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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 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, use of canal water is being promoted.

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

INTRODUCTION

Punjab was annexed by the British in 1849. Irrigation facilities were developed to promote agriculture on commercial scale in Punjab. Sirhind Canal System was constructed in the year 1874-82 for utilizing water of river Sutlej from the Ropar Head Works in the Eastern Punjab. Canals were dug up in Western Punjab to make arid areas cultivable by irrigation. In the irrigated inter-fluvial areas east of the Jhelum and west of the Beas rivers, nine canal colonies were established between 1885 and 1940 (Table 1). An agricultural revolution resulted in increased production of wheat, cotton, and sugarcane in the Punjab. [1, 2]. The new colonies were provided potable water from the canal system which was free of pollutants like Uranium and heavy metals.

After partition of Punjab, most of the canal colonies went to Pakistan. To augment irrigation in Indian Punjab, Bhakra Canal System was

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constructed during 1950-60s. Green revolution started in Punjab during1965-66 and agricultural production started rising exponentially. Enhanced use of fertilizers, pesticides and weedicides brought havoc to the ecology of Punjab. Canal irrigation was not enough to meet irrigation needs of farmers. To maintain wheat-paddy rotation pattern in Punjab, large number of tubewells were installed. The provision of free electricity supply to farmers of Punjab, groundwater was over-exploited and most of the cultivable area has been declared under red zone by the Central Ground Water Board. This is the crux of the problem for the current situation in Punjab. The environment of Punjab has been completely destroyed by the Green Revolution's aftereffects. Heavy metal pollution of groundwater is the result of over-exploitation of the resource.

Table 1. Timeline of Canal Colonies in Punjab under the British [3].

Colony	Period of colonisation	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, She ikhupura	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, Sheikhupura	78,800
Upper Jhelum	1916-21	Jech	Gujrat	42,300
Nili Bar	1916-40	Bari	Montgomery, Multan	1,650,000

High concentrations of heavy metals and uranium (U) in Punjab's subterranean water table have put the province in a predicament [4–7]. During the past 20 years, The 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 the Canal water be used mostly 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 Centre (BARC). The potential of contaminating the 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 Punjab's groundwater is still up for debate, geology is thought to be the primary source [9].

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

Scientists of PAU (Punjab Agriculture University) took lot of initiative to study Arsenic in groundwater and canal water [16, 17]. Some studies were carried out for estimation of heavy metal content in vegetables grown in contaminated soil. Plants absorb heavy metals from the soil solution through their roots. The accumulation of heavy metals from soils to plants depends on many factors such as metal forms, plant species and soil properties [18, 19].

MATERIALS AND METHODS

For collection of samples, 100 ml bottles of superior quality plastic were used. The bottles were washed first with soap solution and then with distilled water. These were rinsed with deionized water and dried. Groundwater from the source was allowed to flow freely before collection in plastic bottles. About 100 ml of water was collected from the running water source. Samples must be filtered through a 0.2micron (µm) filter at the field site to separate the dissolved metal components. Nitric acid (0.5M HNO3) solubilization is required before the determination of total recoverable U. The preservation and digestion of U in acid is used to aid breakdown of complexes and to minimize interferences by poly-atoms.

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

URANIUM IN GROUNDWATER

The PWSSD survey covered 6182 habitations (a village or a group of dwellings) in total 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 micrograms/litre (ppb) and the Permissible Limit (PL) of 60 micrograms/litre (ppb) set by the Atomic Energy Regulatory Board (AERB) of the Bhabha Atomic Research Centre (BARC), Trombay, Mumbai (higher than limits set by all other countries). The 15 microgram/litre (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 are obtained when we analyze the U data based on these limitations. In Punjab, 785 habitations have QA groundwater according to PL criteria; however, when AL criteria are applied, the number increases to 1141. Using the WHO threshold of 30 parts per billion for safe drinking water, the proportion of QA habitations rises to 18% of all habitations included in the PWWSD survey. It is worrisome to provide Punjab's people with clean drinking water after removal of U from the groundwater.

Many variations in U content have been noted [10–14, 21–24] within districts and between habitations, 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 Majha and Doaba belt, the districts of Mansa, Muktsar, Moga, Barnala, Bathinda, Patiala, Sangrur, Ferozepur, and Fazilka in Punjab's Malwa belt exhibit higher U concentration in groundwater (Table 2). However, according to AL criteria, the greatest U concentration in Punjab's ground waters has been found in 15 habitations in the Hoshiarpur district, with values ranging from 2109 to 2277 ppb. This is about 20 times higher than the average U content for the entire province, which is 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 take the average value of 115 ppb into account. Research on the epidemiological impacts of high U concentration in drinking water on public health is desperately needed. Punjab state's district map is displayed in Figure 1.

There is insufficient information available about how U concentration in water affects human health. Overall, the data suggest that below an exposure dose of 30 µg/l (ppb), there is no convincing evidence of impacts. Indeed, until considerably greater exposure dose, 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 kinds of effects: chemical and radioactive. Chemical toxicity risk is always present at all doses, but at higher ones—above roughly 100 μg/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)

Table 2. Uranium concentration and cancer risk corresponding to highest U content in groundwater of 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	Babanian	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 *alias* Lakhmanpura	366.0	9.25	10.37	4.67

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RADIOLOGICAL AND CHEMICAL RISK ASSESSMENT

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

Table 2 represents the highest cancer risk values of Malwa belt districts with a variation from 2.28 x 10^{-4} to 10.37x10^{-4}. In India, AERB guidelines are followed which allow an excess cancer risk level of l.67×10^{-4}. It clearly shows that in the surveyed habitations of Malwa belt districts, excess cancer risk is higher than the maximum acceptable limit set by AERB [25]. Following the standard protocol [14], the mean excess cancer risk for Fazilka district comes out to be 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 habitants of village Kotha in Fazilka district is estimated to be 10.37 x 10^{-4}, which works out to be 10 cancers per 10,000 people. According to Cancer Registry of Government of India, national average of cancer risk is 80 cancers per million population; for Punjab it is 90 cancers per million but for Malwa belt of Punjab, it is much higher at 136 cancers per million population. Our investigation reveals that for Fazilka district in Malwa belt of Punjab, it has assumed alarming proportions at 500 cancers per million [22].

The chemical toxicity of the uranium poses a greater health hazard to kidneys as compared with its radiological toxicity at lower exposure levels [26]. Chemical toxicity and hazard quotient (HQ) are calculated using the standard protocol [14]. If HQ value is less than 1, 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. In a manner of speaking, HQ is a measure of the extent of non-carcinogenic health hazard due to the ingestion of uranium from the 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 only been tested in pilot or laboratory settings. 80–95% of the uranium can be removed by coagulation using ferric or aluminum sulfate at the right pH and coagulant doses; at least 99% of the 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 was exceeded, PWSSD advised installing 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.

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

HEAVY METALS CONTAMINATION IN GROUNDWATER OF PUNJAB

Heavy metal contamination in groundwater of Punjab has been investigated by the present author [27-30] using PWSSD data generated at the sophisticated laboratory at SAS Nagar (Mohali). The source of heavy metals in groundwater may be of geogenic origin. It is augmented by anthropogenic sources, for example, agrochemicals, including fertilizers and pesticides, which are being used by farmers in Punjab with impunity. 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 that are averse to human health [32, 33].

Heavy metals can initially accumulate above natural levels in agricultural soils over time from the continual application of commercial agrochemicals that contain several potentially toxic heavy metals. Their subsequent migration and availability once leached from agricultural soils is influenced by several factors, such as the water pH, redox potential, and type and quality of the soil. Heavy metal pollution of the environment is becoming a serious concern as these metals are omnipresent in the air, soil, and water. Heavy metal pollution of 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, among others, by geological or human-caused means [36]. Because of their high toxicity and detrimental effects on human health, heavy metal pollution is currently one of the biggest environmental concerns. Eighty 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 impacted by trace amounts of heavy metals. However, the same metals may have serious toxicological consequences on humans at larger amounts [39]. However, due to their propensity to collect in the body, trace metals can be hazardous and even harmful to humans even at comparatively low amounts. Recently, the author reported the results of his investigations on heavy metals (Nickel. Cadmium, Chromium, and Lead) using World Bank Project data of PWSSD [20]. It is established that heavy metal accumulation in 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 Punjab groundwater. 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 the 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 Punjabi habitations had significant levels of arsenic contamination, with the threshold established at 0.01 mg/l (ppm). Remarkably, of all Punjabi habitations impacted by arsenic, 60% are located in the districts of Amritsar, Tarn Taran, and Gurdaspur, which make up the Majha belt of Punjab. Almost all of the habitations in SAS Nagar and SBS Nagar are free from arsenic, making them comparatively safer. It is necessary to look into the source of the arsenic in the groundwater of the Majha Belt.

A detailed overview of the districts impacted by high levels of heavy metal contamination is shown 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 that metal is given next. Lead, cadmium, and arsenic are categorized as extremely poisonous.

The last column indicates the mitigation measures to be adopted to get rid of harmful effects of the heavy metal. I consider this study as a preliminary report to highlight the problem being faced by Punjab.

Table 3. Heavy metals concentration in 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, nausea	AMRIT technology [4], RO plants, 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) Pl 0.003 ppm	It can cause cancer and targets 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	Jallandhar and nine more districts.	0.479 (Chaula in Hoshiarpur) PL 0.01 ppm	It is highly toxic.	RO plants, Canal water supply.

CONCLUSIONS

1. The source and origin of heavy metals in groundwaters of Punjab needs to be investigated further. It is being attributed to geogenic origin primarily but augmented by anthropogenic sources such as fertilizers, pesticides, and weedicides.
2. Uranium concentration in groundwater of 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 value of U concentration is 115 ppb in groundwater of Punjab. It is 2-3 times higher in the 8 districts of Malwa belt, which may be a probable cause of higher cancer rate in the Malwa belt of Punjab.
4. Canal water supply is the best and economical system of mitigation adopted by PWSSD.
5. For sustainable development of Punjab, overexploitation of groundwater needs to be checked on war footing. Free electricity used for pumping groundwater needs to 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 turn into a desert state in the coming fifty years. The clock is already ticking for its doom's day!

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APPENDIX

Theoretical Formulation

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

Calculation of Excess Cancer Risk: Excess cancer risk from the ingestion of natural Uranium from the drinking water has been calculated according to the standard method given by the USEPA [1]. CR=Ac×R, where 'ECR' is Excess Cancer Risk, 'Ac' is Activity concentration of Uranium (Bql -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 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 lday -1 × 23250 days; Risk Factor (R) = r× I

Chemical Risk Assessment: The chemical toxicity risk for Uranium is defined in terms of Lifetime Average Daily Dose (LADD) of the 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×IR×ED×EF/AT×BW ×365, where 'C' is the concentration of the uranium (μgl^{-1}), IR is the water consumption rate (4.05 $lday^{-1}$), 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).

Calculation of Hazard Quotient: Hazard quotient (HQ) is the measure of the extent of harm produced due to the ingestion of uranium from the drinking water. HQ=LADD/RfD, where, LADD is Lifetime Average Daily Dose, and RfD is the reference dose = 4.53 µg kg −1 day −1.

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