

Distribution, Source Identification, and Health Risk Assessment of Heavy Metals in Surface and Groundwater Resources of the Sirhind Canal Region, Punjab, India

Savneet Kaur^{1*} and Ajay Kumar²

^{1*}Associate Professor in the Department of Applied Sciences at Desh Bhagat University, Mandi Gobindgarh, Punjab, India

²Research Scholar, Department of Applied Sciences, Desh Bhagat University, Mandi Gobindgarh, Punjab, India
Email: kailleysavneet@gmail.com and bhatiaajay84@gmail.com

*Corresponding Author: kailleysavneet@gmail.com

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ABSTRACT

Water pollution with heavy metals is an important environmental and public health problem, especially in areas that rely heavily on surface water and groundwater for drinking and farming. In the present study, surface water and ground water resources of the Sirhind Canal region of Punjab, India, were studied for the distribution of heavy metals along with their potential sources and health risk assessments. The following metals were measured in the water samples: Iron (Fe), Copper (Cu), Lead (Pb), Nickel (Ni), Arsenic (As), Chromium (Cr), Cadmium (Cd), and Uranium (U). The concentrations of the heavy metals in groundwater were remarkably high compared to surface water, and significant enrichment of iron (0.86 mg/L), uranium (28.6 µg/L), nickel (0.038 mg/L), arsenic (0.014 mg/L), and lead (0.012 mg/L) were observed. The strong positive correlation for some metals indicated by statistical analysis suggested that they were derived from similar geogenic sources and groundwater-rock interaction processes. The following elements were found to be above the BIS and WHO parameters in the groundwater samples: Iron, arsenic, lead, and nickel. The findings have revealed that there might be some health risks in the long-term use of groundwater, and it has also emphasized the need for constant surveillance, groundwater management, and sustainable groundwater quality protection measures in the Sirhind Canal area.

Keywords: Heavy Metals, Surface Water, Groundwater, Sirhind Canal, Iron, Arsenic, Uranium, Health Risk Assessment, Water Quality, Punjab.

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1. INTRODUCTION

The contamination of the aquatic environment with heavy metals is one of the most serious environmental issues because of its persistence, non-biodegradability, and potential negative impacts on the ecosystem and human health. In Punjab, surface and ground water are significant sources of drinking water, irrigation, and domestic water for agricultural and human settlements that are highly dependent on these water sources in the Sirhind Canal command region. But, with more intensive agriculture, urbanization, industrial processes, and natural geochemical activity, water quality has declined due to toxic metal accumulation. The present study on water resources of the Sirhind Canal area found the presence of several heavy metals such as Fe, Cu, Pb, Hg, Ni, As, Cr, Cd, and U in both the surface water and ground water systems. The distribution pattern suggested that concentrations of most of the metals in the groundwater were significantly higher than those in surface water, indicating that groundwater-rock interactions, weathering of minerals, and

accumulation of contaminants on the rocks within the aquifers caused the metals to be present at higher concentrations. The metals that were found to be the dominant metals in both water sources were iron, and elevated concentrations were detected for nickel, arsenic, lead, and uranium in groundwater at multiple sites. Heavy metals can enter aquatic systems from various sources such as dissolution of naturally occurring minerals, agricultural runoff, over-fertilization, leaching from soil and sediments, domestic wastewater discharge, and other anthropogenic activities. When added to water resources, these metals can remain for long periods of time and build up in environmental compartments. High levels of certain metals in drinking water sources are a particular issue as they could lead to negative health effects if the exposure is prolonged. Arsenic and lead can result in neurological issues, developmental problems, cardio effects and high concentrations of uranium can result in kidney damage. Likewise, high levels of iron and nickel may affect water quality and cause chronic health risks. Based on the

*Author for Correspondence: kailleysavneet@gmail.com

findings of the present study, the surface water concentration of heavy metals was generally low, and the compliance rate of drinking water was high, whereas the groundwater was vulnerable to heavy metal enrichment.

The worries over groundwater quality gradually grew in Punjab particularly in highly productive region where the groundwater is the only source of drinking water. Therefore, monitoring of surface water and groundwater over time is important to determine the source of contamination, understand the impacts to the health of the public and the sustainable utilization of water resources in the Sirhind Canal region to protect the health of the people and water resources.

1.2 Objectives of the Study

1. To identify and compare the distribution and variation of Fe, Cu, Pb, Hg, Ni, As, Cr, Cd, and U concentrations in surface water and groundwater resources of the Sirhind Canal region and suggest possible sources of contamination.
2. To assess the environmental and public health risks due to these heavy metal levels by comparing the levels observed with the BIS and WHO drinking water guidelines and determining the appropriateness of the water source for drinking.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The study was conducted in the Sirhind Canal area of Punjab, Pakistan. The Sirhind Canal is an important source of irrigation and recharge of groundwater resources, as it is a tributary of the Sutlej River from Ropar Headworks, Rupnagar District. The ground study area comprises several sites in both urban and rural and agricultural areas that are impacted by canal water and groundwater interaction.

2.2 Sampling Locations and Sample Collection

Water samples were taken from a few surface water and groundwater sources in the Sirhind Canal Command Area. The sampling sites were chosen to cover different hydrogeologic and land-use types. Samples were taken in pre-cleaned polyethylene bottles and sent to the lab for additional analysis.

2.3 Surface Water Sampling

The surface water samples were taken directly from the Sirhind Canal at various locations from the origin of the canal to downstream areas. Standard sampling practices were used to ensure water quality assessment and prevent contamination during the sampling and transportation of water samples.

2.4 Groundwater Sampling

Tube well and hand pump water samples were taken in proximity to the selected sampling sites in the canals.

Representative groundwater samples from the aquifer system were obtained before the sampling by letting water flow for a few minutes.

2.5 Heavy Metal Analysis

Samples collected were analysed for selected heavy metals such as Fe, Cu, Pb, Hg, Ni, As, Cr, Cd, and U. The concentration measured was compared to BIS and WHO drinking water standards to check water quality and contamination level.

2.6 Quality Assurance and Quality Control

All sampling containers used were thoroughly cleaned before use, and analytical work was performed using standard laboratory procedures. Duplicate analysis, instrument calibration, and the use of reagent blanks were used to ensure the accuracy and reliability of analytical results and to perform quality assurance.

2.7 Statistical Analysis

This analysis aimed to assess differences in the concentrations of the heavy metals at sampling points through descriptive statistical analysis. The surface water and groundwater have been compared, and correlation analysis has been performed to find the relationship between the different parameters investigated.

2.8 Heavy Metal Pollution Assessment Criteria

Heavy metal contamination was assessed by comparing the measured concentration to the prescribed limits as given by the Bureau of Indian Standards (BIS) and the World Health Organization (WHO). Water samples that are above the recommended limits were found to be possible contamination and are not suitable for direct consumption.

2.9 Human Health Risk Assessment Methodology

The level of heavy metals present in drinking water was used to evaluate potential health risks from exposure to heavy metals. The assessment was targeted at metals of concern for public health, such as arsenic, lead, nickel, and uranium, and the possible impacts of these metals on human health using available guideline values.

3. RESULTS AND DISCUSSION

3.1 Distribution of Heavy Metals in Surface Water

Table 3 shows the concentrations of heavy metals found in surface water samples. Copper, Ni, Cr, As, and Pb were present at significantly lower concentrations with mean concentrations of 0.011, 0.010, 0.006, 0.002, 0.003 mg/L, respectively. The levels of mercury and cadmium were very small. In general, the heavy metal concentration in all the samples was found to be within the limit prescribed by BIS and WHO, which reflects a relatively low concentration of heavy metals in the region of Sirhind Canal and a good status of surface water in the region.

Table 3. Heavy Metal Concentrations in Surface Water Samples from the Sirhind Canal Region

Heavy Metal	Unit	Minimum	Maximum	Mean ± SD	BIS Limit	WHO Limit
Iron (Fe)	mg/L	0.08	0.34	0.19 ± 0.09	0.30	0.30
Copper (Cu)	mg/L	0.002	0.021	0.011 ± 0.006	0.05	2.00

Lead (Pb)	mg/L	ND	0.006	0.003 ± 0.002	0.01	0.01
Mercury (Hg)	mg/L	ND	0.0004	0.0002 ± 0.0001	0.001	0.001
Nickel (Ni)	mg/L	0.003	0.018	0.010 ± 0.005	0.02	0.07
Arsenic (As)	mg/L	ND	0.004	0.002 ± 0.001	0.01	0.01
Chromium (Cr)	mg/L	0.002	0.012	0.006 ± 0.003	0.05	0.05
Cadmium (Cd)	mg/L	ND	0.001	0.0004 ± 0.0003	0.003	0.003
Uranium (U)	µg/L	1.2	8.4	4.6 ± 2.1	30	30

ND = Not Detected

Iron (Fe) was the predominant heavy metal detected in surface water samples, followed by uranium (U), whereas mercury (Hg) and cadmium (Cd) occurred at trace concentrations. All measured heavy metals remained within BIS and WHO permissible limits, indicating relatively low heavy metal contamination in the Sirhind Canal surface water.

3.2 Distribution of Heavy Metals in Groundwater

Table 4 shows the distribution of heavy metals in groundwater samples and suggests that there is a significantly higher concentration of the metals than in the surface water. Iron (Fe) was the most abundant metal,

ranging from 0.22 to 1.48 mg/L and was on average 0.86 ± 0.37 mg/L, with the levels at some sites being above the limit. Uranium (U) was the second most abundant metal, with concentrations between 8.4 and 54.2 µg/L and a mean value of 28.6 ± 12.7 µg/L. Nickel (0.038 ± 0.018 mg/L), arsenic (0.014 ± 0.007 mg/L), and lead (0.012 ± 0.006 mg/L) also exhibited elevated concentrations, with some samples exceeding drinking water standards. Copper, chromium, mercury, and cadmium were found at relatively low concentrations. The higher concentrations found in groundwater indicate that groundwater–rock interaction, mineral dissolution and anthropogenic activities have a greater influence on groundwater, and thus groundwater is more susceptible to heavy metal enrichment.

Table 4. Heavy Metal Concentrations in Groundwater Samples from the Sirhind Canal Region

Heavy Metal	Unit	Minimum	Maximum	Mean ± SD	BIS Limit	WHO Limit
Iron (Fe)	mg/L	0.22	1.48	0.86 ± 0.37	0.30	0.30
Copper (Cu)	mg/L	0.006	0.052	0.028 ± 0.014	0.05	2.00
Lead (Pb)	mg/L	0.004	0.024	0.012 ± 0.006	0.01	0.01
Mercury (Hg)	mg/L	0.0002	0.0015	0.0008 ± 0.0004	0.001	0.001
Nickel (Ni)	mg/L	0.012	0.074	0.038 ± 0.018	0.02	0.07
Arsenic (As)	mg/L	0.004	0.028	0.014 ± 0.007	0.01	0.01
Chromium (Cr)	mg/L	0.006	0.036	0.018 ± 0.009	0.05	0.05
Cadmium (Cd)	mg/L	0.0004	0.0024	0.0012 ± 0.0006	0.003	0.003
Uranium (U)	µg/L	8.4	54.2	28.6 ± 12.7	30	30

Groundwater samples exhibited substantially higher heavy metal concentrations than surface water. The presence of iron (0.86 mg/L), uranium (28.6 µg/L), arsenic (0.014 mg/L), lead (0.012 mg/L), and nickel (0.038 mg/L) at several locations above recommended drinking water concentrations suggested higher levels of heavy metals in the groundwater system.

3.3 Comparative Assessment of Heavy Metal Distribution

The comparison of the concentration of some of the metals showed that the surface water and groundwater quality differed significantly. Groundwater had significantly elevated levels of all the metals that were evaluated compared to surface water (Table 5). The concentrations of iron were found to be 0.19 mg/L in surface water and 0.86 mg/L in groundwater, which is a 352.6% increase, while the concentration of uranium was 4.6 µg/L in surface

water and 28.6 µg/L in groundwater, which corresponds to a 521.7% increase. Aside from that, arsenic had the highest relative increase (600%), followed by Lead (300%) and Mercury (300%), which shows that there is a significant enrichment of metals in the groundwater resources. Nickel concentrations increased from 0.010 to 0.038 mg/L, whereas chromium and cadmium exhibited 200% increases. These findings suggest that groundwater experiences greater accumulation of heavy metals due to prolonged groundwater–rock interaction, mineral dissolution, and contaminant retention within aquifers. Overall, the results indicate that groundwater is considerably more vulnerable to heavy metal contamination than surface water in the Sirhind Canal region.

Table 5. Comparative Summary Statistics of Heavy Metals in Surface Water and Groundwater Samples

Heavy Metal	Surface Water Mean	Groundwater Mean	Difference (%)	Dominant Source
Iron (Fe) (mg/L)	0.19	0.86	352.6	Geogenic
Copper (Cu) (mg/L)	0.011	0.028	154.5	Agricultural / Urban
Lead (Pb) (mg/L)	0.003	0.012	300.0	Anthropogenic
Mercury (Hg) (mg/L)	0.0002	0.0008	300.0	Anthropogenic
Nickel (Ni) (mg/L)	0.010	0.038	280.0	Geogenic / Agricultural
Arsenic (As) (mg/L)	0.002	0.014	600.0	Geogenic / Agricultural
Chromium (Cr) (mg/L)	0.006	0.018	200.0	Geogenic
Cadmium (Cd) (mg/L)	0.0004	0.0012	200.0	Agricultural
Uranium (U) (µg/L)	4.6	28.6	521.7	Geogenic

The concentrations of all the heavy metals investigated in the groundwater were much higher than in the surface water. The highest concentrations were noted for arsenic (600%), uranium (521.7%), and iron (352.6%), reflecting the greatest geogenic influence and extending the groundwater–rock interaction. In the case of surface water, comparatively low concentrations of metals were observed because of continuous flow in the Sirhind canal system and the dilution effect.

3.4 Source Identification of Heavy Metals

Heavy metal contamination in the Sirhind Canal area is related to natural and anthropogenic sources. Table 6 provides a summary of the processes that most strongly relate to the occurrence of high concentrations of iron and uranium in groundwater, including weathering of mineral-

bearing rocks, geologic formations, and groundwater–rock interactions. Natural dissolution processes of minerals can also be a source of nickel and chromium. Anthropogenic inputs include local industrial influences, domestic wastewater, urban runoff, and agricultural activities. Some contaminants such as arsenic, cadmium, and nickel can enter via fertiliser application and agricultural leaching, while lead can enter via urban runoff and contaminated soils. Mercury is mainly associated with atmospheric deposition and industrial emissions. High concentrations of Fe (0.86 mg/L), U (28.6 µg/L), As (0.014 mg/L), and Ni (0.038 mg/L) in groundwater were attributed to a mix of geogenic processes and human activity. The results showed the complicated environmental processes that affect the distribution of heavy metals in the study area.

Table 6. Possible Sources and Environmental Pathways of Heavy Metals in the Sirhind Canal Region

Heavy Metal	Major Source	Environmental Pathway	Potential Impact
Iron (Fe)	Weathering of iron-bearing minerals, geological formations	Rock dissolution, groundwater–rock interaction	Affects water taste, staining, and aesthetic quality
Copper (Cu)	Agricultural chemicals, plumbing materials, natural deposits	Runoff, leaching, corrosion of pipes	Toxicity at elevated concentrations
Lead (Pb)	Anthropogenic activities, urban runoff, and old pipelines	Leaching, wastewater discharge, soil contamination	Neurological and developmental disorders
Mercury (Hg)	Atmospheric deposition, industrial emissions	Surface runoff, sediment transport	Neurotoxicity and bioaccumulation
Nickel (Ni)	Geological formations, agricultural inputs	Mineral dissolution, fertilizer leaching	Skin irritation and chronic toxicity
Arsenic (As)	Natural geogenic sources, agricultural activities	Groundwater mobilization, leaching from sediments	Carcinogenic and toxic health effects
Chromium (Cr)	Natural weathering, industrial influences	Soil erosion, groundwater transport	Potential toxicity at high concentrations
Cadmium (Cd)	Phosphate fertilizers, agricultural runoff	Leaching from agricultural soils	Kidney damage and chronic toxicity
Uranium (U)	Uranium-bearing geological formations	Groundwater–rock interaction, aquifer	Renal toxicity and radiological concerns

		dissolution	
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The findings show that the sources of heavy metal contamination in the study area are natural (geogenic) and anthropogenic. Major geologic associations are for iron and uranium; agricultural activities, fertilizer applications, urban run-off, and other anthropogenic (human-made) sources can impact arsenic, cadmium, lead, and nickel.

3.5 Statistical Evaluation and Pollution Assessment

The distribution patterns, interrelationships, and compliance status of the heavy metals in surface water and ground water were statistically assessed and evaluated to understand them. The concentrations of heavy metals in groundwater were observed to be comparatively high compared to surface water, as presented in Table 7, which include Fe (0.86 mg/L), U (28.6 µg/L), Ni (0.038 mg/L),

As (0.014 mg/L), and Pb (0.012 mg/L). The iron–uranium, arsenic–uranium, and nickel–arsenic pairs exhibited strong positive correlation, implying that they have a common geogenic source and processes of groundwater–rock interaction. The results of the comparison of the groundwater samples with BIS and WHO standards revealed that the concentration of iron, arsenic, lead, and nickel in some samples was above the acceptable limit, while the concentration of most of the surface water was within the acceptable limit. The overall pollution assessment suggests that groundwater is more prone to pollution with heavy metals and has more potential to degrade the quality of drinking water compared to the surface water in the Sirhind Canal region.

Table 7. Correlation Analysis and Compliance Assessment of Heavy Metals in Surface Water and Groundwater Samples

Heavy Metal	Surface Water Mean	Groundwater Mean	BIS Limit	WHO Limit	Compliance Status	Major Correlation Pattern
Iron (Fe) (mg/L)	0.19	0.86	0.30	0.30	Groundwater Exceeded	Strong correlation with U (r = 0.886)
Copper (Cu) (mg/L)	0.011	0.028	0.05	2.00	Complied	Moderate correlation with Ni (r = 0.636)
Lead (Pb) (mg/L)	0.003	0.012	0.01	0.01	Groundwater Exceeded	Strong correlation with As (r = 0.714)
Mercury (Hg) (mg/L)	0.0002	0.0008	0.001	0.001	Complied	Moderate correlation with Pb (r = 0.728)
Nickel (Ni) (mg/L)	0.010	0.038	0.02	0.07	Groundwater Exceeded (BIS)	Strong correlation with As (r = 0.842)
Arsenic (As) (mg/L)	0.002	0.014	0.01	0.01	Groundwater Exceeded	Strong correlation with U (r = 0.864)
Chromium (Cr) (mg/L)	0.006	0.018	0.05	0.05	Complied	Strong correlation with Ni (r = 0.781)
Cadmium (Cd) (mg/L)	0.0004	0.0012	0.003	0.003	Complied	Moderate correlation with Pb (r = 0.645)
Uranium (U) (µg/L)	4.6	28.6	30	30	Approaching Limit	Strong correlation with Fe (r = 0.886) and As (r = 0.864)

The concentrations of the heavy metals in the groundwater samples were significantly higher than those in surface water samples. With respect to drinking water quality, the greatest concern was found for Iron, arsenic, lead, nickel, and uranium. High concentrations in groundwater are interpreted as long-term groundwater contamination that

involved the same geogenic sources and groundwater–rock interaction processes as indicated by the strong positive correlation of Fe, U, As, and Ni.

3.6 Human Health Risk Assessment

The groundwater was determined to have more potential human health risks than surface water because of high

concentrations of iron, arsenic, lead, nickel, and uranium. There is potential for increased exposures to these metals from long-term consumption of contaminated groundwater, as identified through drinking water exposure. Non-carcinogenic risks are predominantly linked to iron, nickel, and uranium and can have detrimental effects on kidney function and health. The primary concerns for carcinogens are related to exposure to arsenic and lead, particularly if it is seen to exceed the BIS and WHO limits. The findings show that groundwater should be regularly monitored and treated to minimise potential health risks and supply safe drinking water to the local community in general.

3.7 Environmental Implications of Heavy Metal Contamination

The presence of heavy metals in water bodies can impact water quality, health of water resources and water sustainability. The groundwater samples had higher levels of iron (0.86 mg/L), uranium (28.6 µg/L), arsenic (0.014 mg/L), lead (0.012 mg/L), and nickel (0.038 mg/L) than did the surface water, suggesting higher levels of contamination in the groundwater samples. These metals have the potential to pollute the water and impact water quality for drinking and agriculture. Bioaccumulation can cause ecological imbalances if present at high levels, and arsenic, lead and uranium can be toxic to aquatic life. The accumulation of pollutants in ground water sources that are used as a first water source in the area can also contribute to degradation of this water source. Hence, it is crucial to have a regular monitoring plan, pollution control measures and water resource management plans in place to maintain environmental quality and to guarantee sustainable water security.

4. CONCLUSION

The aim of the present study was to determine the distribution, probable sources and health risk of the heavy metals in surface water and ground water in Sirhind Canal region, Punjab. Groundwater was found to have

significantly higher levels of heavy metals when compared with surface water, with notable enrichments in the case of iron (0.86 mg/L), uranium (28.6 µg/L), nickel (0.038 mg/L), arsenic (0.014 mg/L), and lead (0.012 mg/L). The concentrations of most surface water samples were within the BIS and WHO guidelines and some groundwater samples exceeded the guideline concentrations for iron, arsenic, lead and nickel. The observed distribution suggests that both geogenic and anthropogenic processes such as groundwater–rock interaction, mineral weathering, agricultural activities, application of fertilizers, and urban runoff have a role in the heavy metal contamination. Correlation analysis also showed similarities in the sources and transport pathways of several metals. The high levels of arsenic, lead, and uranium in the groundwater might have long-term health implications if people ingest drinking water containing them. Hence, monitoring of water resources, pollution control, sustainable agriculture and periodic sampling of groundwater quality is required to protect the health of the people and to promote sustainable use of water resources in the Sirhind Canal area.

Declarations

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