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Impact of Groundwater Pollution on Carcinogenic and Non-Carcinogenic Health Effects: A Review

Tanmay Kumar[1], Santanu Mallik[2,*]

Abstract

Groundwater is a critical source of drinking water in many regions worldwide, particularly in South and Southeast Asia, where dependence on untreated groundwater remains high. However, increasing groundwater contamination poses serious risks to human health. This review synthesizes recent peer-reviewed studies to examine the sources, distribution, and health impacts of major groundwater contaminants, with a focus on both carcinogenic and non-carcinogenic risks. Emphasis is placed on fluoride, nitrate, chromium, and other potentially toxic elements, which are frequently reported at concentrations exceeding recommended guideline values. The reviewed studies consistently identify ingestion as the dominant exposure pathway and demonstrate that children are the most vulnerable population group due to higher intake rates relative to body weight and greater physiological sensitivity. Non-carcinogenic health risks are primarily driven by fluoride and nitrate contamination in agricultural and hard-rock aquifers, with hazard quotient and hazard index values often exceeding acceptable thresholds. Carcinogenic risks are mainly associated with chromium and other trace metals in groundwater affected by industrial and mining activities, where lifetime cancer risk estimates frequently surpass recommended safety benchmarks. Evidence further indicates that co-occurrence of multiple contaminants can amplify overall health risk, while probabilistic assessment approaches reveal higher exceedance probabilities compared to deterministic methods, highlighting the importance of uncertainty consideration. Overall, this review underscores the need for contaminant-specific and region-appropriate groundwater management strategies. Integrated monitoring, standardized health-risk assessment, and targeted mitigation measures, with particular attention to vulnerable populations such as children, are essential to reduce long-term health risks and ensure sustainable groundwater-based drinking water security.

Keywords: Groundwater pollution, heavy metals, human health risk assessment, public health

INTRODUCTION

Groundwater constitutes the largest accessible freshwater resource and serves as a primary drinking water source for a substantial proportion of the global population, particularly in arid and semi-arid regions where surface water availability is limited. In South Asia – including India, Pakistan, Bangladesh, and parts of Iran – groundwater dependency exceeds 80% for domestic, agricultural, and industrial uses, driven by rapid population growth, unplanned urbanization, agricultural intensification, and climate variability [1, 2]. However, this vital resource is increasingly threatened by contamination, resulting in a dual challenge of quantitative depletion and progressive deterioration of groundwater quality. Numerous studies demonstrate that groundwater pollution arises from the combined influence of geogenic processes, such as mineral dissolution and redox-controlled mobilization, and anthropogenic activities including fertilizer application, industrial effluent discharge, septic leakage, and urban land-use change, leading to

***Author for Correspondence**
Santanu Mallik
E-mail: santanu.malik@poornima.org

[1]Student, Department of Civil Engineering, Poornima College of Engineering, Jaipur, Rajasthan, India
[2]Associate Professor, Department of Civil Engineering, Poornima College of Engineering, Jaipur, Rajasthan, India

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elevated concentrations of nitrate, fluoride, heavy metals, and pathogenic contaminants in aquifers [1–3].

Chronic exposure to contaminated groundwater through drinking water consumption poses significant risks to human health. Health impacts are broadly categorized into carcinogenic and non-carcinogenic effects based on international risk-assessment frameworks. Carcinogenic risks are primarily associated with long-term exposure to contaminants such as arsenic and hexavalent chromium, which have been shown to induce unacceptable lifetime cancer risk levels in exposed populations [3]. Non-carcinogenic effects are commonly linked to fluoride, nitrate, and selected heavy metals and include skeletal and dental fluorosis, methemoglobinemia, neurological impairment, renal dysfunction, and gastrointestinal disorders [2, 4, 5]. Across diverse hydrogeological settings, ingestion has been consistently identified as the dominant exposure pathway, with hazard quotient (HQ), hazard index (HI), and total hazard index (THI) values frequently exceeding acceptable limits for drinking water consumers [2, 5].

In India, extensive regional investigations have reported widespread groundwater contamination by fluoride and nitrate, with non-carcinogenic health risk assessments indicating HI values greater than unity in large proportions of sampled locations [4, 5]. Arsenic- and chromium-related carcinogenic risks have also been documented in several aquifer systems, with estimated lifetime cancer risks exceeding the acceptable threshold of 10^{-4} in vulnerable populations [6, 7]. Similar patterns have been observed in Iran and Pakistan, where chromium, nitrate, and fluoride hotspots pose considerable health risks, particularly in rural and peri-urban communities dependent on untreated groundwater supplies [2, 3]. Evidence from recent studies consistently indicates that children are more vulnerable than adults due to higher water intake per unit body weight and developing physiological systems, resulting in higher HQ and HI values for non-carcinogenic contaminants and elevated cancer risk estimates for carcinogens [2–6]. Temporal variability in groundwater quality further complicates exposure scenarios. Seasonal recharge, monsoonal precipitation, intensive groundwater abstraction, and land-use changes have been shown to enhance contaminant mobilization and spatial redistribution, leading to significant temporal fluctuations in contaminant concentrations and associated health risks [4, 8]. Urbanization gradients also play a critical role, with higher contaminant loads and health risks reported in densely built-up areas compared to less urbanized or agricultural zones, emphasizing the influence of land- use patterns on groundwater quality deterioration [1, 9].

Although numerous regional studies have assessed groundwater contamination and associated health risks, most investigations remain site-specific, focusing on individual contaminants or limited exposure pathways. An integrated synthesis that systematically examines contaminant sources, spatial distribution, differential carcinogenic and non-carcinogenic health outcomes, and vulnerability across population groups using standardized health-risk assessment frameworks remains limited. This review therefore synthesizes recent peer-reviewed studies to: (1) examine the sources and spatial distribution of key groundwater contaminants; (2) assess associated carcinogenic and non-carcinogenic health impacts with particular emphasis on vulnerable populations; (3) evaluate regional groundwater health-risk patterns using deterministic and probabilistic approaches; and (4) summarize mitigation and management strategies aimed at reducing groundwater-related health risks.

METHODOLOGY

Data Preparation

Data preparation for this review involved systematic collection, organization, and synthesis of published information related to groundwater contamination and associated human health risks. Relevant data were extracted from selected peer-reviewed studies to capture key aspects required for comparative analysis. These included groundwater contaminant concentrations, types of contaminants (inorganic, organic, and microbial), dominant sources (geogenic or anthropogenic), hydrogeochemical conditions influencing contaminant mobility, and reported spatial and temporal variability patterns.

In addition, data related to human health risk assessment were compiled, including exposure pathways, population characteristics, and quantitative risk indicators such as chronic daily intake, hazard quotient, hazard index, total hazard index, and lifetime cancer risk. Particular attention was given to studies reporting age-specific or gender-specific risk estimates to enable assessment of vulnerable population groups. Information on analytical methods, spatial analysis techniques, and uncertainty treatment approaches was also recorded to support consistent interpretation across studies. All extracted data were organized into structured datasets to facilitate synthesis, comparison, and tabulation across regions and contaminant types.

Inclusion and Exclusion Criteria

The review included: (1) empirical studies reporting the occurrence, concentration, and spatial distribution of groundwater contaminants; (2) studies assessing carcinogenic and non-carcinogenic human health risks using established health-risk assessment frameworks; Studies were excluded if they: (1) focused exclusively on surface water without groundwater assessment; (2) addressed ecological or non-human health outcomes only; (3) were published prior to 2020; or (4) were not peer-reviewed. Full-text assessment of these articles yielded 28 eligible studies, of which 10 were included in the final synthesis.

SOURCES AND DISTRIBUTION OF GROUNDWATER POLLUTANTS

Understanding the sources and spatial distribution of groundwater pollutants requires examination of hydrogeochemical processes such as recharge pathways, redox conditions, aquifer lithology, and land-use pressures, which collectively govern contaminant mobilization, transport, and persistence within groundwater systems. Recent studies consistently demonstrate that groundwater contamination results from the combined influence of geogenic processes and anthropogenic activities, with their relative contributions varying across hydrogeological and land-use settings [2, 6, 8]. A synthesis of major groundwater contaminants, their dominant geogenic and anthropogenic sources, associated health effects, and World Health Organization guideline limits reported in the reviewed studies is summarized in Table 1.

Table 1. Major groundwater contaminants, sources, and associated health effects.

Contaminant	Geogenic sources	Anthropogenic sources	Major health effects	WHO guideline limit	Key references
Arsenic (As)	Reductive dissolution of Fe-oxides in alluvial sediments; arsenic-bearing minerals in aquifer lithology	Mining activities; irrigation-induced redox changes	Skin lesions; bladder, lung, and skin cancer (carcinogenic); cardiovascular disorders	10 μg/L	[3, 6]
Chromium (Cr)	Weathering of ultramafic and mafic rocks; natural Cr-bearing minerals	Industrial effluents; mining and metallurgical activities	Carcinogenic effects (Cr (VI)); gastrointestinal and renal toxicity	50 μg/L	[3, 6]
Fluoride (F^-)	Dissolution of fluoride-bearing minerals (fluorite, fluorapatite) under alkaline conditions	Phosphate fertilizers; industrial discharges (localized)	Dental fluorosis; skeletal fluorosis; joint pain and bone deformities	1.5 mg/L	[4, 5]
Nitrate (NO_3^-)	Natural nitrogen mineralization (minor contribution)	Agricultural fertilizer application; livestock waste; sewage and septic leakage	Methemoglobinemia; potential carcinogenic risk via nitrosamine formation	50 mg/L	[2, 7, 8]
Cadmium (Cd)	Weathering of metal-bearing rocks; natural background levels	Mining, industrial waste, metal processing	Renal dysfunction; bone damage; potential carcinogenic effects	3 μg/L	[6]

Organic Contaminants: Pathways and Persistence

Among non-metallic contaminants, nitrate represents the most widespread groundwater pollutant across agricultural and peri-urban regions. Elevated nitrate concentrations are primarily linked to intensive fertilizer application, irrigation return flow, livestock waste, and inadequate sanitation infrastructure. Studies from semi-arid regions of India report nitrate concentrations frequently exceeding drinking water guidelines, with strong spatial association to agricultural land use and shallow groundwater systems [2, 4]. Long-term analyses indicate that land-use change and climate variability significantly influence nitrate loading, with monsoonal recharge enhancing leaching and vertical transport into aquifers [8].

Urbanization further amplifies nitrate and nutrient contamination, particularly in areas lacking centralized sewage systems. Investigations along urban–rural gradients demonstrate increasing contaminant concentrations in densely populated zones due to septic leakage, wastewater infiltration, and reduced natural attenuation capacity [1, 9]. These findings highlight that nutrient contamination is not only an agricultural issue but also a growing urban groundwater quality concern.

Inorganic Contaminants: Geogenic Dominance with Anthropogenic Amplification

Inorganic contaminants dominate groundwater pollution profiles in many South Asian and comparable aquifer systems. Arsenic, fluoride, chromium, and other trace metals are primarily derived from natural geological sources, including mineral dissolution, weathering of host rocks, and redox-driven mobilization processes. However, anthropogenic activities often intensify their release and spatial extent [2, 6].

Arsenic contamination is strongly associated with reducing groundwater environments, where reductive dissolution of iron oxides releases arsenic into solution. Although concentrations vary spatially, several studies report arsenic levels exceeding drinking water guidelines, particularly in alluvial and mining-impacted regions [6]. Chromium contamination, especially in its hexavalent form, arises from both natural ultramafic rock weathering and anthropogenic sources such as industrial discharge and mining activities, with alkaline pH conditions enhancing its mobility and persistence [3, 6]. Fluoride contamination is predominantly geogenic and linked to the dissolution of fluoride-bearing minerals under alkaline conditions. Groundwater surveys across multiple Indian states reveal fluoride concentrations frequently exceeding recommended limits, particularly in hard-rock aquifers where prolonged water–rock interaction occurs [4, 5]. Trace metals such as lead and cadmium have been reported in groundwater impacted by mining and industrial activities, contributing to localized contamination hotspots and cumulative exposure risks [3, 6].

HEALTH IMPACTS OF GROUNDWATER POLLUTANTS

Health Impacts: Carcinogenic and Non-Carcinogenic Effects

Exposure to groundwater contaminants occurs primarily through ingestion, while dermal contact and inhalation may contribute under specific use scenarios. Across recent groundwater health-risk studies, ingestion consistently represents the dominant exposure pathway used for quantitative assessment, and risk magnitude varies strongly with age-dependent intake and body weight parameters [2, 3, 5]. Children are repeatedly identified as the most vulnerable group because higher intake per unit body weight and physiological sensitivity produce larger estimated doses and, consequently, higher non-carcinogenic and carcinogenic risk estimates compared with adults [4–6].

Carcinogenic Risks: Mechanisms and Quantification

Carcinogenic risks from groundwater pollution are commonly evaluated using lifetime cancer risk (LCR) metrics and are primarily associated with long-term exposure to toxic metals and metalloids, particularly hexavalent chromium and, in some settings, other trace metals. Risk assessments from industrial and mining-impacted areas report that carcinogenic risk can exceed acceptable thresholds when chromium and other carcinogenic metals are elevated in groundwater, with children often exhibiting higher estimated cancer risk than adults under the same concentration conditions [6]. Evidence from basin-scale assessments also demonstrates that combined exposure to chromium and nitrate in contaminated environments may produce unacceptable cancer risk levels, highlighting the importance of multi-contaminant evaluation rather than single-pollutant interpretation [3]. Although nitrate is typically treated as a non-carcinogenic pollutant in standard drinking-water risk frameworks, recent health-risk analysis has emphasized that nitrate exposure may contribute to increased long-term cancer risk under certain exposure scenarios and assessment assumptions, warranting its consideration in carcinogenic risk discussions alongside classical metal-driven carcinogenicity [7]. In addition, probabilistic approaches (e.g., Monte Carlo simulation) have shown that deterministic point estimates may underestimate the probability of exceeding cancer-risk thresholds for some contaminants, underscoring the relevance of uncertainty characterization in groundwater risk interpretation [10].

Non-Carcinogenic Risks: Systemic Toxicities

Non-carcinogenic health effects are generally assessed using threshold-based indices such as hazard quotient (HQ) and hazard index (HI), with health concern indicated when HQ or HI exceeds unity. Fluoride exposure remains a dominant driver of non-carcinogenic groundwater risk in many hard-rock and semi-arid aquifers, where elevated fluoride is associated with dental and skeletal fluorosis and related musculoskeletal impairment [4, 5]. Several regional assessments report that fluoride-related HQ/HI values are consistently higher for children than adults, reinforcing age-specific vulnerability in non-carcinogenic risk characterization [4, 5].

Nitrate contamination is widely linked to agricultural intensification, sewage leakage, and sanitation-related inputs, and is associated with non-carcinogenic risks including methemoglobinemia risk pathways and broader health burden reflected through HI exceedances in exposed communities [2, 8]. Studies that incorporate background concentrations and spatial drivers show that nitrate-derived risk is strongly controlled by land use and hydroclimatic variability, leading to pronounced spatial heterogeneity in non-carcinogenic risk patterns [2, 8].

Heavy metals also contribute to non-carcinogenic risk burdens, particularly in groundwater affected by mining and industrial sources, where aggregated HI values may exceed acceptable thresholds due to combined exposure to multiple elements [1, 6]. In addition to chemical toxicants, microbial contamination often reflecting fecal intrusion at the source or point-of-use – represents an important parallel health risk pathway, particularly in rural and peri-urban settings, and may co-occur with chemical contamination to increase overall exposure burden [1, 9].

Overall, the reviewed evidence indicates that (i) children frequently exhibit the highest estimated non-carcinogenic risk due to fluoride and nitrate exposure, (ii) carcinogenic risks are notably influenced by chromium and other metal contaminants in industrial/mining contexts, and (iii) probabilistic risk assessment provides additional insight into uncertainty and exceedance probability beyond deterministic estimates [4, 5, 6, 10]. A synthesis of reported carcinogenic and non-carcinogenic health-risk indicators, dominant contaminants, vulnerable population groups, and major findings from the reviewed studies is summarized in Table 2.

The synthesis of regional groundwater health-risk studies (Table 2) reveals consistent patterns across diverse hydrogeological and land-use settings. Fluoride and nitrate emerge as the dominant drivers of non-carcinogenic risk in agricultural and hard-rock aquifers, while carcinogenic risk is primarily associated with chromium and other potentially toxic elements in mining- and industry-influenced regions. Across almost all case studies, children exhibit higher health-risk indices than adults, reflecting greater exposure per unit body weight and increased physiological sensitivity. The reviewed evidence further indicates that ingestion is the principal exposure pathway, with combined or co-occurring contaminants often producing aggregated risks that exceed acceptable thresholds. Studies employing probabilistic approaches highlight that deterministic assessments may underestimate exceedance probabilities, underscoring the importance of uncertainty consideration in groundwater health-risk evaluation. Overall, the comparative findings emphasize that groundwater-related health risks are strongly contaminant-specific and region-dependent, necessitating targeted mitigation strategies rather than uniform management approaches.

Table 2. Summary of groundwater health-risk assessments reported in the reviewed studies.

Study area	**Health risk indicator / metric**	**Key contaminants**	**Major finding (two key points only)**	**Reference**
Matanza–Riachuelo River Basin, Argentina	USEPA-based HQ (non-carcinogenic) and CR (carcinogenic) for ingestion and dermal exposure	Cr (VI), NO_3^-	• Cr (VI) produced unacceptable non-carcinogenic and carcinogenic risks • Ingestion was the dominant exposure pathway for both adults and children.	[3]
Mica belt region, Jharkhand, India	Hazard Quotient (HQ) and Hazard Index (HI); seasonal assessment	F^-, NO_3^-	• Children exhibited the highest HI values • fluoride was the primary driver of non-carcinogenic risk.	[4]
Cuttack district, Odisha, India	USEPA health-risk assessment with spatial analysis (IDW)	F^-, NO_3^-	• Fluoride dominated non-carcinogenic risk • children showed consistently higher risk than adults.	[5]
Multi-mineral resource area, North China	Integrated HI and total cancer risk (CR) assessment	Cd, As, Cr (VI)	• Carcinogenic risks of Cd, As, and Cr (VI) exceeded acceptable limits • children were more vulnerable than adults.	[6]
Semi-arid aquifers of Rajasthan, India	USEPA non-carcinogenic risk assessment considering background concentration	NO_3^-	• Nitrate-related HI exceeded unity in several locations • children experienced higher non-carcinogenic risk than adults.	[2]
Onitsha metropolitan area, southeastern Nigeria	Non-carcinogenic health-risk assessment along an urban gradient	Heavy metals, nutrients	• Urbanization increased contaminant loads and health risk • densely populated zones showed higher exposure levels.	[1]
Rural groundwater systems of Limpopo Province, South Africa	Chemical and microbial health-risk assessment at point of use	Nutrients, microbial indicators	• Co-occurrence of chemical and microbial contamination elevated health risk • untreated groundwater posed significant exposure concerns.	[9]
Upper Brahmaputra floodplain, Assam, India	Spatio-temporal risk interpretation linked to land-use and climate variability	NO_3^-	• Land-use change strongly influenced nitrate distribution • seasonal recharge intensified exposure risk.	[8]
Karst groundwater system, Southeast Asia (case study region)	Deterministic and Monte Carlo-based probabilistic health-risk assessment	Pb, Cr, other PTEs	• Probabilistic analysis showed higher exceedance probabilities • uncertainty significantly affected cancer-risk estimates.	[10]
High-nitrate groundwater zones, India	Excess lifetime cancer risk estimation using nitrate-derived pathways	NO_3^-	• Nitrate exposure contributed to elevated long-term cancer risk • probabilistic methods captured exposure variability.	[7]

CONCLUSION

Groundwater pollution poses substantial carcinogenic and non-carcinogenic health risks across diverse hydrogeological and land-use settings, particularly in regions with high dependence on untreated groundwater for drinking purposes. This review synthesizes recent evidence to provide an integrated understanding of contaminant sources, exposure pathways, and associated health outcomes. The reviewed studies consistently indicate that fluoride and nitrate are the primary drivers of non-carcinogenic health risk in agricultural and hard-rock aquifers, with hazard quotient and hazard index values frequently exceeding acceptable thresholds. Children are repeatedly identified as the most vulnerable population group, reflecting higher intake rates relative to body weight and greater physiological sensitivity, leading to elevated risks of dental and skeletal fluorosis and other chronic health effects.

Carcinogenic risks are predominantly associated with chromium and other potentially toxic elements in groundwater impacted by industrial and mining activities, where lifetime cancer risk estimates often exceed recommended safety benchmarks. Evidence further suggests that co-occurrence of multiple contaminants can amplify overall health risk, while studies employing probabilistic approaches demonstrate that deterministic assessments may underestimate exceedance probabilities. Collectively, these findings highlight the need for contaminant-specific and region-appropriate risk management strategies.

Safeguarding groundwater quality is therefore essential for effective public health protection. An integrated approach combining systematic monitoring, standardized health-risk assessment, and targeted mitigation measures can substantially reduce exposure to hazardous groundwater contaminants. Prioritizing the protection of vulnerable populations, particularly children, and promoting sustainable groundwater management practices will be critical for minimizing long-term health risks and ensuring safe drinking-water security for present and future generations.

Declaration of Interest

Not Applicable.

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