 cancers per million [22].

Table 2. Uranium concentration and cancer risk correspond to the highest U content in the groundwater of the Malwa districts of Punjab.

S.N.	District	Village	Highest U conc. (ppb)	Highest U activity (Bq l ⁻¹)	Highest excess cancer risk (10 ⁻⁴)	Hazard quotient (HQ)
1	Mansa	Maganian	350.3	8.86	9.92	4.47
2	Muktsar	Babarian	80.6	2.04	2.28	1.03
3	Moga	Chotian Khurd	346.7	8.76	9.82	4.43
4	Barnala	Ramgarh	290.6	7.35	8.23	3.71
5	Bathinda	Bhunder	325.1	8.22	9.21	4.15
6	Patiala	Ahru Kalan	267.0	6.75	7.56	3.41
7	Sangrur	Ratoke	230.3	5.82	6.52	2.94
8	Ferozepur	Kotha	331.4	8.38	9.39	4.23
9	Fazilka	Kotha <i>alias</i> Lakhmanpura	366.0	9.25	10.37	4.67

The chemical toxicity of uranium poses a greater health hazard to the kidneys than its radiological toxicity at lower exposure levels [26]. Chemical toxicity and hazard quotient (HQ) were calculated using a standard protocol [14]. If the HQ value is less than 1, the ingestion of uranium in water does not pose any health hazard, but if it is >1, it can lead to deleterious effects on human health. HQ is a measure of the extent of non-carcinogenic health hazards due to the ingestion of uranium from drinking water. Table 2 shows the variation in the values of the HQ from 1.03–4.67 (Muktsar district to Fazilka district).

MITIGATION OF URANIUM

Uranium can be extracted from drinking water using a variety of techniques, some of which have been tested only in pilot or laboratory settings. Approximately 80–95% of uranium can be removed by coagulation using ferric or aluminum sulfate at the appropriate pH and coagulant doses; at least 99% of uranium can be removed using reverse osmosis (RO), anion exchange resin, or lime softening. In Punjab's rural areas, where the permissible limit of 60 parts per billion for U concentration is exceeded, PWSSD advised the installation of RO systems. However, the RO system has been abandoned and rendered obsolete in the majority of Punjabi villages following ten years of trial and error.

PWSSD has determined that using canal water is the best option for providing drinkable water in the Punjab's Malwa area as part of the World Bank Project.

HEAVY METAL CONTAMINATION IN THE GROUNDWATER OF PUNJAB

Heavy metal contamination in the groundwater of Punjab has been investigated by the present author [27–30] using PWSSD data generated at the sophisticated laboratory at SAS Nagar (Mohali). Heavy metals in groundwater may be of geogenic origin. It is augmented by anthropogenic sources, such as agrochemicals, including fertilizers and pesticides, which are being used by farmers in Punjab. It is potentially a significant problem in several community and agricultural areas because plant nutrients and fertilizers can lead to dramatic increases in the concentrations of heavy metals in the water and soil [31]. These heavy metals have the potential to reach levels in the soil, and then in the surface and groundwater, which are averse to human health [32, 33].

Heavy metals can initially accumulate above natural levels in agricultural soils over time due to the continual application of commercial agrochemicals that contain several potentially toxic heavy metals. Their subsequent migration and availability once leached from agricultural soils are influenced by several factors, such as water pH, redox potential, and type and quality of the soil. Heavy metal pollution in the environment is becoming a serious concern, as these metals are omnipresent in the air, soil, and water. Heavy metal pollution in water supplies is a serious environmental problem that has a negative impact on human health, animals, and vegetation [34, 35].

Groundwater can be contaminated by heavy metals such As, Cd, Hg, Fe, Pb, and Se by geological or human-caused means [36]. Heavy metal pollution is currently one of the biggest environmental concerns owing to its high toxicity and detrimental effects on human health. According to a World Health Organization (WHO) report, 80 percent of infections and fatalities in developing nations are attributed to drinking contaminated water, according to a World Health Organization (WHO) report [37]. Drinking water contaminated with heavy metals increases the risk of serious illnesses including cancer [38].

The metabolism and healthy growth of plants and animals are significantly affected by the trace amounts of heavy metals. However, the same metals may have serious toxicological consequences in humans in large amounts [39]. However, owing to their propensity to collect in the body, trace metals can be hazardous and even harmful to humans, even in comparatively low amounts. Recently, the author reported the results of his investigations into heavy metals (nickel, cadmium, chromium, and lead) using World Bank Project data from PWSSD [20]. Heavy metal accumulation in the groundwater of Punjab is a manmade curse, and mitigation measures are suggested to control this disaster.

A summary of our results, based on the study of seven heavy metals in groundwater, is presented in Table 3. Out of 7, arsenic is the most investigated metalloid in the Punjab groundwater.

Table 3. Heavy metals concentration in the groundwater of Punjab and their health hazards

S.N.	Heavy Metal	Affected Districts	Highest Conc. (ppm)	Health Hazards	Mitigation
1	Arsenic	Amritsar, Gurdaspur, Tarn Taran,	0.111 (Khatrai Kalan of Amritsar) Permissible limit (PL) 0.01ppm.	Nausea, diarrhea, cramping, skin rashes, liver, and kidney damage. Acute exposure causes cancer.	AMRIT technology [40], Ion exchange tech. [41], canal water supply.
2	Mercury	Ferozepur, Hoshiarpur, SBS Nagar, Ropar,	0.038 (Hero Kalan in Mansa) PL 0.001 ppm	Effect on kidneys, nervous system, weight loss, cerebral palsy.	RO plants, canal water supply.
3	Iron	Amritsar, Hoshiarpur, Ferozepur, Fazilka, Ropar	14.59 (Bagrian in Amritsar) PL 1.0 (ppm)	An overload of Iron can cause diabetes, hemochromatosis, stomach problems, and nausea.	AMRIT technology [4], RO plants, and canal water supply.
4	Nickel	Hoshiarpur, Moga, Ludhiana	0.947 (Dhurkot Charat Singh in Moga) PL 0.02 ppm	It is carcinogenic, gastrointestinal, and neurological symptoms after acute exposure.	RO plants, canal water supply.
5	Cadmium	Patiala, Ludhiana, Moga	0.162(Kanian Khurd in Moga) PI 0.003 ppm	It can cause cancer and targets the cardiovascular, gastrointestinal, neurological, renal, reproductive, and respiratory systems.	RO plants, canal water supply.
6	Chromium	Hoshiarpur, Ludhiana, Tarn Taran, Amritsar	0.308 (Walipur Khurd in Ludhiana) PL 0.05 ppm	It can cause respiratory problems, kidney and liver damage, skin irritation, and indigestion. Long-term exposure can cause cancer.	RO plants, canal water supply.
7	Lead	Jalandhar and nine more districts	0.479 (Chaula in Hoshiarpur) PL 0.01 ppm	It is highly toxic.	RO plants, Canal water supply.

According to research published in The Tribune on January 2, 2010, a group of scientists from Punjab Agricultural University (PAU) concluded that the primary cause of cancer is the arsenic content of water in the Malwa belt. The PWSSD survey report, on the other hand, is more insightful and deviates from the PAU team's conclusions. Based on the PWSSD assessment, 40% of the Punjabi habitations had significant levels of arsenic contamination, with a threshold of 0.01 mg/l (). Remarkably, of all the Punjabi habitations impacted by arsenic, 60% are located in the districts of Amritsar, Tarn Taran, and Gurdaspur, which comprise the Majha belt of Punjab. Almost all habitations in SAS Nagar and SBS Nagar are free from arsenic, making them comparatively safer. Therefore, it is necessary to investigate the source of arsenic in the groundwater of the Majha Belt.

A detailed overview of the districts affected by high levels of heavy metal contamination is presented in Table 3. For reference, the village and district names, together with the greatest concentration of each heavy metal in parts per million, are provided. The list of health risks associated with this metal is provided below. Pb, Cd, and As are extremely toxic.

The last column indicates the mitigation measures adopted to eliminate the harmful effects of heavy metals. This study is considered a preliminary report to highlight the problem faced by Punjab.

CONCLUSIONS

1. The source and origin of heavy metals in the groundwater of Punjab require further investigation. It is primarily attributed to a geogenic origin but is augmented by anthropogenic sources such as fertilizers, pesticides, and weedicides.
2. Uranium concentration in the groundwater of the Malwa belt is a major cause of concern. Its concentration varies from 80.6 ppm (lowest) in Muktsar district to 366.0 ppm (highest) in Fazilka district.
3. The average U concentration in the groundwater of Punjab was 115 ppb. It was 2-3 times higher in the eight districts of the Malwa belt, which may be a probable cause of the higher cancer rate in the Malwa belt of Punjab.
4. Canal water supply is the best and most economical system of mitigation adopted by PWSSD.
5. For the sustainable development of Punjab, the over-exploitation of groundwater needs to be checked on a war footing. The free electricity used to pump groundwater must be stopped. Diversification of crops and harvesting of rainwater are other measures to be undertaken. The people of Punjab and politicians must read the writing on the wall; otherwise, Punjab will become a desert state in the coming fifty years. The clock is already ticking for doom's day.

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APPENDIX

Theoretical Formulation

The ingestion of uranium through drinking water results in both radiological risk (carcinogenic) and chemical risk (non-carcinogenic). The methodology used for the assessment of radiological and chemical risks due to uranium concentrations in the water samples is described below.

Calculation of Excess Cancer Risk: Excess cancer risk from the ingestion of natural uranium from drinking water has been calculated according to the standard method given by the USEPA [1]. $CR = Ac \times R$, where 'ECR' is Excess Cancer Risk, 'Ac' is Activity concentration of uranium (Bq l⁻¹), and 'R' is Risk Factor.

The risk factor R (per Bq l⁻¹), linked with ingestion of uranium from the drinking water may be estimated by the product of the risk coefficient (r) of uranium (1.19×10^{-9}) for mortality and per capita activity intake I. 'I' for uranium is calculated as the product of life expectancy, assumed to be 63.7 years, i.e., 23250 days, and daily consumption of water as 4.05 l.day⁻¹.

$$I = 4.05 \text{ l.day}^{-1} \times 23250 \text{ days; Risk Factor (R)} = r \times I$$

Chemical Risk Assessment: The chemical toxicity risk for uranium is defined in terms of the Lifetime Average Daily Dose (LADD) of uranium through drinking water intake. LADD is defined as the quantity of the substance ingested per kg of body weight per day and is given by the following equation [2, 3]: $LADD = C \times IR \times ED \times EF / AT \times BW \times 365$, where 'C' is the concentration of the uranium ($\mu\text{g l}^{-1}$), IR is the water consumption rate (4.05 l day^{-1}), ED is the lifetime exposure duration (63.7 years), EF is the exposure frequency (365 days y^{-1}), BW is average body weight of the receptor (70 kg), and AT is the Averaging time, i.e., life expectancy (63.7 years).

The hazard quotient (HQ) is a measure of the extent of harm caused by the ingestion of uranium from drinking water. $HQ = LADD / RfD$, where, LADD is Lifetime Average Daily Dose, and RfD is the reference dose = $4.53 \mu\text{g kg}^{-1} \text{ d}^{-1}$.

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