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Evaluation of Heavy Metal Contamination in Sediments of the Umayo Lagoon, Peru, and the Behaviour of Local Actors

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ABSTRACT

Multidisciplinary studies that integrate socioenvironmental aspects into the assessment of water resources contamination significantly enhance the identification of its sources. In the present study, an assessment of heavy metal contamination in sediments of Umayo Lagoon and the behavior of local actors was conducted. The concentrations of As, Cd, Cu, Hg, Pb, and Zn were determined and evaluated using international regulations. These data enabled the creation of distribution maps to pinpoint accumulation zones of different metals and suggest their possible sources of origin. The results were compared with the behavior of local actors, addressing three analytical characteristics: feelings, thoughts, and attitudes. Evidence showed contamination by As (18.11 mg/kg), Hg (0.19 mg/kg), and Cd (0.96 mg/kg), likely originating from mining activities, cheese plants, and agriculture. In terms of social aspects, intense emotions were expressed due to the presence of diseases and livestock mortality associated with metal contamination, causing anxiety and fear in the population. The incorporation of socioenvironmental aspects in the contamination assessment aligned with the physicochemical results, achieving identification of the sources of Umayo Lagoon.

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INTRODUCTION

The availability and protection of water are fundamental global issues due to the importance of water for humanity and ecosystems (Taipale *et al.,* 2016). Both the quantity and quality of water are commonly used to evaluate these resources, which are highly susceptible to human influence (J. Li *et al.,* 2020). The degradation of water quality can be manifested as a direct or indirect response to pollution, which affects the chemical composition, accumulation of microorganisms, nutrient imbalance and transport of sediments in aquatic systems (López *et al.*, 2013).

Bottom sediments have the ability to accumulate pollutants, either by natural processes such as weathering or erosion or by human activities. Studies have shown the presence of polluting elements in the sediments of water sources such as rivers and lakes (Achi *et al.*, 2021; M. Li *et al.*, 2019; Liu *et al.,* 2016). These sedimentary deposits are important because they allow us to

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monitor pollutants since they act as reservoirs of these substances in the aquatic environment, generating a significant ecological impact on water sources (M. Li *et al.,* 2020). Pollutants are released from sediments and incorporated into the water column in response to atmospheric disturbances, causing concern about the environmental state and its repercussions on human health (He *et al.,* 2019).

Safeguarding human health and the environment requires meticulous synchronization between scientific analysis and community knowledge (Quispe-Mamani, 2021). This combination of approaches involves constant monitoring of pollutants to precisely identify their origins (Lv *et al.*, 2019; Rangecroft *et al.,* 2023) and enables early recognition and effective mitigation of environmental risks, contributing to the well-being of local populations (Blackstock *et al.,* 2020). However, little research integrating social behaviour and environmental monitoring to strengthen the identification of sources of contamination has been conducted (Ferreira-Rodríguez *et al.,* 2021).

Socio-environmental analysis of contamination focuses on the social behaviour of local actors, considering dimensions that include emotional states (Phiri *et al.,* 2023; Sigé *et al.,* 2004), the thoughts generated by social interaction and behaviours such as the actions taken in response to a phenomenon (Ritzer, 1993). Pro-environmental and pro-social behaviours are influenced by environmental awareness, beliefs in positive control, personal responsibility, scarcity of resources, and perceived threats to life and personal health (Phiri *et al.,* 2023; Sigé *et al.,* 2004).

A study carried out in Lake Tanganyika in the Democratic Republic of the Congo reported that problems were produced due to a lack of adequate monitoring, resulting in policies that led to a decrease in biodiversity and water quality due to contamination by human activities (Phiri *et al.,* 2023). To address these problems, multidisciplinary research that integrates social behaviour and the experience of experts is needed (Phiri *et al.,* 2023). According to (Rangecroft *et al.,* 2023), it is important to incorporate commnuity-level socio-environmental factors in environmental monitoring to optimize water management and environmental policies.

The Umayo Lagoon in southern Peru is an important tourist attraction due to its proximity to an Inca cemetery (Sigé *et al.,* 2004). However, it faces pollution-related problems that affect the population that depends on it. The pollution represents a risk for local populations that rely on the lagoon for consumable water and income (Republica, 2020). The local community is demanding that public institutions concerned with the environment take action, as it has been observed that sheep are dying, with the deaths being attributing to the contamination of the lagoon by heavy metals (Proactivo, 2020). Nevertheless, research focused on this lagoon is scarce, and some reports indicate that there is no contamination in its water (De la cruz Toribio & Lazo Solano, 2020; Vilca Quispe, 2022).

The objective of this study was to evaluate the contamination of heavy metals in the sediments of the Umayo Lagoon by identifying contaminants and assessing the behaviour of local actors. The incorporation of social factors in the evaluation of the contamination of the Umayo Lagoon provided information that was used to identify the sources of the heavy metal pollutants. The results from both quantitative approaches suggest that mining, cheese production and agricultural activities have impacts on the quality of the water in the Umayo Lagoon.

METHODS AND MATERIALS

Description of Study Area

The Umayo Lagoon (15° 44’ 34” S and 70° 11’ 23” W) is located to the west of Lake Titicaca (SE Peru) in the Puno region, as shown in Figure 1. The lagoon has an area of 35.38 km^2 (Autoridad Nacional del Agua (ANA), 1979). In addition, in the Umayo lagoon, there is an island of the same name that is part of the Sillustani Archaeological Complex, an important tourist centre in Puno (Sigé *et al.,* 2004).

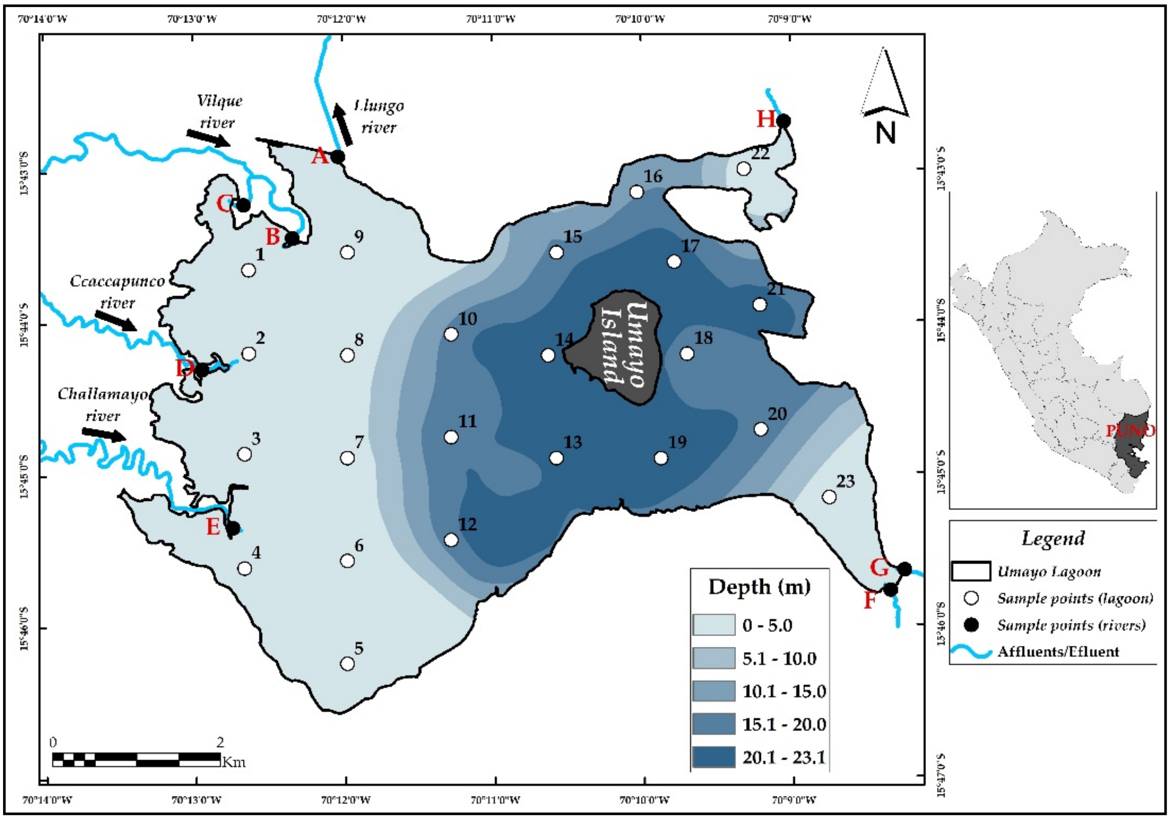

Fig. 1. Location of the sampling points in the Umayo Lagoon., distribution of sample sites in tributaries (B, C, D, E, F, G, H), effluent (A) and inside Umayo lagoon (from 1 to 23).

The Umayo Lagoon has seven tributaries, of which three have permanent flow: Challamayo (E), Ccaccapunco (D) and Vilque (B and C). The Llungo River is the only effluent from the lagoon. In the area, four economic activities developed by the rural population are common: the raising of sheep, South American camelids and cattle ((CEDER), 2015), with cattle being used for the production of artisanal milk and cheese; agriculture, including the cultivation of potatoes, quinoa, cañihua and oats, with oats being used to feed livestock; carachi and silverside fishing, which is carried out by the artisanal fishermen associations of the neighbouring communities; and mining characterized by the exploitation of gold minerals, with the reuse of mining materials, one of which is mercury (SMRL Los Rosales). The geology of the Umayo Lagoon microbasin ranges from the Middle Cretaceous to the Neogene Quaternary (Gobierno Regional de Puno (GRP), 2015), with three main lithostratigraphic units: the Moho group, the Barroso group and the fluvioglacial deposits (Autoridad Nacional del Agua (ANA), 1979; Sigé *et al.,* 2004).

Collection and treatment of samples

Following the National Protocol for the Monitoring of Surface Water Resources of Peru (PNMRH) (ANA, 2016), sampling points were established in the tributaries (B, C, D, E, F, G, H) and in the effluent of the Umayo Lagoon (A) at a distance of 50 m before the mouth (Figure 1). In addition, 23 sampling points were established inside the lagoon following the methodology used by (Salas-Mercado *et al.,* 2023a; Y. Wang *et al.,* 2015), which consists of drawing parallel transects to cover the entire surface of a waterbody and using an Ekman dredge for collection. At all the sampling points, 250 g of surface sediment (5 cm) was collected. The samples were sifted through a 230 μm nylon mesh screen, stored in polyethylene bags, and kept in a cooler with icepacks at 4 °C until further processing and analysis in the laboratory. Likewise, depth data were measured in the Umayo Lagoon (Figure 1).

To determine the concentrations of heavy metals in sediments, the samples were analysed by the internationally accredited ALS CorpLAB laboratory by acid digestion and subsequent analysis by atomic emission spectrometry-inductively coupled plasma (ICP–OES) based on the methods of EPA 3050B and EPA 6010D. The exception was mercury, which was determined by the cold-vapour method (EPA 7471B).

Spatial Analysis

The spatial distribution of heavy metals in the sediments of the Umayo Lagoon was determined by applying the ordinary kriging interpolation method. The concentration data were imported with their respective coordinates into ArcGIS V 10.8.1 software. Subsequently, the normality of the data was verified for each metal, and the data were transformed to a logarithmic scale to observe the trends and obtain better interpolation results (Wu & Li, 2013). Finally, the octant search method was applied to interpolate the concentrations of heavy metals at each sampling point, allowing the lagoon to be zoned.

Social behaviour of local actors

To assess and understand the social behaviour of local actors related to the environmental contamination of the Umayo Lagoon, a qualitative methodological approach was adopted (Hernández-Sampieri & Mendoza, 2018a) based on the grounded theory design of Glaser and Strauss. This methodological strategy employs constant comparative analysis, which allows the identification of categories and concepts to be used in coding, thus establishing a coherent relationship between data and theory (Estrada-Acuña *et al.,* 2021).

Nonprobabilistic sampling was carried out using snowball and convenience techniques, which allowed the selection of 35 participants, including inhabitants, producers, local authorities and community leaders from the area surrounding the study area. The data were collected through semistructured interviews to identify feelings and thoughts, and focus groups were used to record the intersubjectivities between the participants and the documentary reviewers, thus enabling the collection of prior information on the proposed topic (Hernández-Sampieri & Mendoza, 2018b; Valles, 1999).

The data were processed using Atlas.ti v 8.4 software, which allowed us to organize, code and categorize the data generated from the central theme; the conceptualization and integration of these data in the form of a theory allowed the interpretation of the studied phenomenon (Morales-Simfors *et al.,* 2020; Quispe-Mamani, 2021).

RESULTS AND DISCUSSION

Concentrations of heavy metals in the tributaries and effluent of the Umayo lagoon

Table 1 The concentrations of heavy metals in sediments of the tributaries and effluent of the Umayo Lagoon are shown. The total concentration of the metals at the sampling points followed the descending order B> C> A> E> D> G> H> F, while the metals were followed the descending order Zn> Cu> Pb> As> Cd> Hg.

The concentration ranges of the metals were considered with respect to the biological effects. As exceeded the PEL limit at point H and the ISQG limit at points A, B and C. These four sampling points are located in the northern sector, where the lithostratigraphic unit of the Barroso group predominates, which is composed of andesitic basaltic lavas of volcanic origin (Morales-Simfors *et al.,* 2020), and one of the main metals that make up the mineralogy of this type of soil is As (Bundschuh *et al.,* 2012; Morales-Simfors *et al.,* 2020).

Hg exceeded the PEL limit at points B and C; these sites intersect the bifurcation of the Vilque

Table 1. Concentrations of heavy metals at the sampling points in the tributaries and effluents of the Umayo Lagoon.

Sample point (river)		As ($mg\ kg^{-1}$)	Cd ($mg\ kg^{-1}$)	Cu ($mg\ kg^{-1}$)	Hg ($mg\ kg^{-1}$)	Pb ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)
A (effluent)		11.50	1.10	40.50	0.05	28.80	134.70
B (affluent)		14.30	1.90	46.70	0.76	40.60	182.80
C (affluent)		12.20	1.60	43.40	0.62	37.90	167.10
D (affluent)		3.60	1.10	25.00	0.07	26.90	98.00
E (affluent)		3.60	0.90	25.00	0.08	33.90	110.00
F (affluent)		3.60	0.30	28.10	0.11	3.00	68.90
G (affluent)		3.60	0.30	28.40	0.07	25.90	64.90
H (affluent)		36.00	0.30	27.00	{0.04	24.90	33.40
Min		3.60	0.30	25.00	0.04	3.00	33.40
Max		36.00	1.90	46.70	0.76	40.60	182.80
Average		11.05	0.94	33.01	0.23	27.74	107.48
CCME	PEL	17.00	3.50	197.00	0.49	91.30	315.00
	ISQG	5.90	0.60	35.70	0.17	35.00	123.00

River, which runs through the sector where artisanal mining takes place (Salas-Mercado *et al.,* 2023a), indicating that the presence of this metal is due to the gold recovery process. In this process, mercury is added to the extracted gold material, forming an amalgam that is then ground using moving stones (quimbaletes) and mills (Salas-Mercado *et al.,* 2023a). Other pollutants could be derived from the burning of the amalgam to evaporate the mercury that was added during processing, producing intermittent and extremely high concentrations of mercury vapour (Cordy *et al.,* 2013), which could be condensed and precipitated in the form of rain into water bodies.

Cd exceeded the ISQG limit at points A, B, C, D and E, where B, C, D and E are the main tributaries that flow through the areas where mining and artisan cheese production activities are carried out. Cheese production begins with a casein coagulation process that includes the addition of a coagulating enzyme (rennet) to form the curd (solid component of the cheese) and the lactic whey (liquid component), which are separated by filtration. Later, while the cheese is matured in a suitable environment, the whey and byproduct residues are generally deposited as residues in nearby soils and water bodies (Maas *et al.,* 2011). Previous studies reported that approximately 12 and 14% of the total cadmium in cow's milk is transferred to whey (Amer, 2017; Mehennaoui *et al.,* 1999a). The final composition of the lactic whey serum could be transferred as a byproduct by runoff in the rainy season through the surface water and underground beds to the lagoon; consequently, Cd would accumulate in the sediments (Gidikova *et al.,* 2016a). The only effluent (A) would transport Cd out of the lagoon.

Cu and Zn exceeded the ISQG limit at points A, B and C, while Pb exceeded this limit at points B and C. This could be because the Umayo Lagoon and its surroundings are within band VI of the metallogenetic domain of Peru (Acosta *et al.,* 2009). The predominant metals in this region are Au, Cu, Zn and Pb, and their origins are attributed to natural sources. On the other hand, the agricultural development of the area could increase the concentrations of Cu, Zn and Pb due to the removal and subsequent transport of soil to the lagoon (Quispe *et al.,* 2009).

Concentration of heavy metals inside the Umayo lagoon

The concentrations of heavy metals in sediments within the lagoon are shown in Table 2; the average values following the descending order Zn> Cu> Pb> As> Cd> Hg. The As values exceed the PEL limit at 14 sampling points located in the north and central sectors of the lagoon, which is due to the erosion of the slopes in this area belonging to the lithostratigraphic unit of the Barroso group. Due to the bathymetry (Figure 1) of the area, the metal would accumulate at the bottom of the lagoon. On the other hand, Hg and Cd exceed the PEL level at points 1 and 2, respectively. These points are close to the mouths of tributaries B and C (River Vilque) and D (River Ccaccapunco). These two tributaries run close to the site of the artisanal cheese production activities; this would indicate that the Ccaccapunco River is closely related to areas of artisanal cheese production. In this regard, to increase milk production, it is necessary to increase the availbability of fresh food, leading to increased application of fertilizers, mainly in

Table 2. Concentration of heavy metals in sediments of the sampling points inside the Umayo Lagoon.

Sample point (lagoon)		As (mg kg^{-1})	Cd (mg kg^{-1})	Cu (mg kg^{-1})	Hg (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})
1		16.90	2.00	69.60	0.64	54.70	233.10
2		3.60	4.40	36.10	0.12	29.90	129.30
3		3.60	1.00	20.80	0.06	28.90	81.50
4		3.60	0.30	19.60	0.06	28.80	88.40
5		17.10	0.30	15.90	0.08	3.00	22.60
6		3.60	0.30	12.00	0.05	3.00	56.70
7		3.60	0.30	22.10	0.08	3.00	26.10
8		17.60	0.90	50.80	0.23	3.00	130.60
9		19.20	1.80	76.10	0.41	57.00	245.60
10		26.70	1.10	56.40	0.26	41.70	124.20
11		28.80	0.30	47.30	0.26	37.70	97.90
12		30.00	1.00	47.90	0.21	31.90	95.30
13		25.70	0.80	46.40	0.22	31.90	95.30
14		3.60	0.30	0.80	0.10	3.00	0.60
15		32.20	1.40	61.50	0.25	40.70	137.90
16		30.30	1.40	46.40	0.18	30.00	105.50
17		23.70	0.80	43.70	0.19	33.00	93.80
18		28.00	0.90	46.10	0.19	35.80	94.10
19		25.30	0.30	37.60	0.19	26.80	78.00
20		29.10	1.00	40.50	0.18	28.80	77.00
21		24.20	0.80	38.30	0.17	36.90	89.10
22		16.50	0.30	13.40	0.07	3.00	18.30
23		3.60	0.30	16.30	0.05	3.00	16.20
Min		3.60	0.30	0.80	0.05	3.00	0.60
Max		32.20	4.40	76.10	0.64	57.00	245.60
Average		18.11	0.96	37.64	0.19	25.89	92.92
CCME	PEL	17.00	3.50	197.00	0.49	91.30	315.00
	ISQG	5.90	0.60	35.70	0.17	35.00	123.00

Table 3. Range of concentrations of lakes with similar activities around the world.

Country	Lagoon	As	Cd	Cu	Hg	Pb	Zn	Author
Peru	Rinconada	166 - 5355	---	20.3 - 116.1	0.5 – 41.5	21.5 – 85.8	74.3 - 1372	(Salas-Mercado *et al.,* 2023b)
Colombia	Mallorquin	---	0.3 – 0.7	22.6 – 45.9	0.11 – 0.25	1.32 - 1.89	50.3 – 95.0	(Fuentes-Gandara *et al.,* 2021)
Peru	Junin	0.9 – 113.2	0.2 – 4.8	6.20 – 335.4	---	6.8 – 56.7	20 – 21.9	(Custodio *et al.,* 2019)
Egypt	Burullus	---	0.2 – 0.9	8.70 – 32.1	---	15.1 – 34.6	48.5 – 129.2	(El-Amier *et al.,* 2017)
China	Aibi	---	0.01 – 0.7	32.3 – 95.8	0.01 – 1.9	16.3 – 175.8	88.3 – 217.3	(Abuduwaili *et al.,* 2015)
China	Nansi	6.1 – 31.8	0.06 -0.5	19.1 – 56.6	0.02 – 0.09	17.6 – 40.7	52.5 - 134	(L. F. Wang *et al.,* 2014)
China	Yilong	7.8 – 25.9	0.3 – 1.6	15.4 – 66.9	---	30.7 – 88.9	29.6 -122	(Bai *et al.,* 2011)
Peru	Umayo	3.6 - 36	0.3 – 1.9	25 – 46.7	0.04 – 0.8	3 – 40.6	33.4 – 182.8	This study

the form of foliar fertilizers ((DRAP), 2020). These products are superphosphates with phosphate rocks as their raw materials and apatite as the predominant mineral. Apatite is composed of phosphorus and cadmium (Castro-Bedriñana *et al.,* 2021; Rojas, 2022). These results indicate that the fertilization of forage crops results in the transfer of cadmium into livestock feed and ultimately into milk (Mehennaoui *et al.,* 1999b). As mentioned previously, the whey that was dumped into nearby streams would have produced a bad odour (Gidikova *et al.,* 2016b) and downstream contamination of Cd (Castro-Bedriñana *et al.,* 2021b).

Furthermore, the Vilque River flows through the area that is influenced by the artisanal mining activities, this result therefore suggests that the presence of this metal is due to the gold recovery process (Gammons *et al.,* 2006), since the mining tailings, which still contain mercury, are left in the open and are transported to the tributaries through the action of atmospheric agents such as rain, wind and temperature variation (Salas-Ávila *et al.,* 2021). Another path of contamination could originate during the melting process of the amalgam of gold and mercury; this process causes the volatilization of mercury and its subsequent precipitation into water and surrounding soils (Salas-Mercado *et al.,* 2023b). Cd, Cu, Hg, Pb and Zn exceeded the ISQG levels at points 6, 7, 13 and 15, respectively, indicating that these are zones where pollution could have multiple negative effects on the aquatic environment and the living beings that depend on it (Sediment Quality Guidelines for the Protection of Aquatic Life, 1998).

In Table 3, a comparison of the concentrations obtained in this study with those from other research conducted in lakes adjacent to similar industrial activities is presented. These studies reported high contamination levels and recommended taking action. The concentrations of arsenic (As) in this study are below those of the most contaminated lakes in Peru but higher than those in other countries, consistent with Santos-Francés *et al.,* (2017), who noted its prevalence in the Peruvian Andes. Cadmium (Cd) levels exceed those found in international lakes. Furthermore, the authors reported ecological and health risks associated with Cd, indicating the need for measures to reduce its presence. Some monitoring points show high concentrations exceeding those reported in research, suggesting a contribution of this metal from mining and the presence of vehicular transport routes.

Spatial distribution of heavy metals

Figure 2 The spatial distribution of heavy metals in sediments inside the Umayo Lagoon is shown.

Cu, Zn and Pb present a dispersed distribution, covering most of the area in the lagoon, which confirms that the presence of this group of metals is due to natural processes. The highest concentrations of Cd are located near the mouth of the Ccaccapunco River and are distributed from the west to the north of the lagoon, which is consistent with the findings of other studies in which it is mentioned that Cd was derived from agricultural and zootechnical activities due to the use of phosphorite-derived fertilizers with significant concentrations of Cd (Zuzolo *et al.,* 2017). Furthermore, it has been reported that Baiyangdian Lake in northern China is among the water bodies with the highest level of Cd contamination, with concentrations that are in the range of 0.19-2.47 mg kg^{-1}, generating a potential ecological risk for the flora and fauna of this area (Ji *et al.,* 2019). In the present study, the concentrations are in the range of 0.30-4.40 mg kg^{-1}, and it is possible that there are adverse effects on human and animal health.

On the other hand, the highest concentrations of mercury are observed at the mouth of the Vilque River bifurcation, with a maximum concentration of 0.64 mg kg^{-1}; this is due to gold processing activities, including amalgamation with mercury, and tailings with high heavy metal contents. A study carried out in the Viscachani lagoon located in the protected area to the south of the province of La Paz, Bolivia, found a high concentration of mercury (Hg) (up to 23.7 mg kg^{-1}) in the sediments near an area with signs indicating that amalgamation processes for artisanal mining were ongoing (Soung *et al.,* 2021). This concentration is similar to that found

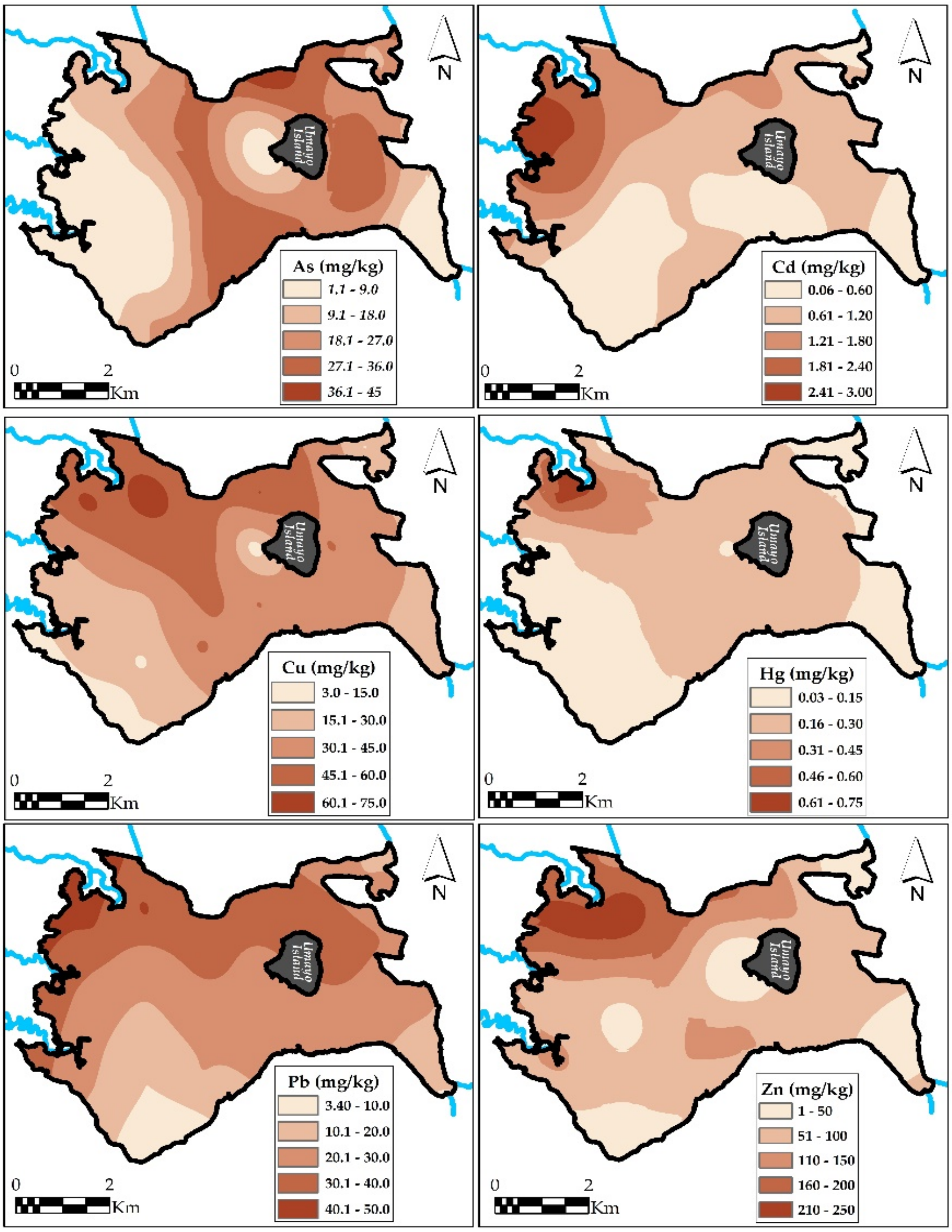

Fig. 2. Spatial distribution of heavy metals in sediments inside the Umayo Lagoon.

in the Madeira River in Brazil (19.83 mg kg^{-1}), which is also affected by this type of mining (Pfeiffer *et al.,* 1991).

Although the leaching of Hg from tailings appears to be a slow process, the migration of the tailings over time may be the most important dispersal mechanism of Hg. The Hg that is transferred to rivers as metallic mercury accumulates mainly in the bottom sediments and generally has a very low mobility. Soils, due to their low chemical mobility, act as key indicators of atmospheric deposition, both by retaining substances as temporary or final sinks and by releasing volatile mercury species. The burning of gold and mercury amalgam in gold mining areas causes a significant release of Hg into the atmosphere. This evaporated Hg precipitates into soils and sediments, accumulating in these areas and reaching remote areas. The direct contributions of Hg from rivers and mining effluents in these remote areas in conjunction with the rates of atmospheric deposition to water bodies, mainly lakes, allow the constant accumulation of Hg.

Social behaviour of local actors

In this section, the results of the socioenvironmental behaviour of the local actors affected by the contamination of the Umayo Lagoon (LU) are analysed and interpreted. In Table 4, the six subcategories of analysis that emerged from the the three main categories of analysis

Table 4. Social behaviour of local actors regarding the contamination of the Umayo Lagoon.

Analysis category	Analysis subcategory	Rootedness (R)	Representative appointment (Testimony of local actors)
Actors' feelings	Diseases and deaths of livestock or domestic animals	42	The press, such as Onda Azul radio, issued an alertwith the news that dead vicuñas were found in 2020; 7 or 8 vicuñas were found dead (quote 12:3). A year ago, we saw that a fellow community member had 12 sheep die; the same thing happened to other community members. When the lake appeared greenish, there was mortality in the lower area of Patas and Qaqsi (quote 21:18).
	Presence of pollution in the Umayo lagoon (LU): time in years	13	This problem of the contamination of the Umayo Lagoon was noticed more or less from 1999 to 2000 (quote 4:1). This contamination has been around for10 years or so, but little by little it is advancing (quote 15:6). The contamination began approximately 5 or 6 years ago (quote 18: 7).
Actors' thoughts	LU pollutants: mining, cheese, solid and liquid waste, and others	92	We see all kinds of contamination, such as mining, drains, bags and bottles that are dumped in the Umayo Lagoon, and it may be contaminated with heavy metals (quote 7:1). Cheese plants do contaminate; I have seen evidence of that. The substances that are released into the river in the Vilque area flow into the lake (quote 7:12).
	Cheese factory/mining and their contributions to the family economy	11	The only good thing that the mining companies are doing is giving work to some men in the community so that they can earn a few pennies. As for the cheese plants, they also provide work for community members and generate economic income for the families involved in the cheese business (quote 26:8).
Attitudes of the actors	Inaction/laziness of institutions and authorities at the central, regional, local and community levels	61	Neither the local authorities nor the regional authorities take interest in this issue. When they are campaigning, they come to offer us all the riches in the world, but once they are in power, there are not the results that they promised regarding the decontamination of the Umayo Lagoon, and they do not take action on the matter (quote 21:13). I am dismayed with the authorities; nobody recognizes the importance of the issue. As fishermen, we also sometimes have crossed hands; we ask the institutions to help us, but they never do (quote 21:4).

Table 4. Social behaviour of local actors regarding the contamination of the Umayo Lagoon.

Analysis category	Analysis subcategory	Rootedness (R)	Representative appointment (Testimony of local actors)
	Demand for institutional intervention and declaration of emergency for the LU	37	Well, what we would like is for this study to lead to the declaration of an emergency, with the enactment of a law. As soon as this comes out, we can make presentations to the different institutions such as PELT, IMARPE, and the Ministry of the Environment, Energy and Mines; they have much work to, and we have to save this lagoon. There is no replacement, and we have to intervene in time (quote 27:54).

used to characterize the socioenvironmental behaviour of local actors are presented: 1) feelings about diseases, mortality of livestock or domestic animals, and the presence of contamination in the LU; 2) thoughts about pollutants in the LU, cheese production and mining and their contributions to the family economy; and 3) attitudes about the inaction/laziness of institutions and authorities at the national, regional, local and community levels and the demand for institutional intervention and a declaration of emergency for the LU. The concentration of information or roots (R) expressed by local actors gives rise to the emergence/origin of the subcategories of analysis.

Regarding the emotional dimension (feelings) of the local actors, the presence of diseases and the mortality of animals in the environment surrounding the LU is one of the factors affecting the feelings of the study participants (R = 42). Feelings are variable and subjective emotional states that arise in the face of various events or phenomena, such as pessimism and optimism, encouragement and discouragement, sadness and joy, anxiety, fear, anger and rejection (Iwasa *et al.,* 2007; Marteau, 2017a). The local actors expressed feelings related to anxiety and fear. These emotions surfaced before what they suppose are the effects of the contamination of their main water resource: perceived threats to life and personal health (Iwasa *et al.,* 2007) that interfere in their quality of life (Tang *et al.,* 2016).

According to local stakeholders, the presence of contamination in the LU has been occurring for more than two decades (R = 13), with increased contamination levels during the last five years. The worsening of the pollution in a water body would be manifested by the eutrophication process (Iwasa *et al.,* 2007), which is the case for the LU.

The analysis of the thoughts of local actors indicates that they believe that the sources of contamination of the LU are diverse, including mining, cheese making, and inadequate solid and liquid waste management, among others (R = 92). Although heavy metals can enter the environment through multiple pathways throughout the stages of ore processing, mining tailings and abandoned mines represent a permanent legacy of environmental contamination long after the mines have been exploited (Hjeresen, 2001). On the other hand, in many countries, improper disposal of solid waste is perceived as the most visible practice of environmental pollution; in addition, unsafe agricultural methods have been shown to contribute to pollution (Ojedokun, 2011; Okumah *et al.,* 2020). The main elements of environmental concern in the cheese industry are pollution from whey and carbon particles, odours and excessive water use. In the department of Puno, the effluents generated by the production of artisan cheese are characterized by a high chemical oxygen demand, with averages of 40499.67 mg l^{-1} and 9271.33 mg l^{-1} of total suspended solids, which exceed the maximum permissible levels stated by national legislation (Flores Arizaca, 2020a).

Nevertheless, although to a lesser extent, local actors report that mining and cheesemaking are sources of employment and economic income for some families in the area and other locations

(R = 11). Faced with this reality, the actors demand the incorporation of green technology to generate environmentally friendly and sustainable economic activities; for example, the interviewees indicated, “I would like to say that the mining and the cheese factory provide work, but need to be managed formally.” and “They do not have a treatment plant, and they are directly polluting the river; that is, the mine and the cheese factories are polluting the river, and they never give us consideration” (quotes 20:17 and 20:18).

Green chemistry offers a variety of mechanisms to address environmental problems of global importance, such as water pollution, at the source. Reducing water pollution at the source has been shown to be more cost effective than abatement or remediation approaches (Hjeresen, 2001). The application of chemistry or green technology to the prevention of contamination of water sources is consistent with the extent to which users and consumers of water adopt environmentally responsible behaviours, which implies the need to develop environmental awareness in people. These behaviours include the proper disposal of waste, recycling, energy conservation and other steps (Ojedokun, 2011); their application necessitates the adoption of training policies as well as incentive and punishment policies.

The attitudes expressed by local actors regarding the environmental contamination of the LU are not very encouraging about the potential to address and solve the problem. On the one hand, the authorities and institutional representatives at the national, regional, local and community levels show inaction and laziness when faced with addressing the problem (R = 61). The socioenvironmental behaviour of the local actors, to a large extent, is in response to the fact that there is still no significant social pressure to address the problem; indeed, there is a low level of cooperation between the actors and other parties, and the lagoon is gradually becoming more contaminated. Proenvironmental and prosocial behaviours are driven by the level of environmental awareness, positive control beliefs, personal responsibility, resource depletion and perceived threats to life and personal health (Phiri *et al.,* 2023; Sigé *et al.,* 2004).

However, the level of knowledge about the environment in local communities is low, which is why counselling and training related to the environment and pollution are necessary (Bakhrani, 2016). According to (Iwasa *et al.,* 2007), people are more willing to make a costly contribution when cooperative action is more effective in mitigating or solving pressing socioenvironmental problems. This socioenvironmental behaviour based on cost–benefit analysis demonstrates an instrumental attitude model that predominates in times of modernity and postmodernity (Tobias & Berg, 2011) or subjective models of expected utility that are based on dual process models (i.e., reflexive and impulsive), although most of our behaviour is controlled by impulsive processes (Marteau, 2017b).

On the other hand, local actors demand institutional intervention and an emergency declaration for the LU (R = 37). These attitudes, mainly from members of the community, tend to be related to the feeling of public concern for the environmental problem, which is produced by social pressure related to lake water pollution (Iwasa *et al.,* 2007). Iwasa et al. (2007) indicated that as long as there is a close link between the actors, the management of the ecosystem will be successful. To reduce the anxiety of local actors who directly deal with the contamination of the lagoon, it is necessary to build greater trust between social organizations and public institutions at different levels (Tang *et al.,* 2016).

Based on the analysis and interpretation of feelings, thoughts and attitudes regarding the contamination of the LU, there are potential strategies to address the contamination of the main water source of the districts and rural localities in the study area. The development of alternative solutions to this environmental problem requires the adoption of several strategies, such as a revaluation of cultural beliefs and practices and social norms related to the access to and use of water resources (Okumah *et al.,* 2020); changes in lifestyle and consumption that result in changes in socioeconomic, political and legal conditions, leading to awareness of environmental issues and sustainable behaviours (Bakhrani, 2016; Flores Arizaca, 2020b;

Ojedokun, 2011; Okumah *et al.,* 2020); and actions to prevent contamination of water sources based on green chemistry (Hjeresen, 2001). All these strategies require the creation of an interdisciplinary team of researchers dedicated to the generation of scientific knowledge of environmental pollution based on participatory and community-scale research (Bakhrani, 2016; Chammas *et al.,* 2020; Tang *et al.,* 2016), which will depend on the cooperation of the local community and institutional actors (Iwasa *et al.,* 2007).

Interaction between the physical and social dimensions

The results of this study reveal a strong connection between the social behaviours of local actors and the heavy metals in Umayo Lagoon. Local actors expressed intense emotions in response to increasing pollution. The presence of diseases and the death of animals in the vicinity of the lagoon have generated feelings of anxiety and fear in the community (interview 12:3). These feelings are consistent with the chemical evidence that shows the dispersion of heavy metals such as As, Cd and Hg in some sectors of the lagoon, suggesting an anthropogenic origin for this contamination (interview 7:1). The strong concern and feelings expressed by local actors reflect the real threat that pollution poses to their environment and quality of life.

The relationship between human activities and pollution is evident from the example of the cheese plants near the Umayo Lagoon. Local tests indicate that these plants release substances that are transported to the river and eventually reach the lagoon (interview 7:12). This is consistent with another analysis of heavy metals that found higher concentrations of Cd near the mouth of the Ccaccapunco River, which may be due to agricultural practices, specifically the use of fertilizers with high Cd contents (interview 7:12). The correlation between human activities and the presence of pollutants in the lagoon highlights the need to address industrial and agricultural practices in the region to mitigate pollution and its consequences on environmental and human health.

The local testimonies and the heavy metal analysis provide consistent evidence for the progressive increase in the contamination over time. Since the late 1990s, signs of contamination have been observed in the lagoon (interview 4:1), and over the decades that followed, this situation has gradually worsened, affecting both aquatic flora and fauna, as well as nearby human communities. The assumptions about contamination that began to manifest themselves approximately six years ago (interview 18:7) are consistent with the concentrations of metals such as Cd and Hg, which showed an increase near the mouth of the river and in other areas (interview 18:7). Sediments in remote lake cores and reservoirs offer an excellent opportunity to trace the history of Hg contamination in gold mining areas and estimate levels of atmospheric deposition. The temporal consistency between the chemical analyses and local testimonies reinforces the importance of adopting preventive and corrective measures to slow the progression of contamination in the Umayo Lagoon.

CONCLUSION

The evaluation of the contamination of the tributaries, effluent and core of the Umayo Lagoon reveals that there is contamination by three metals: As, Cd and Hg. The level of As exceeded international standards (PEL level), and exceeded the ISQG level in tributary H and at points A, B, and C. All these points are located in the northern part of the study area, indicating that the high levels of these metals is a product of natural erosion since the area belongs to the Barroso group, which has a mineralogical composition that includes As. The highest concentrations of Hg (PEL level) were found at points B and C, both of which derive from the Vilque River. This is the only river that passes through the area with mining activity, suggesting that its high concentrations of Hg are due to the gold recovery process used in artisanal mining in the area. Cd (ISQG level) had the highest concentrations at points A, B, C, D and E, which are located in the western part of the lagoon. The area with heavy pollution includes points B and C; All the points except A (effluent) receive water that passes through the areas with activities related to the production of artisanal cheese. It is suggested that to increase milk production, cattle are fed with forages treated with foliar fertilizer, the main component of which is a type of phosphate rock that has high concentrations of Cd.

On the other hand, it is evident that in the sediments collected in the interior of the Umayo Lagoon, there is an accumulation of As, with concentrations that exceed the PEL level. These concentrations are associated with the depths measured, confirming that the As is of natural origin; however, agricultural practices have caused the concentrations in this part of the lagoon to increase. A high Hg concentration (PEL level) was found at point 1, which is associated with the Vilque River, providing evidence that artisanal mining is the main source of contamination. Finally, high Cd (PEL level) concentrations were found at point 2, which is associated with the Ccaccapunco River (D), confirming that Cd pollution is due to the inappropriate disposal of whey during the production of artisanal cheese. The distributions of As and Hg are concentrated on the inlets of the aforementioned rivers, and their movement is directed towards the only effluent from the lagoon.

A nonrational, emotional response emerged from local actors following the pollution of their main water source; the sources of pollution were associated with anthropic activities (mining, cheesemaking and inappropriate waste disposal), although mining and artisanal cheese production contribute to local economies. However, the inaction of the institutional stakeholders and government officials at different levels contributed to the ongoing problem of environmental pollution. This situation, in recent years, has induced lasting anxiety, severe physical symptoms (pain and fatigue), and damage to the immune system, thus decreasing the quality of life of the population and degrading the ecosystem as a whole. The solution to this problem requires the development of trust and socioinstitutional cohesion at different levels, re-evaluation of sociocultural practices related to access to and use of water resources, adoption of responsible and sustainable lifestyles, and generation of green technology in agricultural processes.

In general, the incorporation of socioeconomic information in the evaluation of the contamination of the Umayo Lagoon provided more insights that were used to accurately identify the sources of contamination. This was possible because the data sources provided consistent evidence about the alteration of the water quality in the lagoon due to the presence of heavy metals in sediments, which was caused by mining, cheese production and agricultural activities.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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