

Article

Distribution, Environmental Risks, and Source Apportionment of Heavy Metals in the Lake Sediments and Riparian Soils in Bangong Co Lake of the Qinghai–Tibet Plateau in China

Yuxiang Shao ¹ , Buqing Yan ^{1,*}, Kun Zhang ¹, Bo Zhang ¹, Yunshang Zhang ², Bo Li ³, Yong Chen ¹, Fan Xiang ¹, Xufeng Zhuang ¹ and Shuai Guo ⁴

¹ Research Center of Applied Geology of China Geological Survey, Chengdu 610036, China

² School of Ocean and Earth Science, Tongji University, Shanghai 200092, China

³ School of Earth Sciences and Resources, China University of Geosciences (Beijing), Beijing 100083, China

⁴ Urumqi Natural Resources Comprehensive Survey Center of China Geological Survey, Urumqi 830057, China

* Correspondence: 127961917@139.com

Abstract

The lake systems of the Qinghai–Tibet Plateau, while serving as vital hubs for socio-economic development, have become critical zones of heavy metal contamination, posing severe threats to the fragile “Third Pole” ecosystem and regional environmental security. This study investigated the concentration, distribution, sources, and ecological risks of eight heavy metals (As, Cd, Co, Cr, Cu, Ni, Pb, and Zn) in lake sediments and riparian soils of Bangong Co Lake, a remote alpine lake on the Qinghai–Tibet Plateau. Lake sediment and soil samples were collected and tested from various shoreline types, including natural and human-affected areas. The Pollution Load Index (PLI) was applied to assess contamination levels, and source apportionment was performed using principal component analysis (PCA) combined with the Absolute Principal Component Score–Multiple Linear Regression (APCS-MLR) receptor model. Results revealed that heavy metal concentrations were generally higher in soils than in sediments. Compared to regional background values, elevated levels of most heavy metals were observed in human-affected shores, while natural-type soils exhibited higher concentrations of Co, Cr, Ni, and As. In sediments, only Cd and As were notably elevated in human-affected areas. The PLI results indicated that most sampling sites were either uncontaminated or slightly contaminated, with higher pollution levels occurring primarily in human-affected shoreline zones. Source apportionment demonstrated that heavy metals in sediments were predominantly derived from natural sources such as rock weathering, with anthropogenic contributions being relatively limited. In contrast, soils exhibited significant anthropogenic influences, with industrial, transportation, and agricultural activities contributing substantially to Cu (53.27%), Pb (58.64%), Zn (57.98%), Cd (34.09%), and As (39.87%). The research underscores the differential impacts of human activities on heavy metal accumulation in sediments and soils of high-altitude lake systems. It offers valuable baseline data for monitoring and managing heavy metal pollution in ecologically sensitive alpine regions.

Keywords: Bangong Co Lake; heavy metals; source apportionment; Pollution Load Index; Qinghai–Tibet Plateau



Academic Editor: Anna De Marco

Received: 25 November 2025

Revised: 11 December 2025

Accepted: 13 December 2025

Published: 16 December 2025

Citation: Shao, Y.; Yan, B.; Zhang, K.; Zhang, B.; Zhang, Y.; Li, B.; Chen, Y.; Xiang, F.; Zhuang, X.; Guo, S.

Distribution, Environmental Risks, and Source Apportionment of Heavy Metals in the Lake Sediments and Riparian Soils in Bangong Co Lake of the Qinghai–Tibet Plateau in China.

Sustainability **2025**, *17*, 11274.

<https://doi.org/10.3390/su172411274>

Copyright: © 2025 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the Creative Commons

Attribution (CC BY) license

([https://creativecommons.org/](https://creativecommons.org/licenses/by/4.0/)

[licenses/by/4.0/](https://creativecommons.org/licenses/by/4.0/)).

1. Introduction

Heavy metals, characterized by their persistence and high toxicity, can transfer and accumulate through various pathways such as soil, sediments, and the atmosphere, ultimately entering the food chain [1,2]. These metals pose significant risks to human health and represent an irreversible threat to ecological systems [3,4]. The Qinghai–Tibet Plateau, often referred to as the “Third Pole” of the world, features a distinctive geographic setting and an ecosystem characterized by high altitude, pronounced topographic relief, numerous lakes, young soil development, and high ecological vulnerability [5,6]. Once this pristine ecosystem is disturbed, its restoration presents considerable challenges [7]. Recent studies indicate that background levels of heavy metals in soils of the Qinghai–Tibet Plateau have increased significantly compared to those recorded in the 1970s [8]. Elements such as Pb, Zn, Cu, Hg, and Cd show signs of contamination in soils from urban areas [9,10], agricultural zones [11], pastoral regions [12], industrial developments [13,14], landfills [15], and tourist sites [16] across the plateau. In addition to anthropogenic inputs, natural processes, including geothermal activity and evaporative concentration of lake water, may also contribute to the enrichment of heavy metals in soils and sediments [17,18]. For instance, research in the Shiquan River Basin and the upper reaches of the Yarlung Tsangpo River has reported arsenic concentrations exceeding standards in certain water bodies, sediments, and soils [19,20]. These elevated levels are primarily associated with water-rock interactions involving arsenic-bearing minerals, the inflow of high-arsenic geothermal fluids into rivers, and subsequent precipitation and accumulation processes [21]. Therefore, heavy metal pollution in the fragile plateau environment constitutes a critical and persistent environmental challenge that demands immediate and sustained attention.

Lakes on the Qinghai–Tibet Plateau play an important role in maintaining ecological sustainability [21,22]. Previous studies have shown that although the Qinghai–Tibet Plateau is one of the least human-impacted regions on Earth, significant and increasing amounts of heavy metals have been introduced into the environmental compartments of its plateau lakes through industrial effluents, domestic sewage, and atmospheric deposition associated with recent socioeconomic development [22–24]. Changes in aquatic conditions or hydraulic regimes can lead to the remobilization of heavy metals from sediments and soils into the water column, facilitating their transport to other aquatic systems and resulting in repeated cross-contamination of both water and land [22,25]. This not only increases the pollutant load in plateau lake waters but also exacerbates the ecological risks posed by lake sediments and riparian soils. As a critical transitional zone for the exchange of materials and information within watersheds, the land use type, vegetation characteristics, and soil properties of riparian areas play significant roles in governing the migration and transformation of heavy metals [26,27].

The high-altitude environment and intricate landscape of the Qinghai–Tibet Plateau pose significant constraints on land availability, especially for agricultural land [28]. The plateau’s lakes and river systems, which serve as important carriers for agricultural activities, livestock farming, urbanization, and industrial processes, represent critical zones where aquatic sediments and riparian soils are often focal areas of heavy metal contamination [29–31]. Most previous studies on heavy metals in lake sediments and riparian soils have focused on rivers and lakes in the economically developed eastern and southern China, with limited attention given to plateau lakes and rivers, except for some tourism-developed regions such as Qinghai Lake and Ranwu Lake [23,24]. There is a pressing need to investigate the characteristics, migration mechanisms, and sources of heavy metals in various environmental compartments, including riparian soils, sediments, and water, across numerous plateau lakes.

Located in the remote northwestern Qinghai–Tibet Plateau, Bangong Co Lake is a narrow, transboundary water body straddling China and India [32]. Its limited freshwater resources play a vital role in sustaining regional economic development and environmental sustainability [33,34]. Due to its isolated location and underdeveloped secondary and tertiary industries, the lake remains relatively unaffected by anthropogenic pollution [35]. In recent years, the advancement of the Western Development Strategy has stimulated growth in industry, agriculture, animal husbandry, and tourism within the region [36]. This progress has resulted in significant changes to lakeshore land use patterns. However, the characteristics and sources of heavy metals across these diverse littoral zones remain poorly understood. This study collected and analyzed eight heavy metals (As, Cd, Co, Cr, Cu, Ni, Pb, and Zn) in lake sediments and corresponding riparian soils from various shoreline types around Bangong Co Lake. Pollution Load Index was employed to evaluate the current distribution and potential ecological risks of these metals. Furthermore, correlation analysis, principal component analysis (PCA), and the APCS-MLR (Absolute Principal Component Score–Multiple Linear Regression) receptor model were applied to identify and quantify their potential sources. This work aims to provide a scientific basis for soil management and supporting the ecological sustainability of the Bangong Co Lake basin.

2. Materials and Methods

2.1. Study Area

Bangong Co Lake, a narrow tectonic lake on the Qinghai–Tibet Plateau, is situated between the Karakoram Mountains to the north and the Gangdise Mountains to the south within Rutog County of the Tibet Autonomous Region (Figure 1a) [35,37]. It lies at an elevation of approximately 4240 m above sea level [38]. The lake extends roughly east to west for about 148 km, with a maximum width of 10 km and a narrowest point of only 30 m. It exhibits a distinct east-to-west salinity gradient, transitioning from fresh in the east to saline in the west, and covers a total area of approximately 656 km² [35,37]. Climatically, the region is influenced by the boundary between the mid-latitude westerlies and the Indian monsoon, resulting in a cold, arid environment characteristic of the plateau subfrigid zone [38]. The mean annual precipitation is about 87 mm, and the average annual temperature is 2 °C [39]. Hydrologically, Bangong Co Lake is primarily fed by the Doma River and the Makazangbu River, which enter from the northeastern and southeastern shores, respectively (Figure 1b). There is virtually no surface outflow from the lake, and its water balance is maintained mainly by seasonal precipitation and glacial meltwater.

Geologically, the lake lies along the western segment of the Bangong–Nujiang suture zone, which separates the Qiangtang Terrane to the north from the Lhasa Terrane to the south (Figure 1b) [40–42]. The regional lithology is dominated by carbonate rocks, sandstone, slate, ophiolite, and granitoids, generally trending northwest–southeast across the study area [39,43]. The elongated shape of Bangong Co Lake is accompanied by extended but shallow river and gully systems along its banks. Soils in the lakeshore zone have been relatively less affected by human activity, though growing tourism, grazing, and mining activities are increasingly influencing the region. In addition, the lake's proximity to National Highway G219 and Provincial Highway S520 exposes it to impacts from rising traffic volume (Figure 1c). The local economy remains dominated by animal husbandry, and land use along the lakeshore is relatively homogeneous, consisting largely of unused land with minor areas of cultivated land, woodland, grassland, and residential zones.

2.2. Sample Collection

A field investigation and sampling campaign were conducted in the Bangong Co Lake area in May 2025. Based on the survey results, shoreline utilization around Bangong

Lake is not highly diverse and can be broadly categorized into two dominant types: extensive natural shores and sporadic, point-distributed human-affected shores. The natural shores primarily consist of grassland, woodland, and bare land, while the human-affected shores include areas used for livestock grazing, industrial processing, settlements, tourism, and cultivation.

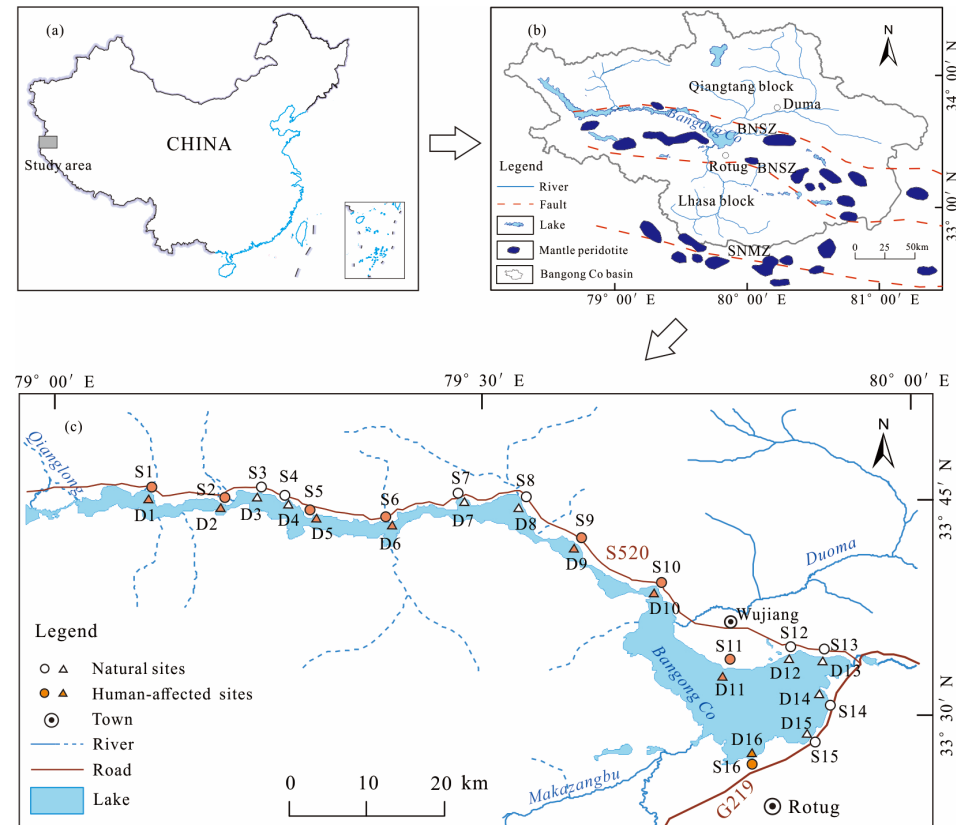


Figure 1. (a) The location of the study area in China; (b) tectonic outline of the Bangong Co lake basin showing the distribution of ophiolites in Bangong–Nujiang Suture Zone (BNSZ) and Shiquan River–Namtsö Mélange Zone (SNMZ) [38,42]; (c) distribution of sampling sites of lake sediments and riparian soils in Bangong Co lake. “S” stands for soil and “D” for sediment.

In mid-June 2025, a set of 16 lake sediment samples and their corresponding riparian soil counterparts was obtained from the area, encompassing both the human-utilized and natural shoreline types of Bangong Co Lake. During sampling, geographic coordinates and shoreline characteristics were recorded using a handheld GPS device (GARMIN eTrex 10, Olathe, KS, USA). Lake sediment sampling was conducted with a columnar sediment corer (KHT0204, 5 cm i.d., Wakbor®, Wenzhou, China). The uppermost 10 cm of sediment from about 4–5 random casts per site were composited and homogenized as one representative sample. These sub-samples were thoroughly mixed and stored in sealed polyethylene bags. Similarly, riparian soils were sampled from areas representative of local land use, with 4–5 sub-samples from the top 0–15 cm layer combined into a single composite soil sample. All samples were collected using a gravity corer or polyethylene scoops to avoid metal contamination. Visible stones and large plant debris were removed during collection. Both lake sediment and riparian soil samples were processed uniformly following standard geochemical procedures. All collected samples were air-dried naturally in a shaded, well-ventilated environment. The preparation protocol adhered to Specification of land quality geochemical assessment (DZ/T 0295-2016) [44], which is specifically designed for the pretreatment of soil and sediment samples in environmental geochemical studies. After drying, the samples were gently disaggregated, homogenized, sieved through a 2 mm nylon

sieve, and stored in sealed polyethylene bags prior to chemical analysis. The location of collected samples is presented in Figure 1c. The specific shoreline conditions corresponding to each sample point are shown in Table 1.

Table 1. The riparian types and descriptions of sampling sites.

Sample ID	Latitude and Longitude	Riparian Type	Surrounding Environment	Sample ID	Latitude and Longitude	Riparian Type	Surrounding Environment
S1 D1	79.14°, 33.74°	Human-affected shore	Building materials products factory	S9 D9	79.61°, 33.70°	Human-affected shore	Pasture, surrounding grazing, and settlements
S2 D2	79.19°, 33.75°	Human-affected shore	Pasture, surrounding grazing, soil slightly saline	S10 D10	79.70°, 33.65°	Human-affected shore	surrounding grazing,
S3 D3	79.23°, 33.76°	Natural shore	Natural bare land	S11 D11	79.77°, 33.56°	Human-affected shore	Village towns, cultivated areas, pasture, and residential water discharge
S4 D4	79.26°, 33.75°	Natural shore	Natural bare land	S12 D12	79.91°, 33.57°	Natural shore	Natural bare land
S5 D5	79.32°, 33.73°	Human-affected shore	Pasture and upstream of basic-ultrabasic rock	S13 D13	79.92°, 33.55°	Natural shore	Natural bare land
S6 D6	79.40°, 33.74°	Human-affected shore	surrounding grazing	S14 D14	79.90°, 33.53°	Natural shore	Woodland, soil slightly saline, and near the national highway
S7 D7	79.47°, 33.75°	Natural shore	Natural bare land	S15 D15	79.88°, 33.47°	Natural shore	Woodland, soil slightly saline, and near the national highway
S8 D8	79.55°, 33.75°	Natural shore	Natural bare land	S16 D16	79.85°, 33.41°	Human-affected shore	Bangong Lake hotel, scenic area, and near the national highway

Note: “S” refers to soil samples and “D” to sediment samples.

2.3. Test Analysis and Quality Control

All samples were analyzed at the laboratory of the Research Center of Applied Geology of the China Geological Survey. During laboratory operations, a subset of each sample was taken for pH analysis, which was tested using an ion-selective electrode. Pulverization of approximately 200 g of each sample was performed using an agate mortar, followed by sieving through a 0.15 mm nylon mesh. For elemental analysis, soil samples were digested with a mixture of HCl, HNO₃, HClO₄, and HF, followed by transfer to volumetric flasks. Concentration of As was measured using atomic fluorescence spectrometry (230E, Beijing Haiguang Instrument Co., Beijing, China). Co, Cu, Ni, and Zn were analyzed by

inductively coupled plasma optical emission spectrometry (Agilent 5800, Thermo Fisher Scientific, Waltham, MA, USA), with the method detection limits of 0.02 mg/kg, 0.2 mg/kg, 0.1 mg/kg, and 0.2 mg/kg, respectively. while Cd and Pb were determined using inductively coupled plasma mass spectrometry (ICAP6300, Thermo Fisher Scientific, USA) with the method detection limits of 0.02 mg/kg and 0.2 mg/kg. Cr was prepared by the powder pellet method and analyzed by X-ray fluorescence spectrometry (PHECDA-PRO, Beijing Anchor Wisdom Technology Co., Ltd., Beijing, China), with the method detection limits of 0.5 mg/kg. The concentrations of heavy metals were determined following the Chinese industry standard DT/T 0279-2016 (Analysis Methods for Regional Geochemical Sample) [45]. To ensure analytical quality, precision, and contamination were monitored through the routine analysis of duplicate samples and procedural blanks (one each per 10 samples), with results indicating high reproducibility and minimal background interference. Certified reference materials (GSS-58, GSS-36) [46] were incorporated into the analytical sequence. The measured values of all elements showed deviations between 0.27% and 8.91% from certified values, meeting accepted quality control criteria [45].

2.4. Data Processing Methods

2.4.1. Pollution Load Index

The Pollution Load Index (*PLI*) is a tool used to assess heavy metal pollution in soils and sediments and to classify contamination levels [47,48]. This index enables not only the evaluation of cumulative contamination characteristics for individual heavy metals but also provides an intuitive representation of comprehensive pollution status caused by multiple metals—at the scale of a single sampling site or an entire region. The method is employed to investigate heavy metal pollution mechanisms across different lakeshore types. The single-factor Pollution Load Index (*CF*) is calculated as follows:

$$CF_i = C_i / S_i \quad (1)$$

where C_i is the measured concentration of heavy metal i in the sample, and S_i represents the corresponding local background value for that element. The local background value is based on the median value from western Tibetan soils [6]. Subsequently, the comprehensive Pollution Load Index for a specific sampling site or region is calculated using the following equation:

$$PLI = \sqrt[n]{\prod_{a=1}^n CF_a} \quad (2)$$

$$PLI_{zone} = \sqrt[k]{\prod_{a=1}^k PLI_a} \quad (3)$$

where *PLI* denotes the comprehensive Pollution Load Index at a single sampling point, n refers to the count of evaluated elements, and k represents the sampling point identifier. PLI_{zone} refers to the comprehensive Pollution Load Index for a specific region. The calculated results for both the single-element indices and the comprehensive *PLI*, along with their corresponding pollution grades, are presented in Table 2.

2.4.2. APCS-MLR Source Analysis

The Absolute Principal Component Score–Multiple Linear Regression (APCS-MLR) is a robust and widely used receptor model in environmental science for quantifying the contributions of various pollutant sources, such as heavy metals or particulate matter [49]. The fundamental principle of the APCS-MLR model is based on mass balance, assuming that the measured concentration of a pollutant at a receptor site is a linear combination of contributions from multiple independent sources.

Table 2. Pollution levels and categories of Pollution Load Index [27].

<i>CF, PLI</i>	Class of Pollution	Pollution Level
<1	0	Uncontaminated
1~2	1	Moderate
2~3	2	Heavy
>3	3	Extreme contaminated

The operation of the model can be divided into four steps. First, Principal Component Analysis (PCA) is performed on the standardized dataset of pollutant concentrations. PCA reduces the dimensionality of the data by identifying a smaller number of underlying factors that explain the majority of the variance in the dataset. These factors are interpreted as potential pollution sources based on the elements with high loadings on them. Second, the calculation of Absolute Principal Component Scores (APCSs) is a crucial step that distinguishes APCS from standard PCA. A “fake” sample with zero concentrations for all pollutants is created. The APCS for each real sample are then obtained by subtracting the factor scores of this zero sample from the original factor scores. This transformation sets the origin of the coordinate system at the background level, making the scores suitable as independent variables in regression analyses to estimate absolute contributions. The third step is Multiple Linear Regression (MLR), where the APCS derived in the previous step are used as independent variables, and the measured concentration of each individual pollutant serves as the dependent variable [49]. The general form of the equation [50,51] is:

$$C_i = b_{0i} + \sum_1^p (b_{pi} + APCS_p) \quad (4)$$

where C_i denotes the measured concentration of a heavy metal, while b_{0i} and b_{pi} are the constant term and regression coefficients from the multiple linear regression, respectively, and $APCS_p$ represents the absolute principal component score. Finally, the contribution of each identified source to the total concentration of each pollutant is calculated. The contribution from source p to pollutant i in a given sample is $b_{pi} \times APCS_p$. The percentage contribution of each source is then determined by normalizing these values against the sum of all estimated contributions.

SPSS v22.0 (SPSS Inc., Chicago, IL, USA) was utilized for multivariate analyses (PCA and APCS-MLR). Descriptive statistics (Mean, Max, Min, CV, and *PLI*) were computed in Microsoft Excel 2013 (Microsoft Corp., Redmond, WA, USA), while ArcGIS 10.4 (Esri Inc., Redlands, CA, USA) and CorelDRAW 18 (Corel Corp., Ottawa, QC, Canada) were applied for geospatial mapping and graphic refinement, respectively.

3. Results and Discussion

3.1. Heavy Metal Concentrations and Spatial Distribution in the Riparian Soils and Lake Sediments

3.1.1. Descriptive Statistics

Descriptive statistics of heavy metal concentrations across different shoreline types are summarized in Table 3. In riparian soils, mean concentrations of Cd (0.19 ± 0.10 mg/kg), Co (13.58 ± 5.45 mg/kg), Cr (87.59 ± 55.17 mg/kg), Cu (27.45 ± 13.09 mg/kg), Ni (52.69 ± 39.65 mg/kg), Pb (21.81 ± 11.43 mg/kg), and Zn (74.68 ± 27.57 mg/kg) were 1.4 to 1.9 times higher in human-affected shores than in natural shores, with their mean concentrations and coefficients of variation of 0.10 ± 0.03 , 10.08 ± 3.19 , 63.39 ± 20.28 , 16.78 ± 6.01 , 39.04 ± 17.49 , 14.41 ± 1.95 , and 51.58 ± 14.52 mg/kg, respectively. These elements also exhibited higher coefficients of variation in human-affected shores, indi-

cating considerable spatial heterogeneity linked to localized anthropogenic inputs. In contrast, As showed the opposite trend, with a higher average level in natural shore soil (17.65 ± 10.35 mg/kg) compared to human-affected shore soil (15.70 ± 6.81 mg/kg). In natural shores, Co, Cr, Ni, and As exceeded the background values of western Tibet [6] by 1.1–1.8 times, while other elements were comparable to or slightly below background. In contrast, all eight heavy metals in soils from human-affected shores showed higher concentrations compared to the background values of western Tibet.

In lake sediments, differences between shore types were less pronounced. A marked exception was Cd, with a 2.1-fold higher mean concentration in human-affected areas. Co, Zn, and As were only slightly elevated (1.1–1.2 times) in human-affected shores, while other elements showed negligible or opposite trends. Compared to the average values of Tibetan lake sediments [52], only Cd in human-affected shores was elevated; all other elements across both shore types remained at or below background levels. Based on sediment quality guidelines (SQGs), the average concentrations of As, Ni, and Cr fell within the TEL–PEL range, indicating a potential for occasional adverse biological effects. Cd levels exceeded the TEL at a few sampling points. Importantly, the mean concentrations of Co, Zn, and Pb were only 26.7–41.2% of their respective TEL values, confirming a negligible ecotoxicological risk from these elements. Compared to the Upper Continental Crust (UCC) [53], Cr, Cu, Ni, and As were elevated in both media. Elevated Cd, Co, Pb, and Zn were found only in human-affected shoreline soils, with concentrations in natural settings comparable to UCC background.

Comprehensive analysis indicates that riparian soils are a more sensitive indicator of anthropogenic impact than lake sediments, showing higher enrichment and greater spatial variability for most metals. Lake sediment pollution is generally low, with notable enrichment primarily linked to natural geogenic processes (e.g., for As, Ni, Cr). The elevated concentrations and higher variability of metals like Cd, Pb, and Zn in human-affected shores strongly point to localized anthropogenic sources.

3.1.2. Spatial Distribution

Figure 2 illustrates the spatial distribution characteristics of heavy metals in the sediments and riparian soils of Bangong Co Lake. The spatial variation trends of most heavy metals were generally consistent within each respective medium, whether in riparian soils or lake sediments. However, significant spatial differences were observed for individual heavy metals between these two environmental compartments. For example, Ni and Cr displayed similar spatial patterns, peaking in the riparian soils at sites 5, 11, and 16. Zn, Co, Cu, and Pb exhibited comparable spatial distributions, with exceptionally high values in soils at sites 1, 2, 5, 11, and 16. The coefficients of variation (CV) for Zn, Cu, and Pb in the sediments were all below 40% (Table 3), indicating relatively limited spatial variability. Only Co exhibited a pronounced anomaly at site 11 (Figure 2). In addition, Cd and As exhibit divergent spatial distribution patterns compared to other heavy metals. Specifically, anomalously elevated concentrations of Cd in soils were primarily observed at human-affected sites such as 1, 2, 9, and 11, while in sediments, notable anomalies occurred at sites 9 and 11, where Cd levels were relatively higher than those in soils. Regarding element As, significantly high values were detected in soils at sites 2, 14, and 15, encompassing both human-affected and natural shoreline types.

Overall, heavy metal concentrations in most riparian soil samples exceeded those in the corresponding lake sediments (Figure 2). The finding is fairly consistent with the characteristics of heavy metals found in the sediments and soils of some plateau lakes and rivers experiencing relatively intense human activity [23,24]. With the exception of As, most anomalously high values are associated with human-affected shorelines, suggesting a

discernible anthropogenic influence on soil heavy metal content. The slightly salinized soil at site 2 and the shrub-woodland cover at sites 14 and 15 may be a major factor contributing to As anomalies in Bangong Co Lake riparian soils [19–21]. The maximum concentrations of most heavy metals generally occur in riparian soils, indicating greater variability in metal accumulation in soils compared to sediments. In contrast, the corresponding sediments exhibit a weaker response to human disturbance, which may be attributed to hydrodynamic equilibrium processes affecting metal dissolution in plateau lake environments or may reflect the relatively limited spatial extent of anthropogenic impacts.

Table 3. Descriptive statistics of heavy metals in sediments and riparian soils of Bangong Co Lake.

Heavy Metals			Cd	Co	Cr	Cu	Ni	Pb	Zn	As	Data Source
Soil	Human-affected shore (<i>n</i> = 8)	Min	0.11	4.79	28.60	8.00	16.30	4.60	30.40	9.20	this study
		Max	0.41	19.20	212.00	46.60	146.00	38.40	106.00	29.80	
		Mean	0.19	13.58	87.59	27.45	52.69	21.81	74.68	15.70	
		SD	0.10	5.45	55.17	13.09	39.65	11.43	27.57	6.81	
		CV	54.3%	40.2%	63.0%	47.7%	75.2%	52.4%	36.9%	43.3%	
	Natural shore (<i>n</i> = 8)	Min	0.06	6.99	37.30	11.40	21.30	11.50	36.80	6.50	
		Max	0.16	15.50	103.00	26.00	76.00	17.40	74.70	33.90	
		Mean	0.10	10.08	63.39	16.78	39.04	14.41	51.58	17.65	
		SD	0.03	3.19	20.28	6.01	17.49	1.95	14.52	10.35	
		CV	28.3%	31.6%	32.0%	35.9%	44.8%	13.5%	28.1%	58.6%	
Sediment	Human-affected shore (<i>n</i> = 8)	Min	0.06	3.43	27.00	5.60	15.10	6.20	25.80	5.30	
		Max	0.64	22.20	78.10	22.00	52.50	17.80	75.10	22.90	
		Mean	0.21	10.89	51.10	14.69	31.74	12.30	50.70	14.20	
		SD	0.23	5.86	17.70	5.78	13.84	3.35	18.29	5.87	
		CV	111.9%	53.9%	34.6%	39.4%	43.6%	27.2%	36.1%	41.3%	
	Natural shore (<i>n</i> = 8)	Min	0.06	5.53	43.50	8.80	18.80	8.30	32.50	6.30	
		Max	0.16	15.50	97.00	27.80	63.80	18.40	75.40	18.70	
		Mean	0.10	9.53	63.30	16.23	34.64	13.43	49.36	12.08	
		SD	0.04	3.26	17.41	6.42	13.43	4.06	15.00	4.38	
		CV	37.8%	34.2%	27.5%	39.6%	38.8%	30.2%	30.4%	36.3%	
UCC		Mean	0.102	11.6	35	14.3	18.6	17	52	1.5	[53]
West Tibetan soils		Median	0.11	9.39	54.68	20.11	24.82	20.73	57.19	14.97	[6]
Tibetan lake sediments		Mean	0.11	13.59	81.25	30.4	60.21	20.32	64.1	33.73	[52]
TEL			0.596	35.7	37.3	-	18	35	123	5.9	[54]
PEL			3.53	197	90	-	36	91.3	315	17	

The units for heavy metal concentrations are mg/L.

3.2. Risk Evaluation of Heavy Metals in Riparian Soils and Lake Sediments

Figure 3 presents the spatial distribution of the Pollution Load Index (PLI), which was evaluated for eight heavy metals at all sampling locations. Refer to the PLI classification (Table 2), the overall PLI values for Bangong Co Lake sediments and riparian soils were 1.11 and 0.87, respectively, indicating moderate pollution in the sediments and an unpolluted status in the soils. Among the sampling sites, five (31.25%) lake sediment samples and nine (56.25%) riparian soil samples were classified as slightly polluted. Similar to the characteristics of heavy metal content, the PLI values in most riparian soil samples were higher than those in the corresponding lake surface sediments, suggesting a more extensive pollution footprint in the riparian zone compared to the lake sediments.

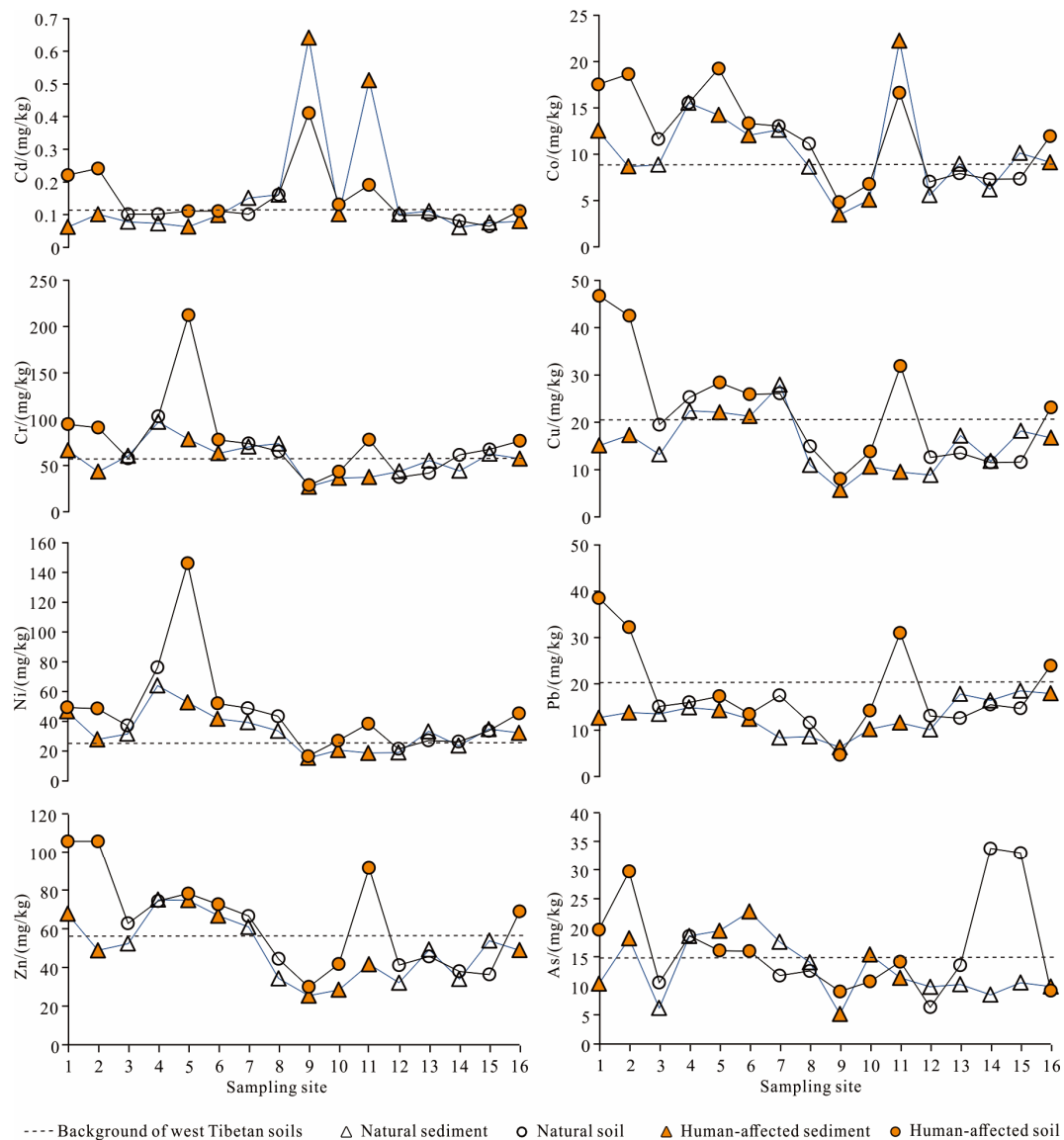


Figure 2. Distribution Characteristics of heavy metals in lake sediments and riparian soils in the natural and human-affected shores.

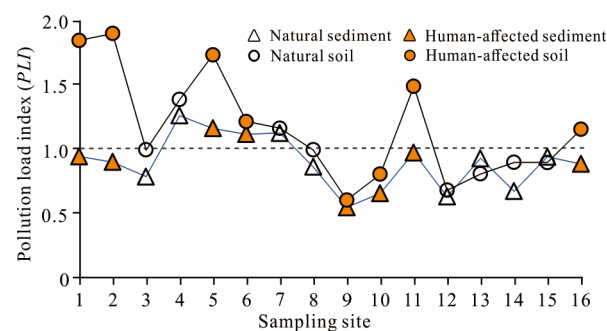


Figure 3. Spatial distribution of Heavy Metal Pollution Load Index (PLI) in lake sediment and riparian soil of Bankong Co Lake.

Based on the classification of lakeshore types, all sampling sites were categorized into natural shores and human-affected shores. The overall PLI values for riparian soils in these two zones were ranked as follows: human-affected shores (1.257) > natural shores (0.958). In contrast, the overall PLI for lake sediments showed a reverse trend: natural shores

(0.881) > human-affected shores (0.876) (Table 3). These results indicate that riparian soils in human-affected shores are in a state of moderate pollution; whereas both natural shore soils and sediments, as well as sediments in human-affected shores, remain unpolluted.

To further elucidate the contamination characteristics of heavy metals in different shore types, polar plots of the PLI for each metal were constructed (Figure 4). The plots reveal that, with the exception of As, the average PLI values of heavy metals in natural shore soils and sediments were generally similar, following the order: Ni > Cr > Co > Cd > Zn > Cu > Pb. Metals exhibiting moderate pollution levels in this category were mainly Ni, Cr, Co, and As in natural riparian soils and sediments. In contrast, clear differences were observed in the average PLI values of heavy metals between soils and sediments in human-affected shores. The order of PLI values was Ni > Cd > Cr > Co > Zn > Cu > Pb > As in human-affected soils, and Cd > Ni > Co > As > Cr > Zn > Cu > Pb in the sediments. Ni in soils from human-affected shores reached moderate pollution levels, while other heavy metals in the soils were present at moderate pollution levels. In sediments, only Cd, Co, and Ni were classified as slightly polluted. Comprehensive analysis suggests that the slight anomalies of Ni, Cr, Co, and As are largely associated with naturally high background levels, whereas the anomalies of Cd, Cu, Zn, and Pb are likely strongly linked to anthropogenic inputs in the region.

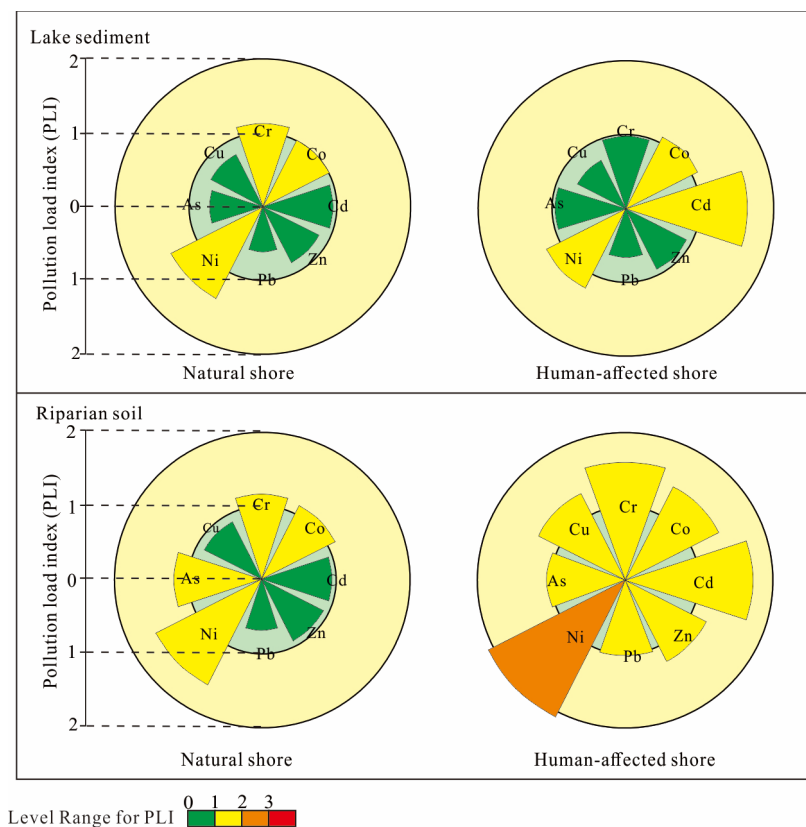


Figure 4. Pollution Load Index (PLI) for each heavy metal in riparian soil and lake sediment of different shores in Bangong Co Lake.

3.3. Source Analysis of Heavy Metals in Riparian Soils and Lake Sediments

3.3.1. Correlation Analysis

Correlation analysis can serve as a method for inferring common origins among heavy metal elements, with significance levels aiding in source identification [35,55]. The correlation matrix for heavy metal concentrations in lake sediments and soils was calculated to explore the heterogeneous sources of these metals (Table 4). The results show that in

lake sediments, Co, Cr, Ni, Cu, and Zn exhibited significant pairwise positive correlations ($r = 0.721\sim 0.969$, $p < 0.01$). As in the sediments was positively correlated with Cu, Co, Ni, and Zn ($r = 0.567\sim 0.684$), suggesting similar sources. In contrast, Cd exhibited significant negative correlations with Cr, Cu, Ni, and Pb ($r = -0.515\sim -0.554$, $p < 0.05$), suggesting that Cd may originate from different sources. In the riparian soils, Co, Cu, Pb, and Zn showed significant pairwise positive correlations ($r = 0.720\sim 0.983$, $p < 0.01$). Significant positive correlations were also found between Cr and Ni ($r = 0.975$, $p < 0.01$) and between Co and Ni ($r = 0.706$, $p < 0.01$). Additionally, moderate positive correlations ($r = 0.517\sim 0.569$, $p < 0.05$) were observed between Cr and Cu, Zn, as well as between Zn and As.

Table 4. Correlation analysis of heavy metals of lake sediments and riparian soils in Bangong Co Lake.

	Heavy Metals	Cd	Co	Cr	Cu	Ni	Pb	Zn	As
Sediment ($n = 16$)	Cd	1							
	Co	0.007	1						
	Cr	−0.174	0.764 **	1					
	Cu	0.159	0.903 **	0.517 *	1				
	Ni	−0.200	0.706 **	0.976 **	0.421	1			
	Pb	0.090	0.720 **	0.320	0.888 **	0.164	1		
	Zn	0.118	0.934 **	0.542 *	0.983 **	0.455	0.868 **	1	
	As	−0.164	0.145	0.194	0.180	0.056	0.276	0.136	1
Soil ($n = 16$)	Cd	1							
	Co	0.091	1						
	Cr	−0.544 *	0.429	1					
	Cu	−0.517 *	0.413	0.721 **	1				
	Ni	−0.515 *	0.467	0.939 **	0.767 **	1			
	Pb	−0.554 *	0.150	0.262	0.321	0.315	1		
	Zn	−0.457	0.604 *	0.801 **	0.834 **	0.915 **	0.372	1	
	As	−0.347	0.390	0.494	0.684 **	0.567 *	−0.040	0.569 *	1

Note: ** $p < 0.01$; * $p < 0.05$.

The robust positive correlations ($r > 0.9$, $p < 0.01$) observed among Co, Cr, and Ni in both sediments and soils (Table 4) may point to a common source. Previous studies have shown that this elemental association is characteristic of mafic and ultramafic rock assemblages, where the weathering of these parent materials can release large amounts of Co, Cr, and Ni into the environment [55]. Meanwhile, it was also observed that elements such as Cu and Zn in the soil and sediments of the study area were correlated with this elemental association, suggesting a partial overlap in their sources. Although not as characteristically siderophilic as Co, Cr, and Ni, Cu and Zn are trace constituents of ferromagnesian minerals found in mafic and ultramafic rocks [40]. Moreover, their subsequent fate is more likely governed by similar surface processes in the plateau environment. Specifically, their low mobility under prevailing pH conditions and strong affinity for clay fractions and Fe/Mn oxides lead to co-transport and co-deposition [14].

Cd and As in the study area exhibited conspicuously weak, absent, or even negative correlations with other heavy metals, indicating that the possible sources of Cd and As are decoupled from those of the other elements. Cadmium is often considered an indicator of anthropogenic pollution, primarily originating from industrial and agricultural activities such as metal smelting, fertilizer application, and wastewater irrigation [9,10]. The sources of arsenic are more complex. In addition to well-known contributors like mining activities and industrial discharges, specific geological settings, such as arsenic-rich mineral deposits or volcanic activities, as well as groundwater processes, also serve as significant sources of

arsenic in plateau regions [21]. Their distinct geochemical characteristics, including higher mobility under redox conditions and high pH in plateau environments [19–21], may have consequently led to their spatial fractionation within the lake basin.

3.3.2. PCA

Principal component analysis (PCA) was applied to the sediment and soil datasets from Bangong Co Lake to delineate their principal heavy metal sources. Prior to analysis, the data were standardized using Z-scores to eliminate the influence of differing units and scales [55]. Bartlett's Test of Sphericity and the Kaiser–Meyer–Olkin (KMO) measure verified the suitability of the data for PCA. KMO values were 0.622 for sediments and 0.560 for soils, both exceeding the 0.5 threshold, and the *p*-value of Bartlett's Test of Sphericity was below 0.01, indicating that the data are suitable for principal component analysis [8]. The results of the principal component analysis are presented in Table 5. Following Varimax orthogonal rotation with Kaiser normalization [8,22], two principal components with eigenvalues greater than 1 were extracted from the sediment samples, with the variance of 66.65% and 15.23%, respectively, explaining the majority of the variability (81.88%) in the sediment heavy metal data. For the soil samples, three principal components with eigenvalues exceeding 1 were identified, explaining 56.15%, 19.54%, and 13.75% of the total variance, respectively, indicating that these components capture most of the variance (89.43%) related to heavy metals in the soils.

Table 5. Principal component analysis for heavy metals in the sediment and soil.

Heavy Metals	Sediment		Soil		
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 3
Co	0.933	0.242	0.782	0.596	0.002
Ni	0.900	0.313	0.182	0.968	0.028
Zn	0.887	0.320	0.929	0.320	−0.035
Cu	0.855	0.277	0.949	0.268	−0.017
Cr	0.848	0.312	0.316	0.910	0.126
As	0.794	−0.136	0.266	−0.090	0.846
Pb	0.045	0.933	0.940	0.013	0.142
Cd	−0.368	−0.738	0.308	−0.346	−0.648
Eigenvalues	5.33	1.22	4.49	1.56	1.10
Variance %	66.65	15.23	56.15	19.54	13.75
Cumulative variance %	66.65	81.88	56.15	75.68	89.43

As presented in Table 5, the first principal component (F1) for lake sediments shows strong positive loadings for Co (0.933), Ni (0.900), Zn (0.887), Cu (0.855), Cr (0.848), and As (0.794). Existing studies demonstrate that ultramafic rocks typically exhibit high concentrations of Ni, Cr, and Co [40,55]. The Bangong Co Lake region is situated within the Bangong–Nujiang suture zone, formed by the collision between the Lhasa and Qiangtang terranes, where mafic and ultramafic rocks are widely distributed (Figure 1b) [40,42]. These elements are likely transported as weathering products of exposed basic rocks and deposited in river or lake sediments via hydrodynamic processes. Additionally, the high background level of As in plateau lake sediments has been attributed to volcanic activity or the evaporative concentration characteristic of saline lakes [20,21]. The As content in the sediments generally increases from east to west (Figure 2), a spatial pattern that corresponds to the salinity gradient of Bangong Co Lake [35], suggesting that evaporative enrichment may play a significant role in the accumulation of As in the sediments.

Therefore, F1 in sediments is interpreted as a natural source, primarily reflecting rock weathering and evaporative concentration in saline lakes. The second principal component

(F2) explains 15.23% of the total variance and is characterized by a strong positive loading for Pb (0.933) and a strong negative loading for Cd (−0.738). Pb and Cd are often associated in various mineral deposits and can be transported through atmospheric processes [8]. In the study area, elevated Cd levels in sediments primarily occur near villages and livestock areas (Figure 1b), while relatively high Pb concentrations are found in tourist zones and adjacent to the main highway (Sites 13–16). This spatial distribution suggests that Cd and Pb in the sediments are mainly derived from anthropogenic activities. Consequently, F2 is indicative of anthropogenic sources such as fossil fuel combustion, transportation, and wastewater discharge from human settlements.

The first principal component (F1) for the riparian soils exhibits strong positive loadings for Cu (0.949), Pb (0.940), Zn (0.929), and Co (0.782), which may have a potential co-association for these heavy metals in the soils. Pb and Zn are primarily released through incomplete combustion of vehicle fuel, as well as tire wear and abrasion [8,55]. Previous studies have reported elevated levels of Pb and Zn in topsoils along the northeast–southwest-oriented Tibetan Highway [56]. Meanwhile, the geogenic association of Pb with Zn and Co with Cu during mineralization processes, coupled with subsequent mining and sorting activities, may also contribute to their enrichment in surrounding soils [8,57]. As discussed above, the spatial distributions of Cu, Pb, Zn, and Co in the riparian soils of the study area are highly consistent, with peak concentrations observed at Site 1 (mining area), Site 11 (village settlement), and Site 16 (tourism zone). This pattern suggests influences from industrial operations, transportation, and anthropogenic waste discharges, supporting the interpretation that F1 represents an anthropogenic source. The second principal component (F2) is dominated by strong loadings from Ni (0.968), Cr (0.910), and Co (0.596). As previously noted, the anomalously high concentrations of nickel, chromium, and cobalt in soils are predominantly observed at Site 5. This location not only serves as a livestock grazing area but also closely aligns with the distribution of ophiolite formations known to be rich in Ni, Cr, and Co (Figure 1b), reinforcing the interpretation of a dominant geogenic source for these elements. Therefore, F2 most likely represents a natural source, primarily dominated by rock weathering. The third principal component (F3) shows strong loadings for As (0.846) and Cd (−0.648). In the study area, soil Cd peaks are mainly found in village and grazing areas, while elevated As concentrations occur in forested lands. Anthropogenic inputs of As and Cd are generally linked to fossil fuel combustion and non-ferrous metal smelting [9,10]. Combined with the local practice of using coal and dried dung for heating—whose combustion residues are often applied as fertilizer in woodland and farmland—these processes may contribute to As and Cd accumulation. Moreover, soils across the Qinghai–Tibet Plateau are generally enriched in As, which is also commonly used in fertilizers, pesticides, and insecticides [19,21]. Thus, the third principal component (F3) likely reflects a mixed influence, though it primarily indicates anthropogenic sources.

3.3.3. APCS-MLR

The source contributions of heavy metals were quantified using the Absolute Principal Component Score–Multiple Linear Regression method (APCS-MLR), with results summarized in Table 6. The comparison between EST (estimated concentration) and OBS (observed concentration) and the regression R^2 of the model were used to evaluate the accuracy of the model. Overall, the EST values of heavy metals in both sediments and soils closely matched the OBS values, indicating a good model fit [24]. The adjusted R^2 values for the heavy metal models ranged from 0.543 to 0.958, most of them exceeding 0.6, demonstrating high reliability of the APCS-MLR analysis.

Elements including Co, Cr, Cu, Ni, Zn, and As in the sediments are predominantly associated with natural sources, with natural contributions of 79.27%, 62.86%, 76.41%,

81.49%, 66.77%, and 82.89%, respectively (Table 6 and Figure 5). Anthropogenic contributions to these elements in the sediments were all below 10%. In contrast, Cd and Pb in the sediments are influenced by human activities to varying degrees, with anthropogenic contributions of 18.47% and 13.74%, respectively. Notably, unknown sources contributed substantially to both Cd and Pb, warranting further investigation. Combined with the principal component analysis, the source apportionment results indicate that sediments in Bangong Co Lake are minimally influenced by anthropogenic activities. It is important to note that these quantitative estimates are derived from a limited dataset ($n = 16$) and that the strong geogenic background in this ophiolite-rich region may lead to some overlap in elemental signatures between natural weathering and certain anthropogenic processes, introducing uncertainty into the source separation.

Table 6. Source contributions and fitting degrees of APCS-MLR model.

Heavy Metals		Cd	Co	Cr	Cu	Ni	Pb	Zn	As
Sediment	F1 contribution %	34.16	79.27	62.86	76.41	81.49	2.50	66.77	82.89
	F2 contribution %	18.47	5.53	6.21	6.65	7.61	13.74	6.46	3.81
	Unexplained variability %	47.37	15.20	30.93	16.94	10.90	83.75	26.76	13.31
	OBS mg/kg	0.15	10.21	57.20	15.45	33.19	12.87	50.03	13.14
	EST mg/kg	0.15	9.40	57.20	15.46	33.19	12.86	50.03	13.14
	R ²	0.631	0.918	0.788	0.778	0.893	0.852	0.872	0.596
Soil	F1 contribution %	7.99	33.98	16.93	52.26	10.04	50.41	38.31	13.06
	F2 contribution %	12.74	37.12	69.88	21.17	76.46	0.99	18.95	6.34
	F3 contribution %	17.92	0.11	7.29	1.01	1.65	8.23	1.56	44.92
	Unexplained variability %	61.35	28.80	5.90	25.56	11.85	40.37	41.18	35.68
	OBS mg/kg	0.14	11.83	75.49	22.11	45.86	18.11	63.13	16.67
	EST mg/kg	0.15	11.83	75.49	22.11	45.86	18.11	63.12	16.67
	R ²	0.543	0.958	0.929	0.967	0.964	0.881	0.958	0.743

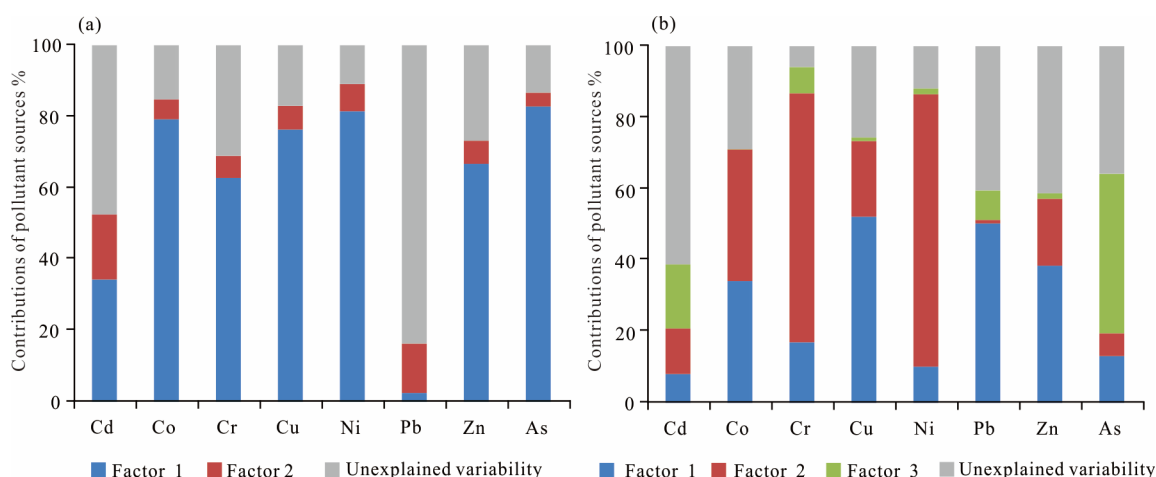


Figure 5. Contribution of pollutant sources to sediment (a) and soil (b) based on the APCA-MLR model.

The contributions of the three factors obtained from PCA to heavy metals in Bangong Co Lake soils are illustrated in Figure 5. The results show that the natural source (F2), primarily from rock weathering, contributed significantly to Ni (76.46%), Cr (69.88%), Co (37.12%), Cu (21.17%), and Zn (18.95%), while its contributions to other metals were below 15%. Factor 1 and Factor 3 predominantly represent anthropogenic sources. Factor 1, potentially indicative of industrial activities, transportation, and wastewater discharge, showed elevated contributions to Cu (52.26%), Pb (50.41%), Zn (38.31%), Co (33.98%),

and Cr (16.93%), with contributions to other elements below 15%. Factor 3, representing agricultural and livestock inputs, contributed notably to As (44.92%) and Cd (17.92%), with contributions to remaining metals below 10%. However, the interpretation of these factors must be approached with caution. The moderate cumulative variance explained by the model and the relatively small sample size increase the uncertainty in both the factor identification and the absolute contribution rates calculated by APCS-MLR. Some elements (e.g., Cu, Zn, Co) show meaningful contributions from multiple sources, suggesting overlapping geochemical signals.

The distribution and sources of heavy metals in Bangong Co Lake are intrinsically linked to the distinctive environmental setting of the Qinghai–Tibet Plateau. First, the dominant natural sources of metals such as Cr, Ni, and Co correspond directly to the widespread weathering of mafic-ultramafic rocks within the Bangong–Nujiang suture zone, a defining geological feature of the region [40,55]. Second, the notable enrichment of arsenic in sediments, correlating with the west–east salinity gradient, underscores the significant role of intense evaporative concentration—a process characteristic of arid and semi-arid plateau climates [19,35,38]. Third, although overall contamination is currently low, the clear fingerprint of anthropogenic activities in soils highlights the heightened vulnerability of this cold, slow-cycling ecosystem to even moderate human pressure [7,8]. Unlike in lowland regions, the combination of slow degradation rates, sparse vegetation, and sensitive hydrology means that once pollutants are introduced, their ecological impacts may be more persistent and far-reaching [23,24]. Therefore, our findings are not merely a site-specific case study but provide critical insights into the geochemical behavior and environmental risks of heavy metals under the coupled influences of unique plateau geology, climate, and increasing human footprint. From a management perspective, these findings may inform the prioritization of lakeshore segments for targeted monitoring and regulation. Although existing risks are relatively low, the clear linkage between human activity and metal accumulation highlights the necessity of preventive strategies to safeguard against increasing pressures from future development.

4. Conclusions

This study identified spatial patterns of eight heavy metals in the lake sediments and riparian soils of Bangong Co Lake, highlighting the contributions of both natural processes and human activities to the coastal environmental media. The results indicated that heavy metal concentrations were generally higher in riparian soils than in sediments. Compared to background values for western Tibetan soils and regional lake sediment benchmarks, elevated concentrations of most soil heavy metals were found in human-impacted shorelines, whereas natural soils exhibited higher levels of Co, Cr, Ni, and As. In sediments, only Cd and As levels were elevated and need special attention. The Pollution Load Index (*PLI*) indicated that heavy metals in both sediments and soils of the Bangong Co Lake area were either uncontaminated or only slightly contaminated, with contaminated sites primarily located along shoreline sections affected by human activity.

The differential correlation patterns effectively discriminate between metal sources. While the cohesive group (Co–Cr–Ni) fingerprints regional bedrock weathering, the isolated patterns of Cd and As underscore their origins from disparate anthropogenic activities and unique geochemical mobility in the plateau environment. PCA and APCS-MLR results revealed that sediment heavy metal concentrations were less influenced by human activities, with most metals primarily originating from natural sources such as the weathering of mafic and ultramafic rocks. In contrast, anthropogenic sources, including fossil fuel combustion, transportation, and wastewater discharge, contributed relatively higher proportions to Cd (18.47%) and Pb (13.74%) in sediments. Soil heavy metal concentrations, however, were

significantly affected by human activities, with anthropogenic input rates reaching 53.27% for Cu, 58.64% for Pb, 57.98% for Zn, 34.09% for Cd, and 39.87% for As. This combination of factors has created a distinctive distribution pattern of heavy metals along the lakeshores of Bangong Co Lake, providing valuable insights into heavy metal migration, accumulation, and soil management in similar environments.

Author Contributions: B.Y.: writing—review and editing, resource, and funding acquisition. K.Z.: investigation. B.Z.: investigation. Y.Z.: investigation. Y.C.: resources and software. B.L.: methodology. X.Z.: supervision. F.X.: writing—review and editing. S.G.: data curation. Y.S.: conceptualization, investigation, and writing—original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the China Geological Survey Project (No. DD20243077).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Buqing Yan, upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zeng, J.; Han, G.; Zhang, S.; Liang, B.; Qu, R.; Liu, M.; Liu, J. Potentially toxic elements in cascade dams-influenced river originated from Tibetan Plateau. *Environ. Res.* **2022**, *208*, 112716. [\[CrossRef\]](#)
2. Mao, Y.; Wang, M.; Wei, H.; Gong, N.; Wang, F.; Zhu, C. Heavy metal pollution and risk assessment of vegetables and soil in Jinhua City of China. *Sustainability* **2023**, *15*, 4241. [\[CrossRef\]](#)
3. Wu, G.; Wang, L.; Yang, R.; Hou, W.; Zhang, S.; Guo, X.; Zhao, W. Pollution characteristics and risk assessment of heavy metals in the soil of a construction waste landfill site. *Ecol. Inform.* **2022**, *70*, 101700. [\[CrossRef\]](#)
4. Rouhani, A.; Bradák, B.; Makki, M.; Ashtiani, B.; Hejman, M. Ecological risk assessment and human health risk exposure of heavy metal pollution in the soil around an open landfill site in a developing country (Khesht, Iran). *Arab. J. Geosci.* **2022**, *15*, 1523. [\[CrossRef\]](#)
5. Fang, X.; Han, Y.; Ma, J.; Song, L.; Yang, S.; Zhang, X. Dust storms and loess accumulation on the Tibetan Plateau: A case study of dust event on 4 March 2003 in Lhasa. *Chin. Sci. Bull.* **2004**, *49*, 953–960. [\[CrossRef\]](#)
6. Li, C.; Kang, S.; Zhang, Q. Elemental composition of Tibetan Plateau top soils and its effect on evaluating atmospheric pollution transport. *Env. Pollut.* **2009**, *157*, 2261–2265. [\[CrossRef\]](#)
7. Chen, F.; Zhang, Y.; Hou, J.; Fan, J. *Scientific Assessment of the Impact of Human Activities on the Ecological Environment of the Qinghai-Tibet Plateau*; China Meteorological Press: Beijing, China, 2023.
8. Yang, A.; Wang, Y.; Hu, J.; Liu, X.; Li, J. Evaluation and source of heavy metal pollution in surface soil of Qinghai-Tibet Plateau. *Huanjing Kexue* **2020**, *41*, 887–893.
9. Wang, L.; Mao, X.; Song, X.; Wei, X.; Yu, H.; Xie, S.; Zhang, L.; Tang, W. Non-Negligible ecological risks of urban wetlands caused by Cd and Hg on the Qinghai-Tibet Plateau, China. *Toxics* **2023**, *11*, 654. [\[CrossRef\]](#)
10. Zha, X.; Deng, L.; Jiang, W.; An, J.; Wang, H.; Tian, Y. Source analysis and distribution prediction of soil heavy metals in a typical area of the Qinghai-Tibet Plateau. *Ecol. Indic.* **2024**, *166*, 112460. [\[CrossRef\]](#)
11. Zha, X.; An, J.; Deng, L.; Gao, X.; Tian, Y. Risk assessment and source apportionment of heavy metals in the soil–water–grain system in a typical area of the central Qinghai–Tibet Plateau. *Ecol. Indic.* **2024**, *168*, 112801. [\[CrossRef\]](#)
12. Luo, J.; Feng, S.; Ning, W.; Liu, Q.; Cao, M. Integrated source analysis and network ecological risk assessment of soil heavy metals in Qinghai–Tibet plateau pastoral regions. *J. Hazard. Mater.* **2025**, *490*, 137780. [\[CrossRef\]](#)
13. Qi, J.; Lu, X.; Sai, N.; Liu, Y.; Du, W. Heavy metal concentrations in soil and ecological risk assessment in the vicinity of Tianzhu Industrial Park, Qinghai-Tibet Plateau. *PeerJ* **2024**, *12*, 18510. [\[CrossRef\]](#)
14. Qiao, D.; Wang, G.; Li, X.; Wang, S.; Zhao, Y. Pollution, sources and environmental risk assessment of heavy metals in the surface AMD water, sediments and surface soils around unexploited Rona Cu deposit, Tibet, China. *Chemosphere* **2020**, *248*, 125988. [\[CrossRef\]](#)
15. Wang, X.; Dan, Z.; Cui, X.; Zhang, R.; Zhou, S.; Wenga, T.; Yan, B.; Chen, G.; Zhang, Q.; Zhong, L. Contamination, ecological and health risks of trace elements in soil of landfill and geothermal sites in Tibet. *Sci. Total Environ.* **2020**, *715*, 136639. [\[CrossRef\]](#)

16. Zhang, T.; Wang, P.; Wang, M.; Liu, J.; Gong, L.; Xia, S. Spatial distribution, source identification, and risk assessment of heavy metals in riparian soils of the Tibetan plateau. *Environ. Res.* **2023**, *237*, 116977. [\[CrossRef\]](#)
17. Li, C.; Kang, S.; Chen, P.; Zhang, Q.; Mi, J.; Gao, S.; Sillanpää, M. Geothermal spring causes arsenic contamination in river waters of the southern Tibetan Plateau, China. *Environ. Earth Sci.* **2014**, *71*, 4143–4148. [\[CrossRef\]](#)
18. Yang, H.; Battarbee, R.; Turner, S.; Rose, N.; Derwent, R.; Wu, G.; Yang, R. Historical reconstruction of mercury pollution across the Tibetan Plateau Using lake Sediments. *Environ. Sci. Technol.* **2010**, *44*, 2918–2924. [\[CrossRef\]](#)
19. Li, Q.; Kang, X.; Xu, M.; Li, K.; Zhu, K. Hydrogeochemical processes of As enrichment and migration in the Surface's critical zone of the Shiquan River basin in the western Qinghai–Tibet Plateau. *J. Hydrol.* **2025**, *646*, 132305. [\[CrossRef\]](#)
20. Zhou, L.; Xu, Z.; Fan, P.; Zhou, J. Enrichment of arsenic in the Yarlung Tsangpo basin, Southern Tibetan Plateau: Provenance, process, and link with tectonic setting. *Appl. Geochem.* **2024**, *165*, 105964. [\[CrossRef\]](#)
21. Xiong, X.; Zhang, K.; Chen, Y.; Qu, C.; Wu, C. Arsenic in water, sediment, and fish of lakes from the Central Tibetan Plateau. *J. Geochem. Explor.* **2020**, *210*, 106454. [\[CrossRef\]](#)
22. Yang, A.; Xing, W.; Wang, X.; Hu, J.; Liu, X.; Li, J. Source and risk assessment of heavy metals in surface sediments of rivers, lakes and their surrounding soils in central Tibet. *China Environ. Sci.* **2020**, *40*, 4557–4567.
23. Wei, P.; Shao, T.; Wang, R.; Chen, Z.; Zhang, Z.; Xu, Z.; Zhu, Y.; Li, D.; Fu, L.; Wang, F. A study on heavy metals in the surface soil of the region around the Qinghai Lake in Tibet Plateau: Pollution risk evaluation and pollution source analysis. *Water* **2020**, *12*, 3277. [\[CrossRef\]](#)
24. Zhang, T.; Wang, M.; Bai, G.; Liu, J.; Li, P.; Zhang, Y.; Xia, S. Distribution characteristics, risk assessment, and source analysis of heavy metals in surface sediments and near-lakeshore soils of a plateau lake in China. *Gondwana Res.* **2023**, *115*, 191–200. [\[CrossRef\]](#)
25. Sheng, W.; Hou, Q.; Yang, Z. Distribution characteristics and ecological risk assessment of heavy metals in sediments from Xiang River. *China Environ. Sci.* **2019**, *39*, 2230–2240.
26. Wang, Y.; Ao, L.; Lei, B.; Zhang, S. Assessment of heavy metal contamination from sediment and soil in the riparian zone China's Three Gorges Reservoir. *Pol. J. Environ. Stud.* **2015**, *24*, 2253–2259. [\[CrossRef\]](#)
27. Lu, C.; Cao, Y.; Xia, Y.; Gu, Q.; Yi, W.; Zhang, Y.; Hua, Z.; Zhao, W. Analysis on the current heavy metal pollution situation in the riparian zone and river in the suburbs and urbans of Hulun Buir. *J. Earth Sci. Environ.* **2023**, *14*, 110–120.
28. Guan, X.; Fang, C.; Lu, S. Analysis of spatial distribution and gravity centers curve dynamic cultivated land changes in China. *J. Nat. Resour.* **2010**, *25*, 1997–2006.
29. Wang, L.; Liu, H. Quantitative evaluation of Tibet's resource and environmental carrying capacity. *J. Mt. Sci.* **2019**, *16*, 1702–1714. [\[CrossRef\]](#)
30. Telbisz, T.; Imecs, Z.; Mari, L.; Bottlik, Z. Changing human-environment interactions in medium mountains: The Apuseni Mts (Romania) as a case study. *J. Mt. Sci.* **2016**, *133*, 1675–1687. [\[CrossRef\]](#)
31. Chen, T.; Jiao, J.; Zhang, Z.; Lin, H.; Zhao, C.; Wang, H. Soil quality evaluation of the alluvial fan in the Lhasa River basin, Qinghai-Tibet Plateau. *Catena* **2022**, *209*, 105829. [\[CrossRef\]](#)
32. Fontes, J.C.; Gasse, F.; Gibert, E. Holocene environmental changes in Lake Bangong basin (Western Tibet). Part 1: Chronology and stable isotopes of carbonates of a Holocene lacustrine core. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1996**, *120*, 25–47. [\[CrossRef\]](#)
33. Hu, M.; Wang, Y.; Du, P.; Shui, Y.; Cai, A.; Lv, C.; Bao, Y.; Li, Y.; Li, S.; Zhang, P. Tracing the sources of nitrate in the rivers and lakes of the southern areas of the Tibetan Plateau using dual nitrate isotopes. *Sci. Total Environ.* **2019**, *658*, 132–140. [\[CrossRef\]](#)
34. Wen, Z.; Zheng, M.; Xu, X.; Liu, X.; Guo, G.; He, Z. Biological and ecological features of saline lakes in northern Tibet, China. *Hydrobiologia* **2006**, *541*, 189–203. [\[CrossRef\]](#)
35. Shao, Y.; Yan, B.; Liu, L.; Yu, X.; Feng, G.; Zhang, K.; Gong, K. Hydrochemical characteristics and quality evaluation of irrigation and drinking water in Bangong Co Lake watershed in Northwest Tibetan Plateau. *Water* **2023**, *15*, 2655. [\[CrossRef\]](#)
36. Lin, L.; Dong, L.; Wang, Z. Hydrochemical composition, distribution, and sources of typical organic pollutants and metals in Lake Bangong Co, Tibet. *Environ. Sci. Pollut. Res.* **2021**, *28*, 9877–9888. [\[CrossRef\]](#)
37. Yang, H.A.; Li, Z.Q.; Ye, B.S.; Jiao, K.Q. New result of glacier inventory in the drainage basins of the Bangong lake in china. *J. Glaciol.* **2003**, *25*, 685–691.
38. Shao, Y.; Yan, B.; Liu, X.; Jang, Q.; Chen, W.; Gong, K.; Yi, H.; Li, B. Characteristics and influencing factors of the hydrogen and oxygen isotopes in summer water bodies in the Bangong Lake Basin, Northwest Tibetan Plateau. *Geoscience* **2024**, *38*, 428–436.
39. Guo, G.; Zhi, J.; Ye, B. *Regional Geological Survey of 1:250,000 Ritu County, Tibet Autonomous Region (I44C003002)*; Jiangxi Institute of Geological Survey: Nanchang, China, 2004; pp. 20–120.
40. Yin, A.; Harrison, T.M. Geologic Evolution of the Himalayan-Tibetan Orogen. *Annu. Rev. Earth Planet. Sci.* **2000**, *28*, 211–280. [\[CrossRef\]](#)
41. Zhao, B.; Shi, R.; Zou, H.; Chen, S.; Huang, Q.; Sun, Y.L.; Yang, J. Intra-continental boninite-series volcanic rocks from the Bangong-Nujiang Suture Zone, Central Tibet. *Lithos* **2021**, *12*, 386–387. [\[CrossRef\]](#)

42. Liu, F.; Yang, J.; Lian, D.; Li, G. Geological features of Neothyan ophiolites in Tibetan Plateau and its tectonic evolution. *Acta Petrol. Sin.* **2020**, *36*, 2913–2945.
43. Li, H.L.; Gao, C.; Li, Z.H.; Zhang, Z.; Peng, Z.M.; Guan, J.L. Age and tectonic significance of Jingzhushan Formation in Bangong Lake Area, Tibet. *Geotecton. Metallog.* **2016**, *40*, 663–673.
44. DT/T 0295-2016; Specification of Land Quality Geochemical Assessment. China Standards Press: Beijing, China, 2016.
45. DT/T 0279-2016; Analysis Methods for Regional Geochemical Sample. China Standards Press: Beijing, China, 2016.
46. Mei, L. Research progress of geological reference materials in China. *Rock Miner. Anal.* **2023**, *42*, 445–463.
47. Tomlinson, D.L.; Wilson, J.G.; Harris, C.R.; Jeffrey, D.W. Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgolnder Meeresunters.* **1980**, *33*, 566–575. [[CrossRef](#)]
48. Angulo, E. The Tomlinson pollution load index applied to heavy metal, ‘mussel-watch’ data: A useful index to assess coastal pollution. *Sci. Total Environ.* **1996**, *187*, 19–56. [[CrossRef](#)]
49. Thurston, G.D.; Spengler, J.D. A quantitative assessment of source contributions to inhalable particulate matter pollution in metropolitan Boston. *Atmos. Environ.* **1985**, *19*, 9–25. [[CrossRef](#)]
50. Zhang, W.; Yan, Y.; Yu, R.; Hu, G. The sources-specific health risk assessment combined with APCS/MLR model for heavy metals in tea garden soils from south Fujian Province, China. *Catena* **2021**, *203*, 105306. [[CrossRef](#)]
51. Zhang, H.; Cheng, S.; Li, H.; Fu, K.; Xu, Y. Groundwater pollution source identification and apportionment using PMF and PCA-APCA-MLR receptor models in a typical mixed land-use area in Southwestern China. *Sci. Total Environ.* **2020**, *741*, 140383. [[CrossRef](#)]
52. Cheng, H.; Li, M.; Zhao, C.; Yang, K.; Li, K.; Peng, M.; Yang, Z.; Liu, F.; Liu, Y.; Bai, R. Concentrations of toxic metals and ecological risk assessment for sediments of major freshwater lakes in China. *J. Geochem. Explor.* **2015**, *157*, 15–26. [[CrossRef](#)]
53. Wedepohl, K.H. Ingerson lecture the composition of the continental crust. *Geochim. Cosmochim. Acta* **1995**, *59*, 1217–1232. [[CrossRef](#)]
54. Macdonald, D.D.; Ingersoll, C.G.; Berger, T.A. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Arch. Environ. Contam. Toxicol.* **2000**, *39*, 20–31. [[CrossRef](#)]
55. Sheng, J.; Wang, X.; Gong, P.; Tian, L.; Yao, T. Heavy metals of the Tibetan top soils Level, source, spatial distribution, temporal variation and risk assessment. *Environ. Sci. Pollut. Res.* **2012**, *19*, 3362–3370. [[CrossRef](#)] [[PubMed](#)]
56. Wang, G.; Zeng, C.; Zhang, F.; Zhang, Y.; Scott, C.; Yan, X. Traffic-related trace elements in soils along six highway segments on the Tibetan Plateau: Influence factors and spatial variation. *Sci. Total Environ.* **2017**, *581–582*, 811–821. [[CrossRef](#)] [[PubMed](#)]
57. Liu, X.; Yang, Z.; Shi, H.; Wu, T.; Yu, T.; Li, B.; Wang, L.; Shao, Y.; He, Z.; Xie, M.; et al. Identification of natural and anthropogenic factors in the spatial pattern of Pb in the surface soil of the Nanliu River Basin. *Ecotoxicol. Environ. Saf.* **2025**, *290*, 117601. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.