Hydrogeochemical Assessment of Groundwater Contamination and Human Health Implications in Bathinda, District Punjab

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Abstract: This comprehensive review critically examines groundwater contamination in Punjab's Bathinda district, a region heavily dependent on this essential resource for domestic, agricultural, and industrial purposes. The review highlights the widespread presence of contaminants such as fluoride, uranium, arsenic, nitrate, and various heavy metals that frequently exceed international and national safety limits. It explores the complex hydrogeochemical processes—both geogenic, including mineral dissolution, and anthropogenic, such as intensive agriculture, industrial discharge, and improper waste disposal—that collectively control groundwater chemistry. The discussion further emphasizes the serious health implications of prolonged exposure to these contaminants, including fluorosis, skeletal and renal disorders, neurological impairment, and carcinogenic outcomes, alongside the degradation of soil fertility and crop productivity. The review synthesizes findings from previous studies on contamination assessment methods, technological and agricultural mitigation strategies, and policy interventions, proposing a roadmap for sustainable groundwater governance in Bathinda to ensure environmental and public health resilience.

Keywords: Groundwater contamination, Hydrogeochemical assessment, Bathinda district Punjab, Heavy metals and uranium pollution, Human health risk assessment, Sustainable groundwater management

1 Introduction

1.1 Background and Context

Groundwater serves as a fundamental source of life and economic stability across arid and semi-arid regions globally, with India—particularly the state of Punjab—illustrating an extreme dependency on this resource (Akhai & Taneja 2024; Akhai & Taneja 2025; Barik et al., 2017; Bhatia & Singh, 2023). In Bathinda district, groundwater fulfills nearly all domestic and agricultural requirements, sustaining high agricultural productivity that significantly contributes to India's food security (Sidhu et al., 2020a, 2020b). However, this heavy reliance has led to escalating issues of groundwater contamination and depletion, emerging as a major environmental and public health challenge (Barik et al., 2017). The expansion of agriculture under the Green Revolution, combined with industrial growth, rapid urbanization, and population pressure, has strained subsurface aquifers, leading to alarming declines in water quality (Gautam et al., 2021; Gautam & Chand, 2023). The contamination of groundwater in Punjab now represents both a hydrological and socio-economic crisis, calling for urgent scientific attention and policy response.

1.2 Problem Statement

The groundwater in Bathinda district contains multiple pollutants, including fluoride, uranium, arsenic, nitrate, and several heavy metals (Sharma et al., 2021; Verma & Anju, 2018). Concentrations of these substances often surpass the permissible limits defined by the World Health Organization (WHO) and the Bureau of Indian Standards (BIS), suggesting serious risks to water safety (Sharma et al., 2021; Verma & Anju, 2018). Uranium levels have been observed to exceed the WHO limit in a majority of samples, and arsenic and mercury concentrations also remain significantly high across various sites (Sharma et al., 2021). The chronic exposure to such contaminants poses grave health threats to the local population, with potential implications for soil quality and food safety, thus amplifying the urgency for systematic assessment and management.

1.3 Rationale of the Review

Although several isolated studies have analyzed specific aspects of groundwater quality in Bathinda, there remains a lack of an integrated review combining hydrogeochemical, environmental, and human health perspectives. Synthesizing such studies is vital for identifying contamination trends, distinguishing between geogenic and anthropogenic sources, and evaluating the success or limitations of mitigation strategies implemented to date (Schwartz et al., 2020). This review, therefore, seeks to consolidate the existing body of research to provide a coherent understanding of Bathinda's groundwater contamination scenario and guide informed decision-making for sustainable management.

2 Regional Overview of the Study Area

2.1 Location and Physiography

Bathinda district lies in the southwestern part of Punjab between latitudes 29°51′ and 30°20′ N and longitudes 74°42′ and 75°37′ E. The area experiences a semi-arid climate with high temperatures during summer and cold winters. Annual rainfall averages between 200 and 400 mm, with most precipitation occurring during the southwest monsoon. Physiographically, Bathinda forms part of the Indo-Gangetic alluvial plain and is characterized by flat topography interspersed with minor undulations. The predominant soil types are aeolian and alluvial, ranging from sandy to loamy textures, which favor infiltration and thus influence recharge patterns of groundwater aquifers.

2.2 Hydrogeological Setting

The district is underlain by multi-layered aquifer systems composed mainly of unconsolidated sediments. The shallow and intermediate aquifers consist predominantly of fine to medium sand, silt, and clay of alluvial origin, derived from the Ghaggar River system. Groundwater recharge occurs primarily through infiltration of rainfall and irrigation return flow, supplemented by seepage from the canal network. The mineralogical composition of aquifer sediments, rich in silicates, carbonates, and clay minerals, strongly influences groundwater chemistry by facilitating geogenic dissolution of elements such as fluoride, arsenic, and uranium (Gautam et al., 2021; Ullah et al., 2023; Upadhyay et al., 2023). The heterogeneous permeability of these sediments enhances vulnerability to surface contamination, especially from agricultural and industrial activities (Sharma et al., 2016).

2.3 Land Use and Anthropogenic Activities

Bathinda forms part of Punjab's agricultural heartland, where intensive cropping patterns and high-yield practices dominate. The widespread use of nitrogen- and phosphate-based fertilizers, along with organochlorine and organophosphate pesticides, has profoundly impacted groundwater quality (Goyal et al., 2024; Huang et al., 2022). In addition, the district hosts multiple industrial facilities, including thermal power plants, textile manufacturing units, and small-scale chemical industries, which release effluents that frequently find their way into nearby water bodies and aquifers (Verma & Anju, 2018). Inadequate waste management infrastructure and unregulated solid waste disposal further contribute to leachate generation, facilitating contaminant infiltration (Gautam et al., 2021). These cumulative anthropogenic pressures have intensified the degradation of groundwater across the region.

2.4 Previous Investigations

A number of hydrogeochemical studies in Bathinda have identified the district as a contamination hotspot. Earlier investigations primarily assessed physicochemical parameters and major ions, while more recent studies have employed advanced geochemical and spatial analytical techniques to quantify trace metals and radionuclides (Sharma et al., 2021; Singh et al., 2021). Results from these studies consistently report fluoride, uranium, and arsenic levels exceeding safe drinking water limits. The evolution of groundwater contamination research in Bathinda reflects a growing understanding of the interplay between natural processes and anthropogenic stressors, forming the basis for integrated environmental risk assessment and management.

3 Hydrogeochemical Characteristics of Groundwater

Groundwater quality in Bathinda reflects both natural geochemical interactions and anthropogenic influences. The principal parameters determining its chemistry include pH, electrical conductivity, total dissolved solids, and hardness, which often exceed recommended standards (Sidhu et al., 2020a, 2020b). Elevated electrical conductivity and TDS indicate significant salinity, largely resulting from leaching of fertilizers and irrigation return flows. Chloride and sulfate ions are abundant, while high nitrate concentrations—commonly associated with fertilizer leaching—represent a serious health concern. The major cations and anions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, F^{-}, HCO_3^{-}, SO_4^{2-}, Cl^{-}) reveal that the groundwater typically exhibits mixed hydrochemical facies, ranging from Ca-Mg-HCO_3 type in recharge zones to Na-Cl or Na-HCO_3 types in discharge areas, as shown in Piper and Gibbs diagram interpretations (Sidhu et al., 2020). These transitions suggest processes of ion exchange, rock-water interaction, and evaporation under semi-arid conditions.

Trace element contamination adds another layer of complexity. Uranium, arsenic, mercury, and fluoride are consistently detected at concentrations exceeding WHO limits (Sharma et al., 2021; Singh et al., 2021). Their occurrence varies spatially, forming hotspots that correspond to geological formations and human activities such as industrial discharge and intensive agriculture. Seasonal variations are pronounced, with monsoonal recharge temporarily diluting pollutants but also facilitating contaminant mobilization through leaching (Gautam & Chand, 2023). Post-monsoon periods typically exhibit higher concentrations due to reduced dilution and stronger water-rock interactions.

Recent monitoring by the Central Ground Water Board (CGWB) and associated agencies during 2023–2024 provides quantitative evidence supporting the persistent contamination of Bathinda's aquifers. Table 1 summarizes the major water quality parameters reported for Bathinda district, highlighting the widespread exceedance of permissible limits for nitrate, fluoride, and uranium. These findings confirm the ongoing deterioration of groundwater quality and the combined influence of agricultural, industrial, and geogenic factors.

Table 1. Groundwater Quality Parameters in Bathinda District, Punjab (2023–2024).

Year	Location / Scope	Parameter / Metric	Value / Observation	Notes / Source	URL / Web Link
2023	Bathinda (Shallow Aquifer Study, Punjab)	Electrical Conductivity	> 3000 µS/cm at several wells (high salinity)	Central Ground Water Board (CGWB), *Ground Water Quality in Shallow Aquifer of Punjab (2023)*	https://www.cgwb.gov.in/cgwbpnm/public/uploads/documents/1708597073344550179file.pdf
2023	Bathinda / Punjab	Fluoride	Hotspot district with values > 1.5 mg/L	CGWB, *Ground Water Quality in Shallow Aquifer of Punjab (2023)*	https://www.cgwb.gov.in/cgwbpnm/public/uploads/documents/1708597073344550179file.pdf
2023	Bathinda / Punjab	Uranium	Bathinda among districts with U > 30 µg/L	CGWB, *Punjab Groundwater Quality Scenario (2023)*	https://www.cgwb.gov.in/cgwbpnm/public/uploads/documents/1742295732461871757file.pdf
2024	Bathinda District	Nitrate	46 % of samples exceed BIS limit (45 mg/L)	CGWB, *Annual Ground Water Quality Report (2024)*	https://www.cgwb.gov.in/cgwbpnm/public/uploads/documents/17363272771910393216file.pdf
2024	Bathinda / Punjab	General contamination status	Multiple exceedances: nitrate, uranium, fluoride	CGWB, *Groundwater Chemical Quality Bulletin – Pre-Monsoon 2024*	https://gwdata.cgwb.gov.in/download/Bulletin/Punjab%20GWQ%20Bulletin%20Pre-monsoon%202024.pdf
—	Bathinda (Punjab)	Uranium (state-level summary)	32.6 % of samples exceed 30 µg/L	Press Information Bureau (PIB), *Punjab Groundwater Contamination Report (2024)*	https://pib.gov.in/PressReleasePage.aspx?PRID=2111857

Note. *Data compiled from secondary publicly available sources (CGWB and government reports). The author does not guarantee the accuracy or completeness of the information, and it is presented solely for academic reference.*

4 Sources and Pathways of Contamination

Groundwater contamination in Bathinda arises from both geogenic and anthropogenic origins, often interacting synergistically. The district's alluvial sediments contain fluoride-bearing minerals and uranium-enriched formations that naturally release contaminants into groundwater (Coyte et al., 2019; Pandit et al., 2022). Average uranium concentrations reach 88 µg L^{-1}, with nearly three-quarters of samples exceeding WHO limits (Sharma et al., 2021). Similarly, arsenic and mercury concentrations average 176 µg L^{-1} and 174 µg L^{-1} respectively, both far above safe thresholds (Sharma et al., 2021). Fluoride contamination primarily results from mineral dissolution within the aquifer (Aryan et al., 2023; Khusulio et al., 2024).

Human activities further amplify natural contamination. Fertilizers and pesticides leach nitrates, phosphates, and heavy metals into aquifers (Sharma et al., 2016; Gautam et al., 2021). Industrial effluents, particularly from thermal power plants and textile units, contribute additional toxic load (Gautam & Chand, 2023). Over-extraction of groundwater for irrigation has lowered water tables, accelerating the concentration of dissolved ions and triggering salinization (Sarkar et al., 2022). The cumulative effect of natural and human factors creates a complex hydrogeochemical environment where contamination becomes self-reinforcing through hydrological feedbacks.

5 Human Health Risk Assessment

Groundwater contamination in Bathinda poses severe public health challenges. The Human Health Risk Assessment (HHRA) framework evaluates these risks through hazard identification, exposure analysis, dose-response assessment, and risk characterization (Herojeet et al., 2023). The U.S. Environmental Protection Agency model is widely adopted to calculate non-carcinogenic (HQ, HI) and carcinogenic (CR) risks (Rashid et al., 2022; Shetty et al., 2024). Ingestion of contaminated drinking water remains the dominant exposure route, while dermal absorption contributes to secondary exposure (Brindha et al., 2020). Children are more vulnerable than adults because of higher water intake relative to body mass and developing physiological systems (Chaudhry & Sachdeva, 2020; Yadav & Kalkal, 2024).

Empirical studies link Bathinda's water contamination to fluorosis, skeletal deformities, kidney damage, neurological disorders, and cancers (Ali et al., 2023; Yetiş et al., 2024). Arsenic exposure causes hyperkeratosis, melanosis, and vascular disorders (Ullah et al., 2022). Comparative studies in nearby districts report hazard index values exceeding unity, confirming significant non-carcinogenic risks, particularly among children (Kapoor & Kumar, 2024; Yadav & Kalkal, 2024). Despite these findings, longitudinal epidemiological studies directly linking groundwater quality to disease prevalence in Bathinda remain limited, underscoring the need for more integrated hydro-biological and health monitoring research (Aryan et al., 2023). Table 2 summarizes the principal contaminants detected in Bathinda groundwater during 2023–2024, along with associated health effects and regulatory guideline limits.

Table 2: Contaminants in Bathinda Groundwater, Health Effects, and Regulatory Limits (2023–2024)

Contaminant	Major Source(s)	Principal Health Effects	WHO Guideline Limit	BIS (IS 10500:2012) Limit	Key References
Fluoride (F^-)	Natural mineral dissolution; phosphate fertilizers	Dental & skeletal fluorosis, bone deformation	1.5 mg L^{-1}	1.0 mg L^{-1}	Aryan et al. (2023); CGWB (2023)
Uranium (U)	Geogenic origin in alluvial aquifers; thermal-plant effluent	Nephrotoxicity, carcinogenic risk	30 µg L^{-1} (0.03 mg L^{-1})	30 µg L^{-1} (0.03 mg L^{-1})	Sharma et al. (2021); CGWB (2024)
Arsenic (As)	Mineral dissolution under reducing conditions; agro-chemicals	Skin lesions, vascular diseases, cancers	10 µg L^{-1} (0.01 mg L^{-1})	10 µg L^{-1} (0.01 mg L^{-1})	Ullah et al. (2022); CGWB (2023)
Nitrate (NO_3^-)	Excess fertilizer,	Methemoglobinemia	50 mg L^{-1}	45 mg L^{-1}	CGWB

	manure, sewage infiltration	(“blue-baby” syndrome)			(2024); BIS (2012)
Lead (Pb)	Industrial effluent, corroded plumbing	Neurotoxicity, anemia, developmental delay	10 µg L^{-1} (0.01 mg L^{-1})	10 µg L^{-1} (0.01 mg L^{-1})	
Mercury (Hg)	Coal combustion, chemical-industry discharge	Renal & nervous-system damage	1 µg L^{-1} (0.001 mg L^{-1})	1 µg L^{-1} (0.001 mg L^{-1})	Sharma et al. (2021)
Chromium (Cr VI)	Electroplating & textile wastewater	Carcinogenicity, skin ulcers, DNA damage	50 µg L^{-1} (0.05 mg L^{-1})	50 µg L^{-1} (0.05 mg L^{-1})	Herojeet et al. (2023); CGWB (2023)

Note. *Data derived from secondary publicly available sources (CGWB, WHO 2022, BIS 2012). The author does not guarantee the accuracy or completeness of these values; they are presented solely for academic and reference purposes.*

6 Hydrogeochemical Modelling and Analytical Tools

Advanced analytical approaches help in understanding groundwater quality trends in Bathinda. Statistical methods such as Principal Component Analysis and Factor Analysis simplify complex datasets and identify pollution sources (Gulgundi & Shetty, 2018; Machiwal & Jha, 2015). Correlation matrices highlight relationships among physicochemical parameters (Khusulio et al., 2024). Geographic Information Systems (GIS) are widely employed to map contaminant dispersion using interpolation methods like Kriging and Inverse Distance Weighting (Thakur et al., 2025). Artificial Intelligence and Machine Learning models—including Support Vector Machines, Random Forests, and Boosted Regression Trees—are increasingly used for predicting groundwater contamination and assessing risk distribution (Awais et al., 2021; Biswas et al., 2025). Water Quality Index frameworks, including the Weighted Arithmetic and Canadian Council models, offer simplified indicators for communication and policy decisions (Naz et al., 2023; Najeeb & Saeed, 2022). Integration of fuzzy logic and GIS enhances predictive accuracy (Chaudhry & Sachdeva, 2021).

7 Environmental and Agricultural Implications

The use of contaminated groundwater for irrigation deteriorates soil quality, leading to salinization, alkalinity, and loss of fertility (Masood et al., 2023). Heavy metal accumulation alters microbial communities and nutrient cycles, reducing crop yield (Devika et al., 2024; Sharafi & Salehi, 2025). Toxic elements absorbed by plants can enter the human food chain, with documented bioaccumulation of nickel and other metals in wheat and rice cultivated in Punjab (Khan et al., 2023; Naz et al., 2022). The ecological impacts extend beyond agriculture, as contaminated runoff degrades aquatic ecosystems, diminishes biodiversity, and alters trophic dynamics (Ahamad et al., 2024; Samaraweera et al., 2024). Such cascading effects highlight the intertwined nature of water quality, soil health, and ecosystem stability.

8 Mitigation and Sustainable Management Strategies

Technological, hydrological, agricultural, and policy-level measures are essential to restore Bathinda's groundwater. Adsorption-based defluoridation, de-uranation using nanomaterials, and membrane filtration technologies have shown promise in removing contaminants (Dhaduti et al., 2025; Dhanya et al., 2022; Vani et al., 2024). Managed Aquifer Recharge and rainwater harvesting can replenish declining water tables (Brar et al., 2019; Raj et al., 2024). Agricultural reforms—such as crop diversification, precision irrigation, and organic farming—reduce fertilizer leaching and water demand (Brar et al., 2021; Jat et al., 2019). Policy interventions must strengthen groundwater regulation, promote efficient pricing mechanisms, and establish real-time monitoring networks (Bhatia & Singh, 2023; Megdal, 2018). Public awareness campaigns and participatory management programs are equally crucial to ensure sustainable community-led water conservation (Chinnasamy & Gupta, 2023; Das, 2024).

9 Research Gaps and Future Directions

Despite extensive research, gaps persist in long-term monitoring, interdisciplinary integration, and field-based implementation. Continuous water quality datasets are scarce, hindering accurate trend analysis (Schwartz et al., 2020). Future studies must integrate hydrogeochemistry, toxicology, and socio-economic factors (Bhatia & Singh, 2024). Artificial Intelligence-based predictive modeling tailored to Bathinda's complex aquifers could enhance early warning systems (Kerketta et al., 2024; Pranjal et al., 2023). Field-scale pilot projects are required to test recharge and remediation strategies and evaluate their socio-economic feasibility (Ciampi et al., 2022; Shafeeque et al., 2023).

10 Conclusion

Groundwater in Bathinda district is severely contaminated with multiple pollutants, posing significant health, agricultural, and ecological challenges. Both geogenic and anthropogenic processes contribute to this degradation, with contaminant concentrations frequently surpassing WHO and BIS limits. Health risk assessments reveal alarming hazard indices and carcinogenic risk values, particularly among vulnerable populations. The integration of hydrogeochemical analysis with advanced modeling and policy measures is essential for developing sustainable solutions. Effective mitigation will depend on combining technological innovations, managed recharge systems, and agricultural reforms with strong governance and public participation. Ensuring the long-term safety of Bathinda's groundwater requires continuous monitoring, interdisciplinary research, and community engagement to protect this vital resource for future generations.

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