Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(3), 494-502 | ISSN:2251-6727

Heavy Metal Dynamics in the Giri Stream: Linking Water Quality to Fish Community Structure

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(Received: 16 March 2026 Revised: 14 April 2026 Accepted: 01 May 2026)

KEYWORDS

Heavy metals, ICP-MS, Giri stream, Himachal Pradesh, fish diversity, Yamuna River, Himalayan tributaries.

ABSTRACT: The Giri stream, a major perennial tributary of the Yamuna River originating in the Himalayan foothills of Himachal Pradesh, serves as a vital freshwater resource supporting local fisheries, irrigation, and biodiversity. This study systematically evaluated heavy metal contamination and ichthyofaunal diversity along longitudinal gradients of the Giri stream, encompassing three representative reaches: the upstream reach at Kharapathar (Shimla), the midstream reach at Giri Pul (Solan), and the downstream reach at Nawada Bridge (Sirmaur), over during 2025–2026.Twelve heavy metals (Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Cd, Hg, Pb) were quantified using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). All metal concentrations were well within the permissible limits prescribed by the World Health Organization (WHO, 2017) and Bureau of Indian Standards (BIS, 2012). A total of 10 fish species belonging to 4 orders and 5 families were recorded, with lowest species richness upstream (1 species) and highest downstream (8 species). Pearson's correlation analysis revealed strong relationship between heavy metals and fish diversity indices. However, this relationship is not causal; instead, it represents a common downstream spatial trend, where both metal concentrations and fish diversity increase along the upstream-to-downstream gradient due to separate ecological and geochemical processes. Overall, the findings suggest that the Giri stream maintains good ecological integrity, characterized by low heavy metal contamination and satisfactory water quality. Nevertheless, periodic monitoring is recommended to ensure the sustained health of the aquatic ecosystem.

1. Introduction

Freshwater ecosystems, though covering less than one percent of Earth's total land area, harbour extraordinary biological diversity and underpin critical ecosystem services including water provisioning, nutrient cycling, and habitat support for thousands of aquatic species [1,2]. Rivers and streams are among the most dynamic of these systems, characterized by longitudinal connectivity, seasonal hydrological variability, and intricate interactions among physical, chemical, and biological components [3]. Disturbances in riverine systems can rapidly propagate downstream, amplifying ecological and human health impacts across entire watersheds.

India hosts one of the largest and most diverse river networks in the world, comprising more than twenty major river basins. Although freshwater ecosystems occupy less than three percent of the country's geographical area, they support approximately 10-12% of recorded biodiversity, including more than 900 freshwater fish species [4]. The rivers of the north-western Himalayan region, including those of Himachal Pradesh, originate in glaciated headwaters and are ecologically highly sensitive to environmental perturbations [5].

Himachal Pradesh is drained by five major rivers: Sutlej, Beas, Ravi, Chenab, and Yamuna, all originating in the Himalayas. The Giri stream is one of the most significant tributaries of the Yamuna River in the state, owing to its importance for inland fisheries, irrigation, and domestic water supply.

Heavy metals are a category of contaminants of particular concern in riverine systems owing to their persistence, non-biodegradability, and tendency to bioaccumulate in aquatic biota [6,7]. In freshwater fish, heavy metals enter via gills, skin, and the digestive system, accumulating in metabolically active tissues such as the liver, kidney, and muscle. Chronic exposure can cause ion-regulatory dysfunction, oxidative stress, reproductive impairment, and mortality, ultimately influencing fish population dynamics [8,9]. For humans, dietary exposure through consumption of contaminated fish is a major pathway for chronic heavy metal toxicity, linked to neurological disorders, kidney damage, and elevated cancer risk [10].

Despite the ecological and socioeconomic significance of the Giri stream, comprehensive investigations into heavy metal contamination and its implications for fish fauna remain limited. Earlier studies in the Yamuna basin have documented elevated heavy metal levels in downstream urban and industrial reaches [11,12], but upstream Himalayan tributaries have received comparatively little attention.

2. Objectives

To analyse the spatial distribution of heavy metal concentrations in the Giri stream and to evaluate potential ecological and health risks associated with fish community structures.

3. Study Area

The Giri stream, a principal tributary of the Yamuna River, is situated in the northwestern Himalayan state of Himachal Pradesh. The state spans 30°22′40″-33°12′40″N and 75°45′55″-79°04′20″E, covering 55,673 km² with an altitudinal gradient of 350-6,975 m, reflecting pronounced physiographic and hydrological heterogeneity. It is bordered by Jammu and Kashmir and Ladakh (north), Punjab (west), Haryana and Uttarakhand (south), and China (east).

The Giri stream originates from the Kupper Peak, Kotkhai region of Shimla district. It flows through the districts of Shimla, Solan, and Sirmaur before joining the Yamuna River near Paonta Sahib in Sirmaur district, close to the Himachal Pradesh-Uttarakhand border. The total length of the stream is approximately 150 km, and its catchment area covers around 2,600 km². The stream is primarily rain-fed, with additional contributions from seasonal snowmelt in its upper catchment, and maintains perennial flow throughout the year. Its catchment falls predominantly in the subtropical climate zone. The stream flows in a north-east to south-west direction and is regionally known as 'Giri Ganga'.

The study was conducted randomly at three sampling sites selected to cover the upstream, midstream, and downstream sections of the stream (Table 1). Site 1 (S1) at Kharapathar in Shimla, Site 2 (S2) at Giri Pul in Solan district, and Site 3 (S3) at Nawada Bridge in Sirmaur district.

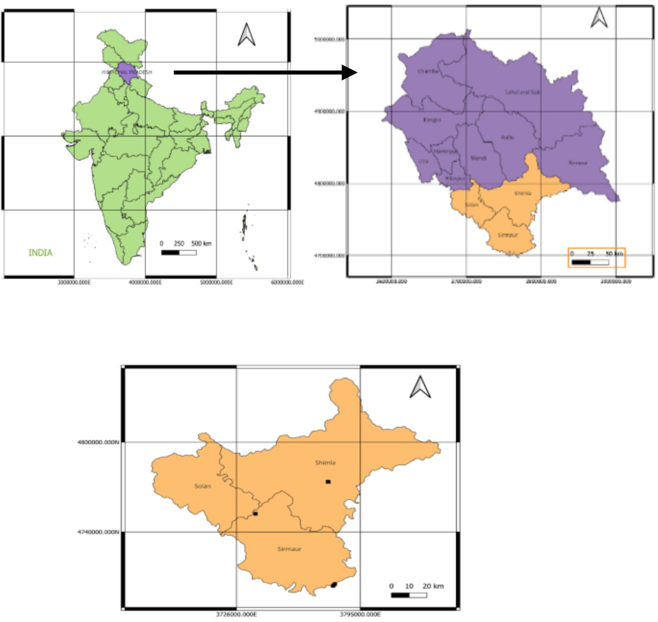

Figure 1: Study Area

4. Methods

4.1 Water Sample Collection

Water samples were collected from each of the three sampling sites randomly following standard procedures for trace metal analysis. At each site, a 1-litre sample was collected in acid-washed polyethylene bottles pre-treated with dilute nitric acid. Prior to sampling, bottles were thoroughly rinsed with distilled water. During collection, each bottle was rinsed three times with stream water before filling. Collected samples were immediately preserved by acidification with 2 ml of concentrated nitric acid (HNO_3) to prevent metal precipitation and adsorption onto container walls. Samples were then transported to the laboratory under controlled conditions. Preservation techniques followed standard methods described in [13].

4.2 Heavy Metal Analysis

The analysis of heavy metal concentrations was carried out at the Advanced Materials Research Centre (AMRC), Indian Institute of Technology, Mandi. Prior to analysis, water samples were filtered through Whatman No. 1 filter paper to remove suspended particulates. Filtered samples were subjected to acid digestion using concentrated HNO_3, with gentle heating until a clear solution was obtained. After cooling, samples were analysed using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Twelve heavy metals were quantified: Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Molybdenum (Mo), Cadmium (Cd), Mercury (Hg), and Lead (Pb). Results were compared with WHO and BIS permissible limits for drinking water.

4.3 Fish Sampling and Identification

Fish specimens were collected from each sampling site using locally appropriate fishing methods, with the assistance of licensed fishermen, to ensure representative capture of resident species. Samples were collected randomly from upstream, midstream, and downstream sections. Collected specimens were preserved in 5-10% formalin solution depending on their size, transported to the laboratory, and identified using standard taxonomic keys of [14,15,16]. IUCN conservation status was assigned to each species.

4.4 Statistical Analysis

Descriptive statistics including mean, standard deviation, and range were calculated for all physicochemical parameters and heavy metal concentrations. Pearson's correlation coefficient was used to assess the relationships among heavy metals and fish diversity indices.

5. Results and Discussion

5.1 Heavy Metal Concentrations

The concentrations of twelve heavy metals at three sampling sites, compared against WHO and BIS permissible limits, are summarised in Tables 1 and 2. All measured values were below the maximum permissible limits of both WHO (2017) and BIS (2012), confirming that the Giri stream does not exhibit significant heavy metal contamination.

A consistent upstream-to-downstream gradient was evident, with higher concentrations recorded at the downstream site for most metals. Zinc (Zn) recorded the highest concentration among all metals at the downstream site (0.0623 mg/l), followed by manganese (Mn; 0.0377 mg/l) and chromium (Cr; 0.0118 mg/l). In contrast, most metals at the upstream site were either below detection limit (BDL) or present in negligible trace amounts. Chromium concentrations (max. 0.0118 mg/l) remained well below the 0.05 mg/l WHO/BIS limit. Manganese (max. 0.0377 mg/l) was within the 0.1 mg/l limit, as was iron (max. 0.0018 mg/l; limit 0.3 mg/l). Nickel (max. 0.0051 mg/l) was below both WHO (0.07 mg/l) and BIS (0.02 mg/l) limits. Copper (max. 0.0066 mg/l) was far below the 2.0 mg/l WHO and 0.05 mg/l BIS limits. Arsenic concentrations (max. 0.0033 mg/l), a metal of particular concern for carcinogenicity, remained within the 0.01 mg/l guideline value. Cadmium (max. 0.00009 mg/l), mercury (max. 0.0003 mg/l), and lead (max. 0.0005 mg/l) were all significantly below their respective permissible limits of 0.003, 0.001- 0.006, and 0.01 mg/l, respectively. These findings are broadly consistent with [17], who reported that heavy metal concentrations in the Giri stream remained within CPCB permissible limits.

This spatial enrichment pattern is attributable to natural processes; accumulation of dissolved minerals, increased dissolved load, and minor surface runoff from downstream catchment areas, rather than significant anthropogenic pollution. The rugged and uneven topography of the Giri basin largely restricts agricultural land use and human settlement, thereby limiting anthropogenic metal inputs.

Table 1: Spatial Variation of Heavy Metal Concentrations in Comparison with WHO and BIS Standards.

S.No	Heavy Metal	Upstream (mg/l)	Midstream (mg/l)	Downstream (mg/l)	WHO Limit (mg/l)	BIS Acceptable Limit (mg/l)

1.	Chromium (Cr)	<0.000	0.0015	0.0118	0.05	0.05
2.	Manganese (Mn)	0.0001	0.0034	0.0377	0.1	0.1
3.	Iron (Fe)	<0.0000	0.0003	0.0018	0.3	0.3
4.	Cobalt (Co)	<0.0000	0.0001	0.0008	-	-
5.	Nickel (Ni)	0.0001	0.0022	0.0051	0.07	0.02
6.	Copper (Cu)	0.0003	0.0025	0.0066	2.0	0.05
7.	Zinc (Zn)	0.0088	0.0022	0.0623	3.0	5.0
8.	Arsenic (As)	0.0001	0.0021	0.0033	0.01	0.01
9.	Molybdenum (Mo)	<0.0000	0.0012	0.0017	-	-
10.	Cadmium (Cd)	<0.00000	0.00003	0.00009	0.003	0.003
11.	Mercury (Hg)	<0.0000	0.0001	0.0003	0.006	0.001
12.	Lead (Pb)	0.0001	0.0001	0.0005	0.01	0.01

Table 2: Descriptive statistics of Heavy Metal concentrations (mg/l) across sampling sites.

S.No.	Heavy Metal	Range	Mean	Standard Deviation
1.	Chromium (Cr)	BDL - 0.0118	0.0044	0.0064
2.	Manganese (Mn)	0.0001 - 0.0377	0.0137	0.0208
3.	Iron (Fe)	BDL - 0.0018	0.0007	0.0009
4.	Cobalt (Co)	BDL - 0.0008	0.0003	0.0004
5.	Nickel (Ni)	0.0001 - 0.0051	0.0024	0.0025
6.	Copper (Cu)	0.0003 - 0.0066	0.0031	0.0031
7.	Zinc (Zn)	0.0022 - 0.0623	0.0244	0.0329
8.	Arsenic (As)	0.0001 - 0.0033	0.0018	0.0016
9.	Molybdenum (Mo)	BDL - 0.0017	0.0009	0.0008
10.	Cadmium (Cd)	BDL - 0.00009	0.00004	0.00004
11.	Mercury (Hg)	BDL - 0.0003	0.0001	0.0001
12.	Lead (Pb)	0.0001 - 0.0005	0.0002	0.0002

(BDL: Below Detectable Limit)

5.2 Ichthyofaunal Diversity

A total of 10 fish species belonging to Class Actinopterygii, distributed across 4 orders (Cypriniformes, Synbranchiformes, Anabantiformes, and Siluriformes) and 5 families (Cyprinidae, Danionidae, Mastacembelidae, Channidae, and Sisoridae), were recorded from the Giri stream during the study period (Table 3). The assemblage was dominated by cyprinid fishes, consistent with the composition of other Himalayan riverine systems. 16 fish species have been previously documented in the Giri stream [18], with Cypriniformes being the most dominant order, followed by Siluriformes and Synbranchiformes, a pattern broadly consistent with our findings.

Table 3: Systematic list of Fish Species Recorded in the Giri stream from 3 different sites.

S.No.	Fish Species	IUCN Status
Class: Actinopterygii		
Order: Cypriniformes		
Family: Cyprinidae		
1.	*Tor putitora* (Hamilton,1822)	Endangered (EN)
2.	*Schizothorax richardsonii* (Gray,1832)	Vulnerable (VU)
	Pethia ticto (Hamilton,	Least Concern (LC)

3.	1822)	
Family: Danionidae		
4.	*Opsarius bendelisis* (Hamilton,1807)	Least Concern (LC)
5.	*Barilius barila* (Hamilton, 1822)	Least Concern (LC)
6.	*Barilius vagra* (Hamilton, 1822)	Least Concern (LC)
Order: Synbranchiformes		
Family: Mastacembelidae		
7.	*Mastacembelus armatus* (Lacepede, 1800)	Least Concern (LC)
Order: Anabantiformes		
Family: Channidae		
8.	*Channa punctata* (Bloch, 1793)	Least Concern (LC)
9.	*Channa orientalis* (Bloch & Schneider, 1801)	Least Concern (LC)
Order: Siluriformes		
Family: Sisoridae		
10.	*Glyptothorax pectinopterus* (McClelland, 1842)	Least Concern (LC)

Table 4: Distribution and Diversity of Fish Species in Upstream, Midstream, and Downstream.

S. No.	Fish species	Upstream	Midstream	Downstream
1.	***Tor putitora*** **(Hamilton, 1822)**	✕	✓	✕
2.	***Schizothorax richardsonii*** **(Gray, 1832)**	✓	✓	✕
3.	***Pethia ticto*** **(Hamilton, 1822)**	✕	✓	✓
4.	***Opsarius bendelisis*** **(Hamilton, 1807)**	✕	✓	✓
5.	***Barilius barila*** **(Hamilton, 1822)**	✕	✓	✓
6.	***Barilius vagra*** **(Hamilton, 1822)**	✕	✕	✓
7.	***Mastacembelus armatus*** **(Lacepede, 1800)**	✕	✕	✓
8.	***Channa punctata*** **(Bloch, 1793)**	✕	✕	✓
9.	***Channa orientalis*** **(Bloch & Schneider, 1801)**	✕	✕	✓
10.	**Glyptothorax** ***pectinopterus*** **(McClelland, 1842)**	✕	✕	✓

Table 5: Fish Diversity Indices across different stream stretches.

Indices	Upstream	Midstream	Downstream
Taxa (S)	1	5	8

Dominance (D)	1.0000	0.2000	0.1250
Simpson (1-D)	0.0000	0.8000	0.8750
Shannon (H′)	0.0000	1.6094	2.0794
Evenness (J′)	0.0000	1.0000	1.0000

The diversity indices (Table 5) quantitatively confirm the upstream-to-downstream enrichment pattern. Shannon's index increased from 0.0000 upstream to 2.0794 downstream, and Simpson's index rose from 0 to 0.875, indicating substantially higher ecological diversity and community stability in the lower reaches. The dominance index decreased from 1.000 (upstream, single species dominance) to 0.125 (downstream, more equitable distribution). Pielou's Evenness was 1.000 at both midstream and downstream sites, indicating uniform species distribution in these areas. Similar downstream increases in fish diversity have been reported in the Rissa Stream, Mandi [19] and in the Sirsa River, Solan [20], supporting the generalizability of these patterns across Himalayan systems.

Table 6: Pearson Correlation between Heavy Metals and Fish Diversity Indices.

Metal	Taxa (S)	Dominance (D)	Simpson (1-D)	Shannon (H′)	Evenness (J′)
Chromium (Cr)	+0.98	-0.99	+0.99	+0.99	+0.87
Manganese (Mn)	+0.99	-0.99	+0.99	+0.99	+0.89
Iron (Fe)	+0.97	-0.98	+0.98	+0.98	+0.85
Cobalt (Co)	+0.96	-0.97	+0.97	+0.97	+0.83
Nickel (Ni)	+0.99	-0.99	+0.99	+0.99	+0.88
Copper (Cu)	+0.99	-0.99	+0.99	+0.99	+0.88
Zinc (Zn)	+0.71	-0.80	+0.80	+0.77	+0.50
Arsenic (As)	+0.99	-0.99	+0.99	+0.99	+0.89
Molybdenum (Mo)	+0.97	-0.98	+0.98	+0.98	+0.86
Cadmium (Cd)	+0.95	-0.96	+0.96	+0.96	+0.82
Mercury (Hg)	+0.97	-0.98	+0.98	+0.98	+0.85
Lead (Pb)	+0.96	-0.97	+0.97	+0.97	+0.84

The Pearson correlation analysis between heavy metals and fish diversity indices (Table 6) revealed strong positive correlations between most metals (Cr, Mn, Ni, Cu, As) and diversity metrics: taxa richness, Shannon index (H'), and Simpson's index (1-D). However, this relationship is not causal.

Rather, it reflects a shared downstream spatial gradient: both metal concentrations and fish diversity increase along the upstream-to-downstream continuum due to independent ecological and geochemical factors. Metal concentrations increase downstream due to cumulative dissolved load, while fish diversity increases due to greater habitat heterogeneity, warmer temperatures, and more diverse microhabitats. All heavy metal values remained well below any ecotoxicologically harmful threshold, indicating that the observed correlations represent a coincidental spatial pattern rather than a direct biological effect. This interpretation is consistent with findings reported in similar Himalayan River studies [21].

5.3 Relationship Between Metal Concentration and Fish Community Structure

Fish community structure in the Giri stream reflects the composition, abundance, diversity, and spatial distribution of fish species, and serves as a sensitive indicator of environmental conditions and water quality. Variations in physicochemical parameters and heavy metal concentrations along the upstream-downstream gradient play a significant role in shaping this structure. Similar relationships between fish assemblages and abiotic factors have been reported from river systems of Himachal Pradesh, where environmental variables strongly influence species composition and diversity [22,23,24]. In relatively less impacted upstream regions, the fish assemblage is typically dominated by pollution-sensitive and ecologically specialized species, indicating better habitat quality and minimal anthropogenic disturbance. In contrast, downstream sections, which are more influenced by increased metal load and human activities, tend to exhibit a shift toward more tolerant and generalist species, often accompanied by changes in species richness and evenness. Such alterations in fish community structure highlight the ecological consequences of heavy metal dynamics, where even sub-lethal concentrations can influence species distribution, behaviour, and survival. Therefore, analysing fish community patterns in conjunction with water quality parameters provides a comprehensive understanding of ecosystem health and the potential impacts of metal contamination in riverine systems like the Giri stream.

6. Conclusion

This study presents the comprehensive integrated assessment of heavy metal contamination, physicochemical water quality, and ichthyofaunal diversity across the longitudinal continuum of the Giri stream, a major Himalayan tributary of the Yamuna River in Himachal Pradesh, India. The principal findings can be summarized as follows:

All twelve heavy metals analysed: Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Cd, Hg, and Pb, were detected at concentrations well within permissible limits set by WHO (2017) and BIS (2012), confirming the absence of significant heavy metal pollution in the Giri stream.

A total of 10 fish species belonging to 4 orders and 5 families were recorded. Species richness and diversity indices (Shannon, Simpson) increased progressively from upstream (1 species) to downstream (8 species), reflecting the influence of increasing habitat heterogeneity, warmer temperatures, and greater nutrient availability.

Pearson's correlation analysis revealed strong positive correlations between most heavy metals and fish diversity indices; an outcome attributed to shared spatial downstream gradients rather than any direct causal relationship. The risk of bioaccumulation and biomagnification of heavy metals in fish is minimal, and no significant ecological or human health concerns are associated with current metal loads in the Giri stream.

The Giri stream currently exhibits good ecological health, with its fish community and water quality reflecting a largely intact Himalayan riverine ecosystem. However, increasing anthropogenic pressures including growing tourism, small-scale

agriculture, and urbanization in lower catchment areas represent potential future threats. Continuous and systematic monitoring of heavy metal concentrations, physicochemical parameters, and biological communities is essential to detect early deterioration and ensure the long-term sustainability of this valuable resource. The present study provides an important baseline for such monitoring efforts and contributes to the broader understanding of pollution dynamics and ecological health in Himalayan River systems.

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