Characteristics and Ecological Risk Assessment of Heavy Metal Contamination in Aquatic Environments

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Abstract: Heavy metals in aquatic environments are persistent, readily transported, and capable of accumulating in sediments and living organisms. This paper analyzes major pollution sources, including industrial discharges, mining activities, agricultural runoff, and urban surface runoff; summarizes the distribution characteristics of heavy metals in the aqueous phase, particulate matter, and sediments; and discusses their chemical speciation, bioavailability, and transfer through food chains. On the basis of a comparison among water-quality compliance assessment, sediment-contamination assessment, and biological-effects assessment, the paper proposes measures involving multimedia monitoring, source-specific pollution control, and the zoned management of contaminated sediments.

Keywords: heavy metal contamination; aquatic environment; sediment; ecological risk; pollution prevention and control

Introduction

Heavy metal contamination is a major concern in the environmental management of rivers, lakes, and reservoirs. After elements such as cadmium, mercury, lead, and chromium enter a water body, they are difficult to degrade naturally and may be redistributed spatially through water transport, particle adsorption, and sedimentation. Copper and zinc are trace elements required for the normal growth of aquatic organisms, but they become toxic when their concentrations exceed physiological tolerance limits. Arsenic is a metalloid; however, because its environmental hazards and migration characteristics resemble those of several heavy metals, it is commonly included in analyses of heavy metal contamination in aquatic environments.

Metal concentrations in water samples primarily reflect contamination conditions at the time of sampling. After entering a water body, some metals are adsorbed onto suspended particles and subsequently settle to the bottom. Sediments thus become an important medium for the long-term accumulation of heavy metals. When hydrodynamic conditions, pH, or redox conditions change, sediment-bound metals may be remobilized and cause secondary contamination. Monitoring concentrations only in the aqueous phase may overlook cumulative risks already present in sediments and aquatic organisms. Ecological risk assessment of heavy metals in aquatic environments should therefore account for pollution sources, partitioning among environmental media, chemical speciation, and biological effects, thereby providing a basis for identifying treatment targets and establishing remediation priorities.

1. Sources and Migration Processes of Heavy Metals in Aquatic Environments

1.1 Natural Release and Anthropogenic Discharge

Natural sources of heavy metals include rock weathering, soil erosion, groundwater recharge, and the atmospheric deposition of particulate matter. The elemental composition of rocks and soils within a watershed determines the natural baseline concentrations in the aquatic environment. In regions rich in metallic mineral resources, certain elements may remain at elevated concentrations in river sediments even in the absence of obvious pollutant discharges. When anthropogenic contamination is evaluated, environmental background values appropriate to local geological conditions should be selected to avoid incorrectly identifying natural enrichment as anthropogenic input.

Anthropogenic discharges are generally characterized by concentrated sources, high intensity, and complex combinations of elements. Mining, mineral processing, and smelting may generate wastewater and solid waste containing copper, lead, zinc, cadmium, and arsenic. Electroplating, battery manufacturing, metal processing, and chemical production are also important sources of chromium, nickel, cadmium, and lead. When industrial wastewater treatment is unstable or seepage-control measures at solid-waste storage sites are inadequate, heavy metals may enter surrounding water bodies through direct discharge, stormwater erosion, and subsurface leakage.

Pollution associated with agricultural activities is generally diffuse. Some fertilizers, pesticides, feed additives, and livestock and poultry manure contain copper, zinc,

arsenic, and other elements. Following excessive long-term application, these elements can accumulate in agricultural soils and subsequently enter rivers through surface runoff. Metal-containing particles deposited on urban roads, originating from tire wear, brake materials, and building surfaces, may likewise enter urban water bodies through stormwater drainage networks during rainfall.

1.2 Migration between Water and Sediments

After entering a water body, heavy metals may remain dissolved or bind to organic matter, colloids, and suspended particles. These forms differ in their mobility and bioavailability. Dissolved metals can readily come into contact with aquatic organisms, whereas particle-bound metals may be transported by flowing water or settle to the bottom. When water pH decreases, some metals adsorbed onto particle surfaces can be released. An increase in dissolved organic matter may promote metal complexation and consequently alter migration distances.

Fine particles readily accumulate in slow-flowing river sections, lake bays, and the central areas of reservoirs, leading to the enrichment of heavy metals in these locations. Clay minerals, iron and manganese oxides, organic matter, and sulfides in sediments can all bind metals. Sediments are not, however, permanently stable pollutant sinks. Hypoxia in bottom waters, changes in pH, flood-induced scouring, and vessel disturbance can alter existing binding states and cause metals to re-enter the water column. Dynamic exchange between water and sediments is therefore an essential consideration when long-term ecological risk is assessed.

2. Fundamental Characteristics of Heavy Metal Contamination in Water Bodies

2.1 Differences in Contaminating Elements and Toxicity

Heavy metals differ substantially in toxicity, mobility, and accumulation characteristics. Cadmium is highly toxic and relatively mobile in the environment, and it can disrupt the growth and reproduction of aquatic organisms. Under certain environmental conditions, mercury can be converted into methylmercury, which has a strong capacity for biological uptake and food-chain transfer. Lead affects the nervous, hematopoietic, and enzymatic systems. Hexavalent chromium generally exhibits greater mobility and toxicity than trivalent chromium.

Copper and zinc participate in numerous physiological processes in aquatic organisms. At concentrations above their appropriate ranges, however, they damage gill tissues, inhibit enzyme activity, and disrupt ion regulation. A high metal concentration does not necessarily indicate the highest ecological risk. For example, zinc concentrations in some sediments may be substantially higher than cadmium concentrations, but cadmium may still contribute more to the overall risk because of its greater toxicity and environmental sensitivity. Assessments should therefore simultaneously consider concentration, toxicity, background level, and chemical speciation.

2.2 Spatial Distribution and Seasonal Variation

Heavy metal contamination commonly exhibits pronounced spatial heterogeneity. Elevated concentrations are frequently observed near industrial outfalls, mine-drainage outlets, tributary confluences, and urban stormwater outlets. After metals enter a river channel, their concentrations may progressively decrease downstream through flow dilution, particle sedimentation, and adsorption by riparian soils. However, additional pollutant inputs can alter the existing distribution when a river passes through industrial, urban, and agricultural areas.

Reservoirs and lakes have relatively weak hydrodynamic conditions, allowing fine particles to settle readily in central reservoir areas, lake bays, and deep-water zones. Rapidly flowing river sections are dominated by coarser particles whose adsorption capacity is comparatively low. When metal concentrations at different sampling sites are compared, sediment particle size and organic-matter content should be analyzed simultaneously to prevent differences in particle composition from being misinterpreted as differences in pollution intensity.

Increased discharge during the wet season can dilute certain point-source pollutants, but rainfall runoff can also transport road dust, agricultural soil, and mining waste into rivers. During the dry season, weaker dilution capacity can allow continuous discharges to increase metal concentrations in the aqueous phase. A single sampling event represents conditions under a particular hydrological regime and cannot adequately characterize annual contamination levels.

2.3 Chemical Speciation and Environmental Activity

Heavy metals in sediments can be divided into acid-extractable, reducible, oxidizable, and residual fractions. The acid-extractable fraction principally includes exchangeable and carbonate-bound forms, which are sensitive to environmental changes and can be readily mobilized and absorbed by organisms. The reducible fraction is primarily associated with iron and manganese oxides and may be released when bottom waters become hypoxic. The oxidizable fraction is mainly bound to organic matter and sulfides, and its stability may decrease when sediments are disturbed and exposed to oxygen. The residual fraction is incorporated into mineral crystal lattices and exhibits

relatively low short-term environmental activity.

A study of Shahe Reservoir collected 19 surface-sediment samples and three sediment-core samples. The mean arsenic concentration in the sediments was 35.85 ± 5.80 mg/kg. The potential ecological risk index at every sampling site was below 150, indicating an overall low-risk level. Speciation analysis showed that chromium and copper occurred predominantly in the residual fraction. Although manganese and zinc presented low risks on the basis of their total concentrations, they exhibited relatively high bioavailability [4]. This case demonstrates that assessments based solely on total concentrations may underestimate the release risks of certain highly active metals.

3. Effects of Heavy Metal Contamination on Aquatic Ecosystems

3.1 Toxic Injury to Aquatic Organisms

Dissolved metals can enter aquatic organisms through the gills, body surface, and digestive tract. After binding to proteins, heavy metals interfere with enzyme activity, ionic balance, and energy metabolism. Long-term exposure of fish to contaminated water may result in gill-tissue damage, impaired respiratory function, disruption of antioxidant systems, and reduced growth rates. Metal accumulation in the liver and kidneys also increases the burden of detoxification and excretion.

Algae are relatively sensitive to metal contamination in water. Elevated metal concentrations can affect chlorophyll synthesis, photosynthesis, and cell division, thereby altering primary productivity. Benthic organisms are in close contact with sediments and can be chronically affected by bioavailable sediment-bound metals. Declines in sensitive species, increases in pollution-tolerant species, and the simplification of community structure may all indicate sustained pollution pressure.

Heavy metal toxicity is also influenced by water hardness, pH, temperature, and dissolved organic matter. Ions such as calcium and magnesium can compete with certain metals for biological binding sites. The binding of organic matter to metals also alters the proportion of free metal ions. Consequently, identical total concentrations do not necessarily produce identical biological effects in different water bodies.

3.2 Bioaccumulation and Food-Chain Transfer

Phytoplankton, benthic organisms, and fish can absorb heavy metals from water, sediments, and food. Metal concentrations in organisms are influenced by species, age, tissue type, feeding habits, and metabolic capacity. Metal concentrations in fish liver, kidneys, and gills are generally higher than those in muscle tissue. Monitoring only edible muscle tissue is appropriate for assessing human dietary risk, but it cannot fully characterize the ecological stress experienced by fish.

Certain metals are transferred through trophic relationships. After plankton absorb metals from the water, they are consumed by small fish, which are subsequently preyed upon by carnivorous fish. Methylmercury exhibits a strong capacity for biomagnification through food chains. Elements such as copper and zinc are subject to biological regulation, and their patterns across trophic levels may therefore differ from those of mercury.

Yi et al. jointly investigated chromium, cadmium, mercury, copper, zinc, lead, and arsenic in water, sediments, and fish from the middle and lower reaches of the Yangtze River. Their assessment indicated that sediments at certain middle-reach sites, half of the lower-reach sites, and some lake sites presented moderate or relatively high potential ecological risks [3]. Joint multimedia investigations can identify long-term accumulation that cannot be detected solely from metal concentrations in water samples.

4. Ecological Risk Assessment of Heavy Metals in Aquatic Environments

4.1 Water-Quality Compliance Assessment

Water-quality compliance should be evaluated using the standard corresponding to the designated function of the water body. China's Environmental Quality Standards for Surface Water divide surface waters into five classes, each corresponding to different protection objectives. Class III waters principally include secondary protection zones for centralized surface-water sources used for domestic drinking-water supply, overwintering grounds for fish and shrimp, migration channels, aquaculture areas, and swimming areas [1].

During assessment, the measured concentration of each heavy metal should be compared individually with its applicable standard limit. If any indicator exceeds its limit, the noncompliant item and the degree of exceedance should be reported. Averaging multiple indicators must not be used to offset an exceedance in an individual indicator. For water bodies with distinct wet, normal-flow, and dry seasons, water-quality conditions should be evaluated separately for each hydrological period.

Table 1. Standard Limits for Selected Heavy Metals and Metalloids in Class III Surface Waters

Parameter	Standard limit ($mg \cdot L^{-1}$)	Principal environmental concern
Copper	1.0	Toxicity to fish and algae at high concentrations
Zinc	1.0	Adverse effects of excessive concentrations on enzymatic systems in aquatic organisms
Arsenic	0.05	Chronic toxicity and accumulation risk
Mercury	0.0001	Potential methylmercury formation and food-chain transfer
Cadmium	0.005	High toxicity and bioaccumulative potential
Hexavalent chromium	0.05	High mobility and toxicity
Lead	0.05	Adverse effects on the nervous and hematopoietic systems

Note: The limits are the basic Class III values specified in the Environmental Quality Standards for Surface Water (GB 3838—2002) [1].

4.2 Assessment of Sediment Contamination

Sediment assessment principally examines the degree of metal enrichment relative to regional background values. The geoaccumulation index accounts for variations in natural composition when comparing measured concentrations with background values and can classify sediments as uncontaminated, slightly contaminated, moderately contaminated, or heavily contaminated. Enrichment-factor analysis uses a relatively stable reference element to correct for differences in particle size and mineral composition and can thereby help determine the extent of anthropogenic input.

The selection of background values is a critical component of sediment assessment. National or large-scale regional soil background values may not adequately represent the natural depositional characteristics of a particular river or lake. Where the study area has distinctive geological conditions, priority should be given to local sediment background values, data from upstream reference sites, or reliable deep-sediment records.

The degree of contamination should not be equated directly with ecological risk. A metal may be substantially enriched relative to its background value but present a low short-term release risk if it occurs predominantly in the residual fraction. Another metal may have a relatively low total concentration but high bioavailability if it occurs mainly in exchangeable or carbonate-bound forms. Sediment assessment should therefore integrate total concentrations with chemical speciation.

4.3 Integrated Ecological Risk Characterization

Potential ecological risk assessment considers both the degree of metal enrichment and differences in toxicity. The method proposed by Håkanson was developed for sediments and can be used to evaluate the risk associated with individual metals and derive an integrated risk classification [2]. Highly toxic elements such as cadmium and mercury are generally assigned greater toxic-response weights, whereas copper, lead, chromium, and zinc receive comparatively lower weights. This method avoids establishing remediation priorities solely according to concentration.

Potential ecological risk classifications are affected by the number of elements assessed, background values, and toxic-response weights. When studies include different sets of elements, their integrated results should not be compared directly. The method also does not account for actual chemical speciation or biological uptake. In practice, water-quality compliance, sediment enrichment, the proportion of bioavailable fractions, and biomonitoring results can be used jointly as complementary lines of evidence.

The risk assessment code primarily determines release risk according to the proportion of a metal present in the acid-extractable fraction. A higher proportion indicates greater sensitivity to environmental changes. Surveys of benthic communities, analyses of fish tissues, and sediment toxicity tests can further validate chemistry-based assessments. Risk conclusions are more reliable when multiple lines of evidence are mutually consistent.

5. Approaches to the Prevention and Control of Heavy Metal Contamination

5.1 Establishment of a Multimedia Monitoring System

Monitoring of heavy metals in aquatic environments should cover water samples, suspended particulate matter,

surface sediments, and representative aquatic organisms. Water samples reflect current exposure conditions, sediments record long-term accumulation, and aquatic organisms indicate actual biological uptake. Industrial outfalls, tributary confluences, slow-flowing depositional zones, drinking-water intakes, and aquaculture areas should be designated as priority monitoring locations.

Sampling schedules should cover different hydrological periods. Monitoring of urban runoff and agricultural nonpoint-source pollution can be intensified after rainstorms, whereas the dry season requires particular attention to pollutant accumulation caused by continuous discharges. In addition to total metal concentrations, sediment analysis should include particle size, organic-matter content, and the speciation of representative metals. Where abnormal water quality is detected but pollution sources remain unclear, source apportionment can incorporate land use, industrial-discharge information, and elemental profiles.

5.2 Source-Specific Pollution Control

Mining areas and tailings storage facilities should improve systems for collecting acid mine drainage, preventing seepage from waste-rock storage sites, and separating stormwater from wastewater. Smelting, electroplating, battery manufacturing, and metal-processing enterprises should separately collect wastewater containing heavy metals and ensure the stable operation of chemical precipitation, adsorption, ion-exchange, or membrane-separation systems. Discharge management should address not only wastewater concentrations but also the storage and disposal of sludge and solid residues, thereby preventing pollutants transferred from water to soil from subsequently re-entering aquatic environments.

In urban areas, runoff inputs can be reduced through first-flush stormwater detention, road cleaning, and improvements to drainage networks. Agricultural areas should regulate the use of copper- and zinc-containing fertilizers and feed additives and reduce direct discharges of wastewater from livestock and poultry operations. Watershed management should also coordinate upstream and downstream measures to prevent pollutants from being displaced to other areas after localized treatment.

5.3 Risk-Based Zoning for Sediment Management

Sediment-management methods should be selected according to the extent of contamination, metal speciation, hydrodynamic conditions, and ecological sensitivity. Dredging may be considered in areas where contamination is concentrated, bioavailable fractions account for a high proportion, and continuous release is occurring. Before dredging, the thickness of the contaminated sediment layer should be determined. Sediment disturbance and contaminant dispersion should be controlled during construction, and dredged material must subsequently undergo safe treatment and disposal.

In areas where contamination is extensive but disturbance presents a high risk, in situ capping or stabilization may be used. Capping materials can isolate contaminated sediments from overlying water, while stabilization materials can reduce metal mobility. The stability of treatment materials and changes in the bottom-water environment should be monitored continuously after remediation. In areas dominated by residual metal fractions and presenting low ecological risk, natural recovery and long-term monitoring may be preferable to unnecessary engineering interventions that could damage aquatic habitats.

Conclusion

Heavy metal contamination in aquatic environments is characterized by diverse sources, substantial migration among environmental media, pronounced spatial heterogeneity, and persistent ecological effects. Industrial discharges, mining activities, agricultural runoff, and urban stormwater constitute the principal anthropogenic sources. Metals entering a water body can transform among dissolved, particle-bound, and sediment-bound forms. Sediments serve both as accumulation media and as potential sources of secondary contamination when environmental conditions change.

Ecological risk assessment should distinguish among water-phase compliance, sediment enrichment, and biological effects. Water-quality standards are suitable for determining whether a water body satisfies its designated function. Sediment assessment identifies long-term contaminant accumulation, while chemical-speciation analysis and biomonitoring can characterize actual migration and uptake risks. Pollution management requires a joint monitoring system covering water, sediments, and aquatic organisms, together with source-specific control measures based on pollution sources and risk levels. Engineering remediation should be implemented for highly contaminated sediments exhibiting active metal release, whereas natural recovery and continuous monitoring should be adopted in low-risk areas. This differentiated approach can improve the precision and effectiveness of heavy metal pollution prevention and control.

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