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# Recent Trends in Heavy Metal Pollution of Groundwater: A Review

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***Abstract***

*Heavy metal pollution in groundwater has emerged as a major environmental and public health concern worldwide due to its persistence, toxicity, and potential for bioaccumulation. Rapid industrialization, urban expansion, intensive agriculture, mining activities, and improper waste disposal have significantly increased the release of heavy metals into subsurface environments. Groundwater, being a primary source of drinking water in many regions, is particularly vulnerable to contamination, posing serious risks to human health and ecosystem sustainability. This review synthesizes recent research trends on heavy metal pollution in groundwater, with emphasis on studies published in the last decade. The review critically examines the sources, distribution, and behavior of heavy metals in groundwater systems, highlighting both natural and anthropogenic contributions. Particular attention is given to the pathways through which heavy metals migrate from soils and sediments into aquifers and their spatial and temporal variability. The health impacts associated with chronic exposure to contaminated groundwater, including carcinogenic and non-carcinogenic risks, are also discussed. In addition, recent advances in detection, monitoring, and analytical techniques used for assessing groundwater contamination are reviewed, along with their advantages and limitations. This study further evaluates commonly adopted remediation and management strategies for controlling heavy metal pollution in groundwater, including physical, chemical, and biological approaches. Emerging treatment technologies and sustainable management practices are also highlighted. By integrating recent findings, this review identifies key research gaps, methodological limitations, and challenges in groundwater contamination assessment and management. The outcomes of this review aim to provide a comprehensive understanding of current research directions and support the development of effective strategies for mitigating heavy metal pollution in groundwater, thereby contributing to improved water resource management and public health protection.*

**Keywords:** Groundwater contamination, heavy metals, human health risk, monitoring techniques, remediation strategies

## INTRODUCTION

Heavy metals are natural constituents of the Earth's crust; however, their concentrations in the environment have increased significantly due to intensified human activities. In groundwater systems, heavy metals, such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) are of major concern because of their toxicity, persistence, and potential to accumulate in living organisms [1–3]. These elements can persist in soils and sediments for long periods and may be mobilized into groundwater through leaching, dissolution, and water–rock interaction processes, thereby entering drinking water supplies and food chains [4, 5].

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The occurrence of heavy metals in groundwater is governed by both natural and anthropogenic factors. Geogenic sources include mineral weathering, dissolution of metal-bearing rocks, and hydrogeochemical processes within aquifers [6, 7]. Anthropogenic activities, such as mining, metal processing, industrial effluent discharge, coal combustion, waste disposal, and agricultural practices have been widely reported as major contributors to groundwater contamination [8–10]. Mining-dominated and industrial regions are particularly vulnerable, where improper handling of waste materials accelerates the release of toxic metals into subsurface water systems [11].

Heavy metals are toxic even at low concentrations and can bioaccumulate through food webs, leading to long-term ecological and human health impacts. Chronic exposure to contaminated groundwater has been associated with severe health outcomes, including neurological disorders, renal dysfunction, cardiovascular diseases, and developmental impairments [12]. In particular, arsenic, cadmium, chromium, and lead are recognized as carcinogenic elements, with prolonged ingestion increasing the risk of skin, lung, bladder, and other cancers [13]. Children are especially vulnerable to heavy metal exposure due to higher intake rates relative to body weight and greater sensitivity during developmental stages [2, 12].

Several studies have reported that although regulatory interventions and improved monitoring have reduced heavy metal exposure in some developed regions, groundwater contamination remains a persistent problem in many developing countries [3, 9]. Rapid industrialization, urban expansion, and inadequate wastewater management continue to pose serious challenges to groundwater quality protection. Consequently, systematic evaluation of groundwater heavy metal pollution, including source identification, concentration assessment, and health risk evaluation, has become a critical area of research [1, 8, 11].

In recent years, researchers have increasingly employed pollution indices, multivariate statistical techniques, and human health risk assessment models to characterize heavy metal contamination in groundwater and to quantify associated risks to human populations [4, 10, 13]. While these approaches have significantly improved the understanding of contamination severity, dominant sources, and exposure pathways, most existing studies remain region-specific, focusing on isolated case studies with limited comparative synthesis. As a result, there is a lack of integrated understanding regarding common contamination trends, methodological consistency, and transferable insights across different hydrogeological and socio-economic settings. Furthermore, variations in the selection of heavy metals, assessment indices, risk models, and analytical techniques across studies make it difficult to draw generalized conclusions or to identify best practices for groundwater quality evaluation and management. Many studies emphasize contamination levels or health risks independently, with comparatively fewer efforts directed toward linking sources, exposure pathways, and health outcomes in a unified framework. This fragmentation highlights a clear research gap in consolidating existing knowledge to support evidence-based decision-making and policy formulation. In view of the growing volume of published studies and the increasing reliance on groundwater as a primary drinking water source, a comprehensive and critical synthesis of existing literature is essential. Therefore, this review was developed to address these gaps by systematically analyzing published research on heavy metal pollution in groundwater. The specific objectives of this review are to: (i) summarize and evaluate the occurrence and distribution patterns of heavy metals in groundwater across different environmental settings; (ii) identify and categorize natural and anthropogenic sources contributing to groundwater contamination; (iii) critically assess the assessment methods, indices, and analytical approaches used in groundwater heavy metal studies. By integrating findings from diverse studies, this review aims to provide a coherent understanding of recent research trends, highlight existing limitations, and identify future research directions for effective groundwater quality management.

## METHODOLOGY OF THE REVIEW

### Literature Search Strategy

A comprehensive literature search was conducted to identify relevant studies addressing heavy metal pollution in groundwater. Major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar, were systematically searched. The search strategy was designed to capture a broad range of studies covering environmental occurrence, contamination sources, analytical techniques, pollution assessment indices, and human health risk evaluation related to heavy metals in groundwater. A combination of keywords and Boolean operators was employed to retrieve relevant publications. Commonly used search terms included groundwater, heavy metals, metal contamination, groundwater pollution, health risk assessment, pollution indices, source apportionment, *and* toxic metals*. These keywords were applied to titles, abstracts, and keywords of published articles. Additional studies were identified through manual screening of reference lists of relevant papers to ensure comprehensive coverage of the topic. Only full-text, peer-reviewed journal articles published in English were considered for inclusion. Duplicate records retrieved from multiple databases were removed prior to screening. The literature search process aimed to capture both regional case studies and broader methodological contributions to provide a balanced synthesis of existing research.

**Inclusion Criteria**

Studies were included in this review if they specifically examined groundwater systems, encompassing both shallow and deep aquifers, and addressed the presence and behavior of heavy metals. Eligible studies reported measured concentrations of heavy metals, such as arsenic, cadmium, chromium, lead, mercury, nickel, copper, zinc, or related toxic elements in groundwater samples. Research articles that assessed groundwater quality using pollution indices, statistical approaches, or human health risk assessment frameworks were considered appropriate for inclusion. Only peer-reviewed journal articles with clearly described methodologies and reproducible analytical procedures were selected to ensure data reliability and scientific rigor. In addition, studies conducted across diverse geographical regions and hydrogeological settings were included to capture spatial variability, source heterogeneity, and differences in contamination patterns associated with varying environmental and anthropogenic conditions.

**Exclusion Criteria**

Studies were excluded from this review if they focused exclusively on surface water, soil, sediments, or biological components without evaluating groundwater systems. Articles that addressed ecological impacts or environmental toxicity without considering groundwater quality or human exposure pathways were also omitted. Non-peer-reviewed literature, including conference abstracts, dissertations, technical reports, policy documents, and unpublished manuscripts, was excluded to ensure the scientific reliability of the reviewed content. Studies lacking quantitative data on heavy metal concentrations in groundwater or failing to describe analytical procedures adequately were not considered. In addition, articles published in languages other than English or those for which full-text access was unavailable were excluded. Duplicate publications or studies presenting overlapping datasets without additional methodological or analytical contributions were also omitted from the review.

## OCCURRENCE AND SOURCES

Heavy metals in groundwater originate from both geogenic (water–rock interaction, natural mineralization, redox-driven mobilization) and anthropogenic processes (mining, smelting, industrial discharge, landfill leachate, sewage, and intensive agriculture). Field evidence across different hydrogeological settings shows that contamination is rarely uniform—rather, it appears as localized hotspots controlled by aquifer lithology, residence time, pH–Eh conditions, and proximity to emission sources. For example, drinking-water monitoring in Iran reported measurable levels of multiple metals and used quality indices to flag sites where metal concentrations warranted concern for supply safety [1]. In India, groundwater from an urban/industrial setting (Chandigarh) showed elevated trace metals including arsenic and other potentially toxic elements, emphasizing the role of mixed urban–industrial pressures and the need to interpret contamination using spatial trends and exposure pathways [2]. Like patterns were reported from China, where shallow versus deep aquifers differed in metal profiles and risk implications, reflecting both geochemical controls and vulnerability of near-surface groundwater to human inputs [3]. A consistent finding in mineralized and mining-influenced terrains is that heavy metals are frequently linked to multi-mineral resource development, with source apportionment approaches indicating contributions from both natural ore-bearing strata and mining-related disturbance. In North China, heavy metal distribution in groundwater from a multi-mineral resource area was explicitly coupled with source apportionment and health-risk analysis, demonstrating how mining belts can generate complex mixed signatures rather than a single-source profile [4]. In agricultural and arid/semi-arid regions, studies increasingly use deterministic and probabilistic frameworks to characterize exposure uncertainty; for instance, probabilistic assessment for arsenic and cadmium exposure highlighted that risk varies substantially depending on concentration distributions and intake assumptions rather than a single-point estimate [5]. Urbanization also plays a major role: along an urban gradient in Onitsha (Nigeria), groundwater quality shifted with land-use intensity, supporting the interpretation that recharge zones close to dense commercial/traffic and waste-handling areas experience higher contamination likelihood [9].

At the same time, broader methodological work has proposed improved indexing approaches for summarizing multi-metal contamination into interpretable risk/quality classes, which is useful when many metals co-occur and spatial decisions are needed [6].

Beyond these site-based studies, recent reviews clarify the mechanisms that govern metal entry and persistence in groundwater. In karst systems, heavy-metal migration is strongly shaped by rapid conduit flow, dual-porosity exchange, seasonal recharge pulses, and the high vulnerability of karst aquifers to surface-derived loads, making “source-to-spring” pathways particularly important for managing pollution [11]. Similarly, industrial-region case studies (, e.g., Pakistan’s industrial clusters) highlight how untreated/partially treated effluents and poor waste controls translate into groundwater metal burdens and management challenges at scale [10]. Finally, remediation-focused syntheses emphasize that the “source” question is inseparable from transport and attenuation: adsorption/desorption, precipitation, complexation, and engineered barriers (, e.g., reactive media) determine whether metals remain immobilized or become bioavailable in groundwater systems [12, 13].

## HUMAN HEALTH AND ENVIRONMENTAL IMPACTS

The primary concern for heavy metals in groundwater is chronic exposure through ingestion (drinking and cooking), with additional contributions from dermal contact and food-chain transfer (irrigation of crops and livestock watering). Numerous regional studies apply standard health-risk frameworks to quantify non-carcinogenic risk (hazard quotient/index) and carcinogenic risk for priority metals, such as As, Cd, Cr, Ni, and Pb. Evidence from Chandigarh showed that multiple metals in groundwater can contribute to measurable human-health risk—especially when exposure is sustained and when sensitive groups (children) are evaluated using age-specific intake rates [2]. In China’s Guanzhong Plain, assessments across shallow and deep groundwater emphasized that risk is influenced by both concentration patterns and aquifer type, and that arsenic can dominate risk even when several metals are present [3]. In Virudhunagar (India), an industrial township groundwater dataset was explicitly evaluated for health risk from multiple metals, illustrating how industrial land use can translate into exposure concern where groundwater remains a key domestic resource [8].

Several papers also highlight why uncertainty handling is increasingly necessary. Probabilistic (Monte Carlo–based) approaches demonstrate that risk estimates can shift meaningfully once variability in concentrations and exposure parameters is propagated—useful for avoiding overconfidence from single-value risk calculations [5]. Likewise, index-based approaches for groundwater heavy metal contamination support communication and prioritization by converting multi-metal chemistry into decision-ready classes; however, such indices must be interpreted alongside actual risk outputs because high index scores do not always map one-to-one with carcinogenic risk drivers (often arsenic) [6]. From an environmental standpoint, heavy metals can reduce groundwater suitability not only for drinking but also for irrigation, with implications for soil accumulation and long-term ecosystem exposure; agricultural-area evidence from Thailand underscored the relevance of evaluating chronic ingestion risk where shallow wells are widely used for daily needs [7]. Monitoring work (, e.g., drinking-water datasets from Iran) further supports that routine screening is essential because even modest concentration changes can push risk metrics across acceptable thresholds depending on local consumption patterns [1].

Finally, environmental impacts and risk management are inseparable from transport and remediation feasibility. Reviews emphasize that metal mobility is governed by hydrogeochemical conditions and that certain settings (, e.g., karst) amplify exposure potential because contaminants can migrate rapidly with limited natural attenuation [11]. Remediation reviews outline why technologies, such as permeable reactive barriers, adsorption-based media, flushing, stabilization/solidification, and other engineered approaches must be selected based on site-specific metal chemistry and hydrogeology [12, 13]. Together, the reviewed studies show that heavy metal pollution in groundwater is not only a contamination issue but also a long-term public health and resource sustainability challenge requiring integrated monitoring, source control, exposure assessment, and treatment planning [2–13].

## DETECTION AND ANALYTICAL TECHNIQUES

Reliable assessment of heavy metal pollution in groundwater depends on rigorous sampling design, appropriate preservation protocols, sensitive laboratory instrumentation, and robust data interpretation techniques. Across the reviewed studies, groundwater samples were typically collected from borewells/handpumps or monitoring wells representing different land-use settings (industrial, mining, agricultural, and urban zones) and, in several cases, the sampling strategy explicitly considered aquifer depth to capture vertical variability in metal occurrence [2,3,8]. Standard practice involved collecting samples in clean high-density polyethylene bottles, filtering where required, and acidifying (commonly with nitric acid) to prevent precipitation and adsorption of dissolved metals onto container walls during storage and transport [8]. Quality assurance and quality control procedures were emphasized through instrument calibration, replicate analyses, use of standards and blanks, and reanalysis/dilution when concentrations exceeded calibration ranges, ensuring measurement repeatability and analytical reliability [8]. For laboratory determination of heavy metals, the studies primarily applied established elemental analysis instruments. Atomic Absorption Spectrophotometry was frequently used for quantifying trace metals in groundwater because of its accessibility and suitability for routine monitoring of elements, such as Pb, Cd, Cr, Ni, Cu, Zn, Mn, and Co [8]. In other investigations, advanced instrumental platforms were used or discussed in terms of capability, including multielement detection at low concentrations and improved selectivity, which is particularly important when metals occur at or near guideline thresholds and when multiple toxic elements must be quantified simultaneously [1, 10, 12]. The reviewed papers collectively highlight that instrument choice should be guided by detection limits, matrix interferences, required throughput, and the target metal suite relevant to local contamination sources.

Beyond chemical measurement, researchers increasingly apply analytical and interpretive techniques to transform concentration data into decision-relevant outputs. Pollution indices are widely used to summarize overall contamination burden, compare sites, and classify groundwater quality into categories for communication and management. Indices, such as the Heavy Metal Pollution Index, Heavy Metal Evaluation Index, and related composite metrics were applied to integrate multi-metal datasets and identify higher-risk locations more efficiently than using single-metal comparisons alone [6, 8]. While indices are useful screening tools, several studies underscore that index interpretation must be aligned with health risk results because dominant risk contributors (often As, Cd, Cr, Ni, or Pb) may drive human risk even when composite indices appear moderate [2, 3, 8]. Multivariate statistics and pattern-recognition tools are also commonly adopted to identify controlling factors and infer contamination sources. Correlation analysis, factor analysis, and clustering are used to distinguish geogenic signatures from anthropogenic inputs, particularly in mixed environments where mining, industry, and agriculture overlap [3, 8]. More advanced machine-learning–assisted source

**Table 1.** Detection and analytical techniques used for heavy metal analysis in groundwater.

| Detection / Analytical Technique | Heavy metal parameters analysed | Key advantage(s) | Major drawback(s) | Ref. |
|---|---|---|---|---|
| Atomic Absorption Spectrophotometry (AAS) | Pb, Cd, Cr, Ni, Cu, Zn, Mn, Co | Widely used; cost-effective; suitable for routine groundwater monitoring | Single-element analysis; lower sensitivity than ICP methods; matrix interference | [8, 9] |
| Cold Vapor Atomic Absorption (CV-AAS) | Hg | High sensitivity and selectivity for mercury | Requires strict handling; volatilization losses possible | [9] |
| ICP–MS (Inductively Coupled Plasma–Mass Spectrometry) | As, Cd, Cr, Pb, Ni, Cu, Zn, Hg | Very low detection limits; simultaneous multi-metal analysis | High operational cost; skilled personnel required; spectral interference | [3, 4] |
| ICP–OES / ICP–AES | Fe, Mn, Cu, Zn, Ni, Cr | Rapid multi-element detection; suitable for higher concentrations | Less sensitive than ICP–MS for trace metals | [4] |
| Wet acid digestion + instrumental analysis | Pb, Cd, Cr, Ni, Zn, Cu, Hg | Enables total metal determination (dissolved + bound forms) | Time-consuming; contamination risk during digestion | [9, 12] |
| Heavy Metal Pollution Index (HPI) | Pb, Cd, Cr, As, Ni, Zn | Integrates multiple metals into a single index; easy interpretation | Masks individual metal contribution; index thresholds vary | [6, 8] |
| Heavy Metal Evaluation Index (HEI) | Pb, Cd, Cr, Ni, Zn | Useful for comparative groundwater quality classification | Does not directly reflect health risk magnitude | [8] |
| Degree of Contamination (Cd) | Pb, Cd, Cr, Ni, Zn | Identifies cumulative contamination intensity | Sensitive to background values; not risk-specific | [6, 8] |
| Multivariate statistical analysis (PCA, FA, CA) | As, Cd, Cr, Pb, Ni, Zn, Hg | Identifies natural vs anthropogenic metal sources | Interpretation subjective; correlation does not imply causation | [3, 4, 9] |
| Self-Organizing Map (SOM) | As, Cd, Cr, Pb, Ni, Zn, Hg | Handles non-linear patterns; effective source apportionment | Requires large datasets; complex interpretation | [4] |
| Deterministic health risk assessment (USEPA-based) | As, Cd, Cr, Pb, Ni | Quantifies carcinogenic and non-carcinogenic risk | Single-value output; uncertainty not captured | [2, 3, 8] |
| Probabilistic risk assessment (Monte Carlo simulation) | As, Cd, Cr, Pb, Ni | Captures uncertainty and variability in exposure | Computationally intensive; needs robust input distributions | [5] |
| GIS-based spatial mapping of metals | As, Cd, Cr, Pb, Ni, Zn | Identifies contamination hotspots and vulnerable zones | Dependent on sampling density and interpolation method | [3, 4, 9, 11] |
| Adsorption / reactive media modelling (PRB concepts) | As, Cd, Cr, Pb, Ni | Supports remediation design and performance prediction | Scaling lab results to field conditions is challenging | [12, 13] |

apportionment has also been used to improve discrimination of source groups and to link hydrogeochemical processes with spatial risk patterns [4]. In addition, probabilistic approaches, such as Monte Carlo simulation are increasingly integrated into risk evaluation to capture uncertainty and variability in exposure parameters and concentration distributions, providing a more realistic interpretation than single-point deterministic calculations [5]. Spatial tools further strengthen groundwater contamination assessment by mapping contamination hotspots and associating them with land use and hydrogeological controls. Several papers used spatial interpretation and mapping to highlight regional differences, identify vulnerable zones, and support targeted monitoring and intervention planning—especially for complex settings, such as mining regions, industrial clusters, urban gradients, and karst aquifers where transport pathways can be rapid and heterogeneous [3, 4, 9–11]. Reviews focused on karst groundwater emphasize that detection programs in such terrains require careful consideration of recharge events, conduit-driven transport, and seasonal variability, which can cause rapid changes in metal concentrations and exposure potential [11]. The analytical techniques applied for groundwater heavy metal detection across the reviewed studies are summarized in Table 1, including the target metal parameters, key advantages, and methodological limitations.

## REMEDIATION AND MANAGEMENT STRATEGIES

Remediation and management of heavy metal pollution in groundwater require an integrated approach that combines source control, risk-based prioritization, and site-appropriate treatment technologies. The reviewed studies consistently indicate that effective management begins with identifying dominant contamination sources—such as mining activities, industrial discharge, waste dumping, or intensive agriculture—and implementing preventive controls to reduce continuous metal loading into aquifers [4,9,10]. Source-oriented actions may include improving industrial effluent treatment, regulating disposal of hazardous wastes, controlling leachate from dumpsites and landfills, and enforcing safer mining practices and tailing management. In settings where non-point agricultural inputs contribute to metal mobilization, better fertilizer and pesticide management, runoff control, and soil protection measures help reduce the transfer of metals from the vadose zone to groundwater [7,11]. Once contamination is established, remediation strategies are typically selected based on hydrogeological conditions, metal speciation, concentration levels, and exposure risk. A widely discussed conventional method is pump-and-treat, where contaminated groundwater is extracted, treated above ground using physical–chemical processes, and then discharged or reinjected. Although pump-and-treat can be effective for plume containment and partial mass removal, it is often costly and time-consuming in heterogeneous aquifers due to slow desorption, diffusion from low-permeability zones, and prolonged tailing effects [12,13]. Therefore, many studies and reviews highlight the growing preference for in-situ treatment, particularly where long-term and sustainable remediation is required.

Among in-situ technologies, permeable reactive barriers (PRBs) are commonly recommended for metal-contaminated groundwater because they can immobilize metals through adsorption, precipitation, ion exchange, and redox reactions while allowing groundwater to flow naturally through the reactive media. The selection of reactive materials depends on target metals and local geochemistry, and common media include iron-based materials, activated carbon, zeolites, limestone, biochar, and other engineered sorbents designed to enhance metal removal efficiency [12,13]. In addition, in-situ immobilization and stabilization strategies aim to reduce metal mobility by altering subsurface geochemistry—such as adjusting pH, promoting precipitation, or enhancing adsorption onto mineral surfaces—thereby limiting exposure even if total concentrations remain unchanged [12]. In-situ soil flushing may also be applied in certain cases to mobilize and remove metals using suitable flushing agents; however, this method requires careful control to prevent secondary contamination and depends strongly on aquifer properties and contaminant chemistry [13]. Management strategies also increasingly incorporate risk-based planning, where remediation priorities are aligned with carcinogenic and non-carcinogenic health risks, vulnerable population exposure, and dominant risk drivers. Studies focusing on health risk assessment demonstraate that metals, such as As, Cd, Cr, Ni, and Pb often dominate risk profiles, implying that remediation efforts should target these priority contaminants first, rather than treating all detected metals with equal emphasis [2–4, 8]. Probabilistic risk assessment further supports risk-informed decision-making by quantifying uncertainty and allowing managers to identify "worst-case" exposure scenarios that may warrant urgent intervention even when average concentrations appear moderate [5]. In highly vulnerable aquifer systems, such as karst terrains, management requires special attention because rapid transport pathways and short residence times reduce natural attenuation capacity, making pollution prevention, continuous monitoring, and protection of recharge zones essential for sustainable control [11]. The remediation and management approaches applied to heavy metal–contaminated groundwater across the reviewed studies are summarized in Table 2, highlighting pollutant-specific treatment options along with their advantages and limitations.

 

**Table 2.** Remediation and management strategies for heavy metal–contaminated groundwater.

| Heavy metal pollutant(s) | Remediation / management method | Key advantage(s) | Major disadvantage(s) / limitation(s) | Ref. |
|---|---|---|---|---|
| As, Cd, Cr, Pb, Ni | Pump-and-treat | Effective for plume containment; well-established technology | High operational cost; long remediation time; limited effectiveness in heterogeneous aquifers | [12, 13] |
| As, Cd, Cr, Pb, Ni | Permeable reactive barriers (PRBs) | In-situ treatment; low energy demand; effective immobilisation via adsorption/precipitation | Requires site-specific design; performance declines as media becomes exhausted | [12, 13] |
| As, Cd, Pb, Cr | Adsorption using reactive media (iron-based media, activated carbon, biochar) | High removal efficiency; adaptable to different metals; suitable for in-situ and ex-situ use | Media replacement/regeneration needed; efficiency depends on groundwater chemistry | [12, 13] |
| As, Cd, Cr, Pb, Ni | In-situ immobilisation / stabilization | Reduces metal mobility and bioavailability; minimal disturbance to aquifer | Does not remove metals; long-term stability uncertain under changing geochemical conditions | [12] |
| As, Cd, Pb | Soil and aquifer flushing | Can remove mobile metal fractions; useful in shallow aquifers | Risk of spreading contamination; requires careful control of flushing agents | [13] |
| As, Cd, Cr, Pb, Ni | Source control and land-use management | Prevents further contamination; cost-effective in long term | Does not address existing contamination; depends on regulatory enforcement | [4, 9, 10] |
| As, Cd, Cr, Pb, Ni | Risk-based management and prioritisation | Focuses remediation on dominant risk drivers; optimises resource allocation | Requires reliable exposure and toxicity data; uncertainty may affect decisions | [3, 4, 5, 8] |
| As, Cd, Pb, Ni | Alternative water supply and blending | Immediate risk reduction for affected populations | Not a permanent solution; may increase dependency on external water sources | [2, 8, 10] |
| As, Cd, Cr, Pb, Ni | Point-of-use treatment (household filters, adsorption units) | Effective for exposure reduction; suitable for rural/remote areas | Maintenance and user compliance issues; limited lifespan of filters | [8, 10] |
| As, Cd, Cr, Pb, Ni | Monitoring and protection of recharge zones | Prevents rapid contaminant entry; critical for vulnerable aquifers (e.g., karst) | Requires long-term monitoring and land-use control | [11] |

At the policy and community level, management includes strengthening groundwater monitoring networks, establishing early-warning systems, enforcing drinking-water guideline compliance, and promoting safe water alternatives where contamination is persistent. Short-term interventions may involve blending, point-of-use filtration, and alternative water supply provision for high-risk communities, particularly in mining and industrial regions where hotspots have been documented [4, 8, 10]. Long-term sustainability, however, depends on combining technical remediation with effective governance, land-use controls, and continuous risk communication to ensure that reductions in metal exposure are maintained over time [9–11]. Overall, the reviewed literature indicates that successful remediation of heavy metal-contaminated groundwater is most feasible when prevention and treatment are implemented together—supported by robust monitoring, risk-based prioritization, and technology selection matched to local hydrogeological and socio-economic conditions [12, 13].

## CHALLENGES, RESEARCH GAPS, AND FUTURE DIRECTIONS

Despite substantial progress in understanding heavy metal pollution in groundwater, several scientific, technical, and management challenges continue to limit effective assessment and mitigation. One of the primary challenges highlighted across the reviewed studies is the strong spatial and temporal heterogeneity of heavy metal concentrations in groundwater systems. Variations in aquifer lithology, hydrogeochemical conditions, recharge dynamics, and land-use patterns result in highly localized contamination hotspots, making extrapolation of findings difficult and complicating regional-scale management [3, 4, 11]. In addition, seasonal fluctuations, particularly in monsoon-influenced and karst regions, can significantly alter metal mobility and exposure potential, yet long-term monitoring datasets capturing such variability remain limited [1, 11]. A major research gap lies in the lack of methodological standardization across groundwater heavy metal studies. Differences in sampling design, analytical techniques, selected metal suites, and pollution or risk indices hinder direct comparison between studies and reduce the transferability of conclusions [2, 6, 8]. While composite indices and health risk assessment models are widely used, their application and interpretation vary considerably, and uncertainty associated with exposure assumptions is not always adequately addressed. Although probabilistic approaches have demonstrated advantages over deterministic assessments, their use is still limited, highlighting a need for broader adoption of uncertainty-based frameworks in groundwater risk evaluation [5]. Another challenge concerns source identification and apportionment in complex environments where geogenic and anthropogenic influences overlap. In mining and industrial regions, natural mineralization, waste rock weathering, and anthropogenic discharge often produce similar chemical signatures, making it difficult to distinguish dominant sources using conventional statistical tools alone [4, 10]. Advanced multivariate and machine-learning–based source apportionment techniques show promise, but their application remains largely case-specific, and integration with hydrogeological process understanding is still insufficient [4]. Similarly, in vulnerable aquifer systems, such as karst terrains, rapid transport pathways and limited natural attenuation complicate both contamination diagnosis and management, underscoring the need for site-specific conceptual models [11].

From a management perspective, the reviewed literature reveals persistent gaps between scientific assessment and practical implementation. Remediation technologies, such as permeable reactive barriers, in-situ immobilization, and pump-and-treat systems are often constrained by high costs, long remediation times, and site-specific feasibility issues, particularly in low- and middle-income regions [12,13]. Moreover, many studies focus on contamination assessment without evaluating the long-term effectiveness of remediation or post-remediation monitoring, limiting evidence-based selection of sustainable treatment strategies [12]. Community exposure reduction measures, including point-of-use treatment and alternative water supplies, are frequently implemented as short-term solutions but are not always integrated into broader groundwater management plans [8, 9]. Future research should prioritize integrated and interdisciplinary approaches that link hydrogeochemistry, source apportionment, exposure pathways, and health outcomes within unified assessment frameworks. Development of standardized monitoring protocols, harmonized index and risk evaluation methods, and regionally comparable datasets would substantially improve synthesis and decision-making across studies [2, 6]. Greater emphasis is needed on long-term monitoring and time-series analysis to capture seasonal dynamics and trends in contamination and risk [1, 11]. Advances in data-driven tools, including machine learning and probabilistic modeling, should be combined with process-based hydrogeological understanding to improve prediction of contamination evolution and to support adaptive management [4, 5, 10]. Finally, future groundwater protection strategies should strengthen the link between scientific evidence and policy by incorporating risk-based prioritization, stakeholder engagement, and socio-economic considerations, thereby ensuring that mitigation of heavy metal pollution contributes to sustainable water resource management and public health protection [8–13].

## CONCLUSION

Heavy metal pollution in groundwater represents a persistent and complex environmental challenge driven by the combined influence of natural geochemical processes and diverse human activities, such as mining, industrialization, urban development, and agriculture. This review has synthesized existing research to provide an integrated understanding of the occurrence, sources, health implications, assessment approaches, and management strategies associated with heavy metals in groundwater systems. The reviewed studies collectively demonstrate that contamination patterns are highly variable across regions, aquifer types, and land-use settings, with shallow groundwater often showing greater vulnerability due to its proximity to surface-derived inputs.

The assessment of groundwater contamination has evolved from simple concentration-based evaluations to more comprehensive approaches that integrate pollution indices, statistical analyses, health risk assessment, probabilistic modeling, and spatial interpretation. These tools have improved the ability to identify contamination hotspots, dominant risk contributors, and exposure pathways, thereby supporting more informed decision-making. However, variations in methodologies and data availability continue to limit comparability across studies, emphasizing the need for greater harmonization and standardization in groundwater quality assessment.

Human health risk remains a central concern, particularly in regions where groundwater serves as the primary drinking water source. Evidence consistently indicates that long-term exposure to heavy metals poses significant carcinogenic and non-carcinogenic risks, with vulnerable populations, such as children facing heightened susceptibility. Environmental impacts further extend the consequences of groundwater contamination beyond drinking water safety, affecting agricultural productivity and ecosystem integrity. Effective remediation and management require a combination of preventive source control, risk-based prioritization, and site-specific treatment technologies supported by continuous monitoring and governance. While several remediation options are available, their success depends on local hydrogeological conditions, contaminant characteristics, and socio-economic feasibility. Overall, this review underscores the importance of integrated, interdisciplinary approaches that bridge scientific assessment with practical management and policy implementation. Strengthening monitoring frameworks, improving methodological consistency, and aligning remediation efforts with public health objectives are essential steps toward ensuring sustainable groundwater resources and long-term protection of human and environmental health.

**Declaration of Interest**
The authors declare no conflicts of interest.

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