Open Journal of Soil Science, 2025, 15(1), 43-69
https://www.scirp.org/journal/ojss
ISSN Online: 2162-5379
ISSN Print: 2162-5360

Sediment Quality Assessment on Bartlett Pond in Laredo, Southern Texas, USA

Maya P. Bhatt[1]*, Ganesh B. Malla[2], Amede Rubio[1], Alfred Addo-Mensah[1]

[1]Department of Biology and Chemistry, Texas A&M International University, University Boulevard, Laredo, Texas, USA
[2]Departjment of Mathematics, Computer, Geology and Physics, University of Cincinnati-Clermont, College Clermont Drive, Batavia, OH, USA
Email: *maya.bhatt@tamiu.edu

How to cite this paper: Bhatt, M.P., Malla, G.B., Rubio, A. and Addo-Mensah, A. (2025) Sediment Quality Assessment on Bartlett Pond in Laredo, Southern Texas, USA. *Open Journal of Soil Science*, **15**, 43-69.
https://doi.org/10.4236/ojss.2025.151003

Received: December 3, 2024
Accepted: January 12, 2025
Published: January 15, 2025

Abstract

This study evaluates the dynamics of trace metals impacts on the ecosystems of the Bartlett Pond, a small shallow wetland pond located in Laredo, Texas by analyzing sediment samples taken from four quadrants of the pond. The concentrations of trace elements in sediment samples are highest for iron (Fe), followed by chromium (Cr), then lead (Pb), with lower concentration of antimony (Sb), cobalt (Co), arsenic (As), cadmium (Cd), and the lowest concentration being thallium (Tl) within Bartlett Pond. The sediment quality of the pond is acceptable for organisms and the environment as trace element concentrations (e.g. As, Cd, Cr, and Pb) are within the probable effect concentration (PEC) of National Ocean and Atmospheric Administration (NOAA) guidelines although the PEC values for Co, Fe, Sb and Tl are not given. Bivariate and multivariate correlation analysis shows that most trace elements exhibit a strong positive correlation among them indicating the same anthropogenic sources and biogeochemical processes control these trace elements concentrations within the pond. We provided a comprehensive snapshot of trace element concentrations in sediments through descriptive analysis, laying the foundation for future environmental risk assessments. Correlation analysis of eight trace elements helped identify relationships, offering insights into pollution sources and potential health impacts. Additionally, univariate and multivariate predictive analyses generated numerous models, extending beyond the interpretation of partial and full regression coefficients. We also included graphical analyses of trace element variations, which are critical for understanding environmental processes and geochemical patterns. These findings advance our understanding about trace metals dynamics in sediments and may be a valuable reference for ecosystems and environmental management of different landscapes.

Keywords

Trace Elements, Sediment, Wetlands, Bartlett Pond, Ecosystem Ecology

1. Introduction

Monitoring environmental conditions primarily in terrestrial and aquatic ecosystems is crucial for human health and prosperity, the health of other organisms residing in those ecosystems, and for the conservation of environment and ecosystems ecology of any biome on the earth. Human activities including land use changes are directly linked with the higher levels of sediment and chemical contaminants through urban runoff. As a result, aquatic ecosystems in urban areas are seriously threatened [1]-[7]. Approximately half of the wetlands in the United States have been lost, with the primary cause being development and agricultural drainage practices as documented by Cunningham and Cunningham, 2021 [8]. The decrease in wetland cover or the conversion of wetlands to other land uses is primarily driven by population growth, urban development, and agricultural expansion in recent years. Human activities over the past few decades have contributed to global challenges such as water scarcity and food insecurity. The loss of wetlands in the area may result in various environmental consequences, including loss of habitat for numerous species, decreased water quantity and degraded water quality, lowered water table levels and increased concentrations of chemicals including contaminants, increased frequency of erosion and flooding in the region, decline in bird diversity, with no migratory birds observed in the region and rising regional temperatures. These impacts highlight the critical importance of preserving wetland ecosystems [7]-[11].

Runoffs from roads and urban centers carry out tremendous amount of various pollutants such as salts, trace metals, polycyclic aromatic hydrocarbons (PAHs) which are very toxic to aquatic organisms [7] [12]-[17]. Various factors contribute to the type and quantity of pollutants in stormwater runoff. These include household hazardous wastes such as pesticides, cleaning agents, insecticides, and paints from urban centers; oils and grease from gas stations and parking lots; industrial wastes; sediments carrying pollutants from construction sites; organic matter, nutrients, and trace metals from business complexes; nutrients, organic matter, and pesticides from agricultural fields; and microorganisms from urban wastewater. These pollutants accumulate in nearby ponds, lakes, and stream ecosystems. The accumulation of various chemicals in aquatic ecosystems alters their natural biogeochemical dynamics.

There are various studies reported about trace element contaminants in surface and groundwater [18]-[23] but the studies about trace elements dynamics in sediment are lacking [2] [18] [24]-[26], particularly in Southern Texas region. The study of trace elements in sediments is essential to understand the ecotoxicological impacts in any landscape as the sediments act as a natural sink for numerous types of contaminants including trace metals and plays a role for metals transformation [25]. The high concentration of trace elements primarily appeared human altered landscape such as mining sites with acidic condition [18] [27]. The mining process provides significant economic opportunities, but it also generates challenges and risks to human health, other organisms, ecosystems, and the environment [27]-[30]. Various mining activities have taken place in Texas, including gold mining in central Texas during the 19th century, coal mining from the 1800s to the 1930s, and, more recently, hydraulic fracturing ("fracking") due to advancements in oil and gas extraction techniques [31] [32]. All these activities contribute to water contamination [28] [31] [32]. Additionally, fly ash from coal power plants contains high levels of radioactive elements, resulting in more radiation than nuclear waste [33].

Microorganisms such as phytoplankton and zooplankton consume contaminants including trace metals from contaminated water/sediments and bioaccumulate them. These contaminants will biomagnify as they enter the food chain posing serious threat to the environment, ecology, wildlife and humans [7] [34]-[37] and especially the top predatory species appeared to be the most seriously affected organism in the environment [37]. For example, pollutants accumulation in phytoplankton is up to 5000, and up to 50,000 in zooplankton, up to 500,000 in small fish, and up to 50 million times higher in large fish or top predator than the pollutant concentration in water itself [37] and they have numerous effects on organisms including direct toxic impacts and long term various effects such as carcinogenic, reproductive disorders, reduced growth, and neurological disorders to humans or other life-forms [1] [7] [8] [38] [39] and damage deoxyribonucleic acid (DNA), changes in species abundances, increased mortality and ultimately affecting the whole ecosystems ecology [16]. Coastal oceans currently receive millions of tons of heavy metals due to direct discharge from municipal wastewater and industries without treatment based on the documented report of Mateo-Sagasta *et al.* (2017) [40].

About 70% of heavy metal contamination comes from e-waste, and batteries make up another 10% to 20% [8]. According to United Nations Environment Programme (UNEP) about 2.1 billion tons of solid waste generated by municipality worldwide in 2023 to 3.8 billion tons by 2050 and global direct cost for waste management was estimated at US$252 billion and including all hidden caused related to this will cost US$361 billon [41]. The world count estimated about 400 million tons of hazardous waste generated each year on the earth which causes substantial harms to humans and the environment, and these wastes are found everywhere and have contaminated every single ecosystem on the earth [42]. Plants can absorb, concentrate, or even decompose toxic contaminants in soil/sediment and groundwater, so that phytoremediation is considered as a main process to control contaminants in the environment and various types of microbes also concentrate metals or change the metals to less toxic forms in some environment [2] [8] [25] [43] [44].

The Bartlett Pond is situated within the Jovita Idar's El Progreso Park complex in East Central Laredo in Texas which is about 12 km north-east of Laredo city center [7]. Soil in the pond is classified as hydric soil type whereas the surrounding area is Copita Soil Series [45] which is well drained fine sandy loam that is moderately alkaline at a pH of 8.2. Hydraulic soils form in response to prolonged saturation, are rich in organic matter, and develop anaerobic conditions in the upper layers, which support the growth of hydrophytic vegetation [46] [47]. Under anoxic conditions, redox reactions significantly influence the dynamics of trace metals.

The authors hope to gain valuable insights by analyzing trace elements in sediment samples into the long-term exposure risks that these trace elements pose risk to organisms, wildlife, and even humans who may rely on these ecosystems for recreation, drinking water, or food sources from contaminated ecosystems. Moreover, sediments provide historical records of environmental contamination, enabling scientists to trace pollution sources, deposition, transport mechanisms, bioavailability, environmental processes, understand changes in water quality over time, and assess the effectiveness of pollution control measures [48]-[50]. Overall, sediment analysis provides a comprehensive tool for protecting biodiversity, safeguarding the whole ecosystems ecology of any landscape. Sediment quality from aquatic ecosystem has not been well understood in the region although there are some documented studies about the water quality [7] [51] [52]. The main objective of this study was to investigate the concentration and sources of trace elements in pond sediments which are responsible for changing the ecosystems ecology of the Bartlett Pond.

2. Study Area

This research was conducted in the Bartlett Pond, an urban retention pond situated within the Jovita Idar's El Progreso Park complex in East Central Laredo, TX (27.554722˚N 99.473889˚W) in Southern Texas (**Figure 1**). Historically, this pond served as a drainage basin for the Upper Zacate Creek system, which is one of the three major tributaries of the Rio Grande at Laredo, Texas. The pond has an area of nearly three hectares, is located about 12 km north-east of Downtown Laredo and its maximum depth is about 4.26 m [7]. Today, the pond is used recreationally as a place for catch and release fishing and non-motorized boating. Additionally, the pond acts as a catchment and pour point of run-off from residential and commercial buildings including the Laredo International Airport and which are potential sources of nonpoint pollution. The City of Laredo Parks and Recreation maintains both the park and pond. Bartlett Pond, which is the second largest pond within Laredo after Lake Casa Blanca is a habitat of many plants including algae and some flowering plants [7]. The site is also a habitat for many animal species including several migratory bird species especially in winter season [10]. Laredo, Texas is situated on the Mexico border with an elevation of about 127.41 m asl and an area about 265.7 km^2 with a large area surrounded by forest.

Rio Grande is the major river system in the area within Laredo, but its water neither enters Bartlett Pond nor in Lake Casa Blanca since the river flows about 14 km south from the pond [7]. Annual average rainfall is 500 mm, and the mean annual temperature is 23.5˚C. The average temperature ranges between 8.9˚C in December and 31.7˚C in August in the Laredo and August is the hottest month of the year with a minimum of 25.2˚C to maximum of 38.2˚C [53].

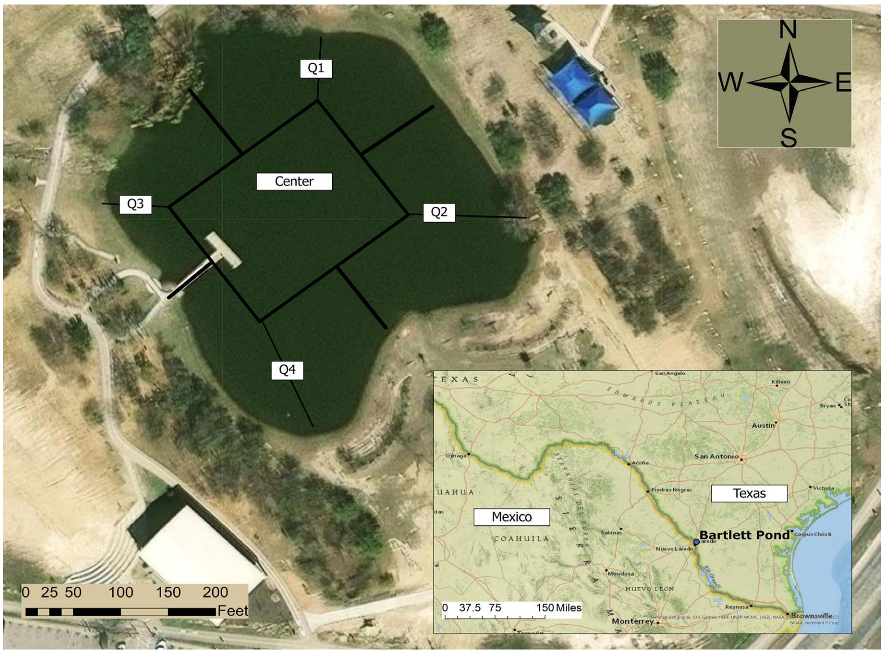

Figure 1. Locations of Bartlett Pond in Laredo, Southern Texas with four quadrants in which 23 samples were collected from quadrant 1 (Q1), 20 from quadrant 2 (Q2) and 24 samples collected from each quadrant 3 and 4 (Q3 and Q4), n = 91.

3. Materials and Methods

3.1. Sample Collection

Bartlett Pond was divided into four quadrants: quadrant-I (Q1), quadrant-II (Q2), quadrant-III (Q3) and quadrant-IV (Q4) and each quadrant had 24 sampling points as in Figure 1 but we collected 23 sediment samples from quadrant 1 and 20 sediment samples from quadrant 2 and 24 sediment samples from each quadrant 3 and 4 based on the site specific condition. With a total of 91 sediment samples were collected from four quadrants of the pond during summer 2018 (**Figure 1**). There are two main inlet points in the pond; one at Q2 (quadrant II), where the surface runoff enters into the pond through the pipe, and the other at Q3 (quadrant III) where more urban surface runoff enters into the pond [7]. Samples were taken in polyethylene bags and later dried and refrigerated at the laboratory of Texas A&M International University (TAMIU) until analysis for trace elements (Fe, Sb, Pb, As, Co, Tl, Cr, Cd).

3.2. Analytical Methods

Acid digestion of trace metals in sediment was done with a CEM MARS 6 Microwave Digestion System (CEM Corporation, Matthews, North Carolina, United States). Trace metal analysis was done with an Agilent ICP-OES 720 Inductively coupled plasma—optical emission spectrometer (Agilent Technologies, Santa Clara, California, United State). Exactly 0.500 g of dried powdered sediment sample was weighed into Teflon digestion vessels, 10 mL of acid mixture (7:3 HNO_3/HF) and digested using EPA method 3051 on the microwave digester. The digested sample was emptied into a 50 mL volumetric flask, diluted to the mark with Milli-Q water and filtered into a sample container through a 0.45 μm polycarbonate filter and analyzed by Inductively Coupled Plasma—Optical Emission Spectrometer (ICP-OES) for metal concentrations against a standard calibration curve by following US EPA 3015A method [54]. Replicate samples, standard reference material (SRM), field blanks and laboratory spikes were treated in the same way.

3.3. Quality Control

The accuracy of the instrument was checked by triplicate analysis of the same samples. Method blanks, spike recovery, and Certified reference material (CRM, CRM015-Sediment 2) analysis were also employed. CRM015-Sediment 2 from Sigma-Aldrich, and SRM 1566b oyster tissue from NIST were analyzed in the same way as the fish to check the accuracy of analysis [7]. The analytical values were within the range of certified values and the overall average recovery of trace metals in standard substances was between 88% and 105%.

3.4. Statistical Tool for Data Analysis

We utilized the statistical tool, Version 30.0.0 (241) of IBM SPSS Statistics software for conducting our analyses. Our analytical approach centered around three primary programs within the software:

1) *Analyze* > *Compare Means*: This module was instrumental in conducting comparisons of means across different groups or conditions, providing valuable insights into the variations and trends within our dataset.

2) *Analysis* > *Correlate* > *Bivariate*: Through this tool, we explored the relationships between pairs of variables, allowing us to assess the strength and direction of associations within our data.

3) *Analyze* > *Regression* > *Linear*: Utilizing this program, we conducted linear regression analyses to model the relationships between one or more predictor variables and a dependent variable of interest, facilitating a deeper understanding of the underlying patterns and predictive factors within our dataset.

4. Results and Discussion

4.1. Spatial Variations in Trace Elements

The concentrations of trace elements in sediments samples were found in the following order: Fe >> Cr > Pb > Sb > Co >> As >> Cd > Tl within Bartlett Pond. Variation pattern of average concentrations with standard deviations of measured trace elements (As, Cd, Co, Cr, Fe, Pb, Sb, and Tl) from quadrant 1 (Q_1) (n = 23), quadrant 2 (Q_2) (n = 20) and quadrant 3 and 4 (Q_3 & Q_4) each n = 24 is presented in **Table 1**. The measured arsenic (As) concentration varies from 0 to 14.8 mg/kg with mean value of 7.68 ± 2.86 mg/kg (n = 91). Quadrants 1, 2, and 4 moderately polluted while quadrant 3 heavily polluted based on the arsenic concentrations in sediment according to EPA sediment guidelines [26]. Cadmium (Cd) concentration varies from 0.14 to 7.3 mg/kg with mean value of 1.45 ± 1.85 mg/kg (n = 91). Quadrants 2, 3, and 4 moderately polluted with cadmium while quadrant 1 appeared heavily polluted based on the EPA sediment guidelines (Onjefu *et al.* 2020) [26]. Cobalt (Co) concentration varies from 2.9 to 14.3 mg/kg with mean value of 7.77 ± 2.34 mg/kg (n = 91). Chromium (Cr) concentration varies from 9.3 to 45.2 mg/kg with mean value of 23.26 ± 6.46 mg/kg (n = 91). Chromium concentration in sediments appeared less pollution to moderate pollution according to EPA guidelines [26]. Iron (Fe) concentration varies from 4587 to 21935 mg/kg with mean value of 12,075 ± 3197 mg/kg (n = 91). Lead (Pb) concentration varies from 9.9 to 50.1 mg/kg with mean value of 22.83 ± 6.53 mg/kg (n = 91). Lead concentration appeared highest at quadrant 4 with moderate pollution and among all sediments samples pollution level of lead is less pollution to moderate pollution according to EPA guidelines [26]. Antimony (Sb) concentration varies from 3.8 to 20.1 mg/kg with mean value of 9.95 ± 3.70 mg/kg (n = 91). Thallium (Tl) concentration varies from 0 to 8.4 mg/kg with mean value of 1.39 ± 1.70 mg/kg (n = 91). The higher concentration of most of the measured trace metals such as (As, Cd, Sb and Fe) appeared at the quadrant (Q_3) site close to the main inlet point of the pond and lead (Pb) and thallium (Tl) appeared higher at the quant close to (Q_4) site.

Table 1. Average trace element concentrations in sediment samples of different sections of Bartlett Pond within Laredo, Southern Texas during summer 2018. All values are in mg/kg. The standard deviations were calculated using n = 21 for Q_1, n = 20 for Q_2, and n = 24 for each Q_3 and Q_4 quadrants.

Trace Elements	Quadrant I	Quadrant II	Quadrant III	Quadrant IV	*TEC	*PEC
As ($mg\cdot kg^{-1}$)	5.72 ± 3.06	7.19 ± 2.50	9.74 ± 2.23	7.92 ± 2.12	9.79	33
Cd ($mg\cdot kg^{-1}$)	1.47 ± 2.34	1.43 ± 1.82	1.39 ± 1.67	1.51 ± 1.60	0.99	4.98
Co ($mg\cdot kg^{-1}$)	6.44 ± 1.60	7.35 ± 2.08	9.34 ± 2.68	7.82 ± 1.91	nd	nd
Cr ($mg\cdot kg^{-1}$)	23.30 ± 8.54	23.41 ± 4.73	23.27 ± 6.87	23.08 ± 5.27	43.4	111
Fe ($mg\cdot kg^{-1}$)	10,238 ± 2802	12,821 ± 1895	13,726 ± 4217	11,562 ± 2183	nd	nd
Pb ($mg\cdot kg^{-1}$)	19.77 ± 4.80	22.62 ± 3.22	24.49 ± 5.76	24.26 ± 9.42	35.8	128
Sb ($mg\cdot kg^{-1}$)	7.23 ± 2.35	9.38 ± 2.98	12.73 ± 6.67	10.24 ± 3.41	nd	nd
Tl ($mg\cdot kg^{-1}$)	1.07 ± 0.99	0.55 ± 0.95	1.76 ± 2.27	2.01 ± 1.79	nd	nd

*TEC (threshold effect concentration) and *PEC (probable effect concentration) data from NOAA Guidelines [24].

4.2. Descriptive Analysis of the Trace Element Concentrations in Sediments: Environmental Implications

The trace element concentrations in sediment samples were analyzed, and the descriptive statistics for eight elements (As, Cd, Co, Cr, Fe, Pb, Sb, and Tl) are summarized in Table 2. The mean concentrations of arsenic (As) and cadmium (Cd) were 7.68 mg/kg and 1.45 mg/kg, respectively, both falling below their Probable Effect Concentrations (PEC), indicating a lower likelihood of harmful ecological effects. However, the chromium (Cr) mean concentration of 23.26 mg/kg is significantly below the TEC of 43.4 mg/kg, suggesting no immediate concern for sediment toxicity.

Table 2. Trace element concentrations in sediments: environmental implications.

Element	Mean (mg/kg)	St. Error	Median (mg/kg)	St. Deviation	Min (mg/kg)	Max (mg/kg)	*TEC (mg/kg)	*PEC (mg/kg)
As	7.68	0.30	7.19	2.86	0.00	14.88	9.79	33.0
Cd	1.45	0.19	0.51	1.85	0.14	7.29	0.99	4.98
Co	7.77	0.24	7.43	2.34	2.87	15.11	-	-
Cr	23.26	0.68	22.50	6.46	9.30	45.17	43.4	111.0
Fe	12074.89	335.17	11707.97	3197.34	4587.41	21934.63	-	-
Pb	22.83	0.68	21.93	6.53	9.89	50.01	35.8	128.0
Sb	9.95	0.39	9.73	3.70	3.88	20.03	-	-
Tl	1.39	0.18	0.82	1.70	0.00	8.38	-	-

*TEC and *PEC data from NOAA Guidelines [24].

Lead (Pb) had a mean value of 22.83 mg/kg, also below the TEC of 35.8 mg/kg, while iron (Fe), showed a wide concentration range, with a mean of 12,074.89 mg/kg. Permissible specific regulatory guidelines for iron concentration are not established by international agencies such as WHO, US EPA, or NOAA. Iron is the most dominant trace element found in the sediment samples of Bartlett Pond, indicating a high likelihood of significant iron intake by aquatic organisms within the pond ecosystem. Iron also interacts with micronutrients and toxic elements [55].

Excessive iron intake can interfere with the utilization of other essential trace elements across various species. For instance, increased ascorbate intake becomes more effective in the presence of high iron levels [55]. Additionally, cadmium absorption can triple in individuals with normal blood hemoglobin but low serum ferritin due to mild iron deficiency, and lead absorption also increases under similar conditions [55]. Low iron status in humans has been linked to elevated concentrations of toxic trace elements [55]. Experimental studies on animals have shown that low dietary iron levels lead to higher absorption and retention of cadmium, cobalt, manganese, and zinc [56].

High concentration of these elements in water samples were reported earlier from this pond due to anthropogenic activities in the region and consequently fish tissue accumulated much higher concentration due to bioaccumulation posing serious threat to humans through food web [7]. High accumulation of lead was found in urban soils and lake-river sediments due to anthropogenic activities [49] [57]. High lead concentration in sediments affects overlying water quality because of release of labile lead from sediment and bioaccumulate in fish which ultimately affects human health [7] [49] [58]-[60]. WHO (2017) [61] standard guideline value of lead concentration in water is less than 10 μg/L and several-folds higher concentration of lead in pond water than standard guideline makes the water unsuitable for consumption [7]. Elements such as cobalt (Co), antimony (Sb), and thallium (Tl), for which there are no established PEC or TEC limits, showed mean values of 7.77 mg/kg, 9.95 mg/kg, and 1.39 mg/kg, respectively. While these elements do not have specific sediment quality guidelines, their concentrations are provided to support further ecological assessment. The variability, indicated by standard deviations and ranges, suggests some spatial or environmental influences on element deposition in the study area.

The dataset offers a comprehensive snapshot of the trace element concentrations in the sediments and provides a foundation for further environmental risk assessments, especially for elements with regulatory thresholds. Protection and restoration of soil-sediment ecosystems from contaminated heavy metals need to characterization and remediation such as immobilization, soil-sediment washing, and phytoremediation techniques [62]-[65], by effective electrokinetic technology using reactive filter media [66] and nano silica mediated remediation strategies observed to be the effective solution for environmental restoration and protection of ecosystems [67].

4.3. The Predictive and Correlation Analyses

The correlation analysis of all eight trace elements is presented in **Table 3**. This correlation analysis is crucial as it helps identify relationships between different trace elements, which can provide insights into environmental pollution sources and their potential health impacts. Understanding these correlations can guide effective monitoring and remediation strategies.

Arsenic (As) shows a strong positive correlation with Cobalt (Co) (0.708) and Antimony (Sb) (0.536), indicating that as the concentration of Arsenic increases, the concentrations of Cobalt and Antimony also tend to increase. Cadmium (Cd) has a moderate positive correlation with Cobalt (Co) (0.397) and Thallium (Tl) (0.317), suggesting a tendency for these elements to increase together. Cobalt (Co) is positively correlated with several elements, including Chromium (Cr) (0.569), Iron (Fe) (0.601), Lead (Pb) (0.530), and Antimony (Sb) (0.690). This indicates that higher levels of Cobalt are associated with higher levels of these elements. Chromium (Cr) shows a strong positive correlation with Iron (Fe) (0.726) and a moderate correlation with Lead (Pb) (0.545), suggesting that these elements often occur together in higher concentrations. Iron (Fe) is positively correlated with Lead (Pb) (0.604), indicating a tendency for these elements to increase together. Lead (Pb) has moderate positive correlations with Cobalt (Co) (0.530) and Chromium (Cr) (0.545), suggesting a relationship between these elements. Antimony (Sb) shows a strong positive correlation with Thallium (Tl) (0.624), indicating that these elements tend to increase together. Thallium (Tl) has moderate positive correlations with Cadmium (Cd) (0.317) and Antimony (Sb) (0.624), suggesting a relationship between these elements. Their correlation analysis was stronger among the trace elements in water samples from the same pond suggesting release of these pollutants from sediment into surface water but the accumulation rate of trace elements in sediment looked different [7]. Anaerobic sediments from streams, ponds and lakes, and marine preserve more pollutants than aerobic sediments [68] [69]. The change in trace metal dynamics in sediments are affected by several factors such as hydrodynamic factors, physico-chemical processes such as sorption, redox conditions, and microbial transformation and hence accurate evaluation is especially important for the assessment of environment [50].

Table 3. The correlation analysis of trace elements.

	As	Cd	Co	Cr	Fe	Pb	Sb	Tl
As	1.000							
Cd	0.343	1.000						
Co	0.708*	0.397	1.000					
Cr	0.309	0.082	0.569**	1.000				
Fe	0.500**	−0.029	0.601	0.726*	1.000			
Pb	0.342	−0.012	0.530	0.545**	0.604**	1.000		
Sb	0.536	0.302	0.690*	0.050	0.257	0.330	1.000	
Tl	0.230	0.317	0.308	−0.039	−0.028	0.038	0.624*	1.000

The correlations marked with * are significant at the 1% level, and those marked with ** are significant at the 5% level.

4.3.1. The Univariate and Multiple Predictive Analyses of Arsenic in Relation to Other Trace Elements

There are strong correlations between arsenic and other trace elements, allowing us to develop predictive models for arsenic levels in conjunction with these elements. Figure 2 illustrates the regression analysis of the relationship between arsenic and cobalt. The model is represented by the equation $\widehat{As} = 0.87\ \text{Co} + 0.94$, with an R-squared value of 0.5012, indicating its effectiveness in forecasting arsenic levels based on cobalt concentrations. Specifically, a 1 mg/kg increase in cobalt in sediment results in a 0.87 mg/kg increase in arsenic levels within the same sediment.

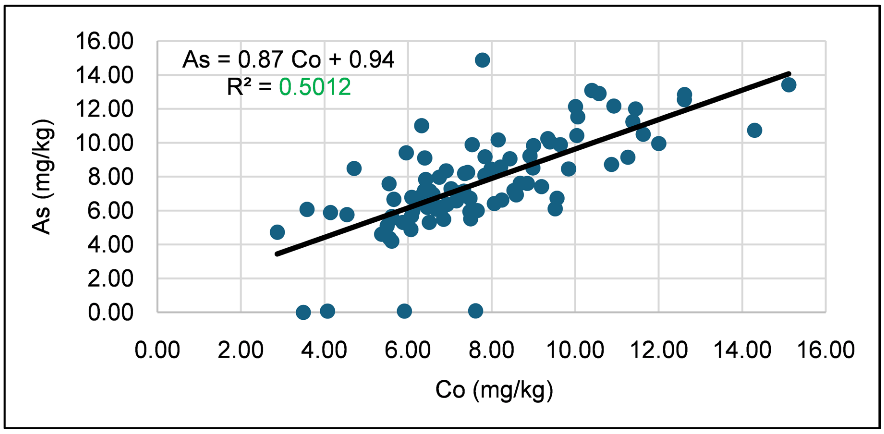

Figure 2. The bivariate distribution of arsenic and cobalt.

We have developed a predictive model for arsenic based on its significant correlation with iron (Fe), as shown in Table 3. However, its practical utility is limited due to a low R^2 value of just 0.25. To derive the multivariate model (Model # 3) in Table 4, all seven remaining trace elements were treated as independent variables and applied the Backward Elimination Regression method. The resulting model demonstrates high significance ($F = 35.868$, $df = (3, 87)$, $p < 0.001$) with an R-squared value of 0.553, signifying its practical utility.

Table 4. Predictive models for estimating arsenic.

Model #	Independent variable(s)	Predictive Model	R^2 value
1	Co	$\widehat{As} = 0.87\text{ Co} + 0.94$	0.501
2	Fe	$\widehat{As} = 0.0004\text{ Fe} + 2.28$	0.250
3	Co, Cr, & Fe	$\widehat{As} = 0.86\text{ Co} - 0.14\text{ Cr} + 0.0001\text{ Fe} + 0.916$	0.553

4.3.2. The Univariate and Multiple Regression Analyses of Cadmium in Relation to Other Trace Elements

Cadmium shows no strong correlation with any trace elements, and as a result, we have not developed predictive models for cadmium in relation to elements like As, Co, Cr, Fe, Pb, Sb, and Tl.

4.3.3. The Univariate and Multiple Regression Analyses of Cobalt in Relation to Other Trace Elements

A predictive model was developed for cobalt since it demonstrated a strong relationship with Sb and Cr. In Figure 3, the regression analysis demonstrates the relationship between cobalt and antimony. The regression model, expressed as $\widehat{Co} = 0.44\text{ Sb} + 3.44$ with an R-squared value of 0.4756, indicates the model's effectiveness in predicting cobalt levels based on known antimony concentrations. The regression coefficient of 0.44 implies that a 1 mg/kg increase in antimony in sediment corresponds to a 0.44 mg/kg increase in cobalt levels within the same sediment sample. Similarly, a predictive model for cobalt with another measured trace element chromium is detailed in Table 4.

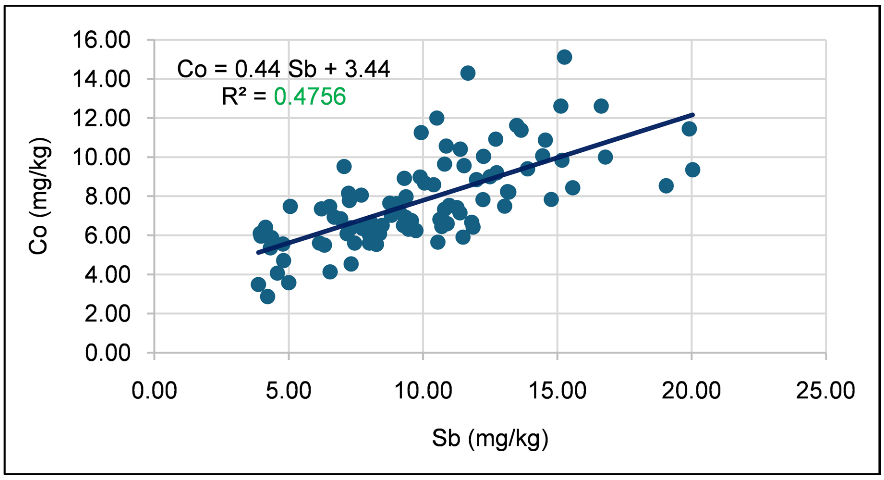

Figure 3. The bivariate distribution of cobalt and antimony.

To determine the multivariate model (Model # 6) in Table 5, all seven remaining trace elements were utilized as independent variables and applied the Backward Elimination Regression method. The resulting model demonstrates high significance (F = 89.738, df = (5, 85), p < 0.001) with an R-squared value of 0.841, signifying its substantial practical utility.

Table 5. Predictive models for estimating cobalt.

Model #	Independent variable(s)	Predictive Model	R^2 value
4	Cr	$\widehat{Co} = 0.92\ Cr + 20.44$	0.982
5	Sb	$\widehat{Co} = 0.44\ Sb + 3.44$	0.475
6	As, Cd, Cr, Sb, & Tl	$\widehat{Co} = 0.20\ As + 0.19\ Cd + 0.16\ Cr + 0.37\ Sb - 0.19\ Tl - 1.16$	0.841

4.3.4. The Univariate and Multiple Regression Analyses of Chromium in Relation to Other Trace Elements

The relationship between chromium and various trace elements has been widely studied, resulting in the development of predictive models. Among these, the only significant relationships involving chromium are with the trace elements iron (Fe) and lead (Pb). Figure 4 presents the predictive model linking chromium to iron, expressed as $\widehat{Cr} = 0.0015\ Fe + 5.55$ with an R-squared value of 0.5276. This model reliably predicts chromium levels based on iron concentrations. Specifically, for every 1 mg/kg increase in iron in sediment, chromium levels increase by 0.0015 mg/kg in the same sample.

Similarly, we have established a predictive model for chromium with another measured trace element lead detailed in Table 6.

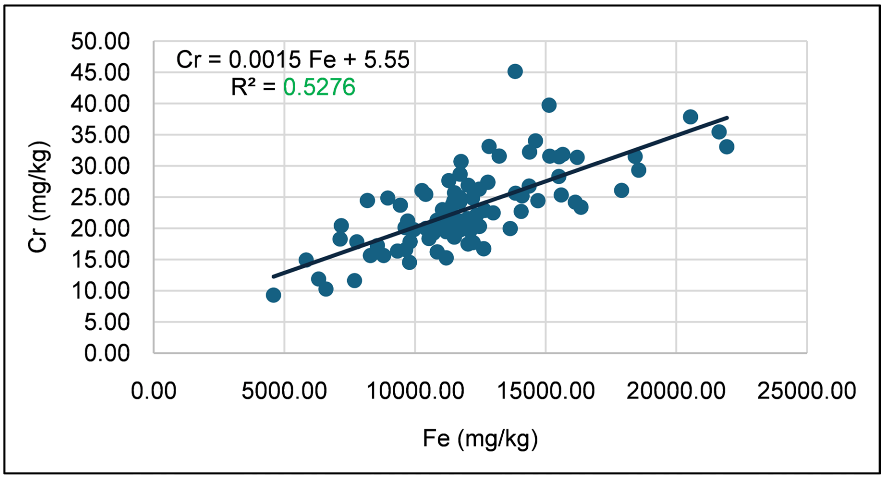

Figure 4. The bivariate distribution of chromium and iron.

Table 6. Predictive models for estimating chromium.

Model #	Independent variable(s)	Predictive Model	R^2 value
7	Fe	$\widehat{Cr} = 0.0015\ Fe + 5.55$	0.527
8	Pb	$\widehat{Cr} = 0.54\ Pb + 10.96$	0.300
9	As, Co, Fe, Pb, Sb, & Tl	$\widehat{Cr} = -0.44\ As + 2.01\ Co + 0.001\ Fe$ $+ 0.15\ Pb - 1.10\ Sb + 0.69\ Tl + 6.32$	0.733

The multivariate model (Model # 9) in Table 6, was developed by utilizing all seven remaining trace elements as independent variables and applied the Backward Elimination Regression method. The resulting model demonstrates high significance ($F = 38.364$, $df = (6, 84)$, $p < 0.001$) with an R-squared value of 0.733, signifying its substantial practical utility.

4.3.5. The Univariate and Multiple Regression Analyses of Iron in Relation to Other Trace Elements

Iron displays a statistically significant relationship with only two trace elements, chromium and arsenic, in sediment samples. In Figure 5, we present a predictive model for iron in relation to the trace element chromium. The regression analysis model for iron with respect to chromium is represented as follows: $\widehat{Fe} = 359.64\ Cr + 3710.1$, with an R-squared value of 0.5276. This suggests the model's effectiveness in predicting iron levels based on known chromium concentrations. The regression coefficient of 359.64 indicates that a 1 mg/kg increase in chromium in sediment results in a 359.64 mg/kg increase in iron levels within the same sediment sample.

Additionally, we have established a predictive model for iron with another measured trace element arsenic detailed in Table 7.

To determine the multivariate model (Model # 12) in Table 7, we began by using all remaining trace elements as independent variables and employed the

Backward Elimination Regression method. The resulting model demonstrates high significance (F = 44.914, df = (4, 86), $p < 0.001$) with an R-squared value of 0.676, signifying its substantial utility for practical applications.

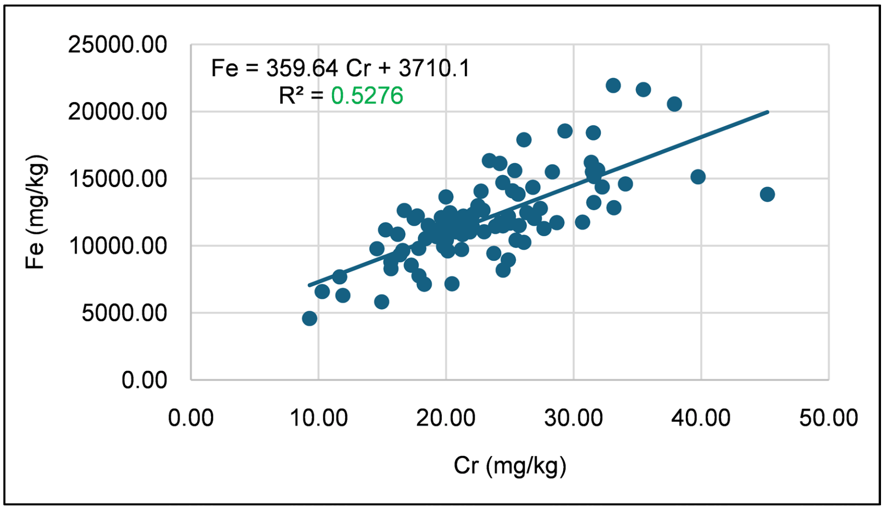

Figure 5. The bivariate distribution of iron and chromium.

Table 7. Predictive models for estimating iron.

Model #	Independent variable(s)	Predictive Model	R^2 value
10	As	$\widehat{Fe} = 558.26\ As + 7785.1$	0.250
11	Cr	$\widehat{Fe} = 359.64\ Cr + 3710.1$	0.527
12	As, Cr, Cd & Pb	$\widehat{Fe} = 369.55\ As + 262.77\ Cr - 318.05\ Cd + 97.37\ Pb + 1362.91$	0.676

4.3.6. The Univariate and Multiple Regression Analyses of Lead in Relation to Other Trace Elements

Lead shows a statistically significant relationship with only iron and chromium among all trace elements. We developed predictive models for lead based on these two elements. Figure 6 presents the regression analysis for lead and iron: $\widehat{Pb} = 0.0012\ Fe + 7.94$, with an R-squared value of 0.3643. This indicates the model's usefulness in predicting lead levels from iron concentrations. The coefficient of 0.0012 suggests that a 1 mg/kg increase in iron leads to a 0.0012 mg/kg rise in lead in sediment samples.

Similarly, we have established a predictive model for lead with another measured trace element chromium, which is presented in Table 8.

To derive the multivariate model (Model # 15) as shown in Table 8, we began the process by utilizing all remaining trace elements as independent variables and employed the Backward Elimination Regression method. The resulting model demonstrates high significance (F = 22.380, df = (3, 87), $p < 0.001$) with an R-squared value of 0.436, indicating its considerable practical utility for applications.

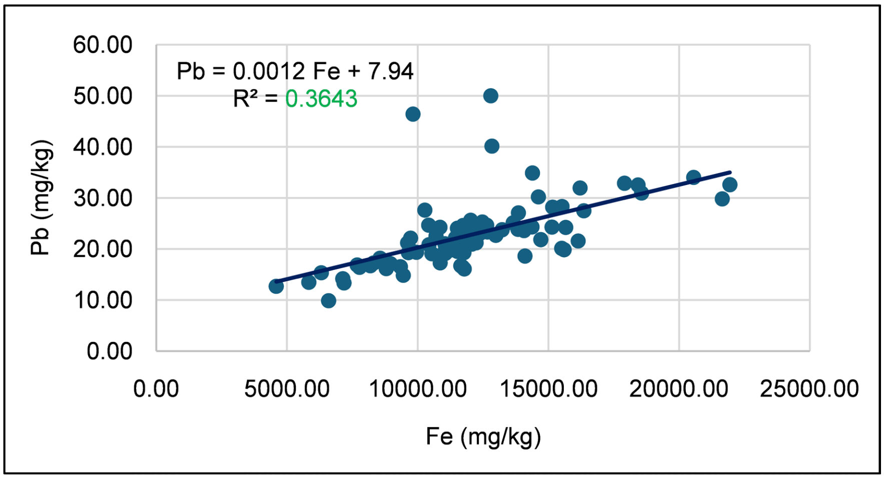

Figure 6. The bivariate distribution of lead and iron.

Table 8. Predictive models for estimating lead.

Model #	Independent variable(s)	Predictive Model	R^2 value
13	Cr	$\widehat{Pb} = 0.55\ \text{Cr} + 10.00$	0.300
14	Fe	$\widehat{Pb} = 0.0012\ \text{Fe} + 7.94$	0.364
15	Cr, Fe, & Sb	$\widehat{Pb} = 0.30\ \text{Cr} + 0.001\ \text{Fe} + 0.41\ \text{Sb} + 3.72$	0.436

4.3.7. The Univariate and Multiple Regression Analyses of Antimony in Relation to Other Trace Elements

Antimony shows a strong correlation with only cobalt among trace elements, and we have developed a predictive model for antimony based on cobalt. Figure 7 presents the regression model: $\widehat{Sb} = 1.09\ \text{Co} + 1.46$, with an R-squared value of 0.4756. This model effectively predicts antimony levels from cobalt concentrations. The coefficient of 1.09 indicates that a 1 mg/kg increase in cobalt leads to a 1.09 mg/kg rise in antimony in sediment samples.

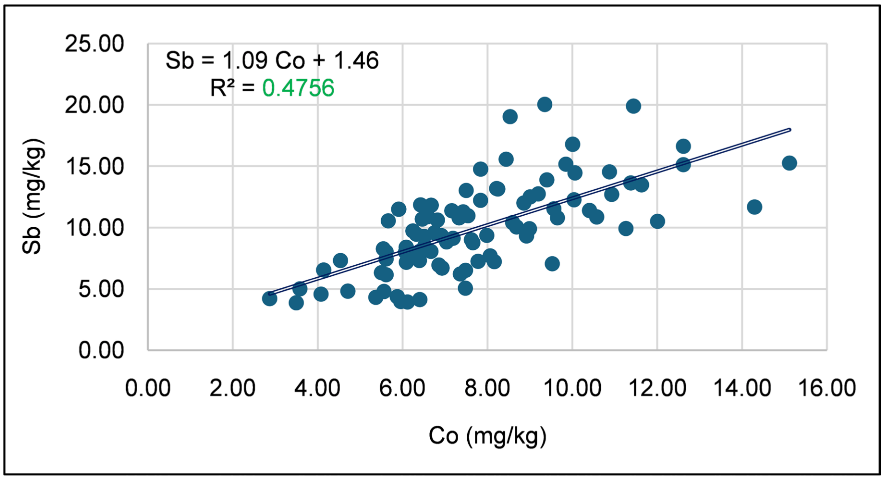

Figure 7. The bivariate distribution of antimony and cobalt.

In order to derive the multivariate model (Model #17) found in **Table 9**, we initiated the process by using remaining trace elements as independent variables and employed the Backward Elimination Regression method. The resulting model demonstrates high significance (F = 74.643, df = (4, 86), $p < 0.001$) with an R-squared value of 0.776, indicating its substantial practical applicability.

Table 9. Predictive models for estimating antimony.

Model #	Independent variable(s)	Predictive Model	R^2 value
16	Co	$\widehat{Sb} = 1.09\text{ Co} + 1.46$	0.475
17	Co, Cr, Pb, & Tl	$\widehat{Sb} = 1.18\text{ Co} - 0.26\text{ Cr} + 0.10\text{ Pb} + 0.81\text{Tl} + 4.51$	0.776

4.3.8. The Univariate and Multiple Regression Analyses of Thallium in Relation to Other Trace Elements

Thallium shows a strong correlation with only antimony among trace elements, and we have developed a predictive model for thallium based on antimony. **Figure 8** presents the regression model: $\widehat{Tl} = 0.29\text{ Sb} - 1.47$, with an R-squared value of 0.3892. This model effectively predicts a thallium level from antimony concentrations. The coefficient of 0.29 indicates that a 1 mg/kg increase in antimony leads to a 0.29 mg/kg rise in thallium in sediment samples.

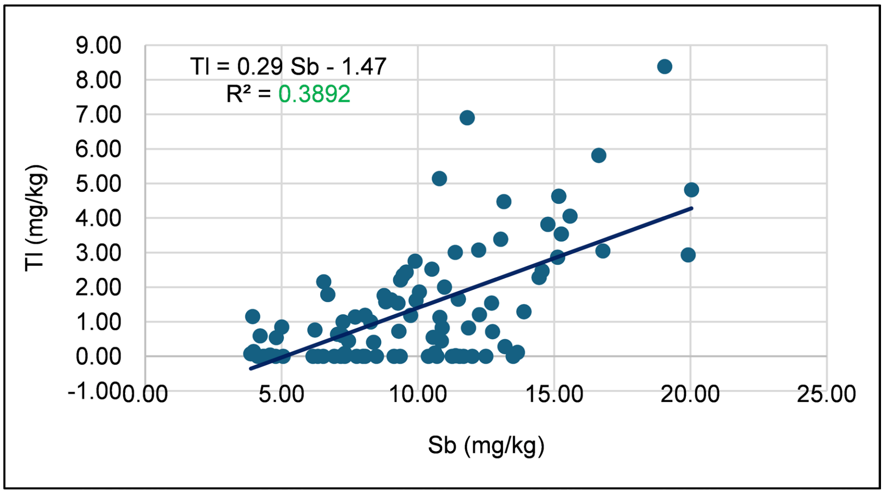

Figure 8. The bivariate distribution of thallium and antimony.

Table 10. Predictive models for estimating thallium.

Model #	Independent variable(s)	Predictive Model	R^2 value
18	Sb	$\widehat{Tl} = 0.56\text{ Sb} - 85.51$	0.556
19	Sb, Cr, Co, Cd, & Fe	$\widehat{Tl} = 0.92\text{ Sb} + 0.08\text{ Cr} - 0.32\text{ Co} + 0.17\text{ Cd} + 0.0001\text{ Fe} - 1.04$	0.486

To determine the multivariate model (Model # 19) in **Table 10**, we began by using the Backward Elimination Regression method, employing all remaining trace elements (Cadmium, Cobalt, Chromium, and Iron) as independent variables. The resulting model shows high significance (F = 16.077, df = (5, 85), $p < 0.001$) with an R-squared value of 0.486. This underscores its considerable practical utility and relevance for applications.

4.4. Graphical Analysis of Trace Element Variations in Sediments

Graphical analysis of trace element variations in sediments is crucial for understanding environmental processes and geochemical patterns. By visually representing the distribution and concentration of trace elements, researchers can identify trends, anomalies, and spatial relationships within sediment layers. The minimum, mean, and the maximum concentrations of measured eight trace metals falling below their Probable Effect Concentrations (PEC) showing a lower likelihood of harmful ecological effects although some sites show moderately polluted based on their concentration, but the pond water quality is unacceptable as the concentrations of these elements appeared exceeding higher than the US EPA (2024) [70] and WHO (2017) [61] standard guidelines. Below, we present histograms for each trace element such as arsenic (**Figure 9**), cadmium (**Figure 10**), cobalt (**Figure 11**), chromium (**Figure 12**), iron (**Figure 13**), lead (**Figure 14**), antimony (**Figure 15**) and thallium (**Figure 16**) with the normal curve superimposed and the mean and standard deviation are provided in the top-right corner of the figures.

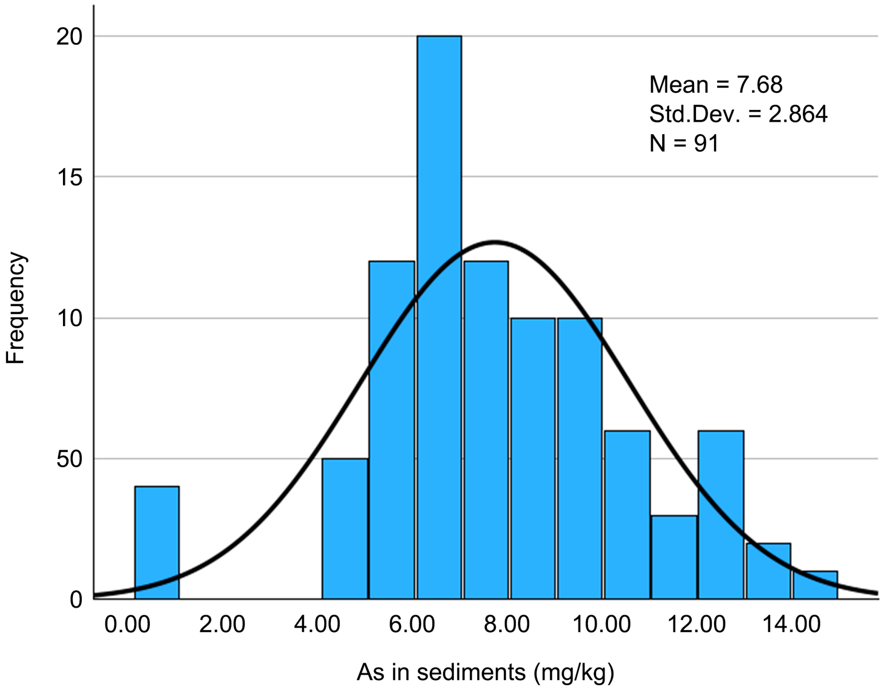

Figure 9. Histogram displaying the spatial variation of the trace element arsenic (As) in sediments. The arsenic distribution is symmetrical.

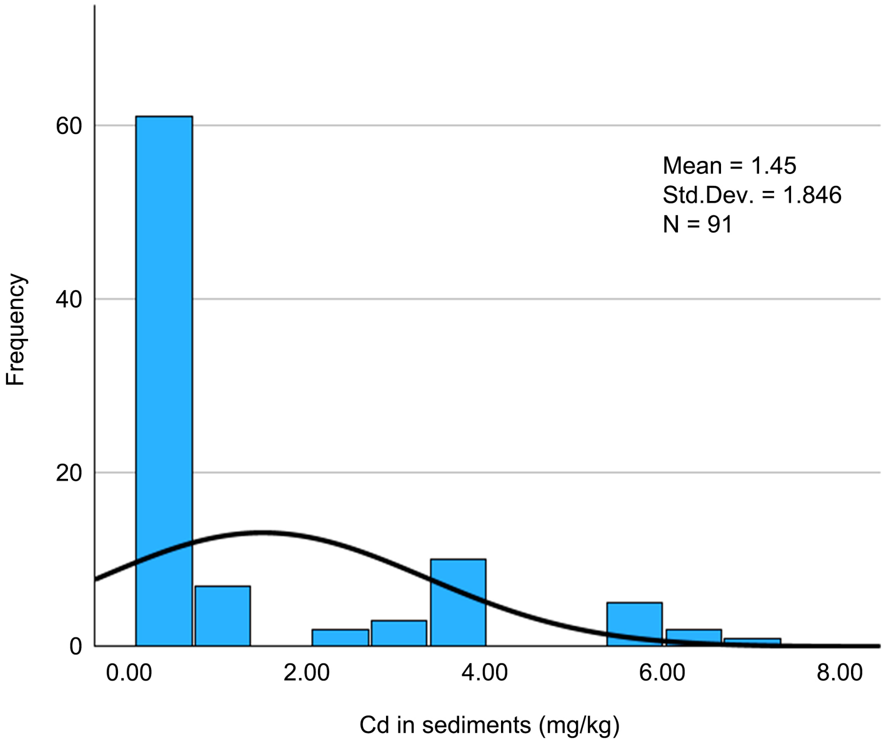

Figure 10. Histogram displaying the spatial variation of the trace element cadmium (Cd) in sediments. The cadmium distribution is positively skewed, with a high frequency of small values and unusual gaps.

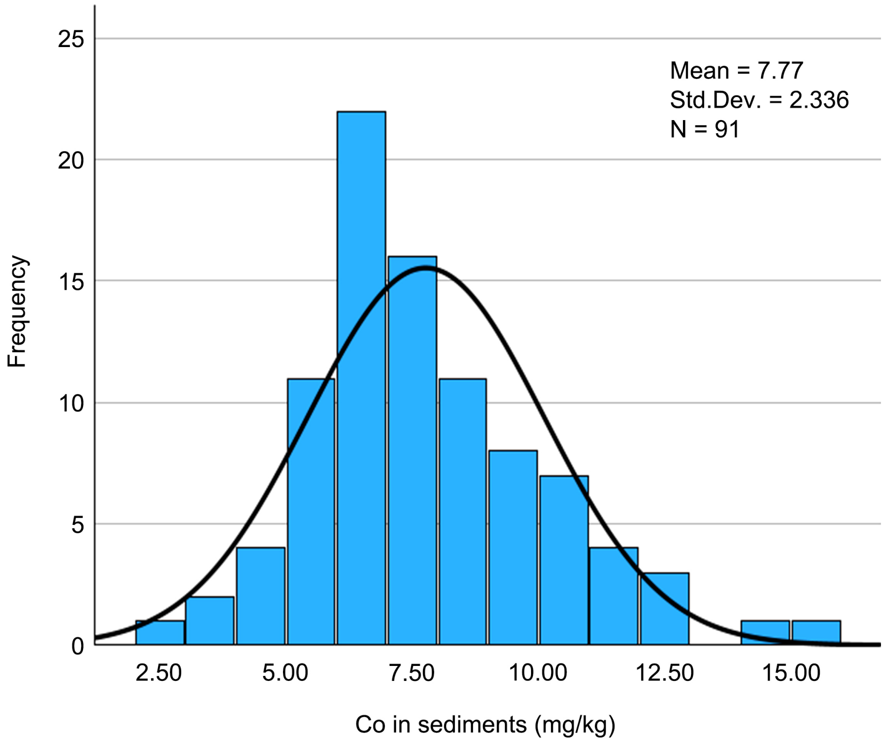

Figure 11. Histogram displaying the spatial variation of the trace element cobalt (Co) in sediments. The cobalt distribution is symmetrical.

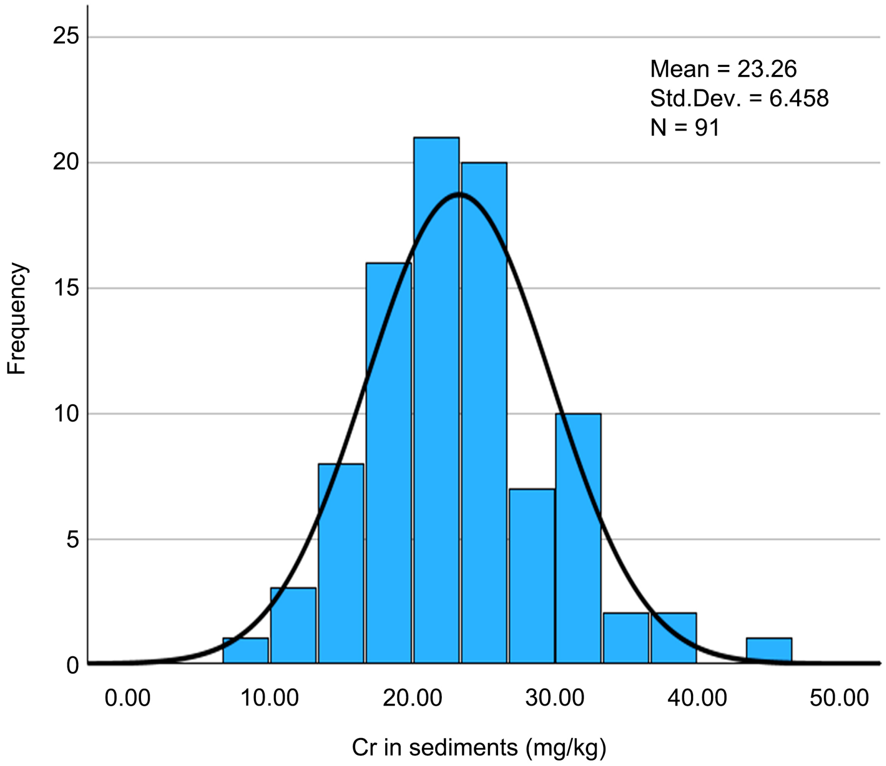

Figure 12. Histogram displaying the spatial variation of the trace element chromium (Cr) in sediments. The chromium distribution is approximately symmetrical.

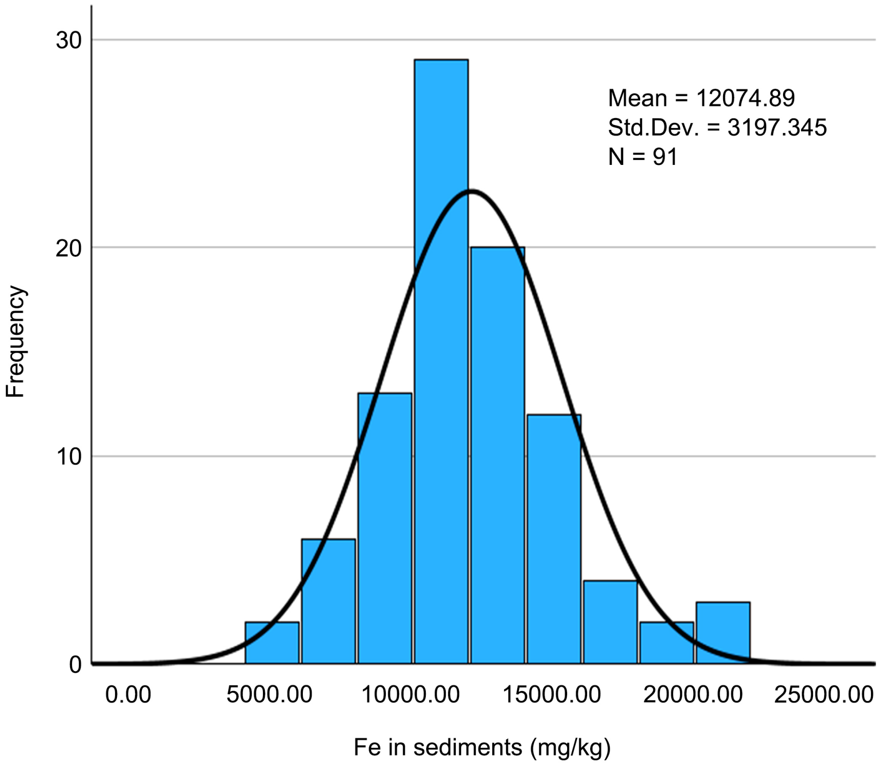

Figure 13. Histogram displaying the spatial variation of the trace element iron (Fe) in sediments. The iron distribution is symmetrical, with a spike in the middle.

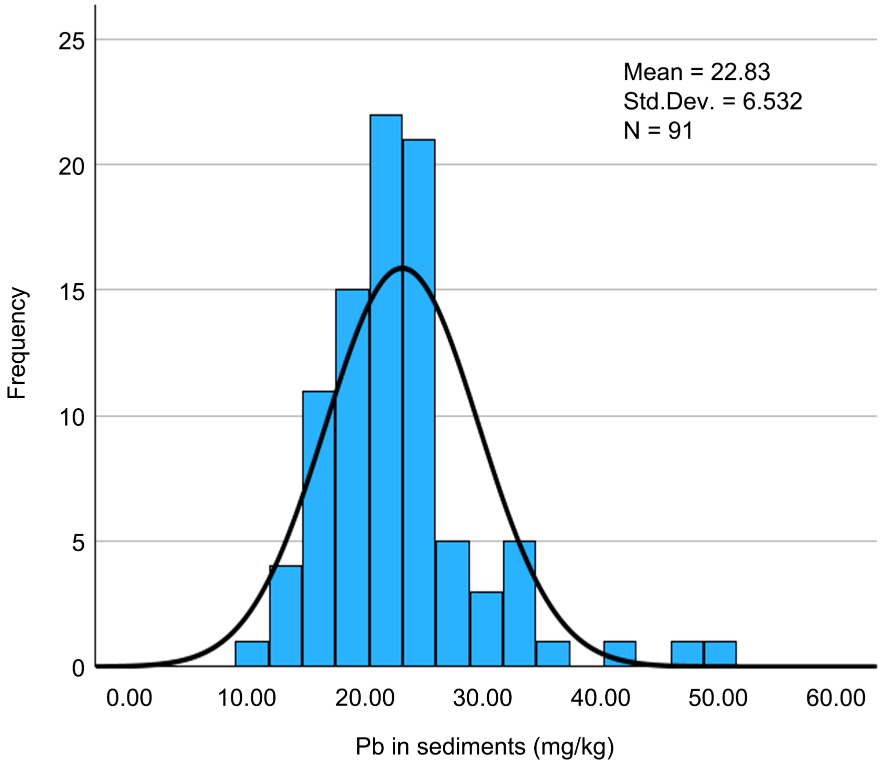

Figure 14. Histogram displaying the spatial variation of the trace element lead (Pb) in sediments. The lead distribution is approximately normal, with spikes in the middle.

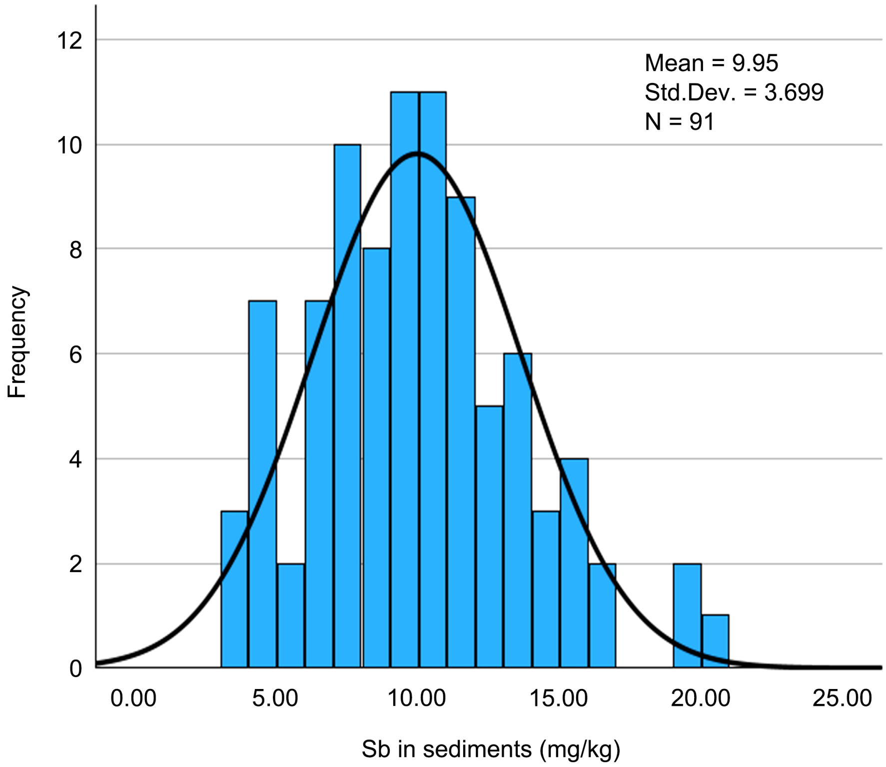

Figure 15. Histogram displaying the spatial variation of the trace element antimony (Sb) in sediments. The antimony distribution is symmetrical.

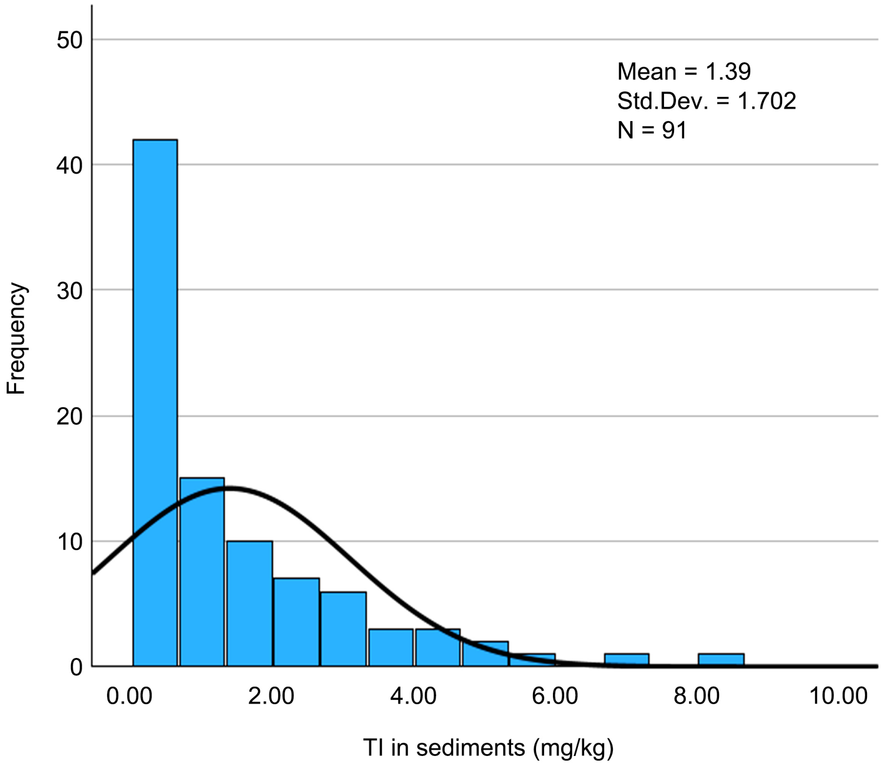

Figure 16. Histogram displaying the spatial variation of the trace element thallium (Tl) in sediments. The thallium distribution is highly positively skewed, with a high frequency of small values.

5. Conclusion

Trace elements were evaluated on sediment samples from Bartlett Pond in Laredo, Southern Texas, to understand the trace metals dynamics within pond ecosystem. Higher concentrations of trace elements were observed at sampling sites near surface runoff inlets, particularly in quadrant II and quadrant III. Iron emerged as the dominant chemical species in sediment samples, with chromium and antimony being the most prevalent contaminant trace elements, followed by lead, cobalt, arsenic, cadmium and thallium. The observed correlations and variability among trace metals suggest ongoing environmental influences that could alter these concentrations over time. Most trace elements were below their potential effect concentration (PEC) as mentioned in US EPA/NOAA, indicating low immediate ecological risk but continuous monitoring is essential to detect any changes in these levels with time although water quality of the pond is unacceptable for drinking and any other purposes as all measured trace elements were exceeding higher than the US EPA and WHO guidelines. Significant correlations between elements like As, Co, and Sb suggest common pollution sources or geochemical processes within the pond, which are critical for source identification and pollution control. The developed models provide a robust tool for predicting trace element behavior, aiding in proactive environmental management and policymaking. Additionally, expanding the scope to include more trace elements and different environmental matrices (e.g., water, biota) would provide a more comprehensive understanding of the environmental dynamics and risks associated with trace element contamination. Overall, this study contributes to the broader field of environmental issues by providing a detailed analysis of trace element contamination in sediments, offering insights that are crucial for protecting ecosystems and public health. Anthropogenic sources, including surface urban runoff and industrial activities primarily control the trace element chemistry in the pond. The relatively higher concentration of trace metals in sediments is primarily due to accumulation with time. Earlier, we reported high concentration of contaminants in two types of fishes such as Bass and Tilapia tissues probably due to biomagnification posing increased health risks to humans who consume those contaminated fishes.

Acknowledgements

The authors would like to thank Aaron Perez, Center for Earth and Environmental Studies of Texas A & M International University for his help to produce the sampling site map (**Figure 1**). The authors would like to thank Cristobal Lopez, Virginia Morales, Erick Vazquez Cano, David Marquez, and Orlando Berumen Alvarez for their help in sediment sampling and sample analysis in the lab at TAMIU. The authors also would like to thank anonymous reviewers for their constructive criticisms with insightful comments to improve the manuscript and members of the editorial office of the journal for their support. Funds from Welch Foundation Grant No. BS-0051 for this research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Brönmark, C. and Hansson, L. (2002) Environmental Issues in Lakes and Ponds: Current State and Perspectives. *Environmental Conservation*, **29**, 290-307. https://doi.org/10.1017/s0376892902000218

[2] Du Laing, G., Rinklebe, J., Vandecasteele, B., Meers, E. and Tack, F.M.G. (2009) Trace Metal Behaviour in Estuarine and Riverine Floodplain Soils and Sediments: A Review. *Science of the Total Environment*, **407**, 3972-3985. https://doi.org/10.1016/j.scitotenv.2008.07.025

[3] Rzetala, M.A. (2015) Assessment of Toxic Metal Contamination of Bottom Sediments in Water Bodies in Urban Areas. *Soil and Sediment Contamination: An International Journal*, **24**, 49-63. https://doi.org/10.1080/15320383.2014.911721

[4] Thom, R., St. Clair, T., Burns, R. and Anderson, M. (2016) Adaptive Management of Large Aquatic Ecosystem Recovery Programs in the United States. *Journal of Environmental Management*, **183**, 424-430. https://doi.org/10.1016/j.jenvman.2016.08.001

[5] Bhatt, M.P., Bhatt, S., and Gaye, B. (2013) Controls on Pond Water Chemistry within Kathmandu Valley, Nepal. *International Journal of Lakes and Rivers*, **6**, 153-172.

[6] Ding, R., Yu, K., Fan, Z. and Liu, J. (2022) Study and Application of Urban Aquatic

Ecosystem Health Evaluation Index System in River Network Plain Area. *International Journal of Environmental Research and Public Health*, **19**, Article 16545. https://doi.org/10.3390/ijerph192416545

[7] Bhatt, M.P., Rubio, A., Malla, G.B., Lopez, C., Morales, V., Cano, E.V., *et al.* (2024) Evaluation of Human Impacts on Bartlett Pond Ecosystem, Laredo, Southern Texas, USA, through Empirical Modeling. *Journal of Environmental Protection*, **15**, 497-526. https://doi.org/10.4236/jep.2024.154029

[8] Cunningham, W. and Cunningham, M. (2021) Environmental Science: A Global Concern. Fifteenth Edition, The McGraw Hill Companies Inc., 375.

[9] Hill, M.J., Greaves, H.M., Sayer, C.D., Hassall, C., Milin, M., Milner, V.S., *et al.* (2021) Pond Ecology and Conservation: Research Priorities and Knowledge Gaps. *Ecosphere*, **12**, e03853. https://doi.org/10.1002/ecs2.3853

[10] ABA (2022) Tenth Annual Laredo Birding Festival. Celebrating Ten Years of Birding the Boarder. American Birding Association.

[11] Keddy, P.A. (2023) Wetland Ecology Principles and Conservation. 3rd Edition, Cambridge University Press. https://doi.org/10.1017/9781009288675

[12] Helmreich, B., Hilliges, R., Schriewer, A. and Horn, H. (2010) Runoff Pollutants of a Highly Trafficked Urban Road—Correlation Analysis and Seasonal Influences. *Chemosphere*, **80**, 991-997. https://doi.org/10.1016/j.chemosphere.2010.05.037

[13] Grung, M., Petersen, K., Fjeld, E., Allan, I., Christensen, J.H., Malmqvist, L.M.V., *et al.* (2016) PAH Related Effects on Fish in Sedimentation Ponds for Road Runoff and Potential Transfer of PAHs from Sediment to Biota. *Science of the Total Environment*, **566**, 1309-1317. https://doi.org/10.1016/j.scitotenv.2016.05.191

[14] Sun, Z., Sokolova, E., Brittain, J.E., Saltveit, S.J., Rauch, S. and Meland, S. (2019) Impact of Environmental Factors on Aquatic Biodiversity in Roadside Stormwater Ponds. *Scientific Reports*, **9**, Article No. 5994. https://doi.org/10.1038/s41598-019-42497-z

[15] Kaushal, S.S., Likens, G.E., Pace, M.L., Reimer, J.E., Maas, C.M., Galella, J.G., *et al.* (2021) Freshwater Salinization Syndrome: From Emerging Global Problem to Managing Risks. *Biogeochemistry*, **154**, 255-292. https://doi.org/10.1007/s10533-021-00784-w

[16] Dixon, H.J., Elmarsafy, M., Hannan, N., Gao, V., Wright, C., Khan, L., *et al.* (2022) The Effects of Roadways on Lakes and Ponds: A Systematic Review and Assessment of Knowledge Gaps. *Environmental Reviews*, **30**, 501-523. https://doi.org/10.1139/er-2022-0022

[17] Shattuck, M.D., Fazekas, H.M., Wymore, A.S., Cox, A. and McDowell, W.H. (2023) Salinization of Stream Water and Groundwater at Daily to Decadal Scales in a Temperate Climate. *Limnology and Oceanography Letters*, **8**, 131-140. https://doi.org/10.1002/lol2.10306

[18] Giddings, E.M., Hornberger M.I. and Hadley H.K. (2001) Trace Metal Concentrations in Sediment and Water and Health of Aquatic Macroinvertebrate Communities of Streams Near Park City, Summit County, Utah. USGS, Department of Interior, Water Resources Investigations Report 01-4213.

[19] Gaillardet, J., Viers J. and Dupre B. (2003) Trace Elements in River Waters. In: Drever, J.I., Eds., *Treaties on Geochemistry*, *Surface and Groundwater*, *Weathering and Soils*, Elsevier, 225-272.

[20] Bhatt, M.P. and Gardner, K.H. (2009) Variation in DOC and Trace Metal Concentration along the Heavily Urbanized Basin in Kathmandu Valley, Nepal. *Environ-*

mental Geology, **58**, 867-876. https://doi.org/10.1007/s00254-008-1562-z

[21] Bhatt, M.P., McDowell, W.H., Gardner, K.H. and Hartmann, J. (2014) Chemistry of the Heavily Urbanized Bagmati River System in Kathmandu Valley, Nepal: Export of Organic Matter, Nutrients, Major Ions, Silica, and Metals. *Environmental Earth Sciences*, **71**, 911-922. https://doi.org/10.1007/s12665-013-2494-9

[22] Boral, S., Sen, I.S., Tripathi, A., Sharma, B. and Dhar, S. (2020) Tracking Dissolved Trace and Heavy Metals in the Ganga River from Source to Sink: A Baseline to Judge Future Changes. *Geochemistry, Geophysics, Geosystems*, **21**, e2020GC009203. https://doi.org/10.1029/2020gc009203

[23] Bhatt, M.P., Malla, G.B. and McDowell, W.H. (2024) Comprehensive Assessment and Analysis of Drinking Water Quality in the Kathmandu Valley: Implications for Public Health and Policy. *American Journal of Water Resources*, **12**, 149-164. https://doi.org/10.12691/ajwr-12-4-5

[24] Buchman, M.F. (2008) NOAA Screening Quick Reference Tables. Office of Response and Restoration Division, National Oceanic and Atmospheric Administration, NOAA OR and R Report 08-1, 34.

[25] Peng, J., Song, Y., Yuan, P., Cui, X. and Qiu, G. (2009) The Remediation of Heavy Metals Contaminated Sediment. *Journal of Hazardous Materials*, **161**, 633-640. https://doi.org/10.1016/j.jhazmat.2008.04.061

[26] Onjefu, S.A., Shaningwa, F., Lusilao, J., Abah, J., Hess, E. and Kwaambwa, H.M. (2020) Assessment of Heavy Metals Pollution in Sediment at the Omaruru River Basin in Erongo Region, Namibia. *Environmental Pollutants and Bioavailability*, **32**, 187-193. https://doi.org/10.1080/26395940.2020.1842251

[27] Sariyildiz, O., Gyawali, B.R., Antonious, G.F., Semmens, K., Zourarakis, D. and Bhatt, M.P. (2024) Stream Chemistry and Forest Recovery Assessment and Prediction Modeling in Coal-Mine-Affected Watersheds in Kentucky, USA. *MDPI Environments*, **11**, Article 40. https://doi.org/10.3390/environments11030040

[28] United States Environmental Protection Agency (2016) Fracking Can Harm Drinking Water. United States Environmental Protection Agency Report.

[29] United Nations Development Programme (2018) Managing Mining for Sustainable Development: A Source Book. United Nations Development Programme, 116.

[30] Wolkersdorfer, C. and Mugova, E. (2022) Effects of Mining on Surface Water. *Encyclopedia of Inland Waters*, **4**, 170-188. https://doi.org/10.1016/b978-0-12-819166-8.00036-0

[31] American Bullion (2018) How Many Gold Mines Are in Texas? Gold Mines in Texas. American Bullion, Inc.

[32] RRC Texas (2024) Historical Coal Mining in Texas. Railroad Commission of Texas.

[33] Scientific American (2007) Coal Ash Is More Radioactive than Nuclear Waste. Springer.

[34] Pandey, J. and Singh, R. (2015) Heavy Metals in Sediments of Ganga River: Up- and Downstream Urban Influences. *Applied Water Science*, **7**, 1669-1678. https://doi.org/10.1007/s13201-015-0334-7

[35] Baran, A., Tarnawski, M., Koniarz, T. and Szara, M. (2019) Content of Nutrients, Trace Elements, and Ecotoxicity of Sediment Cores from Rożnów Reservoir (Southern Poland). *Environmental Geochemistry and Health*, **41**, 2929-2948. https://doi.org/10.1007/s10653-019-00363-x

[36] Klink, A., Dambiec, M. and Polechońska, L. (2019) Trace Metal Speciation in Sediments and Bioaccumulation in Phragmites Australis as Tools in Environmental Pol-

lution Monitoring. *International Journal of Environmental Science and Technology*, **16**, 7611-7622. https://doi.org/10.1007/s13762-019-02305-7

[37] Schlesinger, W.H. and Bernhardt, E.S. (2020) Biogeochemistry: An Analysis of Global Change. 4th Edition, Academic Press, 762.

[38] Rand, G.M. (1995) Fundamentals of Aquatic Toxicology: Effects, Environmental Fate, and Risk Assessment. 2nd Edition, Taylor and Francis, 1148.

[39] Newman, M.C. (2020) Fundamentals of Ecotoxicology: The Science of Pollution. Fifth Edition, CRC Press, 708.

[40] Mateo-Sagasta, J., Zadeh, S.M. and Turral, H. (2017) Water Pollution from Agriculture: A Global Review. FAO and IWMI, 29.

[41] UN Environment Programme (2024) Global Waste Management Outlook 2024. https://www.unep.org/resources/global-waste-management-outlook-2024

[42] The World Counts (2024) Tons of Hazardous Waste Thrown Out. https://www.theworldcounts.com/challenges/planet-earth/waste/hazardous-waste-statistics

[43] Meagher, R.B. (2000) Phytoremediation of Toxic Elemental and Organic Pollutants. *Current Opinion in Plant Biology*, **3**, 153-162. https://doi.org/10.1016/s1369-5266(99)00054-0

[44] Overesch, M., Rinklebe, J., Broll, G. and Neue, H. (2007) Metals and Arsenic in Soils and Corresponding Vegetation at Central Elbe River Floodplains (Germany). *Environmental Pollution*, **145**, 800-812. https://doi.org/10.1016/j.envpol.2006.05.016

[45] CSRL (California Soil Resource Lab) (2024) Soil Web Application, University of California-Davis, Soil Resource Laboratory. https://casoilresource.lawr.ucdavis.edu/soilweb-apps

[46] (United States Department of Agriculture—Soil Conservation Service (1985) National Engineering Handbook. Section 4, Hydrology, USDA-SCS.

[47] Berkowitz, J.F., Vepraskas, M.J., Vaughan, K.L. and Vasilas, L.M. (2021) Development and Application of the Hydric Soil Technical Standard. *Soil Science Society of America Journal*, **85**, 469-487. https://doi.org/10.1002/saj2.20202

[48] Burton, G.A. and Johnston, E.L. (2010) Assessing Contaminated Sediments in the Context of Multiple Stressors. *Environmental Toxicology and Chemistry*, **29**, 2625-2643. https://doi.org/10.1002/etc.332

[49] Gao, L., Li, S., Wang, Z., Liang, Z., Chen, J. and Liang, B. (2018) Contamination, Potential Mobility, and Origins of Lead in Sediment Cores from the Shima River, South China. *Environmental Pollution*, **242**, 1128-1136. https://doi.org/10.1016/j.envpol.2018.07.104

[50] Chiaia-Hernández, A.C., Casado-Martinez, C., Lara-Martin, P. and Bucheli, T.D. (2022) Sediments: Sink, Archive, and Source of Contaminants. *Environmental Science and Pollution Research*, **29**, 85761-85765. https://doi.org/10.1007/s11356-022-24041-1

[51] Basin Highlight Report (BHR) (2022) Rio Grande Basin Program Update. The Texas Clean River Program. Texas Commission on Environment. International Boundary and Water Commission, 1-32.

[52] Torres, L. (2023) Water Quality in the lower Rio Grande. USIBWC Texas Clean Water Program, 1-24.

[53] U.S. Climate (2024) Climate Data of Laredo. https://www.usclimatedata.com/climate/laredo/texas/united-states/ustx0737

[54] Link, D.D., Walter, P.J. and Kingston, H.M. (1999) Wastewater Standards and Extraction Chemistry in Validation of Microwave-Assisted EPA Method 3015A. *Environmental Science & Technology*, **33**, 2469-2473. https://doi.org/10.1021/es990092w

[55] World Health Organizatio (1996) Trace Elements in Human Nutrition and Health. World Health Organization, 360.

[56] Sokoloff, L. (2009) Kashin-Beck Disease: Current Status. *Nutrition Reviews*, **46**, 113-119. https://doi.org/10.1111/j.1753-4887.1988.tb05395.x

[57] Duzgorenaydin, N. (2007) Sources and Characteristics of Lead Pollution in the Urban Environment of Guangzhou. *Science of The Total Environment*, **385**, 182-195. https://doi.org/10.1016/j.scitotenv.2007.06.047

[58] Atkinson, C.A., Jolley, D.F. and Simpson, S.L. (2007) Trace Metal Behavior in Estuarine and Riverine Floodplain Soils and Sediments. *Chemosphere*, **69**, 1428-1437.

[59] Han, L., Gao, B., Wei, X., Gao, L., Xu, D. and Sun, K. (2015) The Characteristic of Pb Isotopic Compositions in Different Chemical Fractions in Sediments from Three Gorges Reservoir, China. *Environmental Pollution*, **206**, 627-635. https://doi.org/10.1016/j.envpol.2015.08.030

[60] Amato, E.D., Simpson, S.L., Remaili, T.M., Spadaro, D.A., Jarolimek, C.V. and Jolley, D.F. (2016) Assessing the Effects of Bioturbation on Metal Bioavailability in Contaminated Sediments by Diffusive Gradients in Thin Films (DGT). *Environmental Science & Technology*, **50**, 3055-3064. https://doi.org/10.1021/acs.est.5b04995

[61] World Health Organization (2017) Guideline for Drinking Water Quality. Fourth Edition Incorporating the First Addendum, 541.

[62] Evanco, C.R. and Dzomback, D.A. (1997) Remediation of Metals Contaminated Soils and Groundwater. Groundwater Remediation Technology Analysis Center (GWRTAC), Technology Evaluation Report, 62.

[63] Wuana, R.A. and Okieimen, F.E. (2011) Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecology*, **2011**, Article ID: 402647. https://doi.org/10.5402/2011/402647

[64] Laghlimi, M., Baghdad, B., Hadi, H.E. and Bouabdli, A. (2015) Phytoremediation Mechanisms of Heavy Metal Contaminated Soils: A Review. *Open Journal of Ecology*, **5**, 375-388. https://doi.org/10.4236/oje.2015.58031

[65] Zheng, X., Lin, H., Du, D., Li, G., Alam, O., Cheng, Z., *et al.* (2024) Remediation of Heavy Metals Polluted Soil Environment: A Critical Review on Biological Approaches. *Ecotoxicology and Environmental Safety*, **284**, Article ID: 116883. https://doi.org/10.1016/j.ecoenv.2024.116883

[66] Ghobadi, R., Altaee, A., Zhou, J.L., Karbassiyazdi, E. and Ganbat, N. (2021) Effective Remediation of Heavy Metals in Contaminated Soil by Electrokinetic Technology Incorporating Reactive Filter Media. *Science of the Total Environment*, **794**, Article ID: 148668. https://doi.org/10.1016/j.scitotenv.2021.148668

[67] Samani, M., Ahlawat, Y.K., Golchin, A., Alikhani, H.A., Fathi-Gerdelidani, A., Ahlawat, U., *et al.* (2024) Nano Silica-Mediated Stabilization of Heavy Metals in Contaminated Soils. *Scientific Reports*, **14**, Article No. 20496. https://doi.org/10.1038/s41598-024-69182-0

[68] Lara-Martín, P.A., Renfro, A.A., Cochran, J.K. and Brownawell, B.J. (2015) Geochronologies of Pharmaceuticals in a Sewage-Impacted Estuarine Urban Setting (Jamaica Bay, New York). *Environmental Science & Technology*, **49**, 5948-5955. https://doi.org/10.1021/es506009v

[69] Chiaia-Hernández, A.C., Günthardt, B.F., Frey, M.P. and Hollender, J. (2017) Unrav-

elling Contaminants in the Anthropocene Using Statistical Analysis of Liquid Chromatography-High-Resolution Mass Spectrometry Nontarget Screening Data Recorded in Lake Sediments. *Environmental Science & Technology*, **51**, 12547-12556. https://doi.org/10.1021/acs.est.7b03357

[70] United States Environmental Protection Agency (2024) National Primary Drinking Water Regulations. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations