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Distribution and Sources of Chemical Elements in Lake Sediments: Evaluation of Anthropogenic and Natural Influences Through Multivariate Analysis in Umayo, Peru

Dante Salas-Ávila[1], **Fermín Francisco Chaiña-Chura**[1], **Germán Belizario-Quispe**[1], **Edgar Quispe-Mamani**[1], **Edgar Vidal Hurtado-Chávez**[1], **Félix Rojas-Chahuares**[1], **Ruth Meza-Duman**[1], **Dante Salas-Mercado**[1*]

[1]Research Institute of Metallurgy, Materials, and Environment, National University of Altiplano of Puno, 21000 Puno, Peru

Abstract

Introduction: Heavy metal contamination of water bodies poses an environmental risk, especially in high-mountain ecosystems that serve as basin headwaters. Sediments play a crucial role since they accumulate various elements that can be released into the water, affecting the quality of the aquatic environment. Many studies do not distinguish between pollution sources in tributaries/effluents and in lakes, which limits precise identification of their origins and behaviour and hinders effective pollution management.

Methods: The objective of this study was to determine the origin of chemical elements in the tributaries/effluent and interior of a high Andean lagoon. Metal samples (Fe, Al, Zn, Cu, Pb, Cr, Ni, As, Cd, and Hg) were collected, and principal component analysis (PCA) was used to identify sources of contamination.

Results: In the tributaries and effluent, Fe, Al, and Zn presented the highest concentrations, with Hg, Cd, and As amounts exceeding the risk thresholds at several points, especially Hg and Cd in the Vilque River. In the lagoon, significant accumulation of Hg and Cd was detected near the tributaries, and high concentrations of As were detected in several areas. The PCA explained 91.65% of the variance, differentiating anthropogenic sources (Hg, Cd, Cu, Zn) from natural sources (Al, Cr, Fe, Ni).

Conclusion: Tributaries transport pollutants, facilitating the accumulation of Hg and Cd in lagoon sediments. The results provide a better understanding of the behaviour of metals in the ecosystem and contribute to environmental management.

Keywords: Conservation of natural resources, Environmental monitoring, Lakes, Heavy metals, Principal component analysis

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***Correspondence to:**
Dante Salas-Mercado,
Email: dsalasm@unap.edu.pe

Introduction

Water quality and the health of aquatic ecosystems are influenced by the chemical composition of sediments (1), which can act as reservoirs of metals (2). Metal elements can be released into water under certain physicochemical conditions, affecting nutrient availability, environmental toxicity, and aquatic biodiversity (3). The accumulation of metals in sediments can result from natural processes, such as rock weathering and erosion, or from human activities, such as mining, agriculture, and the dumping of household waste (4,5).

Environmental studies on metal contamination have focused on comparing metal concentrations with international regulatory standards to assess their impact (6). Although this approach allows the identification of levels of risk, it presents important limitations since it does not provide sufficient information on the sources of the metals or their mobility within the aquatic ecosystem (7). In addition, many investigations do not differentiate between metals in tributaries/effluents and those accumulated in water-body sediments, making it difficult to understand their dynamics and the mechanisms that control their transport and retention (8,9).

In this context, heavy metals can be classified according to their origin as geological or anthropogenic. Elements such as Al, Fe, Cr, and Ni are commonly associated with local lithology. In contrast, others, such as Hg, Cd, Zn, Cu, and Pb, may have a mixed origins (10) since they are present not only in geological materials but also in residues, agricultural inputs, and metallurgical processes (1,11). Therefore, distinguishing between natural and anthropogenic sources is essential for designing effective mitigation and environmental management strategies.

The Umayo Lagoon, located in the Puno region of Peru is an ecosystem of ecological and cultural importance that faces metal contamination. Previous reports have documented high concentrations of metals in its tributaries, especially those associated with activities such as artisanal mining, ranching, and agriculture (12–14). However, these studies have not comprehensively addressed the differentiation of pollution sources or evaluated the relationships between metals in tributaries/effluents and their accumulation in lagoon sediments.

Principal component analysis (PCA) is a statistical tool that reduces the dimensionality of data and reveals patterns in metal distribution in the environment (15). Its application in pollution studies has proven effective for identifying correlations among metals, discriminating pollution sources, and understanding their mobility in aquatic ecosystems (16,17). However, most investigations based on this methodology do not separate metals according to their behaviour in tributaries/effluents and in the interior of water bodies, which could lead to erroneous interpretations of the true sources of contamination and the processes that determine metal accumulation.

Therefore, the main objective of this study is to determine the concentrations and origins of elements in the sediments of the Umayo Lagoon and its tributaries/effluents through PCA. This approach will overcome the limitations of previous studies, providing a more precise evaluation of heavy metal behaviour in the ecosystem and facilitating the design of environmental monitoring and management strategies in the region.

Materials and Methods

Description of the study area

The Umayo Lagoon (15° 44’34” S, 70° 11’23” W) is located in the Puno region, Peru, west of Lake Titicaca (18), at an altitude of 3844 meters above sea level and with an approximate area of 35.38 km^2 (19). It is classified as an endorheic system, where water loss occurs mainly through evaporation, with little natural outflow (20). The lagoon is home to Umayo Island, which is part of the Sillustani Archaeological Complex, a site of substantial tourist interest for its conservation of pre-Inca chullpas, the funerary structures of the Kolla culture (21). From a geological point of view, the microbasin presents lithostratigraphic units with deposits dating from the Middle Cretaceous to the Neogene Quaternary (22). The main geological formations include the Moho Group, the Barroso Group, and fluvioglacial deposits, with the latter predominating (23–25). The hydrographic network of the lagoon consists of seven tributaries, among which those with the greatest and continuous flow are the Challamayo, Ccaccapunco, and Vilque rivers. As the only effluent, the Llungo River intermittently connects to Lake Titicaca via the Illpa River (26).

The main economic activities in the area depend on the lake’s ecosystem and its natural resources. Livestock include cattle, sheep, and South American camelids, resulting in the production of dairy products such as artisan cheese (23). The agricultural activity includes the cultivation of crops such as potatoes, quinoa, cañihua, and forage oats, as well as the harvest of plant species such as totora, llacho, and chara, which are used in animal feed, and the manufacturing of construction materials (26). Artisanal fishing is based on the capture of carachi and silverside and contributes to food security and the local economy (26). Similarly, mining exploitation focuses on the extraction of gold minerals and the recovery of mining burdens, using mercury in refining processes (27).

Sample collection and treatment

Following the National Protocol for the Monitoring of Surface Water Resources of Peru (28), sampling points were established in the tributaries (B, C, D, E, F, G, H), located 50 meters before the entrance, and in the effluent (A) of the lagoon, after the discharge. In addition, 23 sampling stations were set in the water body following the methodology of (29–31), which uses parallel transects to cover the entire lagoon; sediments were collected using an Ekman dredge (Figure 1).

Sampling was conducted during the dry season (June 2024), when the lagoon’s water level is relatively stable, and runoff inputs are minimal. At each station, 250 g of superficial sediment (0–5 cm deep) was collected, sieved through a 230 μm nylon mesh, packed in polyethylene bags, and stored at 4 °C in a cooler with cold packs until analysis in the laboratory.

Metal analysis was carried out at the accredited laboratory ALS CorpLAB using acid digestion and inductively coupled plasma–optical emission spectrometry (ICP-OES), according to the EPA 3050B and EPA 6010D methods. The cold vapour method (EPA 7471B) was used for mercury quantification. Quality assurance and quality control (QA/QC) were ensured through the analysis of certified reference materials (CRMs), method blanks, and sample duplicates to verify the precision and accuracy of the analytical procedures.

Element concentrations in sediments

To evaluate the quality of the sediments in the study area, the concentrations of Fe, Al, Zn, Cu, Pb, Cr, Ni, As, Cd, and Hg were analysed, among which only As, Cd, Cu, Hg, Pb, and Zn are regulated by the Canadian Sediment Quality Guidelines for the Protection of Aquatic Life (32). This guideline establishes two thresholds: the threshold effect level (ISQG), which indicates concentrations that can produce occasional negative effects on aquatic organisms, and the probable effect level (PEL), which represents concentrations where adverse impacts on the ecosystem are highly probable.

Since the mentioned guidelines do not include thresholds for Fe, Al, Cr, or Ni, their evaluation was

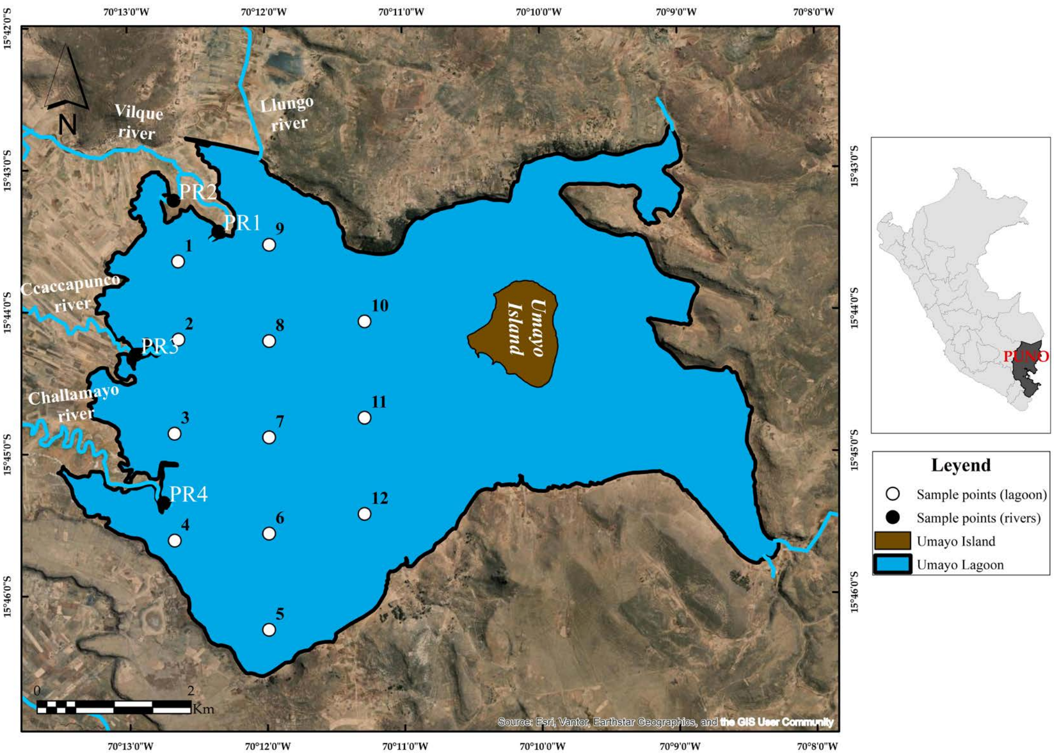

Figure 1. Sampling point locations in influent/effluent streams and within the Umayo Lagoon

based on their geochemical background values, using references established by Turekian and Wedepohl (33) and complemented with information from the Regional Government of Puno (34). Although these metals are not considered priority pollutants under the regulations considered, their presence and variability may indicate geogenic processes or sources of anthropogenic contamination (35).

Identification of pollution sources

To identify the sources of contamination, PCA, which is a procedure that evaluates the underlying structure of data and reduces the dimensionality of the set of variables, was used (15). First, the adequacy of the analysis was verified using the Kaiser-Meyer-Olkin (KMO) index and Bartlett's sphericity test. According to (36), the acceptability levels are as follows: KMO < 0.5, unacceptable; 0.5–0.6, low adequacy; 0.6–0.7, acceptable; 0.7–0.8, good fit; 0.8–0.9, very good fit; and ≥ 0.9, excellent. For the Bartlett test, a p-value < 0.05 indicated that the correlations between variables are sufficient to apply PCA.

Given that the data present different scales and variations, a preliminary standardization step was carried out, in which all the variables were transformed to Z-values, which were calculated according to the following equation:

$$Z = \frac{X_{\mathrm{i}} - X_{\mathrm{avg}}}{X_{\mathrm{std}}}$$

where X_{i} is the value of the variable in a given sample, X_{avg} is the average of the variable, and X_{std}. is the standard deviation of the variable. This transformation guarantees that each variable has a mean of zero and a unit variance, preventing those with higher magnitudes from disproportionately influencing the analysis.

Subsequently, the eigenvectors and eigenvalues of the compensation matrix were calculated to obtain the main components. Each principal component (PC) is expressed as a linear combination of the original variables:

$$PC_k = W_{1,k}X_1 + W_{2,k}X_2 + W_{3,k}X_3 + \cdots + W_{p,k}X_p$$

where PC_k represents the main K-component, X_1 represents the original variables, and $W_{1,k}$ represents the load vectors (coefficients of each variable in the PC). The number of components retained was determined following two criteria: first, at least 70% of the total variance had to be explained, and second, the Kaiser rule, which was used for components with eigenvalues greater than 1 (4). The obtained load vectors indicate the contribution of each variable to each component. These charges are interpreted as positive or negative as follo: > 0.6, moderate; > 0.8, strong (37).

Results

Concentrations of chemical elements in the sediments of the tributaries/effluent of the Umayo Lagoon

The tributaries, particularly the Vilque River (points B and C), were identified as significant point sources of anthropogenic Hg and Cd. Table 1 shows that the total concentrations of metals in the sediments of the tributaries and effluents of Umayo Lagoon decreased in the following order by sampling point: A > G > F > B > E > C > D > H. The first three points presented the highest contributions of Al and Fe. When the concentrations of each metal were averaged across all points, the order was as follows:

Table 1. Concentrations of chemical elements in sediments of the tributaries/effluent of Umayo Lagoon (mg/kg)

Sample Points	Hg	Al	As	Cd	Cr	Cu	Fe	Ni	Pb	Zn
A	0.05	15976	11.50	1.10	26.80	40.50	24935	29.80	28.80	134.70
B	0.76	11228	14.30	1.90	18.80	46.70	21675	29.70	40.60	182.80
C	0.62	9357	12.20	1.60	17.90	43.40	20039	22.90	37.90	167.10
D	0.07	11361	3.60	1.10	12.00	25.00	16662	1.00	26.90	98.00
E	0.08	13083	3.60	0.90	13.00	25.00	18839	1.00	33.90	110.00
F	0.11	19803	3.60	0.30	23.90	28.10	17470	16.00	3.00	68.90
G	0.07	19685	3.60	0.30	29.90	28.40	17785	15.90	25.90	64.90
H	0.04	7085	36.00	0.30	12.90	27.00	13970	1.00	24.90	33.40
Min	0.04	7085	3.60	0.30	12.00	25.00	13970	1.00	3.00	33.40
Max	0.76	19803	36.00	1.90	29.90	46.70	24935	29.80	40.60	182.80
Average	0.23	13447	11.05	0.94	19.40	33.01	18922	14.66	27.74	107.48
SD	0.29	4665	11.06	0.61	6.82	8.95	3339	12.46	11.54	51.90
ISQG *	0.17	---	5.90	0.60	37.30	35.70	---	---	35.00	123.00
PEL **	0.49	---	17.00	3.50	90.00	197.00	---	---	91.30	315.00
Carbonates ***	0.04	4200	1.00	0.04	11.00	4.00	3800	20.00	9.00	20.00

Fe > Al > Zn > Cu > Pb > Cr > Ni > As > Cd > Hg. The highest concentrations of Hg were recorded at points B and C, which are located on the Vilque River. In both cases, the levels exceeded both the base value of the local lithology and the PEL. The highest As concentration was observed at point H, which exceeded both the base value and the PEL. The Cd concentration exceeded the ISQG at points B and C (Vilque River), D (Ccapunco River), E (Challamayo River), and A (Llunga effluent). Similarly, the concentrations of the metals Cu, Pb, and Zn exceeded the ISQG at points B and C of the Vilque River. The concentrations of Al, Cr, Fe, and Ni were higher than the base values at various sampling points, suggesting high contents, even in the absence of clear anthropogenic contributions.

Concentrations of chemical elements in sediments in the Umayo Lagoon

The spatial distribution of metals in the Umayo Lagoon indicates accumulation zones in the northern and central sectors, particularly for Cd, Cu, Pb, and Zn. Table 2 shows that the total concentrations of metals in sediments in the Umayo Lagoon, in descending order by sampling point, were as follows: L9 > L1 > L15 > L16 > L10 > L12 > L13 > L18 > L11 > L2 > L17 > L4 > L3 > L8 > L20 > L19 > L21 > L6 > L5 > L7 > L23 > L22 > L14. In terms of the average concentrations of each metal across all points, the order was as follows: Fe > Al > Zn > Cu > As > Ni > Pb > Cr > Cd > Hg.

Hg reached its highest value in L1, exceeding both the base value and the PEL; a concentration close to the latter was recorded in L9. As reached a maximum at L15, with a value above both the base value and the PEL. Furthermore, the points near the northern, southern, and eastern shores had levels above the PEL and ISQG. The highest concentration of Cd was detected at L2, exceeding the maximum threshold. Similarly, the concentrations at L1, L3, L7, L8, and L9 exceeded the ISQG, indicating an accumulation zone towards the interior of the lagoon. Cu, Pb, and Zn reached their peaks at L9, with values above the base value and ISQG, and high levels were also detected at L1, L10, and L15. Moreover, Al, Cr, Fe, and Ni exceeded the base values at several points, indicating a generalized distribution in the sediments.

Identification of sources of contamination in the tributaries/effluents of the Umayo Lagoon

The PCA revealed two main groups of elements: one linked to anthropogenic sources (Hg, Cd, Cu, and Zn) and another associated with natural lithological contributions (Fe, Al, Cr, and Ni). Table 3 shows the results of the PCA of the metal concentrations in the sediments of tributaries and effluents of Umayo Lagoon, revealing three principal components with eigenvalues greater than 1, which together explained 91.65% of the total variance. The Kaiser-Meyer-Olkin (KMO) sample adequacy test yielded a global and individual value of 0.5, within the ranges reported in environmental studies, indicating the applicability of the analysis.

The first component (PC1) explained 51.78% of the variance and was strongly correlated with Hg, Cd, Cu, and Zn. The second component (PC2) explained 29.15% of the variance and reflected a different grouping, dominated by elements related to the lithological matrix. Unlike PC1, this component included metals typically associated with natural sources. The third component (PC3) explained 10.72% of the variance and was mainly associated with As, with a moderate load, as well as minor associations with Cr and Ni.

Identification of sources of contamination of chemical elements in sediments in the Umayo Lagoon

The PCA of the lagoon sediments indicated two main controlling factors: one representing the joint distribution

Table 2. Concentrations of chemical elements in sediments in the Umayo Lagoon (mg/kg)

Sample Points	Hg	Al	As	Cd	Cr	Cu	Fe	Ni	Pb	Zn
L1	0.64	14839	16.9	2	18.9	69.6	25412	31.8	54.7	233.1
L2	0.12	11850	3.6	4.4	13	36.1	19005	15	29.9	129.3
L3	0.06	12421	3.6	1	11	20.8	15693	1	28.9	81.5
L4	0.06	12699	3.6	0.3	11.9	19.6	17881	1	28.8	88.4
L5	0.08	3442	17.1	0.3	1	15.9	3407	1	3	22.6
L6	0.05	8389	3.6	0.3	9	12	14609	1	3	56.7
L7	0.08	3016	3.6	0.3	1	22.1	3804	1	3	26.1
L8	0.23	12314	17.6	0.9	11	50.8	15312	19	3	130.6
L9	0.41	16736	19.2	1.8	19	76.1	25829	34	57	245.6
L10	0.26	15794	26.7	1.1	16.9	56.4	19108	24.8	41.7	124.2
L11	0.26	14507	28.8	0.3	14.9	47.3	17251	19.8	37.7	97.9
L12	0.21	15505	30	1	16	47.9	17078	20.9	31.9	95.3
L13	0.22	15059	25.7	0.8	14.9	46.4	16746	19.9	31.9	95.3
L14	0.1	3	3.6	0.3	1	0.8	3.3	1	3	0.6
L15	0.25	17607	32.2	1.4	18.9	61.5	19687	24.8	40.7	137.9
L16	0.18	16374	30.3	1.4	20	46.4	19776	23	30	105.5
L17	0.19	14153	23.7	0.8	15	43.7	16383	21	33	93.8
L18	0.19	14529	28	0.9	14.9	46.1	17205	19.9	35.8	94.1
L19	0.19	12079	25.3	0.3	12.9	37.6	14575	17.9	26.8	78
L20	0.18	13363	29.1	1	14.9	40.5	15199	19.8	28.8	77
L21	0.17	11914	24.2	0.8	14	38.3	15172	17	36.9	89.1
L22	0.07	2100	16.5	0.3	1	13.4	2367	5	3	18.3
L23	0.05	2272	<3.6	0.3	1	16.3	2289	1	3	16.2
Min	0.05	3.00	3.60	0.30	1.00	0.80	3.30	1.00	3.00	0.60
Max	0.64	17607	32.20	4.40	20.00	76.10	25829	34.00	57.00	245.60
Average	0.18	11346	18.77	0.96	11.83	37.63	14513	14.81	25.89	92.92
SD	0.13	5355	11.02	0.91	6.44	19.59	7174	10.80	17.16	60.39
ISQG *	0.17	---	5.90	0.60	37.30	35.70	---	---	35.00	123.00
PEL **	0.49	---	17.00	3.50	90.00	197.00	---	---	91.30	315.00
Carbonates ***	0.04	4200	1.00	0.04	11.00	4.00	3800	20.00	9.00	20.00

Table 3. Main components in sediments in the tributaries/effluent of the Umayo Lagoon

Elements	PC1	PC2	PC3
Hg	0.85	–0.20	0.05
Al	–0.24	0.95	–0.12
As	–0.03	–0.62	0.77
Cd	0.92	–0.25	–0.25
Cr	0.10	0.91	0.32
Cu	0.95	0.09	0.30
Fe	0.77	0.46	–0.05
Ni	0.78	0.52	0.33
Pb	0.71	–0.46	–0.16
Zn	0.96	–0.01	–0.25

Table 4. Main components of sediments inside the Umayo Lagoon.

Elements	PC1	PC2
Hg	0.82	0.03
Al	0.92	–0.11
As	0.63	–0.70
Cd	0.53	0.71
Cr	0.95	–0.07
Cu	0.96	–0.08
Fe	0.93	0.15
Ni	0.95	–0.15
Pb	0.91	0.03
Zn	0.92	0.28

of lithogenic and anthropogenic metals, and another dominated by Cd as an independent source. Table 4 shows the results of the PCA of the metal concentrations in sediments from the Umayo Lagoon, revealing two principal components with eigenvalues greater than 1, which together explained 86.09% of the total variance in the data. The KMO sampling adequacy test yielded an overall value of 0.83, with individual values ranging from

0.76 to 0.97, indicating that the data are suitable for this multivariate analysis.

PC1 explained 74.64% of the variance and was strongly associated with the elements Al, Cr, Cu, Fe, Ni, Pb, Zn, and Hg. This indicates that these metals share a common distribution in sediments. PC2 explained 11.45% of the variance and was dominated by Cd.

Discussion

Concentrations of chemical elements in sediments of the tributaries/effluent of the Umayo Lagoon

Table 1 shows that the high concentrations of Hg at points B and C are probably explained by the confluence of two sources: an anthropogenic source, related to artisanal gold mining, in which Hg (38,39), and a natural source. The natural source is derived from the volcanic rocks of the Barroso Group, which contain heavy metals such as Hg, As and Sb, which are products of hydrothermal processes of high sulfidation (40,41).

The high As concentration at point H is mainly due to local geology. Arsenic is present in the matrix of the rocks of the Barroso Group, which originated from volcanic and hydrothermal activity during the Pliocene–Pleistocene. As is released into the environment through weathering and the erosion of secondary minerals such as oxides and sulfides (34,40,42,43). In addition, agricultural practices contribute to the mobilization of As in the environment (44). The high distribution of Cd in several tributaries coincides with areas of artisanal cheese production. This process generates whey, a byproduct that can contain 12%–14% of the Cd in cow milk (45). This residue, which is commonly disposed of in soils or bodies of water, is washed away by runoff in the rainy season and accumulates in water sources during dry periods (46,47).

Cu, Pb, and Zn exceeded the ISQG limits at points B and C of the Vilque River and could also have a mixed origin. On the one hand, the anthropogenic sources could include the use of fertilizers in agriculture and the leaching of solid waste; on the other hand, regional geology could be a source, since the area lies within the metallogenic domain of southern Peru, where these metals are common (40). Agricultural work, such as ploughing, can facilitate the mobilization of these substances (39). Finally, the high concentrations of Al, Cr, Fe, and Ni are closely related to the local geology, particularly the volcanic formations of the Barroso Group previously described in the Study Area section (40,48). These results are consistent with geochemical studies in the region, which reported high concentrations of these elements in volcanic rocks (41).

Concentrations of chemical elements in sediments in the Umayo Lagoon

Table 2 shows a high concentration of Hg at point L1 and a value close to the PEL value at point L9, indicating possible accumulation of this metal in that area. This could be due to Hg entering the lagoon from the Vilque River, which crosses areas with mining/metallurgical activity, and to its subsequent redistribution within the lagoon, which is influenced by hydromorphological factors. The gold recovery activity through amalgamation in these areas could explain this contribution (49). In addition, the values at points L10, L15, and L16, which are adjacent to formations of the Barroso Group and located in steep-slope areas, also exceed the ISQG, suggesting a combined contribution from natural and anthropogenic sources.

The presence of As can be explained by its natural geological origin, linked to the erosion of volcanic rocks of the Barroso Group (as described earlier) (Figure 1). This mobilization can be attributed to rain-induced soil microfracturing and slope (36), as well as to soil removal for agricultural purposes (50), thereby generating an ecological risk of natural origin. With respect to Cd, the accumulation zone around point L2 and the surrounding high values could be attributed to contributions from the Ccaccapunco River and the Vilque River. These basins cross areas with artisanal cheese production, where fertilizers are used to improve forage and increase milk production. Among the fertilizers, phosphate rock-derived foliar fertilizer is common and contains cadmium as an impurity (51–53).

The higher concentrations of Cu, Pb, and Zn at L9 and neighbouring points, such as L1, L10, and L15, could be explained by their proximity to areas with steep slopes within the regional metallogenetic domain. These metals could be transported toward the interior of the lagoon by surface erosion of material rich in metallic minerals. In addition, the widespread presence of Al, Cr, Fe, and Ni above the base values confirms their natural origins. These elements are commonly present in the region's volcanic formations, particularly in the Barroso Group, supporting the hypothesis of a dominant geological source.

Identification of sources of contamination in the tributaries/effluent of the Umayo Lagoon

The results of the PCA presented in Table 3 revealed groupings of metals of anthropogenic and natural origin, clarifying the sources of contamination in the tributaries and effluents of the Umayo Lagoon. The first component, dominated by Hg, Cd, Cu, and Zn, suggests a mainly anthropogenic origin. Hg is associated with the use of mercury in artisanal gold mining activities such as amalgamation with quimbaletes and mills (36). Cd is linked to the application of foliar fertilizer to livestock feed and to the incorrect disposal of whey. Cu and Zn are also related to foliar fertilizer use, as they are part of its chemical composition (53,54).

The second component, represented mainly by Al and Cr and, to a lesser degree, by Fe and Ni, suggests a natural origin linked to local geology, especially to the volcanic formations of the Barroso Group. In this context, Al and Cr are mobilized by erosion processes, while Fe and Ni are associated with surface removal from the soil. The third component, which is moderately associated with As and to a lesser extent with Cr and Ni, indicates a mixed source. Although As has a geological origin, it could be influenced by agricultural activities that transport it from soil to bodies of water (12).

Identification of sources of contamination of chemical elements in sediments in the Umayo Lagoon

Table 4 shows that PC1 reflects a mixture of natural and anthropogenic sources for the detected metals. The metals Al, Cr, Fe, and Ni, which presented strong associations with this component, have a mainly natural origin, linked to the local geology. These metals are mainly derived from the volcanic formations of the Barroso Group, previously characterized in the geological context (12,40). These findings agree with those of previous studies and with the observed distribution in the lagoon.

On the other hand, the association of Cu, Pb, Zn, and Hg with PC1 indicates human influence. Cu and Zn are likely derived from agricultural activities, specifically from the use of fertilizers and pesticides that contain these metals as impurities (55–57). Pb could be related to the use of additives in nearby fuels and lubricants or to the mobilization of contaminated soil (58). In addition to Hg being naturally present in rocks, it is likely to have an anthropogenic source, probably associated with artisanal gold mining, which uses Hg and has been documented as a significant source of contamination in the area. (59,60).

PC2 is dominated by Cd, indicating that its presence in sediments is attributable mainly to human sources. Evidence suggests that this metal is introduced into the ecosystem through artisanal cheese production and the application of foliar fertilizers for cattle feed, which can promote the mobilization of cadmium into water bodies (60,61).

The conceptual diagram illustrates the main natural and anthropogenic sources contributing to the input and accumulation of heavy metals in the Umayo Lagoon. The Vilque River, originating in areas influenced by artisanal gold mining, agriculture, and fertilizer use, serves as a major pathway for transporting Hg, Cd, Cu, Zn, and Pb. The Ccaccapunco and Challamayo Rivers, primarily affected by agricultural activities and fertilizer runoff, contribute Cd, Cu, and Zn to the lagoon. Additionally, the Barroso Group provides a natural source of metals such as Fe, Al, Cr, Ni, and As, derived from weathering and volcanic erosion. All these inputs converge into the Umayo Lagoon, where metals accumulate in surface sediments, reflecting the combined influence of mining, agricultural, and geogenic processes (Figure 2).

Conclusion

The tributary sediments show variable concentrations of Fe, Al, Zn, Cu, Pb, Cr, Ni, As, Cd, and Hg, with the highest levels in the Vilque River (points B and C). Exceedances of Hg over ISQG and PEL limits indicate inputs from artisanal gold mining, while Cd enrichment is associated with cheese production and fertilizer use. As shows a mixed origin, mainly geogenic from the Barroso Group, but its mobilization may be enhanced by agricultural activities.

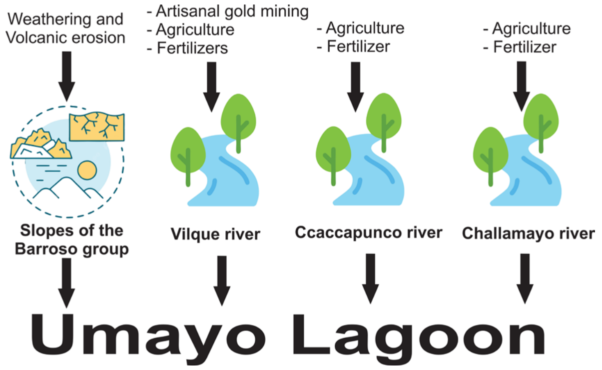

Figure 2. Conceptual diagram of metal transport pathways towards the Umayo Lagoon

The Umayo Lagoon's sediments are rich in Hg, Zn, Cu, Pb, and Cd, especially at L1 and L9, confirming that the Vilque River is the main entry route for pollutants. The spatial distribution of Hg exceeding PEL values reflects environmental risk and dispersion by hydromorphological processes. The presence of As and Cd at L15 and L2, respectively, denotes both natural and anthropogenic influences.

The Barroso Group slopes contribute Al, Fe, Cr, Ni, and As to the system through weathering and volcanic erosion. These metals represent the natural geochemical background, although agricultural activities may increase their mobilization and input into tributary streams.

The PCA results confirm that Hg, Cd, Cu, Zn, and Pb have anthropogenic origins, linked to mining, agriculture, and cheese production, with the greatest impact in the Vilque River and northern lagoon sectors. Conversely, Al, Fe, Cr, and Ni are of geological origin, while As shows a mixed source, reflecting both natural erosion and human influence. Overall, tributaries serve as the primary transport routes, facilitating the accumulation of metals in lagoon sediments.

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Authors' Contribution

Conceptualization: Dante Salas-Ávila, Fermín F. Chaiña-Chura, Dante Salas- Mercado
Data Curation: Germán Belizario-Quispe And Dante Salas-Mercado
Formal Analysis: Dante Salas-Ávila, Fermín F. Chaiña-Chura
Funding Acquisition: Dante Salas-Ávila
Investigation: Dante Salas-Ávila, Fermín F. Chaiña-Chura, Germán Belizario-Quispe, Edgar Quispe-Mamani, Edgar V. Hurtado-Chávez, Félix Rojas-Chahuares, Ruth Meza-Dumán, Dante Salas-Mercado
Methodology: Dante Salas-Mercado, Edgar Quispe-Mamani, Edgar V. Hurtado-Chávez, Félix Rojas-Chahuares
Project Administration: Dante Salas-Ávila
Resources: Dante Salas-Ávila.
Software: Dante Salas-Mercado
Supervision: Dante Salas-Ávila, Fermín F. Chaiña-Chura, Germán Belizario-Quispe
Validation: Dante Salas-Ávila

Visualization: Dante Salas-Ávila, Edgar Quispe-Mamani.
Writing - Original Draft: Dante Salas-Ávila, Fermín F. Chaiña-Chura, Germán Belizario-Quispe, Edgar Quispe-Mamani, Edgar V. Hurtado-Chávez, Félix Rojas-Chahuares, Ruth Meza-Dumán, Dante Salas-Mercado
Writing - Review & Editing: Dante Salas-Ávila, Edgar Quispe-Mamani, Edgar V. Hurtado-Chávez, Félix Rojas-Chahuares, Ruth Meza-Dumán, Dante Salas-Mercado

Competing Interests

The authors declare that there are no known financial interests or personal relationships that could have influenced the results presented in this article.

Ethical Approval

The authors declare that the data presented in this manuscript reflect selected aspects of the research, analysed from a specific perspective. The dataset is sufficiently comprehensive to enable complementary analyses that support the findings presented herein.

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