Libyan Open University Journal of Medical Sciences and Sustainability
(https://oujournals.ly/index.php/LOUJMSS/index)
Volume 2 - Issue 1 - 2026 - Pages 69-79

Health Risk Assessment Associated with the Consumption of Contaminated Groundwater

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تقييم المخاطر الصحية المرتبطة باستهلاك المياه الجوفية الملوثة

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Received: 26-01-2026; Accepted: 08-04-2026; Published: 16-04-2026

Abstract:
Groundwater is a primary source of drinking water for billions of people, but it is increasingly threatened by agricultural, industrial, and domestic pollution as well as natural geological sources. Chronic consumption of water containing heavy metals, nitrate, fluoride, and pathogens may cause non-carcinogenic and carcinogenic health effects. This study reviews the evidence on health risks associated with the consumption of contaminated groundwater. A systematic narrative review was carried out following PRISMA guidelines , and studies reporting groundwater quality together with health risk assessment were screened and analysed. Contaminant concentrations were compared with WHO drinking-water guideline values, and the exposure and risk models of the US Environmental Protection Agency, namely average daily dose, hazard quotient, hazard index, and carcinogenic risk, were used as the analytical framework. The reviewed studies show that nitrate, fluoride, arsenic, and other toxic metals frequently exceed guideline values in shallow and polluted aquifers, particularly in agricultural, industrial, and semi-arid areas. In several studies, hazard quotients exceeded the acceptable level of one for nitrate and fluoride, and arsenic was the main contributor to carcinogenic risk. Children consistently showed higher risk than adults because of their lower body weight relative to water intake. Risk varied with aquifer depth, land use, season, and local exposure assumptions. The findings highlight the need for routine groundwater monitoring, source protection, treatment of contaminated supplies, and the inclusion of health risk assessment in water management policy, with priority for children and communities that depend on untreated wells.

Keywords: Groundwater contamination; Health risk assessment; Drinking water; Heavy metals; Nitrate contamination; Human health; Environmental health.

الملخص:
تُعدّ المياه الجوفية مصدرًا رئيسيًا لمياه الشرب لمليارات البشر، إلا أنها تتعرض لتهديد متزايد من التلوث الزراعي والصناعي والمنزلي، فضلًا عن المصادر الجيولوجية الطبيعية. وقد يُؤدي الاستهلاك المزمن للمياه الملوثة بالمعادن الثقيلة والنترات والفلورايد ومسببات الأمراض إلى آثار صحية غير سرطانية وسرطانية. تستعرض هذه الدراسة الأدلة المتعلقة بالمخاطر الصحية المرتبطة باستهلاك المياه الجوفية الملوثة. أُجريت مراجعة سردية منهجية وفقًا لإرشادات PRISMA، حيث جرى فحص وتحليل الدراسات التي تُوثّق جودة المياه الجوفية وتقييم المخاطر الصحية. قُورنت تركيزات الملوثات بقيم إرشادات منظمة الصحة العالمية لمياه الشرب، واستُخدمت نماذج التعرض والمخاطر لوكالة حماية البيئة الأمريكية، وهي: متوسط الجرعة اليومية، ونسبة الخطر، ومؤشر الخطر، وخطر الإصابة بالسرطان، كإطار تحليلي. تُظهر الدراسات التي تمت مراجعتها أن النترات والفلورايد والزرنيخ والمعادن السامة الأخرى تتجاوز في كثير من الأحيان القيم الإرشادية في طبقات المياه الجوفية الضحلة والملوثة، لا سيما في المناطق الزراعية والصناعية وشبه القاحلة. في العديد من الدراسات، تجاوزت نسب المخاطر المستوى المقبول (واحد) بالنسبة للنترات والفلورايد، وكان الزرنيخ المساهم الرئيسي في خطر الإصابة بالسرطان. وأظهر الأطفال باستمرار مخاطر أعلى من البالغين نظرًا لانخفاض وزنهم مقارنةً بكمية المياه التي يتناولونها. وتفاوتت المخاطر باختلاف عمق طبقة المياه الجوفية، واستخدام الأراضي، والفصل، وافتراضات التعرض المحلية. وتُبرز هذه النتائج الحاجة إلى مراقبة دورية للمياه الجوفية، وحماية مصادرها، ومعالجة المياه الملوثة، وإدراج تقييم المخاطر الصحية في سياسات إدارة المياه، مع إعطاء الأولوية للأطفال والمجتمعات التي تعتمد على الآبار غير المعالجة.

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Libyan Open University Journal of Medical Sciences and Sustainability
(https://oujournals.ly/index.php/LOUJMSS/index)
Volume 2 - Issue 1 - 2026 - Pages 69-79
الكلمات المفتاحية: تلوث المياه الجوفية؛ تقييم المخاطر الصحية؛ مياه الشرب؛ المعادن الثقيلة؛ تلوث النترات؛ صحة الإنسان؛ الصحة البيئية.

1-Introduction

1.1 Groundwater as a Source of Drinking Water

1.2 Sources of Groundwater Contamination

Groundwater contamination represents one of the most pressing environmental and public health challenges globally. Unlike surface water systems, subsurface aquifers exhibit slow flow dynamics and limited self-cleansing capacities, meaning that once pollutants enter the groundwater zone, they can persist for decades or even centuries, making remediation technically complex and economically prohibitive. Generally, the degradation of groundwater quality stems from a multifaceted interaction between natural geological phenomena and intensive anthropogenic activities.

Natural, or geogenic, contamination occurs entirely independent of human intervention and is primarily governed by the geochemical properties of the host rock and soil formations through which water percolates. As groundwater moves slowly through mineral matrices, chemical weathering and rock-water interactions facilitate the dissolution of naturally occurring trace elements. A prime example is the release of arsenic- and fluoride-bearing minerals, which frequently occurs under specific pH and redox conditions within the aquifer (Smedley & Kinniburgh, 2002). High concentrations of these geogenic contaminants render water supplies hazardous for human consumption, leading to chronic health crises such as arsenicosis and skeletal fluorosis. Additionally, in arid and semi-arid regions, high evaporation rates combined with the slow dissolution of evaporite minerals contribute to natural salinization, further limiting freshwater availability.

While natural processes establish the baseline hydrochemistry of an aquifer, anthropogenic activities serve as the most widespread and rapidly accelerating drivers of contemporary groundwater pollution. Among human-induced pressures, agricultural practices constitute a major diffuse source of contamination. The intensive and often improper application of synthetic nitrogen- and phosphorus-based fertilizers, alongside chemical pesticides, results in excess nutrients and toxic compounds that are not fully absorbed by crops. Through rainfall and irrigation, these agrochemicals undergo deep percolation through the unsaturated zone, ultimately accumulating as elevated nitrate and pesticide concentrations in underlying water tables. Furthermore, in many rural and peri-urban areas facing water scarcity, the irrigation of agricultural land with untreated or partially treated municipal wastewater has become a common practice (Lapworth et al., 2012). This introduces significant loads of pathogenic microorganisms, heavy metals, pharmaceuticals, and persistent organic pollutants directly into the shallow hydrological cycle.

Urbanization and domestic infrastructure also exert substantial pressure on subsurface water quality. Aging, poorly maintained, or structurally compromised municipal sewer networks, along with improperly constructed on-site septic systems, frequently leak raw sewage into the surrounding soil. These chronic subsurface leakages elevate microbial pathogen levels, organic carbon, and nitrogenous compounds in urban aquifers. Similarly, inadequately lined municipal solid waste landfills generate toxic leachate as rainwater filters through decomposing refuse, creating concentrated contaminant plumes that migrate downward into vital drinking water reserves.

Finally, industrial operations, mining activities, and commercial energy infrastructure represent severe point sources of hazardous contamination. Unregulated disposal, accidental spills, and surface runoff from industrial and mining sites release heavy metals—such as lead, cadmium, mercury, and chromium—alongside chlorinated solvents and acidic drainage into the subsurface. Moreover, structural corrosion and mechanical failures in underground fuel storage tanks at service stations often lead to the leakage of petroleum hydrocarbons. Compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX), as well as fuel additives, can dissolve into groundwater, creating highly toxic plumes that pose severe carcinogenic and environmental risks. Ultimately, protecting groundwater resources requires an integrated understanding of both natural hydrogeochemical vulnerabilities and the strict regulation of agricultural, urban, and industrial practices.

1.3 Major Groundwater Contaminants

Groundwater quality is threatened by a diverse array of chemical, biological, and radiological pollutants that originate from both geogenic processes and anthropogenic activities. Once introduced into the subsurface environment, these contaminants behave differently depending on their solubility, density, chemical stability, and interaction with the surrounding soil and rock matrices. Understanding

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the primary classes of groundwater contaminants is essential for assessing environmental risks, safeguarding public health, and designing effective water management and remediation strategies.Among the most widespread inorganic chemical contaminants is nitrate , which predominantly originates from agricultural runoff, excessive fertilizer application, livestock waste, and leaking septic systems. Because nitrate is highly soluble and does not readily bind to soil particles, it easily leaches through the unsaturated zone into underlying aquifers. Elevated nitrate levels in drinking water pose severe health risks, most notably methemoglobinemia (or "blue baby syndrome") in infants, as well as potential carcinogenic effects in adults. Alongside nitrate, trace metals and metalloids—such as arsenic, lead, cadmium, chromium, mercury, and fluoride—represent critical toxic threats. While arsenic and fluoride often enter groundwater through the natural dissolution of mineral formations under specific geochemical conditions, heavy metals like lead and chromium are frequently introduced via industrial effluents, mining drainage, and corroding plumbing infrastructure. Even at trace concentrations, these elements are persistent, bioaccumulative, and capable of causing severe neurological, renal, and skeletal damage.Organic contaminants constitute another major category of subsurface pollutants, largely driven by industrial, commercial, and agricultural operations. Volatile organic compounds (VOCs), including industrial solvents such as trichloroethylene (TCE) and perchloroethylene (PCE), are widely used in manufacturing and dry cleaning. Due to their low viscosity and high density, many chlorinated solvents form dense non-aqueous phase liquids (DNAPLs) that sink rapidly to the bottom of aquifers, creating long-term contamination sources that are notoriously difficult to remediate. Similarly, petroleum hydrocarbons—specifically monoaromatic compounds like benzene, toluene, ethylbenzene, and xylenes (BTEX)—frequently enter groundwater through leaking underground fuel storage tanks and pipeline spills. Because they are lighter than water, these compounds typically form light non-aqueous phase liquids (LNAPLs) that float atop the water table, continuously dissolving into passing groundwater and posing acute toxicological and carcinogenic hazards. Furthermore, synthetic agrochemicals, including persistent organochlorine and organophosphate pesticides and herbicides, migrate downward from agricultural fields, disrupting ecosystems and contaminating rural drinking water wells.Biological contaminants, primarily pathogenic microorganisms such as bacteria, viruses, and protozoa, also significantly degrade groundwater quality, particularly in shallow or fractured aquifers. Originating from untreated sewage, failing septic tanks, animal feedlots, and wastewater irrigation, pathogens like Escherichia coli, Salmonella, Cryptosporidium, and enteric viruses can survive in cool, dark subsurface environments long enough to reach nearby abstraction wells, triggering outbreaks of acute waterborne gastrointestinal diseases.Finally, salinization and emerging contaminants present growing challenges to modern hydrogeology. Excessive groundwater extraction in coastal zones frequently induces saltwater intrusion, elevating total dissolved solids (TDS), chloride, and sodium concentrations to levels that render water unfit for drinking or crop irrigation. Concurrently, contaminants of emerging concern (CECs)—including pharmaceuticals, personal care products, endocrine-disrupting chemicals, and per- and polyfluoroalkyl substances (PFAS)—are increasingly detected in aquifers due to wastewater reuse and landfill leachate, highlighting the evolving complexity of protecting global groundwater reserves.

1.4 Health Effects of Groundwater Contamination

The specific toxicological and epidemiological impacts of groundwater pollutants highlight the severe burden of waterborne diseases on human populations. Chronic arsenic exposure, even at relatively low concentrations over extended durations, causes distinctive skin lesions, peripheral vascular and cardiovascular disease, and malignant cancers of the skin, lung, and bladder (Naujokas et al., 2013). Similarly, heavy metals pose persistent systemic threats due to their inability to biodegrade and their tendency to bioaccumulate within human tissues. Cadmium primarily targets the renal system, causing irreversible kidney damage and tubular dysfunction, while simultaneously disrupting calcium metabolism and leading to bone demineralization and fractures; meanwhile, lead severely impairs neurological and cognitive development in infants and young children, resulting in permanent intellectual deficits and behavioral disorders (Järup, 2003).

In addition to trace metals, non-metallic inorganic ions and biological agents account for widespread morbidity across both rural and urban settings. Elevated nitrate concentrations in drinking water are directly linked to infantile methaemoglobinaemia, a potentially fatal condition wherein nitrate reduces to nitrite and interferes with the oxygen-carrying capacity of hemoglobin, and chronic exposure has

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further been associated with adverse reproductive outcomes, thyroid dysfunction, and certain gastrointestinal cancers (Ward et al., 2018). Concurrently, excessive intake of naturally occurring fluoride causes progressive dental fluorosis—characterized by mottling and pitting of tooth enamel—and debilitating skeletal fluorosis, which results in joint stiffness, ligament calcification, and severe bone deformities (Fawell et al., 2006). Beyond chemical toxicity, microbiological contamination from fecal pathogens remains one of the most immediate threats to public health, causing acute diarrhoeal illnesses, cholera, typhoid, and other severe enteric diseases that contribute substantially to global childhood mortality and malnutrition (Bain et al., 2014). Together, these diverse health outcomes underscore the urgent necessity for continuous water quality surveillance, source protection, and effective treatment interventions.

1.5 Importance of Health Risk Assessment

Conventional water quality evaluations often rely on comparing measured contaminant concentrations against established regulatory thresholds, such as those set by the World Health Organization (WHO) or national environmental agencies. While comparing measured concentrations with guideline values shows whether water is compliant, it offers only a binary assessment of safety and does not quantify the actual health risk posed to an exposed population. Regulatory standards alone fail to account for variations in individual physiology, local consumption patterns, cumulative multi-contaminant interactions, or the duration of exposure, leaving a critical gap in understanding the true epidemiological burden of contaminated water supplies.

To overcome these limitations, human health risk assessment (HHRA) provides a systematic, quantitative framework for evaluating the likelihood and severity of adverse health outcomes. Originally formalized through foundational regulatory frameworks, health risk assessment estimates the actual dose people receive through drinking water—as well as secondary pathways like dermal contact during bathing—and compares this chronic daily intake with established toxicological reference values, such as reference doses (RfD) and cancer slope factors (NRC, 1983; USEPA, 1989). This methodological approach yields standardized quantitative metrics, specifically the Hazard Quotient (HQ) and Hazard Index (HI) for non-carcinogenic effects, alongside Incremental Lifetime Cancer Risk (ILCR) estimates for carcinogenic pollutants. Crucially, HHRA stratifies these risk calculations across different age groups, distinguishing between adults, children, and infants. Because children exhibit higher water intake rates per unit of body weight and possess developing metabolic and neurological systems, age-specific modeling consistently reveals heightened vulnerabilities that standard concentration checks would otherwise overlook.

By translating raw hydrochemical data into actionable probabilities of harm, health risk assessment bridges the divide between environmental monitoring and public health protection. It therefore provides a robust scientific basis for prioritising monitoring programs, optimizing water treatment technologies, and formulating targeted policy actions (Li & Wu, 2019). Rather than allocating limited financial and technical resources uniformly across all water sources, water managers and policymakers can use risk assessment outputs to identify high-risk geographic hotspots, target the most hazardous contaminants, and implement immediate protective interventions for the most susceptible demographic groups. Ultimately, embedding quantitative health risk assessment into routine groundwater governance ensures more resilient, equitable, and evidence-based drinking water safety strategies.

2. Problem Statement

Groundwater sources are exposed to chemical and biological contaminants from many sources, and populations that depend on them for drinking and daily use may face chronic health risks, often without knowing it. Studies of groundwater quality are numerous, but they differ in the contaminants measured, the exposure assumptions, and the way risk is reported, which makes it difficult to see the overall picture. There is a need to bring together the evidence on contaminant levels relative to guideline values, to estimate the resulting exposure and non-carcinogenic and carcinogenic risks, and to identify the populations most affected.

3. Research Objectives

Main objective

To assess the health risks associated with the consumption of contaminated groundwater by reviewing water quality, contaminant levels, and their potential health effects.

Specific objectives

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1. To review the physical and chemical characteristics of groundwater reported in the literature.
2. To identify the concentrations of heavy metals reported in groundwater samples.
3. To summarise reported levels of nitrate and nitrite.
4. To compare reported results with international drinking-water standards.
5. To describe how daily exposure to contaminants through drinking water is estimated.
6. To evaluate the non-carcinogenic and carcinogenic health risks associated with exposure.
7. To identify the population groups most vulnerable to health risks.

4. Research Questions What is the level of groundwater quality reported in the studied regions?

1. What are the most important chemical contaminants in groundwater?
2. Do contaminant concentrations exceed international guideline values?
3. What is the daily exposure to contaminants through drinking water?
4. What are the levels of non-carcinogenic and carcinogenic health risk?
5. Which population groups are most vulnerable to health risks?

5. Literature Review

5.1 Groundwater Quality and Contamination

Global assessments show that aquifer degradation is widespread and linked to urbanisation, intensive agriculture, and over-abstraction (Morris et al., 2003; Foster & Chilton, 2003). Rapid population growth and unregulated land-use changes have accelerated the release of domestic sewage, industrial effluents, and agrochemicals into subsurface environments, while excessive groundwater pumping induces hydraulic gradients that draw contaminants deeper into productive aquifers or cause saline intrusion in coastal regions. Consequently, evaluating the spatial and temporal dynamics of subterranean water quality has become a central priority in modern hydrogeological research.

To translate complex multi-parameter hydrochemical datasets into clear, actionable insights for decision-makers, researchers increasingly rely on integrated spatial and statistical evaluation tools. Specifically, water quality indices (WQIs) combined with Geographic Information System (GIS) mapping are widely used to summarise the suitability of groundwater for drinking and to locate pollution hotspots (Adimalla & Qian, 2019). By aggregating multiple physicochemical parameters into a single composite score and interpolating these values across regional landscapes, WQI-GIS frameworks enable scientists and water resource managers to visualize contamination plumes, identify vulnerable recharge zones, and prioritize targeted remediation and protection interventions across affected basins.

5.2 Sources and Types of Groundwater Pollutants

The literature separates geogenic pollutants such as arsenic and fluoride from anthropogenic pollutants such as nitrate, pathogens, metals, and organic compounds (Smedley & Kinniburgh, 2002; Lapworth et al., 2012). Geogenic contaminants originate naturally from the mineral composition of aquifer host rocks, where geochemical processes like mineral dissolution, ion exchange, and shifts in redox or pH conditions release toxic trace elements into groundwater over geological timescales. Conversely, anthropogenic pollutants result directly from human activities at the land surface, entering subsurface systems through diffuse leaching, accidental spills, or inadequate waste disposal infrastructure.

Empirical studies consistently demonstrate that surface land use is a strong predictor of groundwater hydrochemistry: agricultural areas typically show higher nitrate and pesticide concentrations due to intensive fertilizer application and irrigation return flows, whereas industrial and urbanized areas show higher trace metal and organic solvent concentrations stemming from manufacturing effluents, mining drainage, and leaking underground storage tanks (Wu & Sun, 2016). Additionally, in rapidly expanding peri-urban and rural settlements lacking centralized sanitation, domestic sewage and septic tank leakages introduce substantial loads of fecal pathogens and organic matter into shallow aquifers. Distinguishing between natural geochemical backgrounds and human-induced contaminant inputs through spatial and hydrochemical profiling is therefore essential for accurately attributing pollution sources and designing effective aquifer protection measures. (Lamma & Swamy, 2018)

5.3 Toxicological Effects of Groundwater Contaminants

Toxicological reviews describe dose-dependent effects across a wide spectrum of inorganic and organic groundwater pollutants, where the severity of physiological harm depends on contaminant concentration, exposure duration, and individual susceptibility. Heavy metals and metalloids represent some of the most hazardous subsurface contaminants due to their persistence and bioaccumulative potential. Specifically, arsenic, hexavalent chromium, and certain other trace metals are well-

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established human carcinogens capable of inducing oxidative stress, DNA damage, and malignancies in the skin, lungs, bladder, and kidneys, whereas cadmium, lead, and mercury mainly act through systemic organ and neurological toxicity (Tchounwou et al., 2012; Järup, 2003; Naujokas et al., 2013). Chronic cadmium exposure primarily induces renal tubular dysfunction and bone demineralization, while lead and mercury disrupt enzymatic functions and neurotransmission, causing irreversible neurodevelopmental and cognitive impairments, particularly in infants and young children (Lamma, 2021).

Beyond trace metals, common non-metallic inorganic ions present significant non-carcinogenic health hazards when consumed at elevated concentrations. Nitrate and fluoride act mainly through infant methaemoglobinaemia and skeletal and dental fluorosis, respectively (Ward et al., 2018; Fawell et al., 2006). Ingested nitrate is reduced to nitrite in the gastrointestinal tract, oxidizing hemoglobin to methemoglobin and impairing oxygen transport in infants, while chronic intake has also been investigated for potential links to thyroid disruption and adverse reproductive outcomes. Similarly, while trace levels of fluoride support dental health, prolonged consumption of high-fluoride groundwater leads to enamel mottling in developing teeth and progressive calcification of ligaments and joints, resulting in crippling skeletal deformities. Understanding these distinct toxicological mechanisms is essential for establishing safe exposure thresholds and prioritizing public health interventions in affected communities. (Lamma, 2020)

5.4 Human Health Risk Assessment Models

Quantitative human health risk assessment (HHRA) provides a systematic methodology for evaluating the probability and magnitude of adverse health effects resulting from human exposure to contaminated groundwater. The foundational four-step framework of hazard identification, dose-response assessment, exposure assessment, and risk characterisation was formalised by the National Research Council (NRC, 1983) and subsequently adapted for chemical contaminants by the US Environmental Protection Agency (USEPA, 1989). In the initial hazard identification phase, researchers determine which detected groundwater pollutants pose potential toxicological threats based on clinical and epidemiological evidence. Next, dose-response assessment establishes the quantitative relationship between the magnitude of exposure and the incidence of adverse health outcomes, relying on established toxicological benchmarks such as oral Reference Doses (RfD) for non-carcinogens and Cancer Slope Factors (CSF) for carcinogens. (Lamma et al., 2018)

During the exposure assessment phase, models quantify the intensity, frequency, and duration of human contact with contaminated water across primary pathways—predominantly direct oral ingestion and dermal absorption during bathing. It is the basis of most contemporary groundwater studies, which calculate the Chronic Daily Intake (CDI) or Average Daily Dose (ADD), the non-carcinogenic Hazard Quotient (HQ), the cumulative Hazard Index (HI), and the Incremental Lifetime Carcinogenic Risk (ILCR)

5.5 Previous Studies on Health Risks Associated with Groundwater Consumption

Studies in several regions apply this framework. Wongsasuluk et al. (2014) assessed heavy metals in shallow wells in an agricultural area of Thailand and reported health risks from metals, notably arsenic. Wu and Sun (2016) assessed shallow groundwater in an alluvial plain affected by agricultural and industrial activities in China. In semi-arid southern India, Adimalla and Qian (2019) and Adimalla (2020) evaluated nitrate and fluoride and reported higher risk for children than for adults. More recent regional work on heavy metals in groundwater, including comparative multi-regional assessments, extends this approach (Lamma, 2023). Together they indicate that the main contaminants of concern vary by region, but that the assessment method is consistent.

6. Materials and Methods

6.1 Study design

This study uses a systematic narrative review following the PRISMA guidelines (Moher et al., 2009). The review is structured around the four steps of health risk assessment shown in Figure 1.

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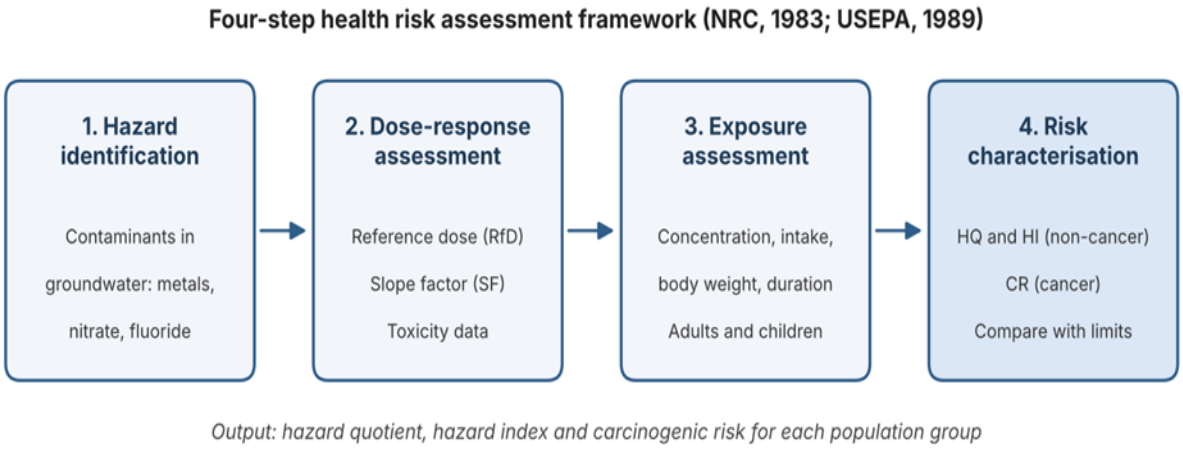


Figure 1. Four-step health risk assessment framework used to structure the review.

6.2 Data extraction

For each study, the location, land use, contaminants, analytical methods, exposure parameters, calculated risks, and population groups were extracted. Concentrations were compared with the WHO drinking-water guideline values (Table 1).

6.3 Health risk assessment framework

The review uses the USEPA approach (USEPA, 1989). Daily exposure through drinking water is the average daily dose (ADD, mg/kg/day):

$$ADD = (C \times IR \times EF \times ED) / (BW \times AT)$$

where C is the concentration (mg/L), IR the ingestion rate (L/day), EF the exposure frequency (days/year), ED the exposure duration (years), BW the body weight (kg), and AT the averaging time (days). The non-carcinogenic hazard quotient and hazard index are:

$$HQ = ADD / RfD \qquad HI = \Sigma HQ_i$$

where RfD is the oral reference dose. A value of HQ or HI above 1 indicates potential non-carcinogenic risk. The carcinogenic risk is:

$$CR = ADD \times SF$$

where SF is the cancer slope factor ($(mg/kg/day)^{-1}$). A CR between 1×10^{-6} and 1×10^{-4} is generally regarded as the acceptable range. Typical exposure parameters used in the reviewed studies are shown in Table 2.

Table 1. WHO guideline values and oral reference doses for selected contaminants (WHO, 2022; USEPA IRIS; reference doses are approximate and should be verified)

Contaminant	WHO guideline value	Oral RfD (mg/kg/day)	Main health effect
Arsenic	10 µg/L	0.0003	Skin lesions, cancers
Cadmium	3 µg/L	0.0005	Kidney and bone damage
Lead	10 µg/L	Not established	Neurodevelopmental effects
Chromium	50 µg/L	0.003 (Cr VI)	Organ toxicity, cancer (Cr VI)
Nitrate	50 mg/L	1.6 (as nitrate-N)	Infant methaemoglobinaemia
Fluoride	1.5 mg/L	0.06	Dental and skeletal fluorosis

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Table 2. Typical exposure parameters used in drinking-water risk assessment

Parameter	Adults	Children
Ingestion rate, IR (L/day)	2.0	1.0
Body weight, BW (kg)	70	15
Exposure frequency, EF (days/year)	365	365
Exposure duration, ED (years)	30	6
Averaging time, AT (days)	ED × 365 (non-cancer); 70 × 365 (cancer)	ED × 365 (non-cancer); 70 × 365 (cancer)

7. Results

7.1 Groundwater quality and contaminant levels

The reviewed studies report that groundwater is often alkaline to slightly alkaline and moderately to highly mineralised in semi-arid regions, with elevated salinity in coastal and over-abstracted aquifers (Adimalla & Qian, 2019; Taylor et al., 2013). Nitrate and fluoride were the most frequently reported chemical parameters exceeding WHO guideline values in agricultural and semi-arid areas. Arsenic, chromium, cadmium, and lead exceeded guideline values mostly in a limited number of shallow wells near agricultural or industrial activities (Wongsasuluk et al., 2014; Wu & Sun, 2016).

7.2 Exposure and non-carcinogenic risk

Daily exposure calculated from the reported concentrations was consistently higher for children than adults, because their water intake per kilogram of body weight is greater: with the parameters in Table 2, children ingest about 2.3 times more water per kilogram of body weight than adults (Figure 2). In several studies, hazard quotients for nitrate and fluoride were above 1 in a share of samples, and children reached the threshold at lower concentrations (Adimalla & Qian, 2019; Adimalla, 2020). Hazard index values combining several contaminants exceeded 1 more often than single-contaminant quotients.

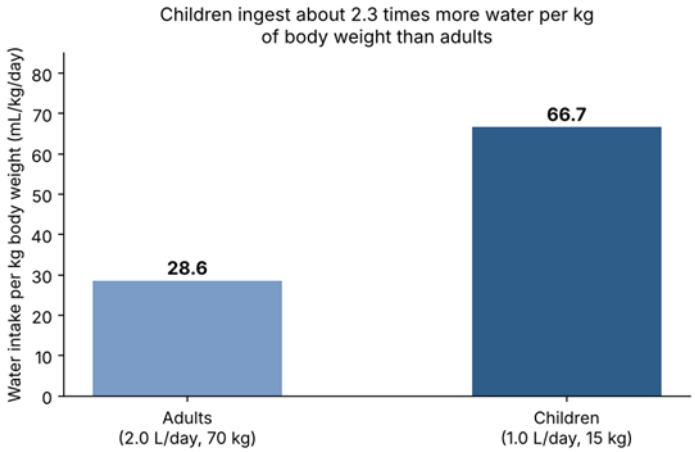


Figure 2. Water intake per kilogram of body weight for adults and children, calculated from the Table 2 parameters.

7.3 Carcinogenic risk

Arsenic was the main contributor to carcinogenic risk where it was measured, and risk values in affected areas could exceed the acceptable 1×10^{-4} level for long exposure (Wongsasuluk et al., 2014; Naujokas et al., 2013). Hexavalent chromium contributed in industrial settings (He & Li, 2020).

7.4 Vulnerable groups and modifying factors

Children and infants were the most vulnerable, followed by people with long-term consumption of untreated water, such as rural households (Ward et al., 2018). Risk was modified by land use, aquifer depth, season, and the exposure parameters assumed, so the same contaminant level can give different risk results in different studies (Wu & Sun, 2016).

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Discussion

The results show that guideline compliance and health risk are related but not identical: water below a guideline value can still contribute to risk when several contaminants combine, and risk estimates highlight children as the critical group even when average values look acceptable (USEPA, 1989). The dominance of nitrate and fluoride in semi-arid and agricultural regions is consistent with their sources, namely fertilisers and sewage for nitrate and mineral dissolution for fluoride (Ward et al., 2018; Fawell et al., 2006).

The role of arsenic in carcinogenic risk reflects both its toxicity and the low acceptable-risk threshold, so small concentrations over decades matter (Naujokas et al., 2013). This also means health effects appear after long exposure and are less visible than infectious outbreaks, and are probably under-recognised in public health records.

Several limitations should be noted. Exposure parameters are usually default values rather than local data, dermal and inhalation routes are generally ignored, and uncertainty in reference doses and slope factors affects the results (USEPA, 1989). Many studies are based on one sampling campaign and do not capture seasonal variation, and the review design does not provide pooled estimates. Future work should combine repeated sampling, local exposure data, probabilistic methods, and health records from the same communities.

Conclusion

The evidence reviewed shows that consuming contaminated groundwater is associated with measurable non-carcinogenic and carcinogenic health risks. Nitrate, fluoride, arsenic, and other toxic metals are the main contaminants of concern, with infants and children identified as the most vulnerable demographic groups due to their higher fluid intake relative to body weight and developing physiological systems. The magnitude of these risks depends heavily on contaminant concentration levels, specific exposure assumptions, surrounding land use patterns, and local hydrogeological aquifer conditions. When local populations rely on unmonitored subterranean sources, chronic exposure over prolonged periods can trigger severe systemic disorders, ranging from acute methemoglobinemia and skeletal fluorosis to irreversible organ damage and oncogenesis.

To address these multifaceted environmental health threats effectively, conventional water quality monitoring must be supplemented by advanced analytical frameworks. Health risk assessment adds critical quantitative information that guideline comparison alone does not provide, as it evaluates actual intake dosages, pathway frequencies, and population-specific vulnerabilities. By calculating non-carcinogenic hazard quotients and carcinogenic risk probabilities, decision-makers can pinpoint precise exposure hotspots, evaluate cumulative toxicological effects, and prioritize targeted remediation actions. Consequently, integrating comprehensive health risk evaluations into regional groundwater management plans and national drinking-water policies is an essential strategy to protect public health and ensure the sustainable management of global water resources.

Recommendations

1. Establish routine groundwater monitoring for heavy metals, nitrate, fluoride, and microbiological indicators, and compare results with WHO guideline values.
2. Include health risk assessment, separately for adults and children, in water quality studies and drinking-water programmes.
3. Control pollution at source through proper use of fertilisers and pesticides, sanitation and wastewater management, and regulation of industrial discharge and waste disposal.
4. Provide treatment or alternative supplies in areas where hazard quotients or carcinogenic risks exceed acceptable levels, with priority for children.
5. Use local exposure data and probabilistic methods in future studies, and repeat sampling across seasons.
6. Raise community awareness of groundwater protection and safe water use, and link water quality data with health surveillance.

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