Bioaccumulation and Environmental Pathways of Heavy Metals in Wetland Birds: Evidence from Feathers and Ecosystem Compartments

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Abstract. Heavy metals pose a persistent ecological risk to wetland ecosystems and their avifauna, yet the pathways and sources of exposure remain insufficiently understood. This study combined two complementary approaches: (1) analysis of long-term (2000–2020) monitoring data from Poyang Lake to assess correlations between bird abundance and waterborne metal concentrations, and (2) targeted sampling in the Houtan Wetland Park to measure Cu, Pb, Zn, Ni, Cr, and Cd in bird feathers and in multiple environmental media (water, sediment, soil, and aquatic plants) across two periods and three sites. In Poyang Lake, correlations varied by species, with some resident waterbirds positively associated with moderate metal enrichment and sensitive migratory species showing negative relationships. In Houtan, Zn consistently exhibited the highest concentrations across all matrices, and feather metal profiles closely paralleled those of sediments and soils, indicating benthic foraging as a key exposure pathway. Metal-specific correlations revealed distinct environmental linkages, and inter-metal relationships in feathers suggested that Cu, Ni, and Cr share common anthropogenic sources, whereas Pb, Zn, and Cd likely derive from diffuse or independent inputs. These findings demonstrate the effectiveness of feathers as non-invasive bioindicators, clarify the element-specific pathways of metal accumulation, and provide a scientific basis for targeted pollution control strategies in urban wetland conservation..

Keywords: Waterbirds; feathers; heavy metals; wetland pollution; Houtan Wetland Park.

1. Introduction

Wetland ecosystems are among the most productive habitats in the world. They give important services like food, water control, and cultural value. In flat areas, wetlands can change how water flows and move solutes.[1] This can lower pollution downstream and keep water quality more stable through the seasons.[2, 3] Wetlands, such as marshes, swamps, fens, and bogs, are also important places for waterbirds and other animals to stop, breed, and feed. Their mixed plants, many invertebrates, and shallow waters help many species live there.[4] Birds use these places for nests, food, and protection from predators. This shows how important wetlands are for nature.

But the same conditions that make wetlands rich in life—nutrient-rich soils and waterlogged ground—also make them store pollution.[5] Heavy metals like mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As) are especially harmful because they are toxic, long-lasting, and not needed for life.[6] Human actions such as mining, industry, and city runoff add more heavy metals into wetlands. When these pollutants enter, they build up in animals and move through food chains. This can cause nerve damage and other health problems in birds.[7]

The results for bird communities are clear. High levels of Hg, Pb, and Zn are linked with fewer species, smaller populations, and changes in bird groups. For example, tests of Roseate spoonbills (Platalea ajaja), Black-bellied whistling ducks (Dendrocygna autumnalis), and Neotropical cormorants (Nannopterum brasilianus) showed mean feather Hg levels higher than 7.4 $\mu g\ g^{-1}$. This is above the normal background level of 5 $\mu g\ g^{-1}$, which shows global contamination. [7] Pb levels in duck feathers reached 212 $\mu g\ L^{-1}$, which is above the level that can cause poisoning. These results show that wetlands are at high risk from human pollution.

On this global background, two wetlands show good case studies. Poyang Lake, the largest freshwater lake in China, is an important wintering site for many migratory birds. It has seen strong environmental changes in the past twenty years, including shifts in heavy metal levels. [8] Houtan Wetland Park in Shanghai is very different. It is an urban wetland shaped by restoration and heavy human use, but it still faces pollution risks. This study uses long-term monitoring data from Poyang Lake and new sampling from Houtan Wetland Park. The goals are: (1) to check how bird numbers change with heavy metal levels; (2) to measure heavy metals in feathers and the environment; (3) to find links that show main exposure paths; and (4) to trace possible sources of pollution by comparing metals. These steps help us understand how birds are exposed to heavy metals in wetlands. They also support better management to lower pollution, protect bird populations, and keep wetlands healthy.

2. Materials and methods

2.1. Study site and sampling

Fieldwork was conducted at Houtan Wetland Park, located along the Huangpu River in Pudong District, Shanghai, China. The park represents a restored urban wetland that combines ecological purification, flood control, and biodiversity conservation functions, making it an exemplary site for examining contaminant dynamics in metropolitan wetlands. We carried out sampling campaigns in May and July 2025. Following a south-to-north transect across the main water system, three fixed sampling stations (S1, S2, S3) were established to capture spatial gradients in hydrology and potential pollutant inputs. S1 was positioned at the southern inflow zone, S2 at the central transition area connecting step-pool wetlands and open water, and S3 at the northern outflow section adjacent to the Huangpu River.

At each site, we collected multiple environmental media and avian materials under standardized procedures. Water samples were taken from the surface layer (0–20 cm), with aliquots acidified for trace metal determination. Surface sediments (0–5 cm) and riparian soils (0–10 cm) were obtained by compositing subsamples within a 2–3 m radius. Dominant macrophytes, including *Phragmites* and associated aquatic vegetation, were sampled to represent plant uptake pathways. Naturally molted bird feathers were gathered opportunistically from the wetland floor and shoreline. All sample types were collected in triplicate (n = 3) at each station to ensure statistical robustness. Field blanks, equipment blanks, and parallel samples were included as quality controls. All materials were preserved under cold storage and transported promptly to the laboratory for subsequent analysis.

2.2. Samples pretreatment and detection of heavy metals

All solid samples, including feathers, plants, soils, and sediments, were freeze-dried to completely remove moisture. The dried materials were then cut into small fragments and finely ground into a uniform powder to improve homogeneity and enhance digestion efficiency. Approximately 50 mg of each homogenized solid sample was accurately weighed into digestion vessels. For water samples, 1 mL of representative solution was pipetted into separate vessels. Each sample was treated with 3 mL of concentrated nitric acid (HNO_3). The vessels were then sealed and heated at 180 °C for 4 hours to achieve complete digestion. After cooling to room temperature, the digested solutions were quantitatively transferred to volumetric flasks and diluted to a fixed volume with ultrapure water. The final solutions were analyzed for heavy metal concentrations using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Prior to analysis, the instrument was calibrated with multi-element certified standard solutions. Calibration curves were constructed across appropriate concentration ranges, and instrument stability was verified by repeated measurements of internal standards. Recovery rates for spiked samples were maintained within 85–115%, and relative standard deviations (RSDs) for replicate analyses were generally below 10%.

Strict QA/QC procedures were applied throughout sample handling and analysis. All reagents and containers were pre-cleaned to minimize contamination. Procedural blanks, equipment blanks, and field blanks were included with each batch to detect potential background interference. Replicate digestions (n = 3) were performed for each sample type to assess reproducibility.

2.3. Statistical analysis

All statistical analyses were conducted using OriginPro 2025 (OriginLab, Northampton, MA, USA). Data were first examined for normality and homogeneity of variance. Linear regression was applied to evaluate relationships between metal concentrations in bird feathers and those in environmental media. In addition, Pearson correlation analysis was performed to assess the strength and significance of associations among different matrices. Statistical significance was set at $p < 0.05$.

3. Results and discussions

3.1. Relationship between bird population sizes with heavy metal concentrations in water from Poyang Lake

The correlation analysis between the abundance of various bird species in Poyang Lake and the concentrations of six heavy metals (Cu, Pb, Zn, Ni, Cr, and Cd) in surface water revealed species-specific patterns, with significant relationships ($p < 0.05$) varying in both direction and magnitude (Figure 1). Several species, including gadwall, northern pintail, Eurasian wigeon and white-napped crane, exhibited significant positive correlations with Cu and Zn, suggesting a possible tolerance or adaptive foraging strategy in environments with elevated but sub-toxic levels of these metals.[9] In contrast, species such as gadwall, Siberian crane and white-napped crane showed marked negative correlations with Ni and Cd, indicating potential sensitivity to contamination and possible avoidance of polluted habitats.[2] The predominance of positive associations among more pollution-tolerant and resident species aligns with previous findings that certain waterbirds can persist in, and even exploit, habitats with moderate metal enrichment due to dietary plasticity and detoxification mechanisms.[10] Comparable trends have been reported in studies where waterbirds' feathers, acting as bioindicators, reflected both bioaccumulation from aquatic food webs and differences in ecological niche, with tolerant species often displaying higher feather Cu and Pb concentrations without apparent population decline.[1, 7] Overall, these findings emphasize that heavy metal contamination in wetland waters can exert divergent ecological effects, shaping avian community composition by selectively disadvantaging sensitive taxa while allowing tolerant populations to remain stable or even increase in abundance.

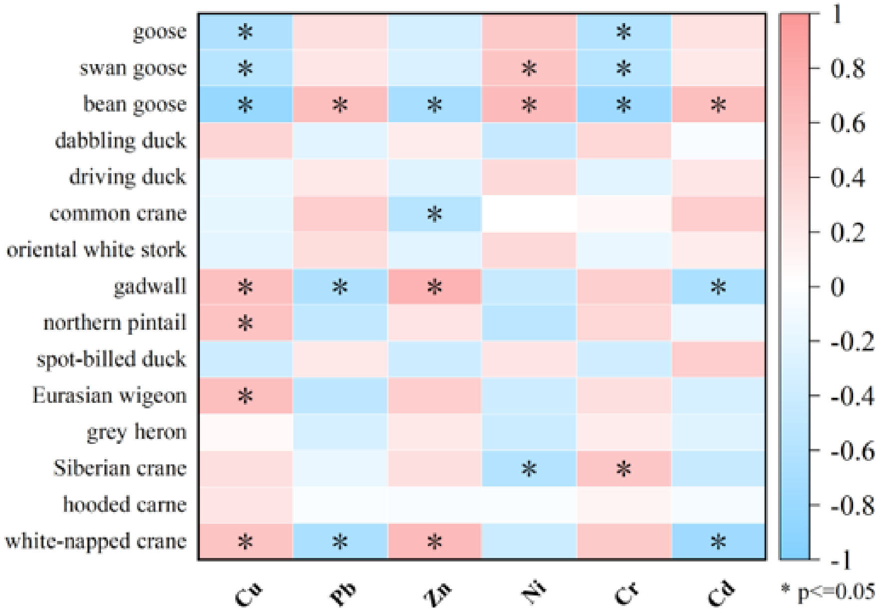

Figure 1. Correlation heatmap of bird population and heavy metal concentrations in water at Poyang Lake

Taking Pb as an example to further elucidate the role of heavy metals in shaping avian population dynamics in Poyang Lake, simple linear regressions were performed between waterborne Pb concentrations and the abundances of three representative species—bean goose, gadwall, and white-napped crane (Figure 2). The results revealed a significant positive relationship for bean goose ($p < 0.05$), indicating that populations of this species increased with rising Pb levels, potentially reflecting dietary habits or habitat use strategies that enable persistence in moderately contaminated environments.[11] In contrast, gadwall and white-napped crane exhibited significant negative relationships (both $p < 0.05$), suggesting that higher Pb concentrations were associated with reduced abundance, likely due to lower tolerance thresholds or avoidance of polluted feeding grounds.[12] These divergent responses mirror patterns reported in other wetland systems, where heavy metal gradients have been shown to differentially influence waterbird species depending on their foraging guilds, migration strategies, and physiological detoxification capacities.[13, 14]

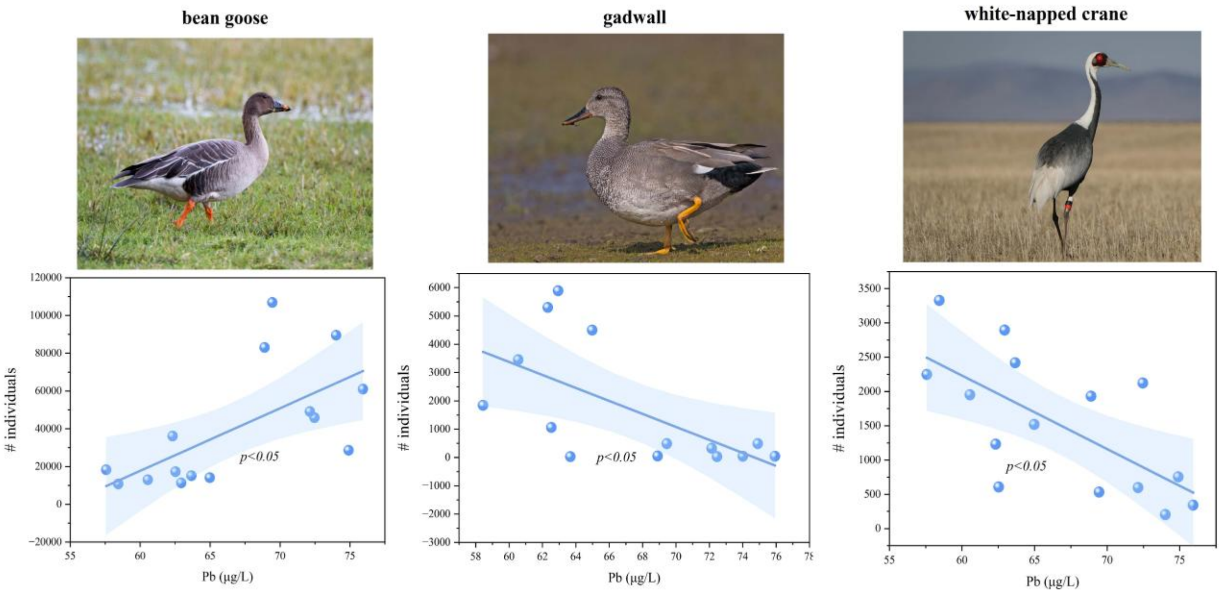

Figure 2. Linear regression of bird population sizes with Pb concentrations in water for bean goose, gadwall, and white-napped crane.

3.2. Spatial-temporal Variation of Heavy Metal Concentrations in Environmental Media and Bird Feathers at Shanghai Houtan Wetland Park

Across all sample types in Houtan Wetland Park, the six target metals (Cu, Pb, Zn, Ni, Cr, Cd) showed clear differences in concentration (Figure 3). Zn consistently dominated, ranging from 177-1091 μg L^{-1} in water to 84.6-284.1 mg kg^{-1} in sediments, soils, and plants. In contrast, Cd remained lowest in every medium, with average values nearly two orders of magnitude lower than Zn. Cu and Cr generally occupied intermediate positions, whereas Pb and Ni varied depending on the matrix. Sediments and soils held markedly higher levels than water, in some cases exceeding aqueous concentrations by more than 100-fold, highlighting their strong metal-binding capacity.[15, 16] The overall concentration order was Zn > Cu/Cr > Pb/Ni > Cd, and this pattern was stable across both sampling periods (T1 and T2) and all sites (S1–S3).

Metal accumulation in bird feathers largely paralleled that of sediments and soils. Zn was again most abundant, followed by Cu, Pb, Ni, and Cr, with Cd remaining lowest. The Zn values were similar to or slightly above those reported for waterbirds in other East Asian wetlands,[17] pointing to long-term exposure. Pb levels matched those recorded in the Yangtze flood plain, but were lower than in highly industrialized wetlands of northern China,[18] reflecting regional variation in contamination sources. The resemblance between feather and sediment patterns suggests benthic feeding as a major exposure route.[8] Elevated Cu and Zn may partly reflect their physiological roles, while Pb, Ni, and Cr are more likely linked to industrial emissions, urban dust, or contaminated prey.[19] Because feathers integrate exposure during molt, they serve as a longer-term archive of bioavailable metals.[20, 21] Consistent with earlier reports of strong feather–sediment correlations,[22, 23] our findings reinforce the utility of feathers as non-invasive indicators of wetland pollution.

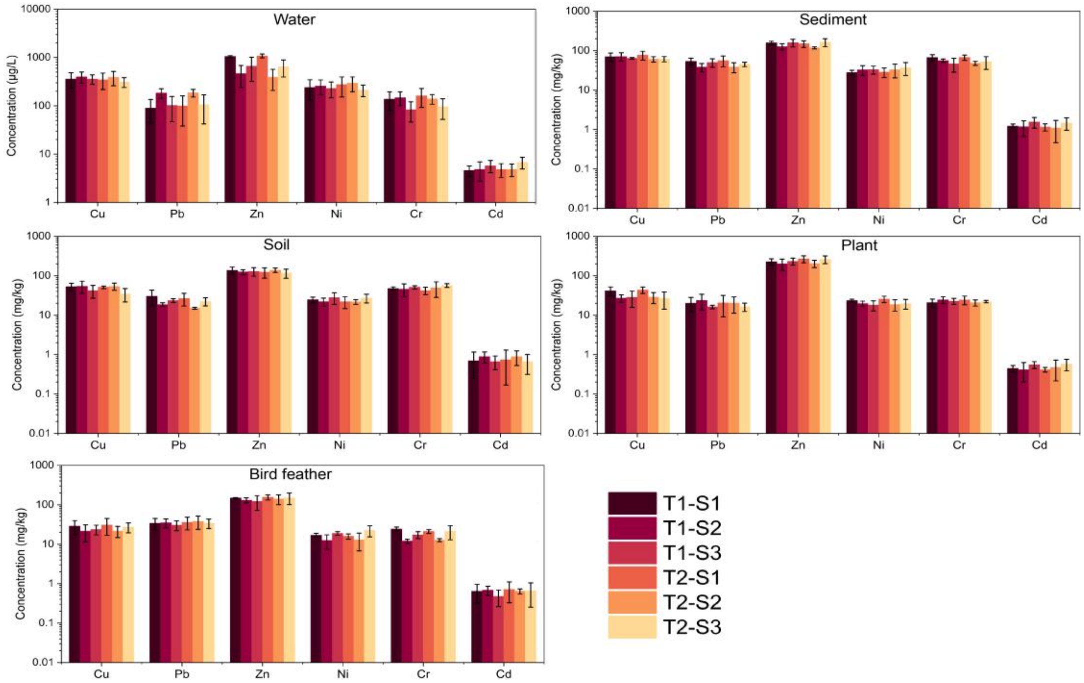

Figure 3. Heavy metal concentrations in different environmental media and bird feathers across sampling sites and periods at Houtan wetland park

3.3. Correlation Analysis of Heavy Metals among Different Environmental Media and Bird Feathers

Correlation analysis across environmental media in Houtan Wetland Park revealed a coherent structure of relationships among water, sediment, soil, and aquatic plants, with Pearson's r values ranging from 0.72 to 0.90 ($p < 0.05$; Figure 4). Feathers showed the strongest association with sediments ($r = 0.79$, $p < 0.05$), while moderate but significant correlations were observed with aquatic plants ($r = 0.69$) and soils ($r = 0.65$). In contrast, the feather–water correlation was weaker. These findings suggest that birds acquire most metals through benthic foraging and plant-based pathways, rather than direct contact with dissolved fractions. Comparable studies have similarly reported that sediment chemistry accounts for a large proportion of variation in feather metal loads in benthic-feeding waterbirds.[23, 24]

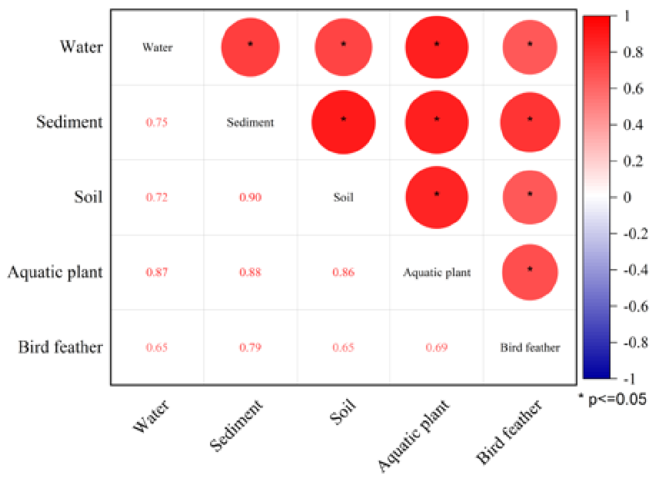

Figure 4. Overall correlation of heavy metal concentrations between environmental media and bird feathers at Houtan wetland.

Element-specific analyses (Figure 5) highlighted differences in bioaccumulation routes. Copper exhibited its highest correlation with aquatic plants ($r = 0.59$, $p < 0.05$), indicating assimilation via vegetation or associated invertebrates, consistent with higher Cu levels previously observed in herbivorous species.[25] Lead aligned most closely with sediments ($r = 0.58$, $p < 0.05$), reflecting its strong affinity for particulate matter and persistence in benthic habitats [Ref6]. Zinc showed moderate correlation with water ($r = 0.47$), pointing to its greater mobility and possible uptake through planktonic prey.[26] In contrast, Ni and Cr displayed weak or negative correlations with environmental compartments, suggesting limited dietary availability or behavioral avoidance.[14, 27] Cadmium exhibited consistently low associations across all media ($r < 0.30$), consistent with earlier reports that feathers are poor Cd indicators due to preferential storage in internal organs.[7, 28]

Overall, these results confirm feathers as effective non-invasive indicators of heavy metal exposure,[6] but also underscore that bioaccumulation pathways differ among elements. Strong correlations with sediments point to benthic foraging as a dominant route, while moderate associations with plants and soils reflect mixed diets and secondary trophic transfers. The variability among metals highlights the influence of geochemical speciation, environmental partitioning, and foraging ecology. Therefore, the choice of indicator species should consider feeding strategy and habitat use to best capture contamination pathways in urban wetlands.[21]

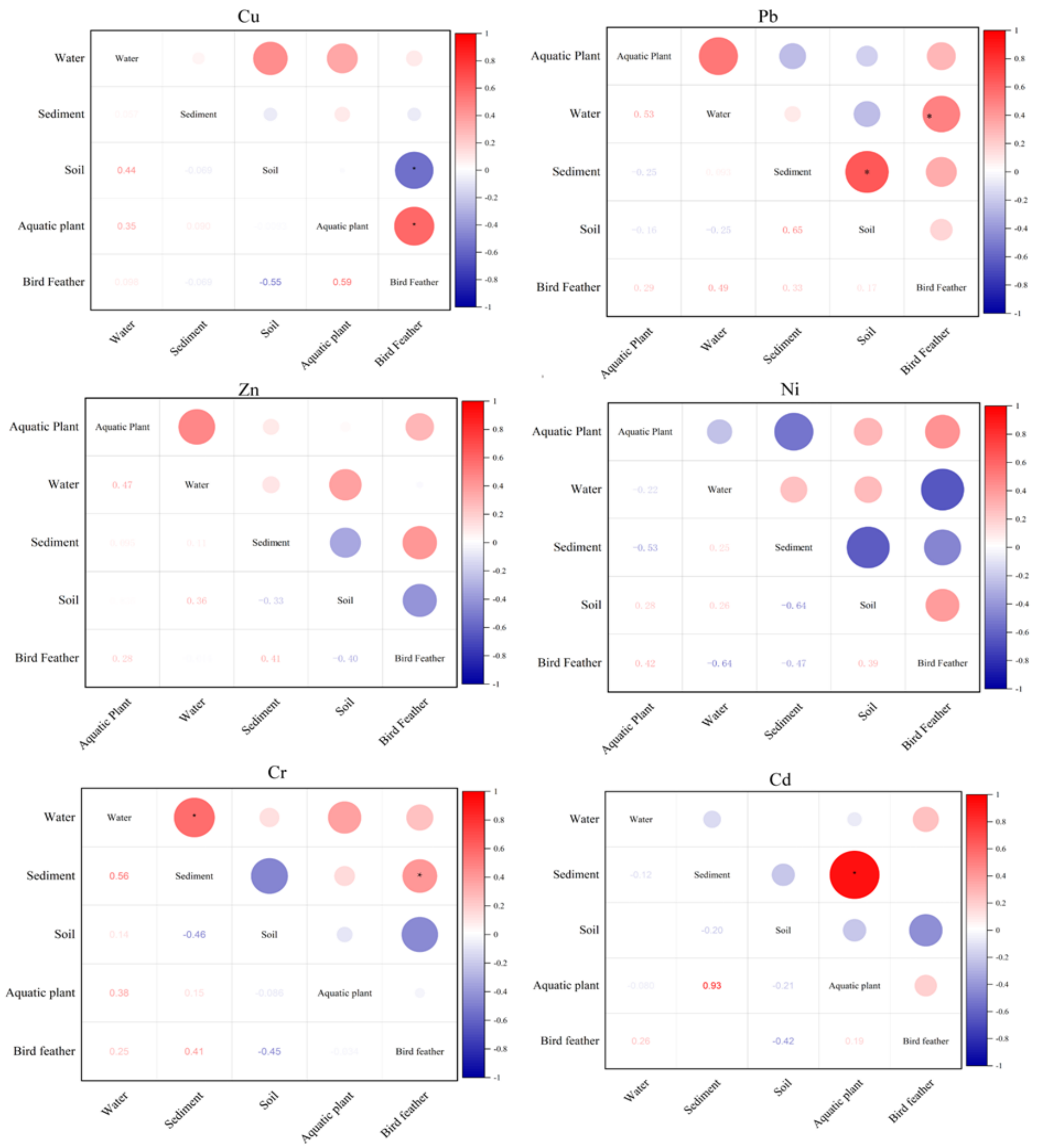

Figure 5. Element-specific correlation analysis of heavy metal concentrations among environmental media and bird feathers at Houtan wetland.

3.4. Source appointment and environmental implication

The inter-metal correlation matrix for bird feathers (Figure 6) provides valuable insights into potential common sources and pathways of heavy metal exposure. Significant positive associations were observed between Cu and Ni ($r = 0.64$, $p < 0.05$) and between Ni and Cr ($r = 0.55$, $p < 0.05$), suggesting that these elements may originate from shared anthropogenic inputs, such as industrial emissions, urban runoff, or metal alloy wear, all of which are known to contribute Ni- and Cr-rich particulates alongside elevated Cu.[11, 29] The moderate positive correlation between Cr and Cd ($r = 0.40$) further implies that these metals could co-occur in certain localized pollution sources, possibly linked to metallurgical processes or phosphate fertilizers.[3, 30] Conversely, the generally weak or negative correlations involving Zn and Cd with most other metals indicate more diffuse or independent sources, consistent with Zn's widespread occurrence in both natural and anthropogenic inputs and Cd's often agricultural origin.[4, 8] The absence of strong Pb correlations with any other element may reflect distinct contamination pathways—such as vehicular emissions or site-specific historical deposits—that are not closely coupled with other metals in the birds' foraging environment.[31] Taken together, the observed correlation structure points to at least two major contaminant groupings influencing feather metal burdens: (1) a Cu–Ni–Cr complex likely linked to industrial and urban particulate sources, and (2) more independent inputs of Zn, Cd, and Pb from diffuse or localized activities.

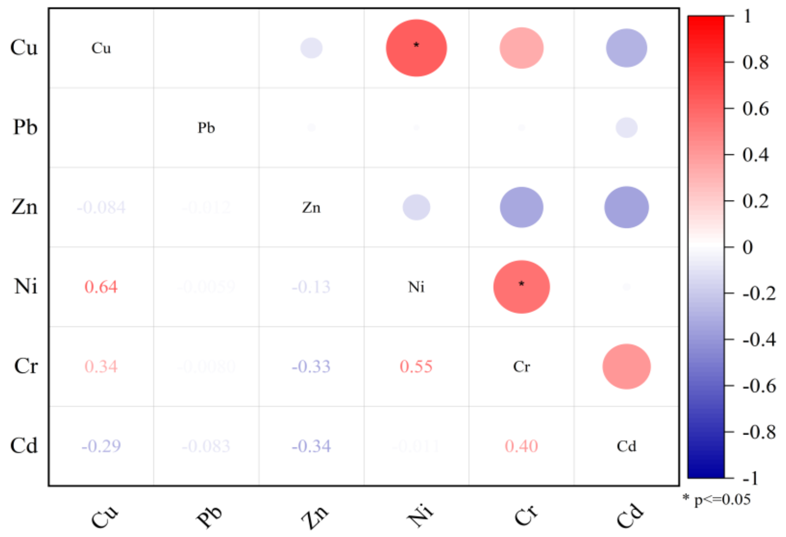

Figure 6. Correlation analysis of heavy metal concentrations in bird feathers.

4. Conclusion

This study combined long-term monitoring data from Poyang Lake with targeted field sampling in the Houtan Wetland Park to investigate the relationships between heavy metal concentrations in waterbird feathers and multiple environmental media. At Poyang Lake, species-specific correlations between bird abundance and waterborne metals indicated divergent tolerance levels, with some resident species positively associated with moderate metal enrichment while sensitive migratory taxa exhibited negative relationships. In the Houtan Wetland, Zn consistently dominated across all environmental matrices, and feather metal profiles closely mirrored those of sediments and soils, underscoring benthic foraging and sediment-associated prey as key exposure pathways. Inter-metal correlations within feathers suggested that Cu, Ni, and Cr likely share common anthropogenic sources, while Pb, Zn, and Cd may originate from more independent or diffuse inputs. Collectively, these findings highlight the value of feathers as non-invasive bioindicators capable of integrating multi-pathway metal exposure, provide insight into element-specific contamination sources in urban wetlands, and underscore the need for targeted management strategies that address both sediment-bound and diffuse pollutant inputs to protect avian communities and wetland ecosystem health.

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