

Heavy Metal Contamination and Its Chemical Effects on Water Quality

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Abstract

Heavy metals and metalloid elements can enter aquatic environments through mining, industrial activities, wastewater discharge, agriculture, urban runoff, and natural geological processes. Metals such as lead, mercury, cadmium, chromium, arsenic, copper, and nickel can influence water quality through changes in chemical composition, speciation, solubility, redox behavior, and interactions with sediments and dissolved organic matter. Their environmental significance depends not only on total concentration but also on chemical form and bioavailability. Heavy-metal contamination can affect aquatic organisms and create concerns for drinking-water resources and food chains. This paper examines nine major dimensions of heavy-metal contamination, including sources, chemical speciation, water chemistry, sediment interactions, bioavailability, ecological effects, human-health concerns, monitoring, and remediation.

Keywords

Heavy Metals; Water Quality; Metal Contamination; Chemical Speciation; Lead; Mercury; Cadmium; Arsenic; Aquatic Ecosystems; Water Remediation

Introduction

Heavy metals and related trace elements occur naturally in rocks, soils, and aquatic systems, but human activities can increase their concentrations in surface water and groundwater. Mining, metallurgy, manufacturing, fossil-fuel combustion, wastewater, and urban activities are important sources.

The behavior of metals in water is controlled by chemical conditions such as pH, oxidation-reduction potential, ionic strength, dissolved organic matter, and the presence of suspended particles and minerals.

Unlike many organic contaminants, metals cannot be destroyed by ordinary degradation processes. They can, however, change chemical form, move between water and sediments, or become incorporated into biological systems.

Understanding metal chemistry is therefore essential for assessing water quality, identifying pollution sources, evaluating ecological and health risks, and designing effective remediation strategies.

1. 1. Sources and Pathways of Heavy-Metal Contamination

Heavy metals enter aquatic environments through mining drainage, metal processing, industrial effluents, wastewater, landfill leachate, agricultural inputs, atmospheric deposition, and urban runoff. Natural weathering of mineral deposits can also contribute

metals to water.

Once released, metals may travel in dissolved form or attach to suspended particles. Their transport depends on water flow, particle concentration, chemical conditions, and interactions with sediments.

Identifying major sources and pathways is important for controlling contamination before metals become widely distributed.

2. 2. Chemical Speciation of Metals in Water

A metal may exist in several chemical forms in an aquatic system. Speciation can involve free ions, inorganic complexes, organic complexes, colloidal forms, or particle-bound species.

The chemical form of a metal strongly influences its solubility, mobility, reactivity, and biological availability. For example, changes in pH can alter the proportion of dissolved and precipitated metal species.

Speciation analysis can therefore provide more useful information about environmental risk than measurements of total metal concentration alone.

3. 3. Influence of pH and Redox Conditions

pH is one of the most important variables controlling metal behavior. Acidic conditions can increase the dissolution of minerals and release certain metals into water, while higher pH may promote adsorption or precipitation for some elements.

Redox conditions can also change metal oxidation states and mobility. Changes between oxygen-rich and oxygen-poor environments can influence the behavior of iron, manganese, arsenic, chromium, and other elements.

Monitoring pH and redox conditions alongside metal concentrations improves interpretation of water-quality data.

4. 4. Interaction with Sediments and Dissolved Organic Matter

Sediments can act as both sinks and potential secondary sources of heavy metals. Metals may bind to clay minerals, iron and manganese oxides, sulfides, carbonates, and organic matter.

Changes in environmental conditions can cause previously bound metals to become mobile. Disturbance, changes in pH, oxygen depletion, or altered chemical conditions can therefore release contaminants from sediments.

Dissolved organic matter can also form complexes with metals, affecting their mobility and biological availability.

5. 5. Effects on Aquatic Organisms and Ecosystems

Heavy metals can interfere with enzymes, cellular membranes, respiration, reproduction, growth, and other biological processes. Toxicity varies among species and depends on exposure concentration, duration, metal form, and environmental conditions.

Some organisms can accumulate metals from water and food. Persistent contamination may therefore affect aquatic communities and contribute to transfer through food webs.

Ecological monitoring combined with chemical measurements provides a more complete assessment of contamination effects.

6. 6. Heavy Metals and Human Health Concerns

Contaminated water can contribute to human exposure through drinking water, food preparation, aquatic foods, irrigation, and recreational contact. Health effects depend on the specific element, chemical form, dose, exposure route, and duration.

Lead and mercury can affect neurological systems, while cadmium can affect the kidneys and bones. Arsenic exposure has been associated with multiple adverse health outcomes. These examples illustrate why chemical monitoring is important for protecting water resources.

Risk assessment must consider both measured concentrations and realistic exposure pathways.

7. 7. Monitoring and Analytical Determination

Reliable measurement of heavy metals requires appropriate sampling, preservation, preparation, and instrumental analysis. Techniques such as atomic absorption spectrometry, inductively coupled plasma optical emission spectrometry, and inductively coupled plasma mass spectrometry can provide sensitive elemental measurements.

Quality assurance includes blanks, calibration standards, certified reference materials, replicate analyses, detection limits, and control samples. Where relevant, speciation methods can provide additional information about chemical form.

Consistent monitoring allows changes in contamination levels to be detected and supports regulatory and remediation decisions.

8. 8. Treatment and Remediation of Metal-Contaminated Water

Heavy-metal removal can involve precipitation, adsorption, ion exchange, membrane filtration, coagulation, electrochemical treatment, or combinations of these methods. Selection depends on metal concentration, water chemistry, treatment objectives, and

economic

considerations.

Adsorbents such as activated carbon, mineral materials, and engineered sorbents can bind selected metals. Chemical precipitation can convert dissolved ions into less soluble forms that can then be separated.

Effective remediation should also consider the management and disposal of metal-containing treatment residues.

9. 9. Prevention and Future Approaches

Preventing heavy-metal release is generally more sustainable than treating contamination after it occurs. Industrial process controls, wastewater treatment, safer material management, mining controls, and improved waste handling can reduce metal inputs.

Future research is exploring selective sorbents, nanostructured materials, membrane systems, electrochemical approaches, and low-cost treatment technologies. Improved sensors may also support rapid field monitoring.

Combining source reduction, chemical monitoring, ecological assessment, and effective treatment can strengthen long-term water-quality protection.

Diagram

The diagram below summarizes the relationship between heavy-metal sources, chemical speciation, changes in water quality, ecological effects, and remediation.

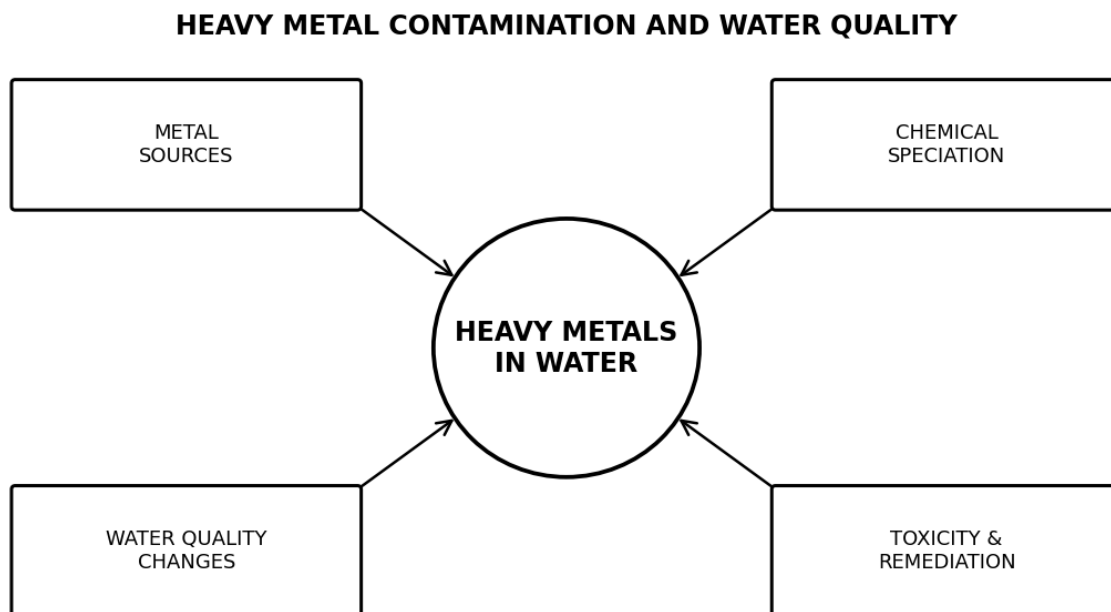


Figure 1. Simplified overview of heavy-metal contamination and its chemical effects on water quality.

Conclusion

Heavy-metal contamination can alter water chemistry and create ecological and human-health concerns. The environmental behavior of metals depends strongly on speciation, pH, redox conditions, sediment interactions, and dissolved organic matter.

Total metal concentration alone may not fully describe environmental risk because different chemical forms can have different mobility and bioavailability. Reliable analytical monitoring and knowledge of water chemistry are therefore essential.

Long-term protection requires prevention at contamination sources, continuous monitoring, appropriate treatment, and responsible management of contaminated sediments and wastes. Advances in analytical and remediation technologies can further improve the management of metal-contaminated water.

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