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Abstract

Metal processing has played a key role in modern industrial development. In addition to economic prosperity, the residuals from these processes have resulted in a legacy of environmental contamination. While there are numerous laboratory studies of metal leaching from slag piles, there remains a lack of information on the impacts of iron slag weathering under ambient environmental conditions. This study builds on previous work where environmental weathering of an abandoned iron slag pile at Carp Lake, located adjacent to the Mississippi River in Davenport, Iowa, USA, was found to have contaminated soils and terrestrial vegetation with cadmium, copper, nickel, lead, and zinc. Lake water, lake sediment, and vegetation (*Ceratophyllum demersum*) were collected, processed, and analyzed to determine concentrations of the previously cited metals in each compartment. Metal concentrations in water were distributed homogeneously across Carp Lake. Notably, Cd and Pb concentrations exceeded US Environmental Protection Agency criteria for acute and chronic exposure, respectively. Average sediment metal concentrations were highest at the site located closest to the slag pile. *C. demersum* (coontail) appeared in Carp Lake after major regional flooding in 2019 and contained measurable concentrations of Cd, Cu, Ni, Pb, and Zn; Cd and Ni were present in plant tissue at levels that exceeded literature reports. While metal concentrations in coontail suggested that the plant might be used to recover select metals from Carp Lake, its role as a pathway for metal accumulation and biomagnification in aquatic wildlife and migratory waterfowl remains an important issue for further study.

KEY WORDS

Metal contamination, water, sediment, aquatic vegetation, slag, flooding

INTRODUCTION

Iron smelting produces a large volume of residual waste materials that require appropriate management to minimize environmental impacts. While contemporary slag disposal is highly regulated, historically, slag was often considered to be inert and was dumped without much consideration to the risks posed to local ecosystems (Evans 1989; Pitak et al. 2015). Due to inherent inefficiencies in older metal separation processes and the lack of mandatory environmental controls, historic slag deposits often contain higher concentrations of heavy metals than slag produced using modern extraction processes (Piatak *et al.* 2015; Vitkova *et al.* 2010). These factors make the identification and management of historic slag deposits a significant challenge. While contemporary studies have confirmed that the weathering can mobilize metals from slag (Manz and Castro 1997; Yanguo *et al.* 2003; Vdović *et*

al. 2006; Kierczak *et al.* 2013; Pitak *et al*. 2015, Singh and Viadero 2022), there remains a need to understand the environmental impacts of iron slag that has been exposed to ambient environmental conditions for decades.

Historic slag piles vary significantly in size and composition. For example, the Coniston slag pile in Sudbury, Ontario, Canada, is 400,000 m^2 (~99 Ac; Souter and Watmough 2017) while the Ely Copper Mine in Vermont, USA, is 7,300,000 m^2 (1,804 Ac; Seal *et al*. 2010). In contrast, the number and characteristics of small and medium sized slag piles is unknown. Accordingly, there are few studies of the environmental impacts of historic slag piles (Piatak and Seal 2012). Piatak *et al.* (2015) reported that concentrations of slag-derived Al, Cr, Cu, Fe, Mn, Pb, and Zn often exceed generic US EPA soil screening levels for human contact. Further, the composition of environmental contamination was found to be proportional to the bulk composition of the slag (Piatak *et al.* 2015).

The current study was conducted at Carp Lake, located on Pool 16 in the lower impounded reach of the Upper Mississippi River, in Davenport, IA, USA (Figure 1). The iron foundry slag pile located on the eastern shore of the lake was shown to be a source of metal contamination in terrestrial soils and vegetation (Singh and Viadero 2022). This work extends the findings on slag pile weathering over at least 5 decades to water, sediment, and aquatic vegetation in Carp Lake.

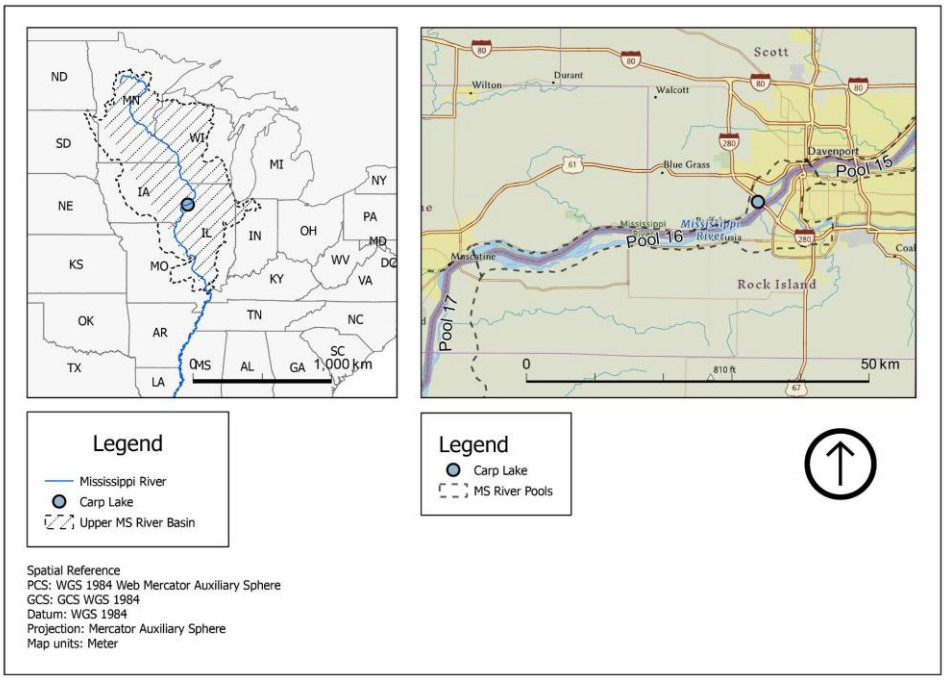


Fig. 1. Maps of Carp Lake in the Upper Mississippi River Basin (left) and Mississippi River Pool 16 (right)

The site is in the 100-year floodplain and becomes connected to the Mississippi River during high water events (Iowa Flood Center 2019). The surrounding land is zoned M-2 heavy industrial; however, a number of single-family houses were 'grandfathered in' and are located adjacent to the property to the south and west. Carp Lake was once a sand quarry reported to have started operating in the 1920s, though no written records are available to substantiate that assertion. The lake has a surface area of ~3.72 ha (9 Ac) with a maximum depth of ~4.3 m (14 ft) (Figure 2). Between the 1930s and the 1980s, slag from a local iron foundry was disposed of on the east shore of Carp Lake. In the absence of historic records, it was not possible to know how frequently slag was dumped on the site. Similarly, the quality/characteristics of the slag were not documented.

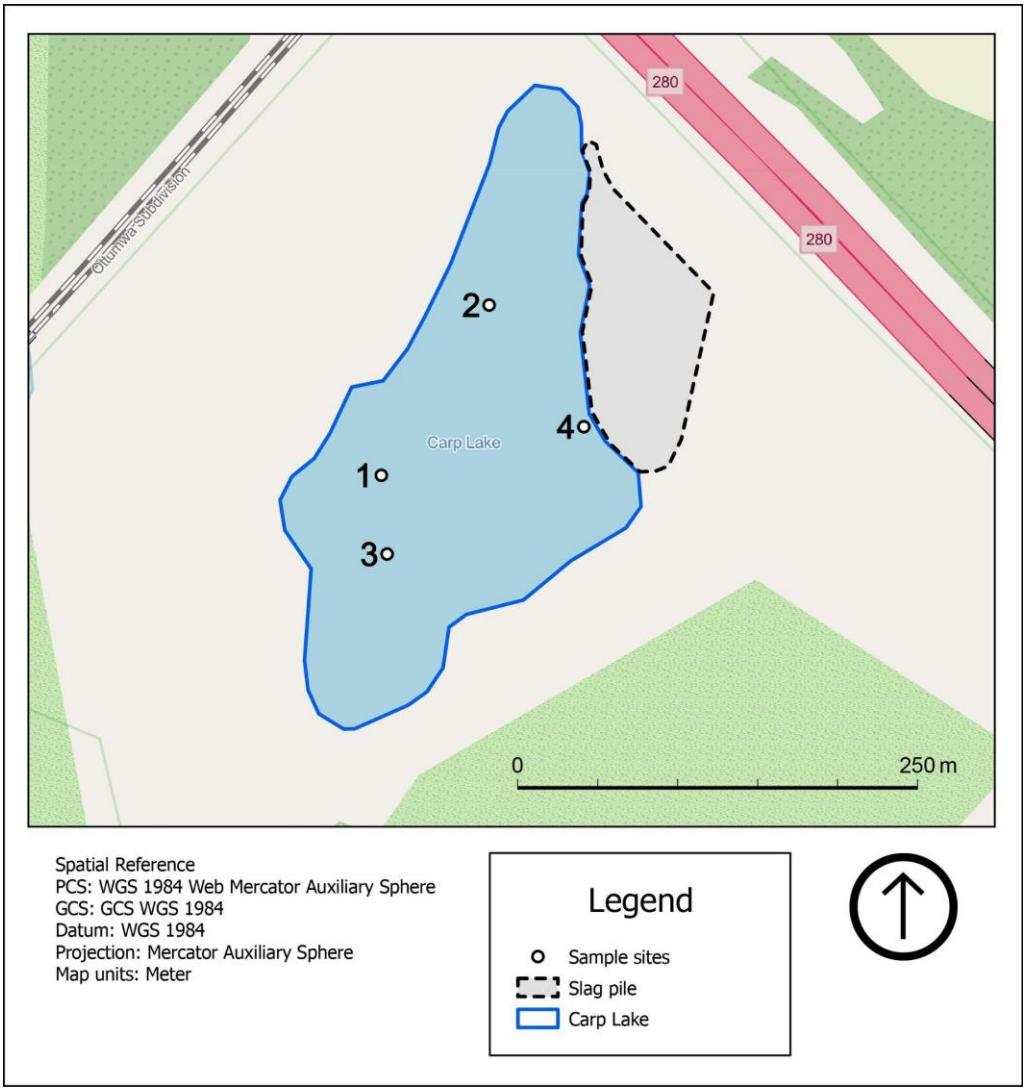


Fig. 2. Map of Carp Lake, the slag pile, and locations of study sites

The proliferation of *Ceratophyllum demersum* after major regional flooding in 2019 provided an opportunity to study the accumulation of metals in plant tissue. Additionally, Carp Lake is in the Mississippi River flyway, the largest route for migratory birds in North America (US FWS 2025). The site is also located in the range of painted turtles (*Chrysemys picta*), red-eared sliders (*Trachemys scripta elegans*), snapping turtles (*Chelydra serpentina*), and Blanding's turtles (*Emydoidea blandingii*; IA DNR 2025). Blanding's turtles are endangered in Iowa and Illinois and are being considered for federal listing (US FWS 2026).

MATERIALS AND METHODS

Field Sampling and Analysis

Triplicate surface water and sediment samples were collected from a small boat at 4 sites on Carp Lake to assess the potential impact of metals derived from the slag pile. Sample locations were recorded using a Trimble GeoExplorer 7x (see Figure 2). Samples were collected in June 2018 and July 2019. Samples of aquatic vegetation (*Ceratophyllum demersum; C. demersum*) were collected along with water and sediment samples in July 2019. *C. demersum* was not observed in Carp Lake before 2019.

Zero head space water samples were collected at a depth of ~10 cm (4 in) in acid washed Nalgene® bottles. Water pH, specific conductance, turbidity, and air and water temperature were measured in the field using a Hach 2100 multiparameter meter. Nitrate nitrogen and orthophosphate concentrations were also measured in the field using a LaMotte SMART 3 colorimeter according to US EPA equivalent methods (Method 352.3 for nitrate (US EPA 1993) and Method 365.3 for orthophosphate (US EPA 1978)).

Sediment samples were collected from the top 5 cm (~ 2 in) layer of bottom sediment using an AMS Bottom Dredge and were stored in acid washed Nalgene® bottles. Since *C. demersum* was suspended in the water column, samples were collected by hand and stored in plastic sample bags.

Sample Preparation and Analysis

In the laboratory, water samples were filtered and total suspended solids concentrations were determined according to Standard Methods for the Analysis of Water and Wastewater (APHA 2017). The balance of the filtered water sample was acidified with 2% nitric acid. Extractable concentrations of cadmium, copper, iron, lead, nickel, and zinc

were determined using a Thermo Scientific iCE 3300 Flame Atomic Absorption Spectrophotometer (FAAS) according to Method 7000b (US EPA 2015c).

Sediment samples were also examined to identify the presence of benthic macroinvertebrates prior to further processing. Sediment was then air dried at room temperature, ground into powder using a porcelain mortar and pestle, and sieved. The fine powder was serially dried at 103 to 105°C in a convection oven, allowed to cool in a desiccator then weighed. The process was repeated until the change in dry mass was less than 5%. Coontail samples were rinsed with type 2 lab water to remove surface contamination. Debris was collected and inspected. Vegetation was then dried at 103 to 105°C and finely ground using a mortar and pestle. Solid samples were cooled in a dessicator and the dry mass was measured. This process was repeated until the change in dry mass was less than 5%.

Sediment and vegetation samples were then digested following US EPA Method 3050B (US EPA 1996) to determine the extractable concentrations of metals. After digestion, samples were brought to 100 mL with type 2 laboratory water and clarified by centrifugation. Extractable concentrations of cadmium, copper, iron, lead, nickel, and zinc were determined using a Thermo Scientific iCE 3300 Flame Atomic Absorption Spectrophotometer (FAAS) according to Method 7000b (US EPA 2015c). Trace metal grade reagents and traceable standards were used in all sample digestions and metals analysis.

Data Reduction and Statistical Analysis

Analytic data were examined to determine if outliers were present. In this study, outliers were any data, x, that met the criteria in Equation 1.

Equation 1. $Q_1 - 1.5IQR < x > Q_3 + 1.5IQR$

where Q_1 = first quartile, Q_3 = third quartile, and IQR = interquartile range (US EPA 2000).

Analytic values below the method detection limit (MDL) were treated in subsequent data reduction steps as the detection limit per US EPA guidance (US EPA 2015a). This approach provided the most conservative estimate of the potential impacts of metals on water quality.

Statistical differences among the concentrations of heavy metals in water, sediment, and vegetation were assessed using one-way ANOVA at 95% confidence. Pearson correlations were performed to determine the strength of a

linear relationship, *r*, between individual metals in water, sediment, and plant tissue. The strength of the correlation between metals was strong when $0.7 \leq |r| \leq 1.0$ (Moore *et al.* 2013).

Analytic Quality Assurance and Quality Control

For quality assurance/quality control purposes, samples were collected in triplicate. Triplicate data were reported as an average after testing the data for outliers as detailed previously. Analytic recoveries were performed on at least 10% of samples. All calibration and sensitivity check solutions were prepared from certified standard reference solutions using type 2 laboratory water acidified to 2% with trace metal grade nitric acid (HNO_3). The 2% HNO_3 makeup solution was used as a matrix blank in subsequent FAAS analysis.

RESULTS AND DISCUSSION

Carp Lake Water

A summary of basic water quality characteristics of Carp Lake in June 2018 and July 2019 is presented in Table 1. There were no significant differences in pH or specific conductance at 95% confidence; the average pH and specific conductance were 8.87 and 319 µS cm^{-1}, respectively. Significant increases (at 95% confidence) in orthophosphate concentrations and turbidity were observed in 2019.

Table 1. Carp Lake water quality characteristics in 2018 and 2019.

	Site 1		Site 2		Site 3		Site 4	
Parameter	2018	2019	2018	2019	2018	2019	2018	2019
pH	8.58	8.33	9.80	8.72	8.54	8.72	9.33	8.91
SC, µS cm^{-1}	330	384	266	361	265	360	265	361
Turbidity, NTU	2.5	14.8	3.7	8.0	2.4	15.9	2.4	18.3
NO_3, mg L^{-1}	4.40	4.40	4.40*	BDL*	BDL	BDL	4.40*	BDL*
PO_4, mg L^{-1}	BDL*	0.40*	BDL*	0.20*	BDL*	0.20*	BDL	BDL

Below Detection Limit (BDL; NO_3 = 0.44 mg L^{-1}, PO_4 = 0.05 mg L^{-1}).
* Statistically significant difference at 95% confidence ($p < 0.05$).

153 Elevated orthophosphate and turbidity were attributed to the highest and longest flooding ever recorded in the Upper
154 Mississippi River Basin which occurred between April and June 2019 (US ACE 2025). The City of Davenport's
155 wastewater treatment plant (WWTP) is located ~1.6 km (1 mi) upstream from Carp Lake, on the Mississippi River
156 (Figure 3; 0.117 $m^3 s^{-1}$ (26.8 MGD) and and 0.26 $m^3 s^{-1}$ (60 MGD), design average flow and maximum design flow,
157 respectively; City of Davenport 2023). During 2019 flooding, Davenport's WWTP was inundated with flood water
158 and discharged sewage directly into the Mississippi River (Scott County EMA 2019). The exact magnitude of the
159 discharge has never been quantified. However, these observations are consistent with Schmadel *et al.* (2019) who
160 found that small impoundments (<1 km^2) play a dominant role in nitrogen, phosphorus, and sediment retention when
161 compared to rivers and lakes. Further, the impacts of extreme climate events such as record setting floods on the
162 failure of WWTPs is an issue of increasing concern (Zouboulis and Tolkou 2015; Li *et al.* 2023; and Karimaee *et al.*
163 2026). Since solids in domestic wastewater are known to contain elevated phosphorus (Gutierrez *et al.* 2020; Vianini
164 *et al.* 2026), at least a fraction of the elevated orthophosphate in Carp Lake could be directly attributed to the release
165 of solids from the WWTP.

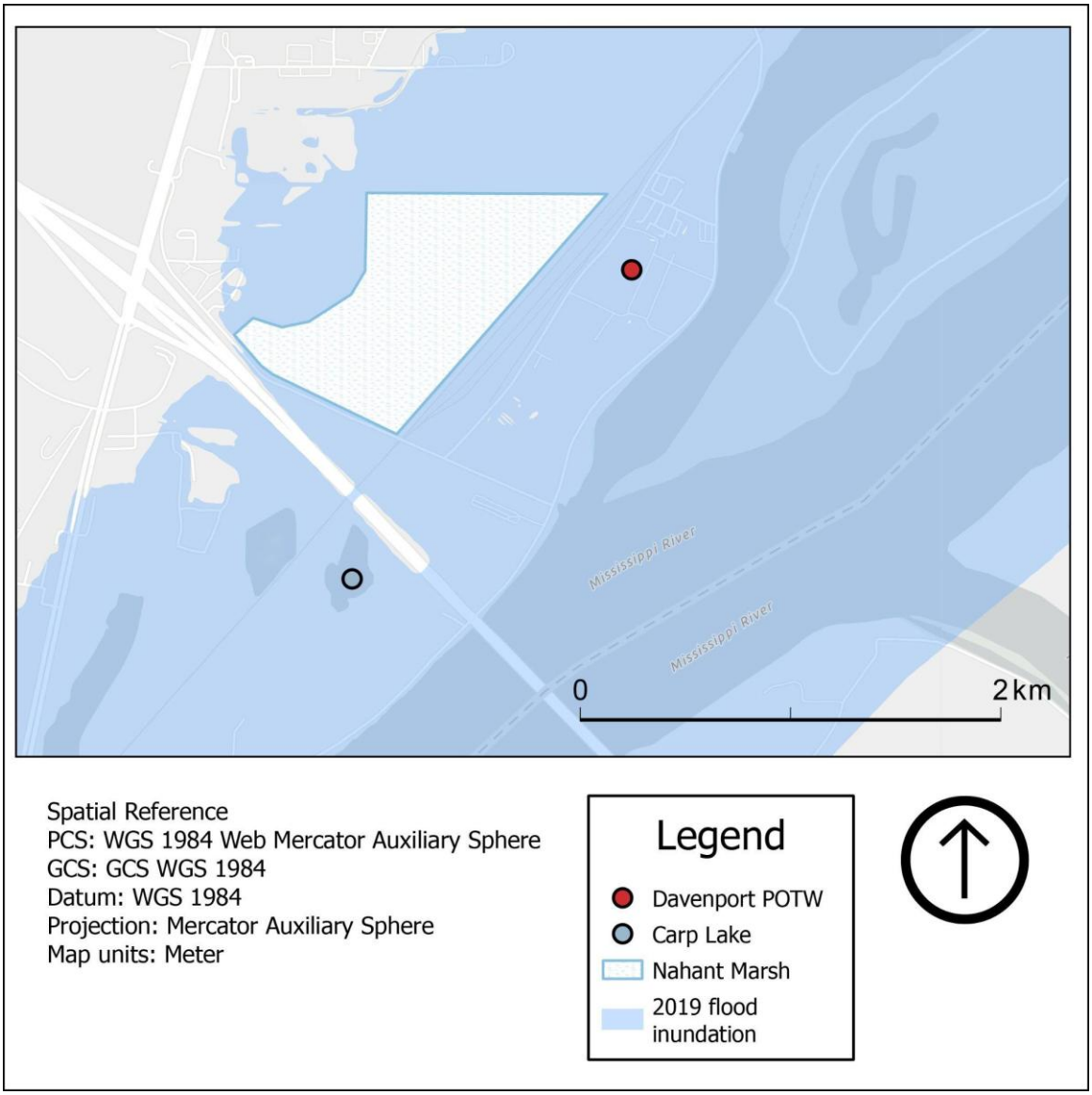


Fig. 3 Map of Carp Lake in proximity to the Davenport, IA, wastewater treatment plant and the extent of Mississippi River Flooding in 2019

Average metal concentrations in Carp Lake water are presented in Table 2. There were no significant differences (at 95% confidence) in the concentration of metals in Carp Lake water between 2018 and 2019. Likewise, there were no statistically significant differences in metal concentrations across sites. Consequently, individual metals were distributed homogeneously across Carp Lake sampling sites which indicates that the lake was relatively well mixed over the study period.

Table 2. Average concentrations of metals and their respective standard errors (parentheses) in Carp Lake water.

Site	Cd, mg L^{-1}	Cu, mg L^{-1}	Ni, mg L^{-1}	Pb, mg L^{-1}	Zn, mg L^{-1}
1	0.012 (0.003)	0.006 (0.001)	0.030 (0.003)	0.042 (0.019)	0.013 (0.002)
2	0.019 (0.010)	0.005 (0.002)	0.024 (0.002)	0.045 (0.016)	0.016 (0.003)
3	0.015 (0.004)	0.007 (0.001)	0.027 (0.003)	0.041 (0.016)	0.013 (0.002)
4	0.014 (0.003)	0.003 (0.001)	0.023 (0.003)	0.052 (0.014)	0.011 (0.001)
Average	0.015	0.005	0.026	0.045	0.013
CMC[1]	0.002	0.030[+]	0.470	0.065	0.120
CCC[2]	-[†]	-	0.052	0.003	0.120

[1] Criterion Maximum Concentration (acute exposure),[2] Criterion Continuous Concentration (chronic exposure; US EPA 2015b), [+] determined from the Biotic Ligand Model (BLM) for a hardness of 120 mg L^{-1} (US EPA 2014), [†]criterion vacated by US District Court in 2023 (US EPA 2023).

In comparison to recommendations for acute and chronic exposure, the average Cd concentration was 7.5 times higher than the aquatic life ambient water quality criterion for acute exposure (US EPA no longer lists criteria for chronic Cd exposure; US EPA 2023). Likewise, the average Pb concentration was almost 22 times higher than the criteria for chronic exposure in freshwater.

Previously, environmental weathering was identified as the source of Cd, Cu, Ni, Pb, and Zn in the soil and vegetation on and around the Carp Lake slag pile (Singh and Viadero 2022). Similar effects of environmental weathering from iron slag piles were cited by Pitak *et al*. (2015), Wang *et al*. (2021), and the Committee on Electric Arc Furnace Slag (2023).

Correlation analysis (Table 3) was conducted to determine the strength of [linear] relationships between individual metals in Carp Lake water. Half of the correlations between metals in Carp Lake water were positive and half were negative. Riley and Mayes (2015) reported positive correlations between metals (Al, Cd, Cr, Cu, Ni, and Pb) for two steel slag piles in the United Kingdom. However, the water pH at sites in those studies ranged from 10.3 to 12.3. The lack of a definitive pattern of correlation between metal concentrations in Carp Lake water is likely due to the relatively low metal concentrations and an average water pH (8.87) close to the solubility products of the hydrated forms of the metals studied in this work (Stumm and Morgan 1996).

Table 3. Correlation between metals in Carp Lake water. Strong correlations ($r > 0.7$) are indicated in bold typeface.

	Cd	Cu	Ni	Pb	Zn
Cd	1.00				
Cu	-0.03	1.00			
Ni	-0.63	0.73*	1.00		
Pb	0.03*	**-1.00***	**-0.74***	1.00	
Zn	**0.74**	0.54*	0.05*	-0.55*	1.00

*Statistically significant difference at 95% confidence ($p < 0.05$).

Carp Lake Sediment

Average metal concentrations and their respective standard errors in Carp Lake sediments are presented in Table 4. There were no statistically significant differences (at 95% confidence) between sediment metal concentrations at Carp Lake study sites between 2018 and 2019. However, unlike Carp Lake water, metals in sediments appeared to be heterogeneously distributed across study sites. Sediment concentrations of Cu, Pb, and Zn were lowest at Site 1, located furthest from the slag pile. Conversely, Cu, Ni, Pb, and Zn concentrations were highest at Site 4, located in closest proximity to the slag pile. However, these patterns were not significant at 95% confidence.

Table 4. Average metal concentrations and their respective standard errors (in parentheses) in Carp Lake sediments.

Site	Cd, mg kg^{-1}	Ni, mg kg^{-1}	Pb, mg kg^{-1}	Cu, mg kg^{-1}	Zn, mg kg^{-1}
1	1.1 (0.1)	8.9 (3.3)	20.7 (2.5)	46.2 (7.3)	109.6 (11.1)
2	1.4 (0.1)	21.0 (0.6)	19.9 (0.8)	42.8 (3.1)	109.7 (5.5)
3	1.1 (0.1)	14.4 (2.4)	10.2 (1.6)	18.8 (2.9)	46.6 (11.2)
4	1.3 (0.1)	23.1 (0.2)	26.6 (2.6)	50.5 (6.6)	115.4 (3.9)

Correlation analysis was conducted to develop additional insights into the possible relationships between metals in Carp Lake sediment (Table 5). Correlations between metals in Carp Lake sediment were positive. Strong correlations were determined for Ni and Cd, Pb and Cu, Zn and Cu, and Zn and Pb. The strong correlations between Cu, Pb, and Zn in the sediment were attributed to similarities in the solubilities of these metals. In an ideal solution, the minimum solubilities of hydrated Cu, Pb, and Zn occur at pH 8.8, 9.2, and 9.0, respectively (Stumm and Morgan 1996). Su *et al.* (2022) also reported that metal concentrations in sediment are frequently greater than aqueous phase metal concentrations.

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Table 5. Correlation between metals in Carp Lake sediment. Strong correlations ($r > 0.7$) are indicated in bold typeface.

	Cd	Cu	Ni	Pb	Zn
Cd	1.00				
Cu	0.49*	1.00			
Ni	**0.89***	0.20*	1.00		
Pb	0.53*	**0.97***	0.53	1.00	
Zn	0.57*	**0.99***	0.63*	**0.93***	1.00

* Statistically significant difference at 95% confidence ($p < 0.05$).

Impacts on aquatic fauna

Notably, no benthic macroinvertebrates were found in any sediment samples collected at Carp Lake. This was concerning given the diverse benthic macroinvertebrate communities present in adjacent, upstream waterbodies (IA DNR 2025). Riley and Mayes (2015), Hull *et al.* (2014), and Koryak *et al.* (2002) attributed the adverse impacts of steel slag discharges on benthic communities to elevated metal concentrations as well as benthic habitat smothering by chemical precipitates. Further, Fairchild *et al.* (2012) reported that heavy metals (Cd, Cu, Zn, and Pb) in weathered slag sediments adversely impacted the growth and survival of benthic macroinvertebrate communities in the Upper Columbia River (Washington, USA). Their findings included an 80% mortality and 94% decrease in biomass of amphipods in laboratory studies of the toxicity of smelter slag. Likewise, Sloto and Reif (2011) noted similar adverse impacts to benthic macroinvertebrate communities in streams surrounding the Hopewell Furnace National Historic Site (Pennsylvania, USA), where local waters were impacted by elevated As, Cr, Cu, Pb, Ni, and Zn. Likewise, Agbam *et al.* (2025) reported that at cadmium concentrations below 0.1 mg kg^{-1}, sensitive aquatic insect species (*Ephemeroptera, Plecoptera,* and *Trichoptera*) can survive and maintain relatively high biodiversity and abundance. However, due to bioaccumulation, adverse impacts to species diversity and abundance increase at Cd concentrations greater 0.1 mg kg^{-1}. This finding is especially important in Carp Lake where the average Cd concentration in sediment (1.2 mg kg^{-1}) was more than 10 times the threshold for impacts reported by Agbam *et al.* (2025). Further, relatively little is known about the synergistic and/or antagonistic effects on benthic macroinvertebrates when exposed to multiple metals on a chronic and/or acute basis. However, Monchanin *et al.* (2021) noted that the physiology and behavior of macroinvertebrates can be adversely impacted at levels of metals (As, Cd, Hg, and Pb) that are considered permissible for humans. Consequently, it is likely that the benthic

macroinvertebrate community in Carp Lake was adversely impacted by metals in sediment. However, it was not possible to study this further, given the absence of macroinvertebrate samples to examine.

This finding has implications for the future management of Carp Lake and similar sites. For example, in areas with little to no alkalinity in receiving waters, special attention should be paid to the possible mobilization of metal contaminants from sediment. However, the relative advantage of a particular pH is difficult to assess. For example, at a more circumneutral pH, habitat smothering by metal precipitates might be reduced; however, dissolved metals are also known to have deleterious impacts on benthic communities. Consequently, productivity in sites like Carp Lake is only likely to improve when metals are removed from the system.

Aquatic Vegetation

C. demersum was the main form of aquatic vegetation observed at Carp Lake in 2019. In contrast, coontail was not observed in previous years. The presence/absence of coontail was also observed in National Agricultural Imagery Program (NAIP) imagery for the site (Figure 4). *C. demersum* was found from the shoreline to depths of up to ~2.4 m (8 ft).

The emergence of coontail corresponded to the significant increase in orthophosphate concentrations in Carp Lake water in 2019. It is possible that coontail propagules existed in Carp Lake prior to 2019. However, its prolific growth was not observed until the site was flooded with orthophosphate. This is supported by Lombardo and Cooke (2003) and Song *et al.* (2017) who reported on coontail's affinity for phosphorus. While coontail is not rooted in lake sediment, *C. demersum* has been shown to promote the release of phosphorus from sediments (Dia *et al.* 2015). Consequently, coontail can be expected to grow even after dissolved phosphorus concentrations decrease. No coontail was present at Site 1 where the water was more than ~3 m (10 ft) deep.



Fig. 4 Aerial images of Carp Lake in 2017 and 2019. National Agricultural Imagery Program (NAIP) imagery acquired on October 22, 2017 (left) and on August 1, 2019 (right) from https://ortho.gis.iastate.edu/arcgis/services.

Average metal concentrations in coontail plants are presented in Table 6. Metal concentrations in coontail plants decreased in the following order: Zn>Ni>Cu>Pb>Cd. The average cadmium concentration in coontail at Carp Lake was 2 to 5 times greater than typical levels reported by Kabata-Pandias (2010). This was also supported by a report where accumulation occurred when coontail was exposed to aqueous Cd concentrations as low as 0.01 μg L^{-1} (Ornes and Sajwan 1993). This finding suggests that coontail might be used to recover metals from Carp Lake, which is consistent with Mishra et al. (2006) who reported on the effective removal of lead in laboratory experiments using *C. demersum*. However, since metals are not biodegradable, plant matter would need to be harvested from the lake

and disposed of properly. Based on findings reported by Quadri *et al*. (2022), failure to remove coontail will continue to exacerbate the accumulation of metals in Carp Lake.

Table 6. Average metal concentrations in *C. demersum*.

Site	Cd, mg kg^{-1}	Ni, mg kg^{-1}	Pb, mg kg^{-1}	Cu, mg kg^{-1}	Zn, mg kg^{-1}
2	1.0	7.5	4.0	7.0	35
3	1.0	6.5	4.0	6.5	25
4	1.0	8.5	5.0	8.0	40
Typical*	0.05-0.2	0.1-5	5-10	5-30	27-150

*Kabata-Pendias (2010)

Exposure pathways for aquatic and semi-aquatic fauna

Given the average Cd concentration in Carp Lake water (0.015 mg L^{-1}) and elevated levels of Cd in coontail tissue, consideration must be given to the role coontail plays as a pathway for the biomagnification of metals in the food chain. This is especially relevant given the importance of Carp Lake and similar sites to environmental receptors. For example, Carp Lake sits in the Mississippi River Flyway, a major bird migration route across central North America. Since coontail is known to be part of the diets of a variety of waterfowl including the American Coot *(Fulica americana),* wood duck *(Aix sponsa),* and mallard *(Anas platyrhynchos)*, coontail is a viable pathway for Cd accumulation in biota (Borman *et al.* 1997). Likewise, the region is home to painted turtles (*Chrysemys picta*), red-eared sliders (*Trachemys scripta elegans*), snapping turtles (*Chelydra serpentina*), and Blanding's turtles (*Emydoidea blandingii*). The presence of Blanding's turtles is particularly notable since they are endangered in Iowa and Illinois and are being considered for federal listing (US FWS 2026). Little is known about the potential effects of Cd on Blanding's turtles. However, Cd is reported to be toxic to other freshwater turtles (Dong *et al.* 2024; Huo *et al.* 2017). There were no correlations found between metals in Carp Lake sediments and coontail plants. This was attributed to the fact that coontail is a free floating, submerged, rootless plant (Matagi *et al*. 1998).

SUMMARY AND CONCLUSIONS

This study provides additional insights into the potential risks and impacts of metals from the historic slag pile to water quality, sediment, and aquatic vegetation at Carp Lake, which can be used to inform future assessments of similar sites. Metal concentrations in Carp Lake were highest in sediment and lowest in water. The concentrations of metals in Carp Lake water were homogeneously distributed across Carp Lake study sites. Cadmium and Pb in water

were the greatest concerns in Carp Lake water as they exceeded the US EPA criteria for acute exposure and chronic exposure, respectively. Consequently, additional consideration should be given to the presence and potential movement of metals in ground water. Carp Lake sediment was a sink of heavy metals. Metal concentrations were highest at the site located closest to the slag pile. The proliferation of *Ceratophyllum demersum* after major regional flooding in 2019 provided an opportunity to study the accumulation of metals in plant tissue. Given the location of the study site in the Mississippi River Flyway, particular attention should be paid to the role coontail might play in exposing wildlife to metals and subsequent biomagnification through the food web. Additionally, in the future, the number of study sites in Pool 16 should be expanded to better define the relationships between the proliferation of aquatic vegetation and regional flooding.

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Contributions

RCV and AS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, review, and editing,

RK: Formal analysis, Methodology, Visualization, Writing—review and editing

EDT and SB: Formal analysis, Validation, Visualization, Writing—review and editing

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DECLARATIONS

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Data Availability Statement (DAS)

The satellite imagery used in Figure 4. are publicly available from the US Department of Agriculture's National Agricultural Imagery Program (NAIP). Datasets generated and/or analyzed in this study are available from the corresponding author upon reasonable request.

Ethics Declarations

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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