

Review on the Assessment of Trace Elements in Groundwater and their Toxicity with Public Health Concerns

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Manuscript received online 11 September 2025, accepted on 21 October 2025

Abstract : Groundwater contamination by trace elements poses a significant public health risk worldwide. Toxic metals such as arsenic, lead, cadmium, and mercury enter groundwater through natural geochemical processes and anthropogenic activities, including industrial waste disposal, agricultural runoff, and mining. Chronic exposure to these elements has been linked to severe health conditions such as cancer, neurological disorders, organ damage, and developmental impairments. This review explores the primary sources of trace elements in groundwater, methods for their detection, associated health risks, and mitigation strategies. Advanced monitoring systems, policy interventions, and community-based approaches are essential for ensuring groundwater safety. Future research should focus on the impact of climate change, emerging contaminants, and sustainable remediation techniques.

(Keywords : Groundwater, Contaminants, Trace elements, Toxicity, Public Health, Sustainability).

Introduction

Groundwater is a critical freshwater resource on Earth for human consumption and use. However, its quality is increasingly threatened by trace element contamination, originating from both natural and human-induced sources. Groundwater deuteriation, caused due to industrial pollution, municipal waste, and agricultural induced activities such as, irrigation water, fertilizers, soil and water amendments, animal manures, sewage effluents and sludges, and pesticides, can pose public health concern and affect the whole ecosystem.

While certain trace elements such as iron, zinc, and copper are essential for biological functions, their excessive accumulation in water supplies can result in toxic effects. Conversely, highly toxic elements like arsenic, lead, and cadmium have no biological function and pose severe health risks. Trace elements present in groundwaters originating from natural geochemical origins do not necessarily reflect the abundance in earth materials; because of differences in their reactivity and mobility and to site-specific hydrogeochemical conditions as well as to changes induced by anthropogenic activity¹. Trace elements are categorized into four viz., alkali and alkaline earth metals, transition metals, metalloids and the non-metals, and heavy metals². There are 15 trace elements which are essential for human health viz., iron, zinc, copper, chromium, selenium, iodine, fluorine, manganese, molybdenum, cobalt, nickel, tin, silicon, vanadium, and arsenic, but only for the first 10 of these has compelling evidence indicated that they are essential nutrients³. Trace elements are crucial for biological, chemical, and molecular cell activity, their excess or deficiency can result in bone health⁴, weakened immunity, increased susceptibility to oral and systemic infections, delayed physical and mental development, and lower productivity, severe body malfunction or, in the worst conditions even death⁵.

High concentration of trace elements in shallow groundwater pose a threat to agricultural production and public health. Excess

accumulation in plants cause phytotoxicity, can adversely affect humans and animals that consume those plants; can seep through the root zone into groundwater, re-emerging in surface waters through drainage¹. The benefit of trace elements to plants is evident when present in adequate amounts, as deficiencies can hinder growth^{6,7}, such as Fe deficiency causing chlorosis by inhibiting chlorophyll synthesis. While Fe shortage is not necessarily due to low input but rather interactions with bicarbonate or nitrate, it significantly impacts plant development, and similar effects are seen with Zn, Cu, or Co deficiencies. However, excessive heavy metals can interfere with physiological and biochemical processes, disturbing nutrient absorption, translocation, and metabolism. These toxic elements may disrupt protein and enzyme synthesis, leading to metabolic turbulence that ultimately inhibits plant growth and reproduction. In severe cases, heavy metal toxicity can result in plant death⁸, highlighting the necessity of maintaining an optimal balance of trace elements.

Understanding the sources, mobility, and health implications of these contaminants is essential for devising effective management strategies. This review aims to analyse the occurrence, toxicity, and regulatory aspects of trace elements in groundwater while exploring mitigation strategies and future research directions. This review aims to highlight the sources of trace elements in groundwater, sampling techniques, testing methods, regulations and exploring the common toxic trace elements and their health risk viz., long term risk and short-term effects.

2. Sources of Trace Elements in Groundwater

Natural sources of trace elements in groundwater primarily include rock weathering, volcanic activity, and soil composition. These processes contribute to the presence of trace elements such as arsenic, manganese, strontium, and nickel in groundwater systems. Rock weathering, particularly in areas with significant

mineral deposits, can lead to the release of trace elements into groundwater through the dissolution and chemical alteration of minerals. Enhanced rock weathering due to anthropogenic activities, such as mining, can accelerate the release of trace elements into groundwater. In the Wardha Valley coalfields, India, rock-water interaction was identified as a key regulatory process for groundwater chemistry, with metals like cadmium, iron, nickel, and lead surpassing desired limits due to acidic conditions⁹. In the South Eastern Desert, Egypt, water-rock interaction and dissolution processes in bedrock from various geological formations were significant contributors to trace element distribution in groundwater¹⁰.

Volcanic activity can introduce trace elements through the deposition of volcanic ash and gases, which subsequently infiltrate groundwater systems. Giammanco et al. (1998)¹¹ studied the comparison between trace elements abundance in Etna's groundwater and that in the groundwater of other areas of Italy. Result showed that, in general, Etna's waters, like other volcanic ground waters, are enriched in Li, Mn, Si, V, As and Mo. Further more, in the areas of Mount Etna, Italy, where the contribution of volcanic gas to the aquifers is greatest, ground waters are also enriched in B, Se, Co, Hg, Al, Fe and Ni. The results clearly show that the water is not fit for drinking water as per standard set by WHO.

Soil composition, influenced by both natural and anthropogenic factors, also plays a crucial role in determining the trace elements content in groundwater. In the Subarnarekha River Basin, the spatial distribution of trace elements such as arsenic, barium, and manganese in groundwater is linked to the soil composition and industrial activities in this region¹².

Anthropogenic activities such as industrial waste disposal, mining, and agricultural practices including excess use of pesticides, and

fertilizers, also play a crucial role in trace element contamination. These activities can exacerbate the natural processes, leading to elevated concentrations of potentially toxic elements in groundwater, posing health risks to locals.

A recent case study showed that, thirteen parameters including trace elements (B, Cr, Mn, Fe, Co, Ni, Zn, As, Sr, Ba and Pb) have been monitored on 53 sampling points nearby industries, from a hydrogeochemical survey conducted in surface and groundwater. Pollution around the Patancheru industrial area, Asia's largest industrial area, increased during the past one and half decade due to discharge of industrial effluents in surface water bodies. R-mode factor analysis identified four factors responsible for data structure explaining 75% of total variance in surface water and two factors in groundwater explaining 85%, and allowed to group selected parameters according to common features. Sr, Ba, Co, Ni and Cr were associated and controlled by mixed origin with similar contribution from anthropogenic¹³.

2. Methods for Measuring Trace Elements

Accurate detection and quantification of trace elements in groundwater are essential for assessing water quality and potential health risks. Several analytical techniques are commonly used to measure the concentration of trace metals, each offering specific advantages in terms of sensitivity, accuracy, and feasibility. One of the most advanced techniques is Inductively Coupled Plasma Mass Spectrometry (ICP-MS), which provides highly sensitive detection of trace metal concentrations at ultra-low levels¹⁴. This method is widely used in environmental monitoring due to its ability to analyze multiple elements simultaneously with high precision.

Another frequently employed technique is Atomic Absorption Spectroscopy (AAS), which is effective in determining metal concentrations in water samples¹⁵. AAS is based on the principle of element-specific light

absorption, making it a reliable and cost-effective method for measuring trace elements such as lead, arsenic, and cadmium.

For rapid screening, X-ray Fluorescence (XRF) serves as a non-destructive technique that allows for quick identification of trace elements in solid and liquid samples¹⁶. While XRF is efficient for preliminary analysis, it may not provide the same level of precision as ICP-MS or AAS for low-concentration elements in groundwater.

Regulatory bodies such as the World Health Organization (WHO), the United States Environmental Protection Agency (EPA) and the Bureau of Indian Standards (BIS) have established permissible limits for toxic elements in drinking water¹⁷⁻¹⁹. These guidelines ensure public safety by setting threshold concentrations for hazardous trace metals, reinforcing the need for continuous monitoring and compliance with international standards.

By utilizing these advanced analytical methods and adhering to regulatory standards, researchers and policymakers can effectively monitor groundwater quality, assess contamination risks, and implement necessary interventions to safeguard public health.

3. Health Risks of Trace Elements

The presence of toxic trace elements in groundwater poses significant health risks, particularly when contamination levels exceed safe limits. Prolonged exposure to these elements through drinking water and food consumption can result in severe short-term and long-term health complications.

3.1 Common Toxic Elements and Health Effects:

Among the most hazardous trace elements, arsenic is particularly concerning due to its strong carcinogenic properties. Chronic arsenic exposure has been linked to skin lesions, lung and bladder cancer, cardiovascular diseases, and neurological

disorders^{20,21}. The arsenic crisis in Bangladesh serves as a stark example of the devastating impact of contaminated groundwater on public health²².

Lead, another highly toxic metal, poses severe risks, especially to children. Even at low concentrations, lead exposure can cause developmental delays, cognitive impairment, and reduced IQ levels²³. In adults, lead toxicity is associated with hypertension, kidney damage, and reproductive issues²¹.

Cadmium accumulates in the human body, primarily affecting kidney function. Long-term exposure to cadmium-contaminated groundwater can lead to renal dysfunction, osteoporosis, and an increased risk of fractures. Inhalation or ingestion of cadmium also elevates the risk of lung and prostate cancer²⁴. Excess Fluoride intake can lead to severe health hazards, including dental and skeletal fluorosis.

Mercury is another neurotoxic element that significantly impacts human health. It is particularly dangerous for pregnant women and infants, as it can impair fetal brain development

and cause lifelong cognitive and motor deficits²⁵. Additionally, mercury exposure can result in tremors, vision impairment, and immune system dysfunction^{26,27}.

3.2 Exposure Pathways : The most common route of human exposure to these toxic elements is drinking contaminated groundwater. Consumption of untreated or poorly filtered water directly increases the risk of poisoning and chronic health disorders²⁸. Another major exposure pathway is food chain bioaccumulation. When crops and aquatic organisms absorb trace elements from contaminated soil and water, these metals enter the human diet²⁹. Over time, accumulation of these toxins in the body can lead to serious health conditions.

Table 1 presents common trace elements found in groundwater, their permissible limits as recommended by the World Health Organization (WHO), the Environmental Protection Agency (EPA), and the Bureau of Indian Standards (BIS), along with associated health effects^{17-19,30}. The inclusion of BIS limits provides a regional regulatory perspective relevant to water quality assessment in India.

Table-1
Trace Elements, Permissible Limits, and Associated Health Effects

Element	WHO Limit (mg/L)	EPA Limit (mg/L)	BIS Limit (mg/L)	Health Effects
Arsenic	0.05	0.05	0.05	Skin lesions, cancer, cardiovascular diseases
Lead	0.05	-	0.1	Neurological disorders, developmental delays
Cadmium	0.005	0.005	0.001	Kidney damage, bone demineralization
Chromium	-	0.1	0.05	Respiratory problems, carcinogenic effects
Mercury	0.001	0.002	0.001	Neurological and renal impairment
Fluoride	1.5	4.0	1.0	Dental and skeletal fluorosis
Nitrate	50.0	10.0 (as N)	45.0	Methemoglobinemia (blue baby syndrome)

In certain occupations and communities, dermal absorption also plays a role in exposure. Frequent skin contacts with contaminated water, especially among industrial and agricultural workers, may contribute to the gradual uptake of toxic elements.

Understanding the health risks associated with trace element contamination is crucial for developing effective prevention and mitigation strategies. By implementing regular groundwater testing, public awareness campaigns, and stricter regulatory policies, the burden of waterborne trace metal toxicity can be significantly reduced.

5. Public Health and Risk Assessment

Certain population groups, including children, pregnant women, and rural communities, are particularly vulnerable to the adverse effects of trace element contamination in groundwater. These populations face increased health risks due to prolonged exposure and limited access to safe drinking water.

To evaluate the health risks associated with trace elements, various risk assessment tools are employed. Two key approaches include the Hazard Quotient (HQ), which measures non-carcinogenic risks, and the Cancer Risk Index (CRI), which assesses the probability of developing cancer due to prolonged exposure to carcinogenic elements^{31,32}. These assessments help policymakers and health organizations identify high-risk areas and prioritize intervention strategies.

Preventive measures play a crucial role in mitigating associated health risks. Regular testing of groundwater sources ensures early detection of toxic elements that enables timely intervention. Public awareness campaigns educate communities about the hidden dangers of trace element contamination, empowering them to adopt safe water consumption practices. Additionally, clean water initiatives, including the implementation of Advanced purification

technologies and alternative water sources, contribute to reduce exposure and improve public health outcomes.

6. Strategies to Reduce Contamination

The contamination of groundwater by trace elements presents a significant environmental and public health challenge. Effective remediation strategies are essential to reduce metal toxicity and ensure safe drinking water. Various physical, chemical, and biological methods have been developed to remove or mitigate the impact of trace elements in groundwater.

6.1. Physical Remediation Methods :Physical remediation techniques primarily focus on the filtration and separation of contaminants from water. Activated carbon filtration is widely used to remove metals like lead and mercury through adsorption³³. Similarly, reverse osmosis (RO) is an advanced filtration technology that uses a semipermeable membrane to effectively remove arsenic, cadmium, and other harmful trace elements³⁴.

Another physical approach is ion exchange, which involves replacing toxic metal ions in water with less harmful ions using specialized resins³⁵. This method is particularly effective for removing heavy metals such as lead and cadmium from drinking water supplies³⁶.

6.2 Chemical Remediation Methods:Chemical techniques play a crucial role in transforming toxic trace elements into less harmful or more easily removable forms. Coagulation and flocculation involve adding chemical agents (e.g., aluminum sulfate, ferric chloride) to contaminated water, which bind with metal particles and facilitate their removal through sedimentation³⁷. Chemical precipitation is another widely used approach, where contaminants are converted into insoluble forms that can be filtered out. Lime softening, for example, helps in the removal of heavy metals by increasing the pH and promoting metal precipitation³⁸.

Electrochemical treatments, such as electrocoagulation, use electric currents to destabilize and separate metallic ions, making them easier to remove. This method has gained attention for its efficiency in treating water contaminated with lead, arsenic, and chromium³⁹.

6.3 Biological Remediation Methods :

Bioremediation is an eco-friendly and cost-effective approach that utilizes natural biological processes to remove contaminants⁴⁰. Phytoremediation, for instance, involves using metal-accumulating plants to absorb and store heavy metals from contaminated water⁴¹. Hyperaccumulator species such as *Eichhorniacrassipes* (water hyacinth) and *Brassica juncea* (Indian mustard) have been widely studied for their effectiveness in removing toxic elements^{42,43}.

Microbial remediation, or bioaugmentation, employs bacteria and fungi capable of transforming or immobilizing toxic metals. Certain microbial strains, such as *Pseudomonas* and *Bacillus*, have shown promising results in arsenic and lead remediation^{44,45}.

6.4 Emerging and Advanced Technologies :

Recent advancements in nanotechnology have introduced nanomaterials like graphene oxide, carbon nanotubes, and iron oxide nanoparticles, which exhibit superior adsorption capacities for heavy metal removal⁴⁶⁻⁴⁸. Additionally, hybrid technologies that integrate physical, chemical, and biological approaches are being developed to enhance remediation efficiency.

Effective remediation strategies are critical for mitigating trace element contamination in groundwater. While traditional methods such as filtration, coagulation, and precipitation remain widely used, emerging technologies like bioremediation and nanotechnology offer promising alternatives. A combination of these techniques, along with proper regulatory measures, can ensure safe and sustainable water resources for affected communities.

7. Challenges and Future Research

One of the key challenges in groundwater contamination is the impact of climate change, as rising temperatures and extreme weather events significantly alter groundwater chemistry, influencing the mobilization of trace elements. Changes in precipitation patterns and increased droughts can further exacerbate the concentration of toxic metals, posing serious risks to water quality and public health.

Another emerging concern is the presence of new contaminants such as microplastics, pharmaceuticals, and nanomaterials, which pose additional threats to groundwater safety. These pollutants are not yet fully regulated, and their long-term effects on human health and ecosystems remain uncertain, highlighting the urgent need for further research and policy development⁴⁹⁻⁵².

Additionally, there are significant data gaps and monitoring deficiencies in current groundwater assessment methods. The lack of real-time monitoring systems and comprehensive datasets limits the ability to track contamination patterns accurately. To address this, the integration of advanced technologies such as GIS-based mapping and real-time sensor networks is essential for assessing spatial and temporal variations in contamination levels. These innovations can enhance early detection and facilitate more effective groundwater management strategies.

By addressing these challenges through interdisciplinary research and technological advancements, future studies can improve our understanding of trace element behavior in groundwater and develop more effective mitigation strategies. Climate Change Impacts, Rising temperatures and extreme weather events alter groundwater chemistry, influencing trace element mobilization.

8. Conclusion

Trace element contamination in groundwater remains a pressing global issue, posing severe risks to human health and ecosystems. Effective mitigation requires a multidisciplinary approach, integrating scientific research, policy regulations, and community-

based interventions. Advances in monitoring techniques and filtration technologies offer promising solutions, but continuous research is needed to address emerging threats and climate-induced changes. Ensuring safe drinking water must remain a priority for policymakers, researchers, and local communities alike.

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