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A Review on Heavy Metal Contamination in the Water Bodies of Himachal Pradesh

Shivali Sharma, *Harinder Singh Banyal, Neha Bains, Rajender Pal, Monika Singh

Department of Biosciences, Himachal Pradesh University, Summer Hill
Shimla (H.P.) – 171005, India
*Corresponding author Email: dr.harinderbanyal@gmail.com

Introduction

Freshwater ecosystems serve as the lifeblood of our planet, playing a fundamental role in maintaining biodiversity and driving numerous ecological processes. These dynamic systems rely on a delicate interplay of factors, including continuous water flow, sediment and organic matter input, natural variations in temperature and light, and a thriving network of aquatic organisms. While freshwater is crucial for human existence supporting transportation, agriculture, and daily consumption. Its broader ecological significance has often been overshadowed by its direct utility to society (Baron et al., 2002). However, freshwater ecosystems are increasingly under siege from a variety of stressors, both natural and anthropogenic. Habitat fragmentation, invasive species, pollution, and excessive sedimentation are accelerating ecosystem degradation, disrupting ecological balance, and threatening aquatic biodiversity (Bertrand et al., 2018). Among the most pressing threats is heavy metal contamination, a persistent and global environmental hazard (Javed & Usmani, 2016). These toxic metals infiltrate aquatic environments through natural processes such as volcanic eruptions and rock weathering, but human activities such as industrial discharges, mining operations, wastewater release, and agricultural runoff significantly amplify their prevalence (Hashem et al., 2017; Timothy & Williams, 2019).

Highly toxic metals like Chromium (Cr), Nickel (Ni), Copper (Cu), Zinc (Zn), Cadmium (Cd), Lead (Pb), Mercury (Hg), and Arsenic (As) pose severe threats to aquatic organisms. Due to their non-biodegradable nature, these contaminants persist in water bodies, accumulating in sediments and bioaccumulating in the food chain (Stankovic et al., 2014). Their prolonged presence disrupts the ecological equilibrium, weakening aquatic life and leading to biomagnification, which can have devastating consequences for predators at higher trophic levels. Furthermore, these pollutants pose significant health risks to human population that rely on contaminated water sources for drinking, fishing, and irrigation. Exposure to heavy metals has been linked to severe health conditions, including neurological disorders, kidney damage, and various forms of cancer, emphasizing the urgent need for stringent monitoring and mitigation strategies (Ali & Khan, 2018).

As freshwater ecosystems continue to face mounting pressures, comprehensive conservation efforts, effective pollution control measures, and sustainable water management practices are imperative to safeguard these invaluable resources for future generations. This review aims to comprehensively assess the extent, sources and ecological consequences of heavy metal contamination in the water bodies of Himachal Pradesh.

Area of Study

Himachal Pradesh (Fig.1), a state in Northwestern Himalayas, lies between 30°22′40″ N to 33°12′40″ N latitude and 75°45′55″ E to 79°04′20″ E longitude, covering an area of 55,673 sq.km., with varied elevation ranging from 350 – 6975 meters above mean sea level (Anonymous, 2025). The state is endowed with numerous water bodies in the forms of rivers, lakes, streams and reservoirs. The Sutlej, the Beas, the Ravi, the Chenab and the Yamuna are the major rivers flowing through the state, which are fed by different tributaries/streams. The Govind Sagar Reservoir, the Pong dam Reservoir and the Pandoh Reservoir are the major reservoirs of the state. These differential water bodies act as life-line of the state, harbouring varied biotic communities and acts as major water supply to local inhabitants.

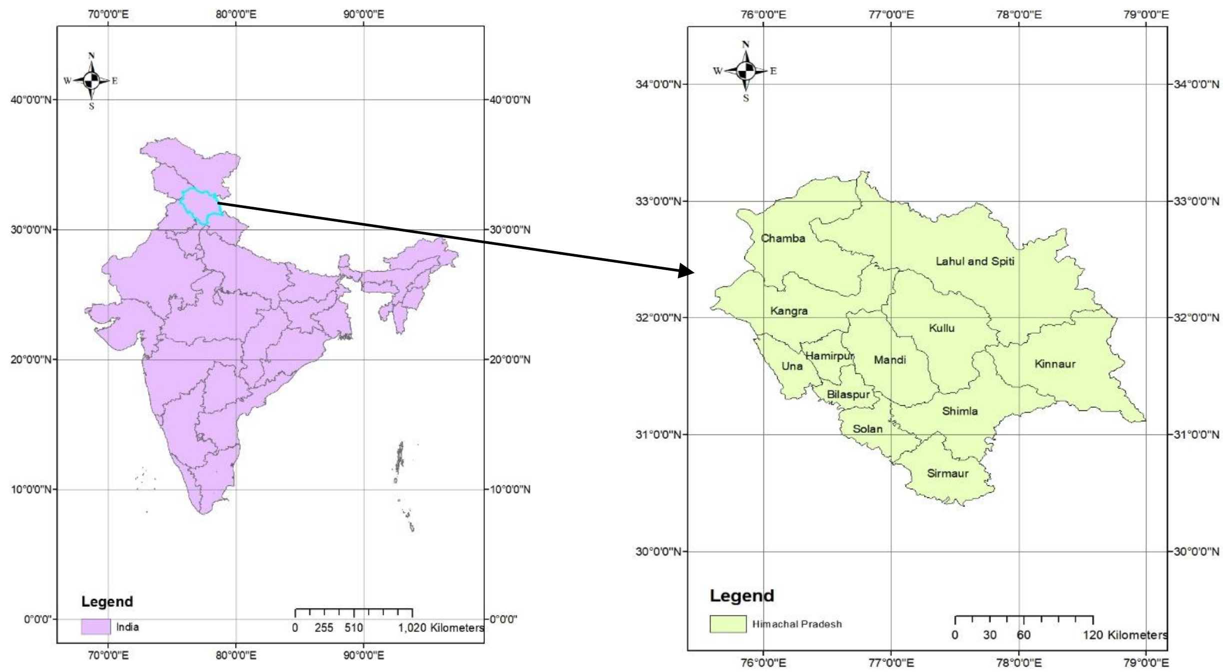

Fig. 1 Map showing area of study.

Materials and Methods

This review follows a systematic approach by conducting an extensive literature search using databases like Google Scholar, Scopus, Sci-Hub, ResearchGate, Web of Science etc. and relevant literature on the bases of heavy metal contamination in different water sources of Himachal Pradesh, focusing on sources, ecological impacts and mitigation strategies was compiled. Statistical findings from reviewed studies were compiled to highlight concentration ranges and exceedances of permissible limits.

Results and Discussion:

Heavy metal contamination in Himachal Pradesh's water bodies has emerged as a critical environmental concern, posing significant risks to aquatic ecosystems and human health. Heavy metals such as lead, mercury, cadmium, arsenic and chromium are naturally occurring elements that enter water bodies through industrial effluents, mining activities, agricultural runoff, and improper waste disposal (Ali et al., 2019). While some heavy metals, such as zinc, copper, and iron, are essential for biological processes, excessive concentrations pose significant risks to aquatic ecosystems and human health (Fu & Wang, 2011). The presence of trace amounts of copper and zinc in water is beneficial, as they are crucial for enzymatic reactions and metabolic functions in aquatic organisms (Huang et al., 2014). Additionally, iron is vital for oxygen transport in aquatic life, and some metals exhibit antimicrobial properties that help control bacterial populations (Sanchez-Marin et al., 2017). However, these benefits are highly concentration-dependent, and even essential metals can become toxic at elevated levels.

Excessive heavy metal contamination in water bodies leads to bioaccumulation and biomagnification, resulting in severe ecological and health effects (Tchounwou et al., 2012). Toxic metals like mercury and lead have no known biological benefits and are highly hazardous even in small quantities. Mercury, when converted into methylmercury, accumulates in fish and poses serious neurological risks to humans (Driscoll et al., 2013). Lead exposure is linked to cognitive impairments and organ damage, while cadmium can cause kidney dysfunction and increased mortality in aquatic life (Jaishankar et al., 2014). These metals persist in water bodies for extended periods, affecting biodiversity, reducing water quality and disrupting aquatic food chains (Gautam et al., 2016). Effective remediation strategies such as bioremediation, chemical precipitation, and advanced filtration are crucial for mitigation of heavy metal pollution (Gupta et al., 2012). While heavy metals play an essential role in biological functions at trace levels, their excessive accumulation poses serious environmental and health hazards, highlighting the need for strict monitoring and pollution control measures.

Several researchers have assessed heavy metal contamination in the surface waters of rivers, streams, and lakes, as well as in groundwater from various sources across Himachal Pradesh.

The Baddi-Barotiwala Industrial Belt faces severe groundwater contamination, with Fe, Cu, Pb, and Mn exceeding safe drinking water limits due to unregulated industrial expansion and untreated effluent discharge (Kamaldeep et al., 2011). Similarly, the Sirsa River in Nalagarh valley suffers from elevated Cr, Fe, Mn, and Ni levels, exacerbated by industrial effluents, agricultural runoff, and riverbed mining (Herojeet et al., 2015).

Groundwater analysis in Kandaghat, Solan by Chauhan et al. (2014) showed seasonal variations in heavy metals (As, Cd, Fe, Pb, Zn), though within permissible limits. The contamination sequence for surface water was Pb > As > Zn > Cd > Fe, whereas groundwater followed Cd > As > Zn > Fe > Pb. Urban areas exhibited the highest contamination levels, with seasonal fluctuations influencing concentrations. The Markanda River in Kala-Amb was found to contain Zn and As in minor amounts, while Cr emerged as the dominant pollutant (Kashyap et al., 2015a).

A study on Kunthbyog Lake in Mandi district highlights seasonal variations in heavy metal contamination. While most heavy metals, including Pb, Zn, Mn, Cu, Fe, As, and Ni, remained within permissible limits set by the USEPA and WHO, Cd levels exceeded the safe threshold (0.01 mg/L) during the pre-monsoon and monsoon seasons. The study observed a consistent concentration trend (Fe > Zn > As) across seasons, with overall higher levels recorded before the monsoon. This seasonal fluctuation suggests that the anthropogenic activities such as local waste disposal, agricultural runoff and atmospheric deposition contribute to contamination (Kashyap & Verma, 2015). Similarly, a study on Rewalsar Lake by Kashyap et al. (2015b) found significant seasonal variations, with higher metal concentrations during the pre-monsoon season. Iron consistently exceeded permissible limits year-round, while Pb, Mn, Fe, Cd, and As surpassed drinking water standards before the monsoon, making the lake unsuitable for consumption and emphasizing the need for strict monitoring. A long-term study on Rewalsar Lake reveals a shift in pollution sources over the past 50 years from natural lithogenic origins to anthropogenic influences after 1990. Increased Pb from fossil fuel combustion and Cr from fertilizers highlight the need for continuous monitoring and stringent pollution control measures (Meena et al., 2017).

Furthermore, analysis made by Kashyap et al. (2015c) in Yamuna River near an industrial hub found that while most heavy metal concentrations remained within safe levels, Cr and As slightly exceeded WHO standards. Pollution indexing indicated minimal overall impact, except for Cr, which showed severe contamination. Principal Component Analysis (PCA) identified industrial, municipal and sewage discharges as primary pollution sources. Moreover, Zn and Fe concentrations in the Yamuna River near the Paonta Sahib industrial area were found to be within permissible limits but showed higher concentrations in the pre-monsoon season (Kashyap et al., 2016). The Satluj River shows significant heavy metal contamination, with Cd, Cr, and Mn surpassing WHO and BIS drinking water limits (Sharma & Walia, 2016).

In the Solan block, research by Rana et al. (2016) indicates that heavy metal concentrations in surface and groundwater vary across different land-use systems and seasons. Urban areas exhibited the highest contamination levels in surface water, while forest land use showed elevated Fe and Zn in groundwater. Seasonal trends revealed higher As, Zn and Pb levels during the rainy season, with Cd peaking in summer and Fe in winter. Despite these fluctuations, mid-hill land use practices in Solan do not significantly degrade water quality. A study on the River Beas found that while Ca, Mg, K, Na, and Cu remained within safe limits, Cd and Pb concentrations exceeded WHO and BIS standards (Sharma & Walia, 2017). An analysis of groundwater by Rout et al. (2017) in Nalagarh tehsil, Solan district revealed significant spatial variations in heavy metal ion fluxes, with the presence of Cd, Hg, Pb, Fe, Cu, Cr, Mn and Zn at varying concentrations across 25 locations, totalling 11.104 mg/L. Some of these exceeded safe limits, raising concerns about water quality and public health. There is significant heavy metal contamination in the groundwater of Solan and Shimla districts, with concentrations of As, Co, Cr, Ni, and Pb exceeding the safety limits set by WHO and USEPA. The risk assessment suggests that both children and adults face considerable non-carcinogenic and carcinogenic health hazards due to prolonged exposure through drinking water and dermal absorption (Kumari et al., 2021).

Sahil & Bhardwaj (2021) assessed the effects of urbanization on water bodies in Shimla, Dharamshala, Mandi, and Kullu, concluding that heavy metal levels in surface water remained within IS 10500:2012 and WHO drinking water standards. Seasonal variations also significantly influenced heavy metal levels in streams around the Shoghi-Shimla-Dhali bypass, with all metals remaining within permissible limits except Hg. Road construction activities led to heavy metal contamination, adversely affecting the physico-chemical and biological properties of surface water (Banyal et al., 2022). In the Baddi region, water quality assessments found Fe, Zn, Cu, Cr, Pd and Cd at varying levels, with some exceeding permissible thresholds (Sethi et al., 2022).

Kaur et al. (2022) analyzed heavy metal contamination in the groundwater of Solan and Shimla districts, the findings of their study indicate significant heavy metal contamination in the groundwater with concentrations of As, Co, Cr, Ni, and Pb exceeding the safety limits set by WHO and USEPA. The risk assessment suggests that both children and adults face considerable non-carcinogenic and carcinogenic health hazards due to prolonged exposure through drinking water and dermal absorption.

The presence of heavy metals in aquatic environments has detrimental effects on both ecological and human health. Heavy metals disrupt the physiological and biochemical functions of aquatic organisms, leading to bioaccumulation and biomagnification in the food chain (Kumar et al., 2019). Contaminated water consumption can cause neurological disorders (lead poisoning), kidney damage (cadmium toxicity), and carcinogenic effects (arsenic exposure) (Sharma et al., 2020). Irrigation with contaminated water leads to soil degradation and accumulation of heavy metals in crops, posing a risk to food safety (Singh & Gupta, 2018).

The increasing contamination of Himachal Pradesh's water bodies underscores the urgent need for comprehensive regulatory interventions, sustainable industrial practices and proactive pollution management to protect these vital water resources. Several approaches can help mitigate heavy metal contamination in the water bodies of Himachal Pradesh:

1. **Wastewater Treatment Plants**: Implementation of advanced treatment methods like adsorption, coagulation and membrane filtration can reduce heavy metal concentrations (Chandel et al., 2021).

2. **Sustainable Mining Practices**: Regulation of mining activities and proper waste disposal can prevent heavy metal leaching into water bodies (Verma et al., 2017).
3. **Phytoremediation**: The use of plants like *Eichhornia crassipes* (water hyacinth) and *Typha angustifolia* to absorb and detoxify heavy metals is an eco-friendly solution (Sharma et al., 2020).
4. **Public Awareness and Policy Implementation**: Strengthening environmental policies and increasing public awareness can help control pollution sources and promote sustainable practices (Singh & Gupta, 2018).

Conclusion:

Heavy metal contamination in the water bodies of Himachal Pradesh is an escalating environmental threat, endangering both aquatic ecosystems and public health. Industrial discharge, mining activities, agricultural runoff, and untreated municipal wastewater are driving pollution levels to alarming heights. The toxic accumulation of heavy metals disrupts biodiversity, contaminates drinking water sources, and poses severe health risks. To combat this crisis, a combination of advanced wastewater treatment, sustainable mining practices, and innovative solutions like phytoremediation is crucial. Strengthening environmental policies and fostering active community involvement can play a pivotal role in restoring the purity of these precious water resources.

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