

Spatial Distribution, Ecological Risk and Analysis of Sources of Trace Metal Elements in Surface Sediments of Pond Thomas (Brenne), France

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ABSTRACT

This study aims to contribute to understanding the processes influencing the spatial distributions of trace metal elements in surface sediments of Brenne's ponds (France) and assess potential pollution levels in the area. It was motivated by the lack of knowledge regarding the hydrogeochemical dynamics of limnic entities, which are ponds. To achieve this, 25 sediment samples were collected from Pond Thomas, considered as a 'sentinel pond', and underwent analysis for grain size, total organic carbon (TOC) concentrations, and trace metal elements (TMEs) (specifically Cu, Ni, Pb, As, Zn, Cr, and Cd). The results revealed that trace metal elements are primarily concentrated in two areas: the northwest section and the upstream region in the southern part of the pond. Applying various pollution indicators such as the enrichment factor (EF), geo-accumulation index (I_{geo}), and potential ecological risk index (RI), it was found that Pb and As are the most enriched elements, with respective EFs of 3.5 and 4.9. Their average concentrations exceed geochemical background values by 4 and 5.68 times in certain samples. The sediments in the southern part of the pond showed moderate contamination levels for As and Pb, with moderate to severe pollution ($2 < I_{geo} < 3$), reaching a maximum I_{geo} of 2.26 for As. Although the RI values across the pond are relatively low, Cd and As still pose moderate potential ecological risks. Additionally, principal component analysis and Pearson correlation analysis indicated two sources of TMEs in the area: Zn, As, Ni, Cd, Pb, and Cr are primarily from natural sources, while Cu appears to have a local anthropogenic origin.

Keywords: geochemistry, spatial distribution, grain size, ecological risk, sediments, pond.

INTRODUCTION

Over the last two decades, there has been a surge in scientific interest in deep-water bodies like lakes and dams, primarily due to their archival potential for precise paleoenvironmental reconstructions (Arnaud et al., 2004). Simultaneously, research efforts have also concentrated on peatlands (Shotyk, 1996; Weiss et al., 2002), thereby complementing the findings from studies on lakes and ice cores (Boutron et al., 1972). The significance of these environments lies in their thickness sediment layers

spanning multiple decades, often remaining undisturbed, unlike man-managed water bodies such as ponds and marshes.

Indeed, ponds, a prevalent water body type in our regions (numbering 500,000 in France) according to (Bartout et al., 2013; Downing et al., 2006), lack the storage capacity due to their typically small watershed sizes and periodic dredging. However, they exhibit dynamics akin to large water bodies (Oertli et al., 2013). The relatively thin sediment thickness in most of these water bodies may not facilitate reconstructing the water body's history or environment. Nevertheless,

they significantly contribute to understanding sediment transfer processes and associated metal loads. Factors such as grain size distribution, mineralogical composition, presence of aquatic vegetation, and water currents contribute to spatial heterogeneity in metal concentrations. Studies undertaken on certain lakes and dams (Bebars et al., 1997; Moussa, 2018) validate these spatial disparities, emphasizing the influence of these factors mentioned above.

The hydrogeochemical dynamics characterizing these limnic entities are particularly intriguing due to their ability to retain various chemical compounds within bottom sediments and the physicochemical conditions of their deep levels (Nedjai, 2019). Their thermal stratification largely regulates chemical exchanges between water masses and sediments based on the oxygen state of the deep layer (hypolimnion), making these entities sources of emission of undesirable chemical compounds at times and adsorbent sinks at others (Lewis, 1983). This dynamic, prominently observed in lakes and dams due to their considerable depths, is also present in shallow water bodies like ponds but is more fragile there (Haouchine et al., 2019); it is susceptible to climatic influences and inputs from slopes (Azaroual et al., 2014; Meybeck, 1995). Additionally, water flows within the water mass directly influence this dynamic, creating preferential currents that result in the formation of small flow axes in the basin (Dallas, 2008; Benoist and Champetier, 2015). These axes tend to concentrate sediment deposits and likely the accumulated metal load (Förstner and Wittmann, 2012; Pena and Picot,

1991). Despite their low inputs due to the small size of their watersheds, the high density of these ponds significantly increases their scientific importance in understanding their role in storing and emitting metals that could elevate concentrations in associated tributaries and potentially impact the internal biotic chain. Therefore, they serve as reliable indicators of water and sediment quality stored in their limnic basins and more broadly in their watersheds.

Hence, this study, part of the regional project “Dynétangs,” where Pond Thomas is considered among the “sentinel ponds,” aims to comprehend the processes governing the spatial distributions of trace metal elements (specifically Cu, Ni, Pb, As, Zn, Cr, and Cd) in surface sediments of Brenne’s ponds (France). Factors such as grain size, organic matter content of sediment deposits, and local geochemical background are crucial for understanding the dynamics of these metals within the ponds. Furthermore, this approach helps identify areas sensitive to potential metal micropollution in these fishery ponds.

STUDY AREA

Pond Thomas is situated in the Brenne Regional Natural Park, approximately 40 km west of Châteauroux in the southwest of the Indre department, within the Centre-Val de Loire region of France. Specifically, it occupies the upstream part and head of the watershed in the “Foucault sector” and is part of a small watershed (Fig. 1). The

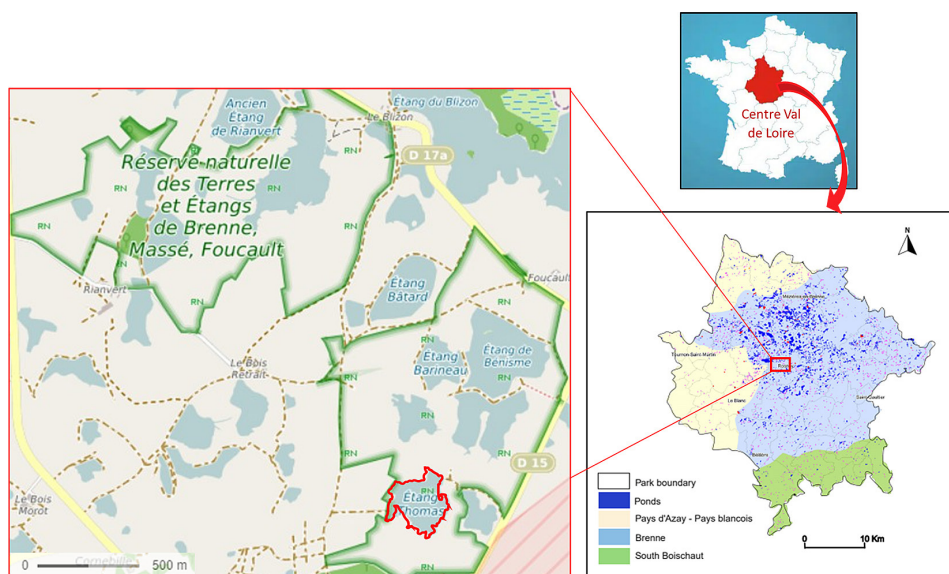


Figure 1. Location of Pond Thomas

hydrographic network is relatively straightforward: Pond Thomas feeds into Pond “Blizon”, through a chain of ponds, which then flows into “Blizon” Stream, followed by “Cinq Bondes” Stream, before finally reaching the “Claise” Watercourse.

The area features a relatively flat topography punctuated by small, flat-bottomed basins, with a geological composition primarily consisting of hard clayey-sandstone, locally known as “grison,” and clay-sandy soil (Rasplus et al., 1989). The region experiences a degraded continental climate with a notable oceanic influence. Recorded temperatures range from 6.9 °C for minimums to 16.08 °C for maximums, averaging around 11.54 °C. Precipitation levels have averaged 700 millimeters annually over the past five years.

The watershed of Pond Thomas is mainly covered by forests and shrub vegetation in the west, while agricultural land dominates the eastern part. In the southern basin, there is a deciduous forest with predominantly pedunculate oaks, and to the southeast, heaths and scrubland that form part of the ground of the national marine base. (topographic-map.com and geoportail.gouv.fr.).

MATERIALS AND METHODS

A total of 25 surface sediment samples were collected from Pond Thomas aboard a rubber dinghy during a sampling campaign in May 2019. These sediments were retrieved using an Ekman grab sampler following an approximate spatial

grid of 35 by 35 meters, except for certain restricted navigation areas such as fish farming zones and sandy shores (Fig. 2).

The samples intended for analysis were taken directly from the top 3 to 5 centimeters of sediments retrieved in the sampler, which is a shallow depth due to the low sediment input ratio ($Ad/Ao = 14.9$) (Table 1). Each bulk surface sediment sample was sealed in a plastic bag, labeled, and stored at 4 °C before being processed and analyzed in the laboratory.

Analytical methods

The samples underwent drying in an oven at 45 °C for 72 hours. Following this, a grain size analysis was conducted to characterize the sediment texture, adhering to ISO 14688-2017 standards. Three main classes were segregated based on Wentworth's classification (Wentworth, 1922): clay (< 4 µm), silt (4–63 µm), and sand (> 63 µm).

For chemical analyses, the samples were ground into < 20 µm powders using an agate mortar. The concentrations of trace metal elements were determined by ICP-MS using a Thermo X[®] – Series 2, following detailed analytical procedures proposed by (Pearce et al., 1997; Lee et al., 2003; Košler, 2007; Dolor et al., 2009). The analysis of organic matter (% total organic carbon) was carried out using Rock-Eval pyrolysis – version 6, with detailed analytical procedures described by (Lafargue et al., 1998; Sebag et al., 2005).

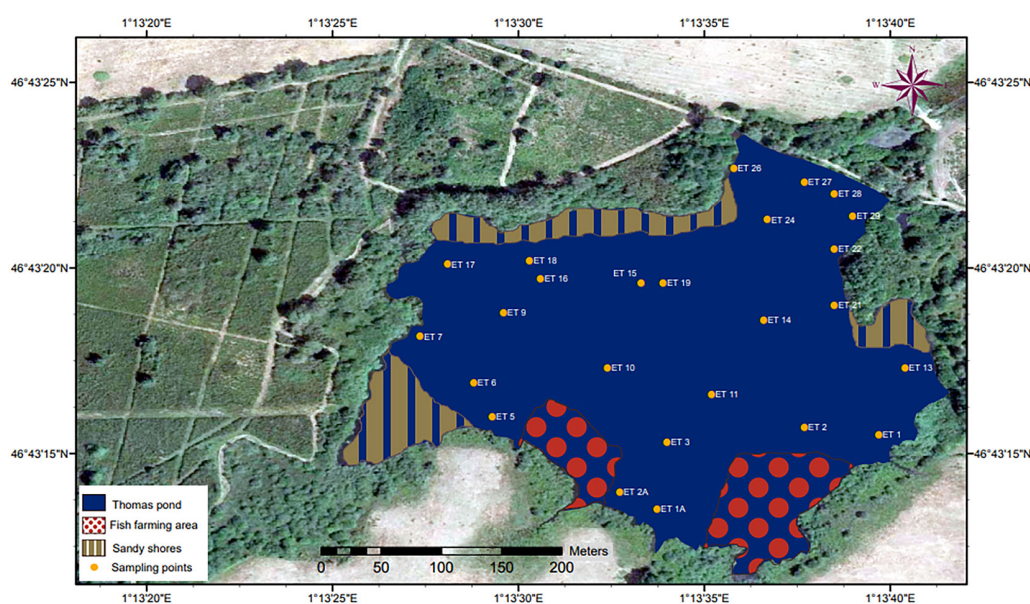


Figure 2. Map representing the sampling points of surface sediments, Pond Thomas

Table 1. Characteristics of Pond Thomas and its watershed

Characteristic	Value
Surface area of the pond (ha)	7.4
Perimeter of the pond (m)	1435.04
Average depth of the pond (m)	2,25
Average water level of the pond (m)	1.25* *Estimated over a period of 30 months of on-site measurements
Average volume of the pond (m ³)	225039.81
Surface area of the pond's watershed (ha)	110
Perimeter of the pond's watershed (m)	4700
Sediment input ratio (Ad/Ao)	14.9* *Indicates a low to medium sediment input
Last draining of the pond* *The pond is emptied periodically for cleaning or fishing purposes	8 years ago
Year of last fishing	2017

Analysis and data processing

The raw LA-ICP-MS data are processed using ICPMS Data Cal software, developed by Yong Sheng Liu (Liu et al., 2008). The spatial variability of the different analyzed elements is represented in iso-content maps using the interpolation functionalities of the ArcMap™ module of ArcGIS Desktop version 10.8 by Esri®. The interpolation method considered is the inverse distance weighting (IDW) method (Kravchenko and Bullock, 1999; Benazzouz, 2011).

Three factors have been selected to assess the risk associated with concentrations of trace metal elements, which may help to distinguish the respective contributions of potentially anthropogenic and natural sources present in the studied area. The concentrations of trace metal elements (TMEs) from the geochemical background (Table 2) were extracted from the literature (Darmendrail et al., 2000), where we opted for the reference values from the Châtre sector (Indre department). This choice is based on the local nature of these values, making them representative of the studied area.

Enrichment factor

Developed by Ackerman (Ackerman, 1980) and widely used (Bastami et al., 2015; Sutherland, 2000; Wang et al., 2020b), it minimizes the influence of grain size and mineralogical differences between samples. Its use involves choosing a normalizing metal element, usually aluminum or iron due to their natural abundance in the terrestrial environment (Rubio et al., 2000). For this study, iron was selected as the normalizing

element due to the lack of available data for aluminum. The enrichment factor (EF) definition can be expressed by the following formula:

$$EF^i = (C_s^i / Fe_s) / (C_b^i / Fe_b) \quad (1)$$

where: e_s – represent the concentrations of the specific metal studied and iron in the samples, while and represent the values of the natural geochemical background of the studied metal and iron. To describe the enrichment status of trace metal elements, EF values are generally divided into 6 categories (Table 3) (Buat-Menard and Chesselet, 1979).

Index of geoaccumulation

The geo-accumulation index (I_{geo}) is a widely used index to quantitatively measure the level of metal pollution in aquatic sediments (Müller, 1969; Förstner et al., 1980). This index establishes a relation between the measured concentration of a trace metal element in the fine fraction of sediments and the background concentration of the same TME in the local geochemical environment. The calculation of I_{geo} is based on the following formula:

$$I_{geo} = \log_2 [C_s^i / (1.5 \times C_b^i)] \quad (2)$$

where: the constant 1.5 is used as a “background matrix correction coefficient” to compensate for potential uncertainty in the background concentration induced by lithogenic effects and/or surface processes. The most commonly accepted classification for the index is: $I_{geo} \leq 0$: not polluted; $0 < I_{geo} < 1$: not polluted to moderately

Table 2. Reference values of the natural geochemical background in the Châtre sector (Indre department) and associated toxic response factors for the studied trace metal elements

Elements	Fe ₂ O ₃	Cr	Ni	Cu	Zn	As	Cd	Pb
Background values (mg/kg)*	3.46	52	25	20	78	12	0.4	41
Toxic response factor		2	5	5	1	10	30	5

Note: *BRGM standard, surface flood silt: high clay component assuming a stable basin.

Table 3. Relation between EF and contamination

EF	<2	2–5	5–20	20–40	>40
Grade of contamination	Unpolluted	Minor	Moderate	Severe	Very severely

polluted; $1 < I_{geo} < 2$: moderately polluted; $2 < I_{geo} < 3$: moderately to severely polluted; $3 < I_{geo} < 4$: severely polluted; $4 < I_{geo} < 5$: severely to extremely polluted; and $I_{geo} > 5$: extremely polluted (He et al., 2019; Sutherland, 2000).

Potential ecological risk index

The potential ecological risk index (RI) is a widely accepted statistical method for quantifying the superimposed effect of heavy metals on the environment (Hakanson, 1980). RI is designed to consider not only the enrichment or depletion of trace metal elements compared to the geochemical background but also the variations in toxicological levels among different TMEs, synergistic effects of multiple elements, and the environmental tolerance limits (Fang et al., 2019). The calculation of RI follows this formula:

$$RI = \sum_{i=1}^n E_r^i = \sum_{i=1}^n T_r^i \times (C_s^i / C_b^i) \quad (3)$$

where: the term refers to the potential ecological risk coefficient of an individual heavy metal element, and the term denotes its toxic response factor (Table 2). According to (Förstner et al., 1980; Hakanson, 1980), the following terminologies are suggested for values and RI:

- $E_r^i < 40$, low ecological risk; $40 < E_r^i \leq 80$, moderate ecological risk; $80 < E_r^i \leq 160$, higher ecological risk; $160 < E_r^i \leq 320$, much higher ecological risk; and $E_r^i > 320$, severe ecological risk.
- $RI < 150$, low ecological risk; $150 < RI < 300$, moderate risk; $300 < RI < 600$, high risk; and $RI > 600$, significantly high risk.

Three statistical methods were used to complement the data interpretation tools for the sediments. Initially, descriptive statistics were

employed to analyze parameters of central tendency and dispersion (mean, standard deviation, minimum, maximum), which characterized the behavior of each variable studied (Table 4). Subsequently, a Pearson correlation matrix was generated (Table 5) to gain a preliminary understanding of the phenomena within the system. The third statistical processing step involved principal component analysis (PCA) (Figure 6). PCA offers insights into possible contamination processes in the pond sediments or the source of certain trace metal elements (TMEs). These statistical calculations were conducted using XLSTAT 2015 software.

RESULTS AND DISCUSSION

Table 4 provides a summary of the grain size, TOC, and concentration of trace metal elements in the surface sediments of Pond Thomas.

Grain size and total organic carbon

The grain size classification of sediments in the studied area is presented on the ternary diagram (Fig. 3). The content of sand, silt, and clay ranges from 0.4% to 93.8%, from 2% to 28.7%, and from 4.2% to 86.3%, with averages of 32.94%, 13.46%, and 53.59%, respectively.

The 25 surface sediments are predominantly clay with 53.59% and sand with 32.94% (it is very difficult to distinguish between sand deposits carried and deposited naturally in the pond and those used anthropogenically to consolidate the shores). This assessment is corroborated by the diagram in Figure 3 and the clay distribution map (Fig. 4a), which also highlight a notable difference in grain size composition between the peripheries (southeast, northeast, east) and

Table 4. Descriptive statistics of grain size, total organic carbon, and trace metal element concentration in surface sediments of Pond Thomas

Parameter	Sand	Silt	Clay	Cu	Cr	Zn	Ni	Pb	Cd	As	Fe ₂ O ₃	TOC
Unit	%			mg/ kg					%			
Min	0.40	2.00	4.20	17.56	90.32	82.20	11.27	111.36	0.34	56.20	3.50	0.32
Max	93.80	28.70	86.30	41.39	185.21	141.53	21.04	224.06	0.89	86.37	4.41	5.21
Mean	32.94	13.46	53.59	22	114.94	116.79	16.28	165.29	0.67	68.19	3.99	2.95
S.D.	28.67	6.48	24.83	4.70	22.16	12.91	1.95	30.72	0.14	10.07	0.23	1.32

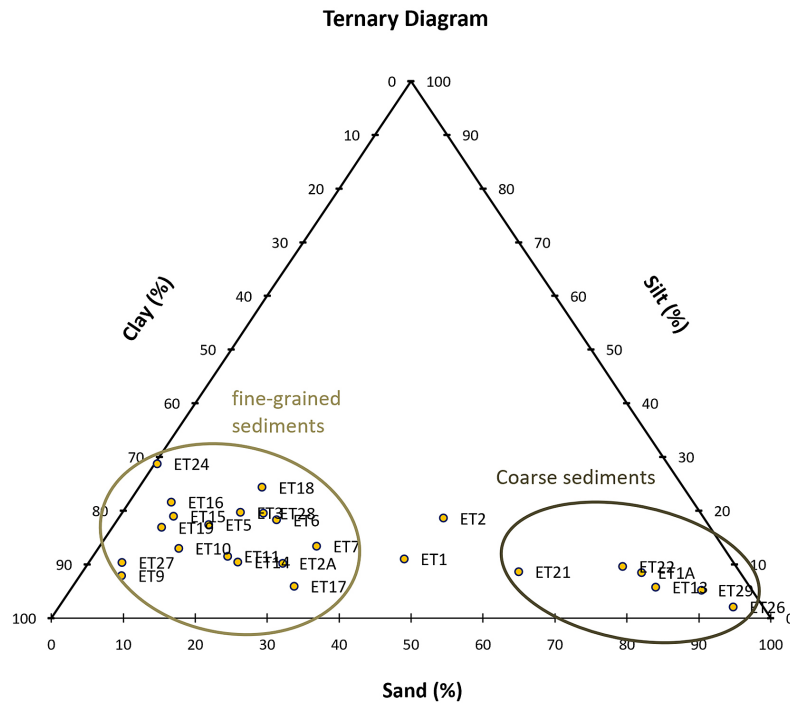


Figure 3. Ternary grain size diagram of surface sediments in pond Thomas

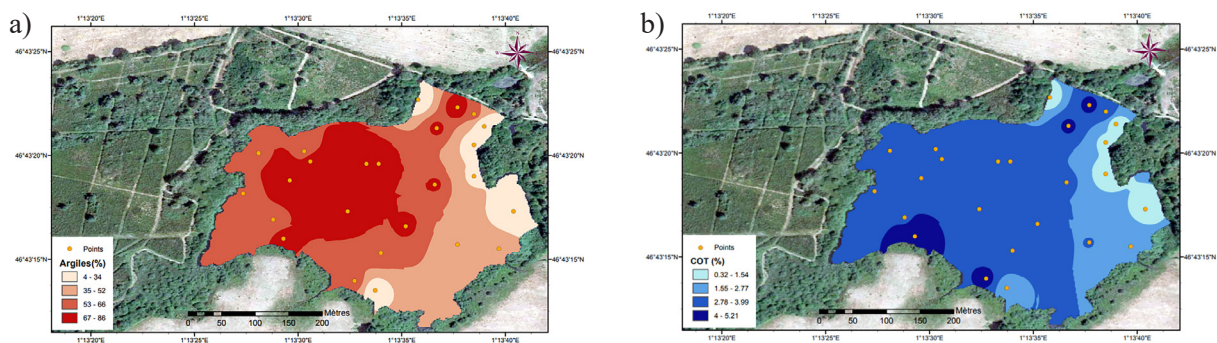


Figure 4. Distribution of clay percentage (a) and TOC concentration (b) in surface sediments of Pond Thomas

the other parts of the pond. Sediments in the center exhibit a finer composition, mainly clay. This distribution is likely influenced by drainage from the slopes through micro-affluents and the pond’s morphology. The greater depth in the pond’s center, coupled with the forest to the

west acting as a wind and waves barrier, creates a sheltered environment conducive to the accumulation of fine sediments.

The TOC content ranges from 0.32% to 5.21%, averaging 2.95%. As depicted in Figure 4b, TOC distribution is relatively uniform throughout the pond,

except for the East bank, which shows the lowest TOC levels. The spatial distribution of TOC mirrors that of clay, with elevated TOC and clay content on the southwest bank and along the upstream-downstream axis of the pond (Fig. 4a and 4b). Consequently, TOC levels in coarser sediments are notably lower compared to finer sediments.

Concentrations of trace metal elements and their spatial variations

Figure 5 showcases notable zoning characteristics of trace metal element concentrations in the surface sediments of Pond Thomas. We observe: a concentrated distribution in the south and center, decreasing towards the shores for cadmium; an upstream-north gradient for chromium; an upstream-downstream gradient

for nickel, arsenic, and zinc. Localized concentrations of lead and copper are also present at certain sampling points. The comparison of trace metal element concentrations in these sediments with the reference values of the natural geochemical background of the “Châtre” sector (Table 2) allows us to show that:

- Chromium exhibits a relatively homogeneous spatial distribution throughout the pond, with high concentrations reaching up to three times the local geochemical background value. These values are considered moderate natural anomalies, attributed to soil development in limestone clays (Baize, 2016).
- Nickel shows concentrations half as important as the geochemical background upstream, and can even be three times lower near tree vegetation. A similar spatial

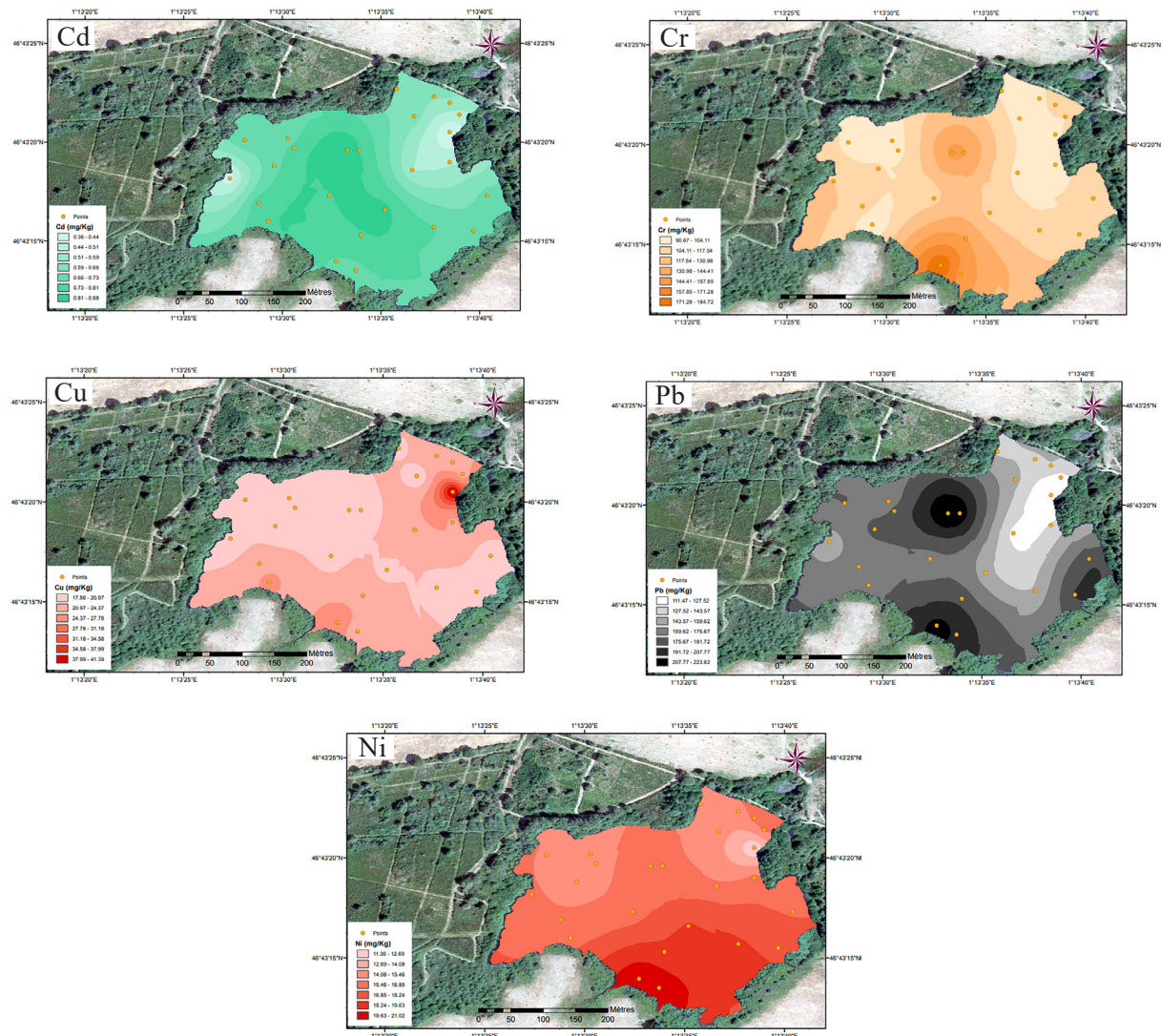


Figure 5. Spatial variations of trace metal element contents (Cd, Cr, Cu, Pb, Ni) in surface sediments of Pond Thomas

distribution to nickel is observed for arsenic and zinc, which show respective enrichments of seven and two times compared to the local geochemical background.

- In the center of the pond, cadmium concentrations exceed those of the shores (west and northeast), with values twice the local background; these concentrations are likely related to lithology and specific surfaces.
- Lead shows a heterogeneous spatial distribution, with very high concentrations (five times higher than the geochemical background value), especially in two areas of the pond. These concentrations are interpreted as significant natural anomalies, linked to “metallotecte” zones rich in minerals (lead, zinc, barite, pyrite) (Baize, 2016).
- The spatial distribution of copper is homogeneous throughout the pond, but with a notable difference between the northeast shore and the rest of the pond, where the concentration is twice the geochemical background.

The concentrations of trace metal elements vary spatially, creating concentration zones that could potentially constitute pollution hotspots. Two such zones can be distinguished:

- Northwest zone (vegetation cover): This can be explained by the presence of a biogeochemical cycle that occurs between soils and plants. Plants absorb trace metal elements through their roots and redistribute them in their various organs. These elements then return to the soil, either directly (root decomposition) or indirectly (enrichment of upper horizons through aerial parts decomposition), in more mobile and bioavailable forms. (Baize, 2016; Kabata-Pendias, 2011);
- South zone (upstream): A fishing pit accumulates fine sediments strongly, creating a potentially polluted area. This accumulation is likely due to the coprecipitation of trace metal elements with the fine grain size present in this zone. Additionally, the bioaccumulative capacity of fish contributes to this accumulation. When fish are exposed to high metal concentrations, they can stimulate the production of metallothionein (MT), which protects cells until the metals are expelled from tissues. MT typically forms complexes with cadmium, copper, and zinc (Saiki, 1995; Cosson, 1995).

Identification of potential sources

The elemental composition of aquatic sediments is primarily controlled by their sources and secondarily by transport and biological processes (Fang et al., 2019). To facilitate the distinction of TMEs sources in the surface sediments of Pond Thomas, Pearson correlation analysis (Table 5), which has been frequently used and proven highly effective (Baptista Neto et al., 2000; Sutherland, 2000; Fang et al., 2019; Xu et al., 2020), is employed in this study. The hierarchy of correlation coefficients (r) proposed by (Cohen, 1988) is adopted to quantitatively describe the accompanying relationship between TME concentrations, TOC, and grain size: $0.1 < r < 0.3$, weakly correlated; $0.3 < r < 0.5$, moderately correlated; and $0.5 < r < 1.0$, strongly correlated. The results show that:

- The moderate to strong correlations among Cd, Pb, As, Cr, Zn, and Ni in the sediments of the study area imply that a majority of the sediments could originate from common sources.
- TOC shows strong correlations with clays and silts, but it also exhibits a strong negative correlation with the sandy fraction, which is explained by a higher adsorption degree for the fine fraction: high specific surface area. Cd and Pb are moderately correlated with TOC. This indicates that Cd and Pb accumulations are influenced by organic matter deposition (Amara et al., 2016; Steinnes, 2013; Madejón, 2013; Alloway, 2013).
- Copper is weakly to moderately negatively correlated with all elements except with sands, where it is weakly positively correlated. This suggests an anthropogenic source (possibly sands used for bank consolidation). As, Cr, Ni, and Zn show no correlation with grain size. This result suggests that these elements are not absorbed by sediments during transport but are intrinsic components of the sediments.
- Conversely, other TMEs show weak to moderately negative correlations with grain size, corroborating the adsorption effects of fine-grained sediments on heavy metals. It has been verified that the mobility, variability, and bioavailability of trace metal elements are greatly reduced when they are complexed by organic matter (Schneider, 2016).

Multivariate analysis (PCA) illustrated in Figure 6 indicates that 46.28% of the

Table 5. Pearson correlation matrix (n)

Variables	Sand	Silt	Clay	TOC	Cr	Ni	Cu	Zn	As	Cd	Pb
Sand	1										
Silt	-0.665	1									
Clay	-0.981	0.506	1								
TOC	-0.897	0.644	0.867	1							
Cr	-0.051	0.003	0.058	0.175	1						
Ni	0.029	-0.052	-0.020	0.158	0.694	1					
Cu	0.293	-0.190	-0.288	-0.172	0.059	-0.279	1				
Zn	0.015	-0.056	-0.003	0.198	0.445	0.854	-0.398	1			
As	-0.081	0.057	0.079	0.252	0.222	0.627	-0.169	0.728	1		
Cd	-0.470	0.319	0.459	0.490	0.341	0.469	-0.439	0.477	0.566	1	
Pb	-0.288	0.153	0.292	0.340	0.697	0.534	-0.387	0.551	0.315	0.708	1

system’s variance is explained by Component F1, 18.98% by Component F2, and 9.35% by Component F3. The remaining components were not considered for discussion.

The first group, showing a negative contribution on axes F1 and F2, appears to be characterized by a clay-silt composition and the presence of organic matter in the form of clay-silt-humic complexes. The clays, silts, and TOC in this group are likely of internal natural origin. In contrast, the second group, with a positive contribution on axis F1, seems to correspond to sandy sediments. The presence of sands, silica dioxide (SiO₂), and copper in this group suggests a potentially anthropogenic but internal source within the watershed. This source could be related to development activities and pond management (including sand addition) as well as agriculture practiced to the east of the pond, where copper is used to combat crop fungal

diseases (The use of copper in agriculture, 2020). The third group, showing a negative contribution on axis F1 and positive on axis F2, appears characteristic of sandy sediments composed of trace elements in inclusion. Thus, Ni, Zn, As, and Cr share a common internal origin. The fourth group, with a negative contribution on axis F1, seems to represent a terrigenous system associated with erosion, corresponding to an internal origin within the watershed, where lead and cadmium are also associated.

Axis F3 confirms the uniqueness of Cu and clearly shows that this element has a different origin from other trace metal elements.

Evaluation of pollution levels

To clarify the degrees of enrichment/depletion of trace metal elements in sediment samples and to better understand the current state of the

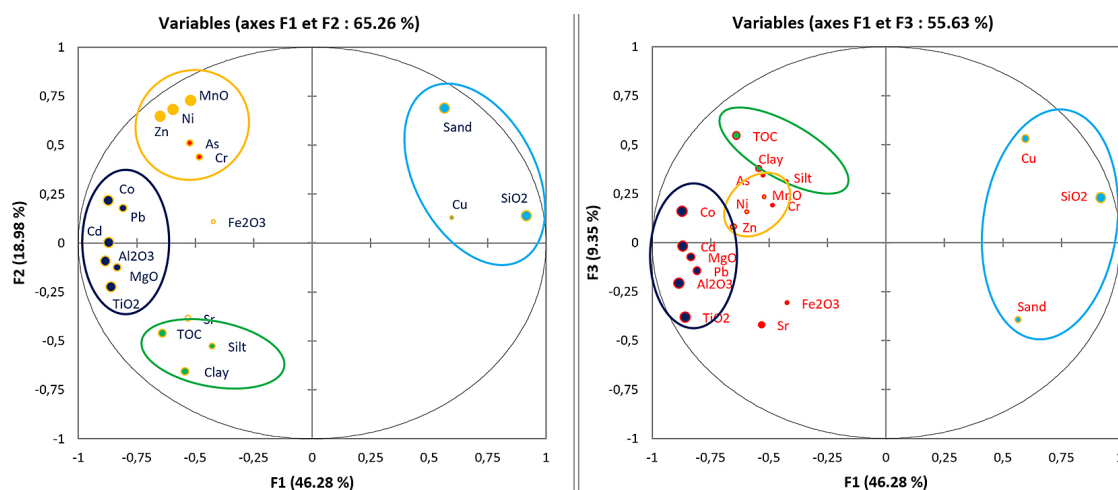


Figure 6. Representation of principal component analysis for surface sediment data in Pond Thomas

environment, the enrichment factor, geoaccumulation index (I_{geo}), and ecological RI were calculated using Formulas 1, 2, and 3.

As shown in Figure 7, EF values range from 3.94 to 6.35 for As, 0.84 to 1.84 for Cd, 2.43 to 4.59 for Pb, 0.69 to 2.04 for Cu, 0.44 to 0.74 for Ni, 1.45 to 3.14 for Cr, and between 1.04 and 1.65 for Zn. In terms of average values, they are ranked in descending order: As (4.93) > Pb (3.49) > Cr (1.92) > Cd (1.44) > Zn (1.03) > Cu (0.96) > Ni (0.56). EF values are < 2 for Cd, Zn, Cu, and Ni at all sampling points. This implies that there is no contamination or enrichment of these TMEs in the pond. For Cr, no contamination is present except at certain points where the threshold is > 2 (6 sampling points, corresponding to 24% of the total points).

All samples were slightly ($2 < EF < 5$) enriched in Pb. In comparison, enrichment in As reached a degree of minor contamination ($2 < EF < 5$) to weakly moderate ($5 < EF < 20$) at certain sampling points (the entire southern part of the pond), making it the most enriched TME in the study area.

Similar to EF, the Geo Accumulation Index can also be used to estimate the degree of metal pollution. As shown in Figure 8, the calculated I_{geo} values in sediments ranged from 0.21 to 1.24 for Cr, -1.73 to -0.83 for Ni, -0.77 to 0.46 for Cu, -0.50 to 0.27 for Zn, 1.64 to 2.26 for As, -0.80 to 0.57 for Cd, and 0.85 to 1.86 for Pb. The average I_{geo} values are in the order of As (1.90) > Pb (1.40) > Cr (0.53) > Cd (0.11) > Zn (-0.01) > Cu (-0.47) > Ni (-1.21), which resembles the

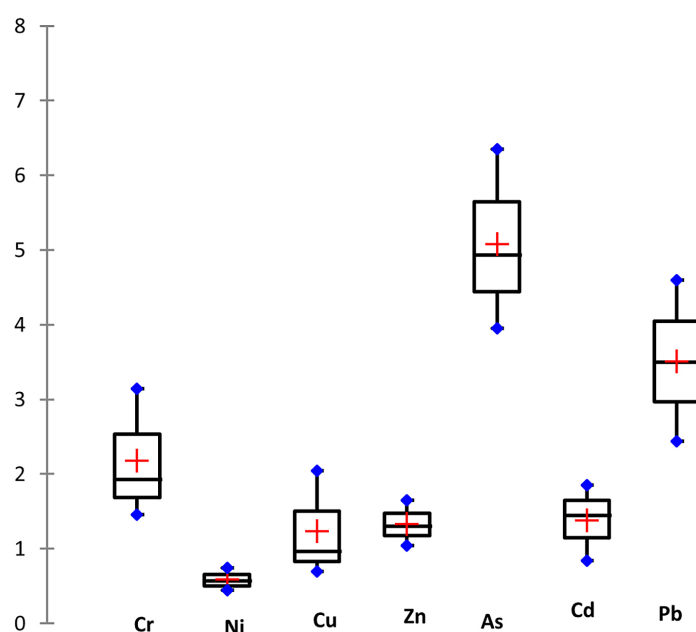


Figure 7. Enrichment factors of TMEs in surface sediments of pond Thomas, Brenne

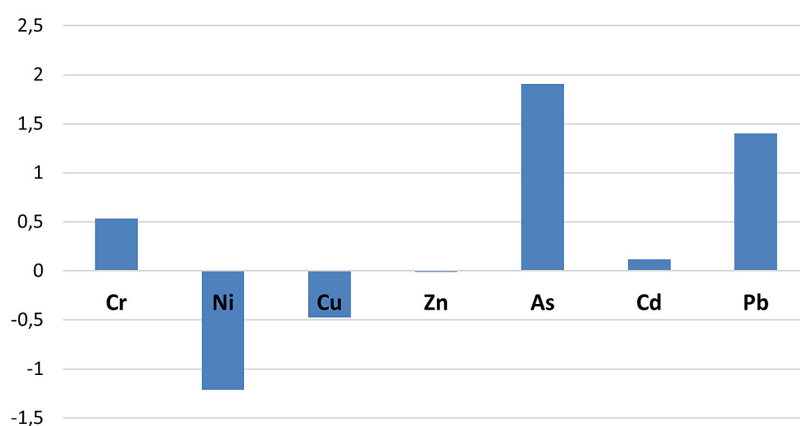


Figure 8. Index of geoaccumulation of TMEs in surface sediments of pond Thomas, Brenne

sequence of average EF values. According to the pollution classification system based on I_{geo} , all surface sediment samples from Pond Thomas are not polluted by Ni and Cu. The majority of sediments are non-polluted to moderately polluted ($0 < I_{geo} < 1$) by Zn, Cr, and Cd. However, the sediments at the site are moderately contaminated by As and Pb, with moderate to severe pollution ($2 < I_{geo} < 3$) at certain points (southern part of the pond), where the maximum I_{geo} value is 2.26.

The potential ecological risk coefficient values for each trace metal element range from 3.47 to 7.12 for Cr, 2.25 to 4.20 for Ni, 4.39 to 10.34 for Cu, 1.05 to 1.81 for Zn, 46.83 to 71.97 for As, 25.73 to 67.13 for Cd, and 13.58 to 27.32 for Pb. The potential risk of each trace metal element is ranked as $As > Cd > Pb > Cu > Cr > Ni > Zn$ (in descending order). The values are < 40 , except for As and Cd, which represents a low ecological risk for the pond. RI values range from 103.79 to 168.85 (average of 141.85), with $RI < 150$ in 12 sampling points (~48%) and $150 < RI < 300$ in 13 points (~52%), indicating that most of the study area faces a low to moderately low ecological threat regarding trace metal pollution.

CONCLUSIONS

In this article, we present a qualitative and quantitative study on the current state of surface sediments in Pond Thomas and its potential contamination by trace metal elements.

The geochemical and statistical analysis allows us to draw the following conclusions:

- TMEs in the study area primarily originate from natural sources: terrigenous (runoff) and mineralogical (inclusion); except for copper, which likely comes from a local anthropogenic source related to watershed development activities and agriculture.
- The concentrations of TMEs relative to geochemical backgrounds reveal significant enrichments, ranging from two to seven times the values of the local geochemical background for chromium, copper, lead, cadmium, zinc, and arsenic.
- This study has provided a reliable initial diagnosis of metal contamination in Pond Thomas. The results also revealed the existence of a diffuse source of sediment enrichment, with an enrichment order of TMEs in surface sediments as follows: $As > Pb > Cr > Cd > Zn > Cu > Ni$.

- The majority of the study area faces a low to moderately low threat due to trace metal pollution, with arsenic and cadmium identified as the main pollutants. In the future, it will be essential to closely monitor these two elements as they may pose risks to ecology and the environment.

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