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Article

Assessment of Heavy Metals Pollution in Selected Alpine Wetlands of Lesotho

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Abstract

The catchments that contain ecologically critical wetlands supplying the Mohale and Polihali dams under the Lesotho Highlands Water Project (LHWP) are increasingly threatened by expanding agriculture, mining activities, and uncontrolled livestock grazing. Hence, the present study was conducted to assess heavy metal contamination and wetland health across the three higher-altitude sub-catchments in Lesotho: Senqunyane, Khubelu, and Sani. A total of 24 water samples were collected from six wetlands in March 2025 to determine concentrations of copper, iron, manganese, lead, and zinc in accordance with APHA standards. Pollution Load Index (PLI) and Heavy Metal Pollution Index (HPI) were calculated to evaluate water quality. All sites exceeded the HPI safety threshold of 100, with Sani Top showing the highest PLI (5.54), indicating severe contamination primarily driven by Manganese and lead. Lead emerged as the dominant pollutant due to its low permissible limits, exacerbating HPI scores across wetlands. Heavy metal concentrations generally declined with increasing altitude, with lead and copper displaying the steepest decreases, while manganese peaked at mid-altitudes (2750 m), potentially linked to local geochemical processes and organic matter decomposition. Principal Component Analysis (PCA) explained 40.6% of total data variance, revealing tight clustering at higher altitudes (3000 m), reflecting uniform, geogenically controlled water quality, whereas lower elevations displayed more variable and anthropogenically influenced patterns. Despite high-altitude sites appearing chemically stable, they carry higher dissolved ions, suggesting treatment needs for water hardness. In contrast, low-to-mid elevation wetlands showed more variable and hazardous metal loads, necessitating targeted management strategies including buffer zones, liming, and pollution source tracing. Findings highlight land use and hydrology in wetland water quality. Continuous monitoring of Lesotho's alpine wetlands is vital to address heavy metal pollution, guide evidence-based policy, and support prioritized monitoring, mitigation, and restoration for sustainable downstream water management.

Keywords: toxic metals; high altitude wetlands; Pollution Load Index (PLI); Heavy Metal Pollution Index (HPI); altitude gradient

1.0. Introduction

Heavy metal pollution in alpine wetlands poses serious threats to ecosystem integrity, biodiversity, and downstream water quality [1,2]. These fragile high-elevation environments act as natural filters and are rich in biodiversity, regulating nutrient cycling, sediment retention, and water purification [3,4]. Contamination disrupts aquatic and terrestrial systems, impacting human communities dependent on water resources and ecosystem services [5,6]. Due to limited buffering capacity and sensitivity to climatic and chemical perturbations, alpine wetlands are particularly vulnerable to long-lasting degradation when exposed to heavy metal pollution [7].

Research across global mountain systems, such as Zoige Plateau, Hengduan Mountains, in Asia, and northern Pakistan, revealed clear altitudinal patterns, with higher altitudes influenced by geological weathering, while mid- and low-elevations show anthropogenic inputs from agriculture, transport, and industry [8,9]. Even remote alpine zones now exhibit anthropogenic contamination, contradicting assumptions of pristine high-altitude systems [10]. [11] quantified soil contamination gradients and found mid-altitude peaks in Cd and Pb. [12] linked low-altitude metals to agricultural products such as fertilizers, pesticides, etc., while high-altitude As and Cr reflected geogenic origins [13] revealed elevation effects on both soil and plant uptake in the Zoige Plateau, and [14] identified relative ecological risks across Hengduan wetlands. In Pakistan, valley-floor roads intensified Cd and Pb inputs below 3,200 m [15], while Swat Valley lakes showed low contamination except Cu and Cd [16]. Overall, metal concentrations decline with altitude, but mid-elevation hotspots present ecological risks [17].

In African mountain systems, limited research has examined heavy metal contamination patterns across elevational gradients in wetlands. [18] reported heavy metal contamination in highland wetlands on Mount Cameroon ($\approx 2,000$ m), with metals ranked $Mn > Zn > Cr > Ni > Cu > Co > Pb > Fe > Al$, reflecting both anthropogenic and geogenic sources. In Ethiopia, Lake Tana, a high-elevation lake system, showed Cr and Fe levels above aquatic guidelines [19], while the Awetu watershed had extreme Pb (2005.94 mg/kg), As (623.32 mg/kg), and Cr (375.00 mg/kg) in sediments [20]. The Bale Mountains, an afroalpine wetland of Ethiopia, remain unassessed for heavy metal contamination despite their critical hydrological importance [21]. Kenyan studies reveal seasonal variations in contamination, with River Thiba sediments showing Cr (39.9–42.6 mg/kg), Ni (85.1–396.5 mg/kg), and Mn (1678.4–1766.4 mg/kg) [22], while Lake Elementaita waters contained 0.04–3.14 mg/L of metals, often above WHO limits [23]. However, these studies lack systematic elevation-based analysis, resulting in a poor understanding of altitude's role in heavy metal risks and hindering effective management.

Pb, Cd, As, and Cr enter wetlands through natural and anthropogenic pathways, including mining, agriculture, atmospheric deposition, and geological erosion [24,25]. Studies across India and other mountainous regions have shown that wetlands in agricultural and industrial catchments accumulate heavy metals beyond permissible limits [28,33]. In alpine regions, cold climates, snowmelt hydrology, and low buffering capacity increase metal mobility [26,27], while topographic variation further affects retention, though poorly quantified [28,29]. Despite recognition of risks, few studies examine how altitude shapes contamination in alpine wetlands [10,30]. Analytical approaches such as Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES), Positive Matrix Factorization (PMF), and indices like Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI), and Potential Ecological Risk Index (RI) effectively trace sources and assess pollution [24,26,31,32], but remain underused in African alpine wetlands.

In Lesotho, alpine wetlands provide crucial hydrological services, including streamflow regulation, groundwater recharge, and water purification [33], yet face growing pressures from agriculture, overgrazing, and transboundary atmospheric deposition [34]. Climate change further intensifies risks by altering rainfall, temperature, hydrology, and redox conditions, affecting metal solubility and transport [7,27]. Wetlands can sequester metals with removal efficiencies ranging from 12.35% to 91.01%, depending on species and conditions [3], suggesting potential for natural attenuation. However, comprehensive assessments across altitudinal gradients are urgently needed to guide sustainable management within Integrated Catchment Management (ICM) [35].

Therefore, this study is aimed at evaluating heavy metal concentration in Lesotho's alpine wetlands across elevations through field sampling, pollution indices (HPI, PLI), and multivariate source apportionment. This would address a critical research gap by generating altitude-stratified data and a methodological framework for monitoring and managing heavy metal risks.

2.0. Materials and Methods

2.1. Study Area

The present study was conducted in Lesotho at elevations ranging from 2,500 to 3,089 meters above sea level (masl), within the mountain agro-ecological zones (AEZs) of Mokhotlong and Ha-Mohale, focusing on three sub-catchments, viz. Khubelu, Senqunyane, and Sani under the Upper Senqu main catchment. Two alpine wetlands were selected from each sub-catchment, resulting in six study sites: Lets'eng-la-Likhama and Koting-sa-ha Ramosetsana in the Khubelu catchment, Khorong and Tenesolo in the Senqunyane catchment, and Khamoqana and Khalong-la-Lichelete in the Sani catchment. The study area, covering sub-catchments of the Senqu River across Mokhotlong and Thaba-Tseka districts, is illustrated in Figure 1, which presents the geographical map of Lesotho with its ten districts within the African continent and highlights the alpine wetland study sites. Figure 2 shows the Global Positioning System (GPS) map of the Upper Senqu main catchment with its three sub-catchments (Khubelu, Senqunyane, and Sani) and the associated wetlands, while Table 1 provides the coordinates and altitudinal characteristics of the selected wetland ecosystems.

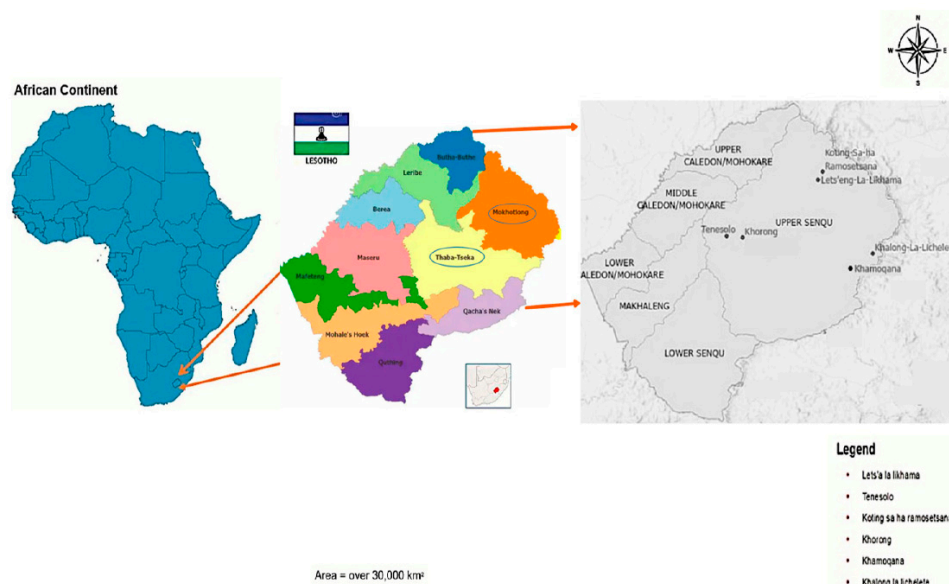


Figure 1. Geographical map of Lesotho showing its ten districts within the African continent and highlighting the study sites located in alpine wetlands. The circled districts, Mokhotlong and Thaba-Tseka, represent the areas where the study was conducted, while the black dots mark the locations of the alpine wetlands.

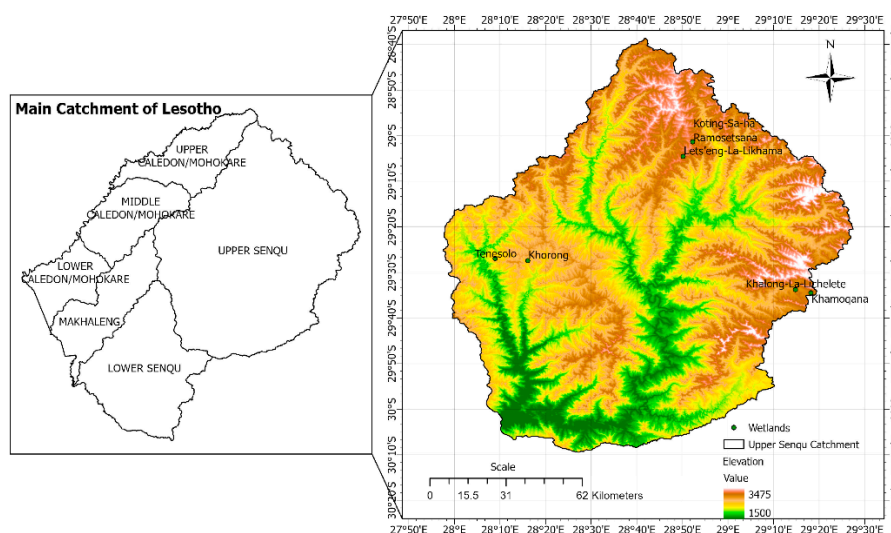


Figure 2. The GPS map illustrates the main catchment area (Upper Senqu), which encompasses three sub-catchments, viz. Khubelu, Senqunyane, and Sani, along with associated wetlands. The map was generated using ArcGIS software (Version 3.5.x).

Table 1. Elevations and geographic coordinates of the study [20] areas.

Sub -catchment	Wetlands	Coordinates		Altitude (masl)
		Latitude	Longitude	
Senqunyane	Khorong	-29.43708	28.26923	2500-2550
	Tenesolo	-29.44836	28.14759	2552-2600
Khubelu	Letšeng - La- Likhama	-29.076355	28.836095	3040-3800
	Koting -sa-ha Raramosetsana	-29.022686	28.871324	3087-3155
Sani Pass	Sani Top	-29.563552	29.247207	2891-2995
	Khamoqana	-29.457178	28.268094	2839-2880

2.1.1. Senqunyane Sub-Catchment

The Senqunyane sub-catchment is located in the central mountain region of Lesotho and forms part of the upper Senqu River system (Figure 1). It is characterized by rugged highland topography and alpine wetland ecosystems. Two wetlands were selected within this sub-catchment for study: Tenesulu and Khorong. These wetlands are vital hydrological units as they serve as major tributaries to the Mohale Dam, one of the key reservoirs under the Lesotho Highlands Water Project (LHWP). The ecological integrity of these wetlands directly influences water yield, quality, and seasonal flow regulation into the dam.

2.1.2. Khubelu Sub-Catchment

The Khubelu sub-catchment lies in the northeastern part of Lesotho and is integral to the ongoing Polihali Dam development, which forms part of Phase II of the LHWP (Figure 1). Two wetlands were selected in this sub-catchment: Koting-sa-ha Raramosetsana and Letšeng-La-Likhama. These wetlands act as feeder systems to the Polihali Dam. The Khubelu area presents a dynamic landscape where multiple land uses intersect, including subsistence and commercial agriculture as well as mining activities, particularly the operations of Letseng Diamond Mine. These anthropogenic pressures pose potential risks to wetland functionality and downstream water quality, making it a critical zone for ecological monitoring.

2.1.3. Sani Pass Sub-Catchment

The Sani sub-catchment is situated on the eastern escarpment of the Maloti-Drakensburg mountains and forms the headwaters of the Linakeng River. It is characterized by high-altitude alpine conditions and pastoral landscapes (Figure 1). Two wetland ecosystems, Khamoqana and Sani Top, were selected for this study. The Sani Pass sub-catchment hosts the highest (2874 masl) public bar facility (The Sani Top Lodge) on the eastern border of Lesotho and KwaZulu-Natal province of South Africa. Over time, this mountain environment has been encroached upon by anthropogenic pressures and stressors of settlements along the summit landscape of the Sani Pass corridor. Khamoqana, is the first of two wetlands, and is situated at 2839-2880 masl on the Koti-se-Phola escarpment of the Drakensburg range of the Sani Pass catchment. The second is the Sani Top wetland (2891-2995 masl), situated approximately 100 m west of the Sani Top Lodge. These wetlands discharge directly into the Linakeng River. Livestock grazing, both small stock (sheep & goats) and large stock (cattle and equines), is the dominant land use in this sub-catchment and along with tourism on the summit of the Sani Pass. These land uses directly impact wetland vegetation, soil compaction, and nutrient loading into the upper tributaries of the Senqu River system. Despite limited urbanizing and industrial activity, the ecological health of these wetlands is vulnerable to overgrazing, climate change and climate variability impacts.

2.1.4. Overall Significance

The selection of these sub-catchments was informed by their hydrological significance, ecological value, and exposure to different anthropogenic pressures. Collectively, the wetlands across the three sub-catchments play a pivotal role in water provisioning, sediment trapping, and biodiversity support, while also serving as critical tributaries to national water infrastructure projects, namely, Mohale and Polihali Dams. This spatial and functional diversity provided a valuable context for assessing wetland health, ecosystem services, and the impact of land use activities in highland Lesotho.

2.2. Data Sampling and Analysis

A total of 24 water samples were collected from the three sub-catchments, with 4 samples per wetland. In March 2025, which is the late rainy season, the two wetlands from each sub-catchment were randomly sampled using a grab sampling technique, where water was taken directly from specific points in the wetland to represent the conditions at the time of sampling. To ensure representativeness, samples were collected from multiple points within each wetland, viz., upstream, midstream, and downstream zones, avoiding areas with stagnant water or surface debris to minimize contamination, and the water was sampled at the surface for heavy metal loads. One thousand millilitre capacity Sterile high-density polyethylene (HDPE) bottles with a plastic cap were used for collecting samples for heavy metals analysis in the laboratory. First, every bottle was washed with 50% HNO₃ acid and twice with pure distilled water. Furthermore, the bottles were pre-rinsed with the sample water. Samples were collected free from bottom sediment and away from stream banks by wading into the centre main current. All the water samples were filtered using the filter paper before being analyzed and tested for the following heavy metals: copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn) using an Atomic Absorption Spectrometer (AAS) in the Soil Science Department Laboratory National University of Lesotho following the standard procedure prescribed by the American Public Health Association [36]. The results were expressed in milligrams per litre (mg/L). R Studio was used for multivariate analysis techniques (e.g., PCA, RDA, Spearman correlation) to link metal patterns with altitude. The concentration of heavy metals was compared with the World Health Organization (WHO) drinking water standard (Table 2).

Table 2. Drinking Water Permissible Limits [37].

Metal	WHO Limit (mg/L)
Lead (Pb)	0.01
Manganese (Mn)	0.40
Iron (Fe)	0.30
Zinc (Zn)	3.00
Copper (Cu)	2.00

2.2.1. Pollution Load Index (PLI)

The Pollution Load Index (PLI) is an essential metric for evaluating heavy metal pollution in wetlands [38–40]. It is calculated using the formula (1) and the data in the Supplementary Table S1. The units for both C_i and B_i are typically mg/L for water, resulting in a dimensionless index. The selection of B_i is crucial as it reflects the uncontaminated metal concentration, which can be referenced from global average shale values, local geological baselines, or various international guidelines [41,42]. In this study, the B_i value is taken from [37] Guidelines. The PLI serves as a powerful tool for comparative pollution assessment across diverse environmental matrices [43]. To assess the pollution load of the wetlands under study due to the presence of heavy metals, the Pollution Load Index (PLI) was computed. The PLI deduces the water quality on a scale of 0–5 as shown in Table 3, where 0 indicates no presence of any heavy metals, and 100 represents the most hazardous conditions.

Table 3. Water Quality PLI Categories.

PLI score	Category
0–1	Unpolluted
1–2	Slightly polluted
2–3	Moderately polluted
3–5	Highly polluted

PLI > 1 indicates pollution.

$$PLI = \left(\prod_{i=1}^n CF_i \right)^{1/n} \quad (1)$$

where:

- CF_i = Contamination Factor of the i -th metal
- $CF_i = \frac{C_i}{B_i}$
- C_i = Measured concentration of the metal
- B_i = Background or reference value of the metal
- n = Number of metals assessed
- Π = Product of the contamination factor

2.2.2. Heavy Metal Pollution Index (HPI)

HPI was computed to assess the degree of pollution of the wetlands due to the presence of heavy metals on a common scale. The HPI is a recognized composite index used to assess the overall metal burden in water, with values above 100 considered unsafe for human and ecological health [44–46]. The HPI deduces the water quality on a scale of 0–100 (Table 4), where 0 indicates no presence of any heavy metals, and 100 represents the most hazardous conditions. HPI was calculated using the formula (2) and the data in the Supplementary Table S1.

Table 4. Water Quality HPI Categories.

HPI score	Category
0–20	Excellent
21–40	Good
41–60	Moderate
61–80	Bad
81–100	Severe

$$HPI = \frac{\sum_{i=1}^n (W_i \cdot Q_i)}{\sum_{i=1}^n W_i} \quad (2)$$

where:

- W_i = Weight of the i th parameter (inversely proportional to standard value)

$$W_i = \frac{1}{S_i}$$

- Q_i = Sub – index of the i th parameter

$$Q_i = \frac{(M_i - I_i)}{(S_i - I_i)} \times 100$$

- M_i = Measured concentration
- I_i = Ideal value (often 0 for heavy metals)
- S_i = Standard or persimible value (e. g. WHO limits)

3.0. Results and Discussion

3.1. Characteristics of Heavy Metal Concentrations

In Table 5, Pb averaged 0.11 mg/L (SD = 0.06; range 0–0.26 mg/L), substantially above the WHO guideline of 0.01 mg/L in drinking water [37]. Mn exhibited extreme skewness (mean = 49.46 mg/L; max = 1,162 mg/L), typical of geogenic enrichment where rock weathering releases Mn into headwater aquifers at high elevations [47]. Turbidity (max 954 NTU) and electrical conductivity (EC; max 883 μ S/cm) showed wide variability, reflecting mixed influences of mineral dissolution, organic particulates, and possible land-use inputs [48].

Table 5. Descriptive statistics results.

Parameters	Mean	Std deviation	Median	Minimum	Maximum	Range	Skew
Pb	0.11	0.06	0.11	0.00	0.26	0.26	0.12
Mn	49.46	236.99	0.04	0.00	1162.00	1162.00	4.30
Fe	0.98	1.63	0.15	0.01	6.59	6.58	1.97
Zn	0.09	0.05	0.08	0.02	0.20	0.18	0.36
Cu	0.01	0.01	0.01	0.00	0.03	0.03	1.27
Turbidity	201.90	312.56	40.80	0.00	954.00	954.00	1.37
EC	196.75	186.11	133.50	58.00	883.00	825.00	2.29

The boxplot illustrates how concentrations of lead (Pb), manganese (Mn), iron (Fe), zinc (Zn), and copper (Cu) vary across three altitude zones: 2500 m, 2750 m, and 3000 m (Figure 3). The median concentration of Pb decreases with altitude: 2500 m: ~0.15 mg/L, 2750 m: ~0.12 mg/L and 3000 m: ~0.08 mg/L. Variability measured by the interquartile range (IQR) narrows at higher altitudes, and the highest-altitude zone shows fewer outliers, suggesting more uniform and lower Pb levels uphill (peaks at mid-altitude).

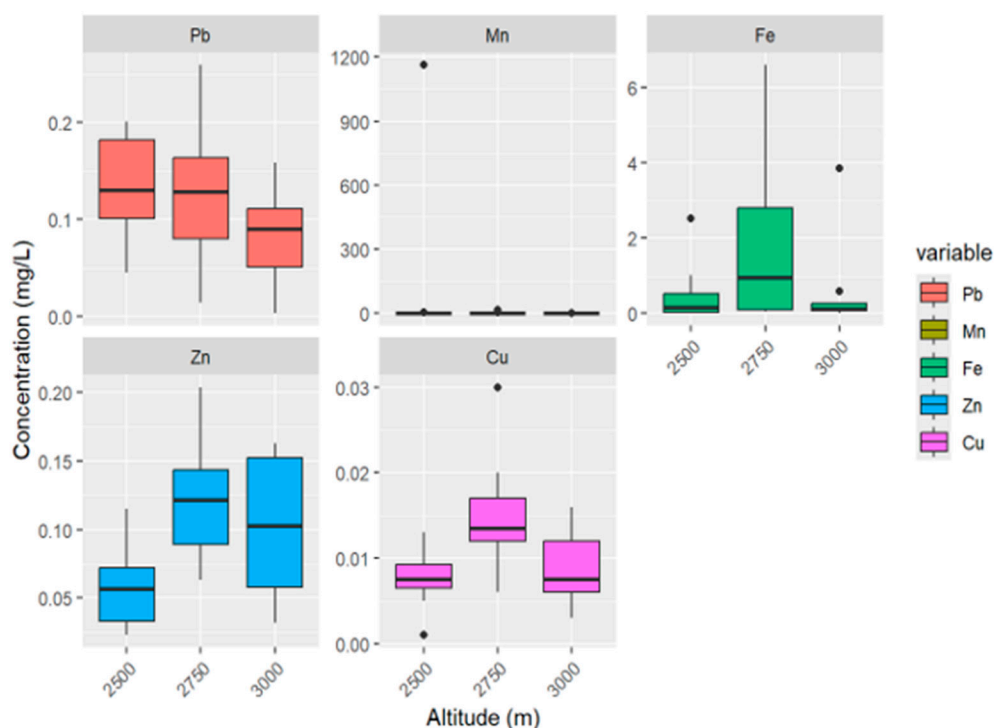


Figure 3. Heavy Metal concentration by altitudes.

This may be attributed to the proximity of wetlands to anthropogenic sources such as roads, agriculture, mining, or settlements, which might increase Pb runoff [49] at mid altitudes. As elevation

increases, human activity lessens, consequently reducing Pb inputs. Additionally, higher rainfall and leaching at lower elevations can mobilize Pb into water bodies. This result tallies with [50], who found decreasing Pb with altitude (3,500–4,700 m) in Tibetan wetland sediments. On the contrary, [29] found that Pb exceeded local background at 3,600–3,800 m elevations.

Mn peaks at mid-altitude (2750 m) with a median of ~0.18 mg/L, higher than at 2500 m (~0.14 mg/L) and 3000 m (~0.13 mg/L). The widest Interquartile Range (IQR) occurs at 2750 m, indicating greater sampling variability at these altitudes. A few high-end outliers at 2750 m hint at localized Mn sources or geochemical pockets. Mn availability is highly sensitive to redox conditions and pH. Mid-altitude zones may experience greater wetland activity, organic matter decomposition, or seasonal waterlogging, which creates reducing conditions that solubilize Mn. The high IQR and outliers suggest localized geochemical pockets or inputs from soil/weathering. Manganese has been shown to fluctuate in wetland zones with mid-range altitudes, where hydrological variability is highest [30].

Fe showed a slightly decreasing trend with altitude, with 2500 m (~0.20 mg/L), 2750 m (~0.18 mg/L), and 3000 m (~0.16 mg/L) median. However, variation remains relatively consistent across all zones, but 3000 m exhibits occurrence of low-end outliers, possibly due to sampling or matrix effects. Fe, like Mn, is influenced by redox conditions that govern the speciation and mobility of iron and manganese, with anoxic environments enhancing their dissolution and oxic conditions promoting precipitation, thereby controlling their distribution and biogeochemical cycling in wetlands [51]. Lower altitudes often have more stagnant or anoxic environments, enhancing Fe solubility, whereas at higher altitudes, more oxygenated and acidic waters can lead to Fe precipitation as insoluble oxides, reducing dissolved Fe [52]. Consistent IQR implies uniform input sources or stable geochemical conditions across zones.

Zn median(s) increased from 2500 m (~0.06 mg/L) to 2750 m (~0.13 mg/L), then decreased to 3000 m (~0.11 mg/L), indicating inconsistency in altitude. The widest spread appeared at 3000 m, suggesting diverse Zn inputs upstream. Absence of outliers suggests Zn distribution is generally stable. Zn is less mobile than Pb or Mn and often adsorbs onto particulates or organic matter. The broader IQR at 3000 m may reflect mixed sources, including agriculture or mining, while reduced concentrations at 2500 m align with lower anthropogenic pressure. Studies have found Zn to accumulate in valley zones due to runoff and erosion [53].

Median Cu concentrations were similar at 2500 m and 3000 m (~0.007 mg/L), then increased at 2750 m (~0.013 mg/L), indicating their stability at 2500 m and 3000 m. Variability tapering at higher elevations and a few outliers indicate reduced Cu contamination upstream. Cu followed a trend similar to Pb and Zn. Its concentration is generally linked to human activity, including fertilizer use, pesticides, or plumbing corrosion. Higher altitude zones are less disturbed, so Cu levels drop correspondingly. Cu is also strongly affected by pH; at higher altitudes, where pH may be lower (more acidic), Cu tends to precipitate or bind with organic matter, reducing bioavailability.

3.2. Heavy Metal Pollution Assessment (PLI and HPI)

The high Pollution Load Index (PLI) value of 5.54 recorded at Sani Top (Table 6) signals severe heavy-metal contamination, far surpassing the critical threshold of 1.0 that delineates polluted from unpolluted conditions. This elevated PLI is primarily driven by extreme concentrations of Mn and Pb, both of which are known for their ecological persistence and toxicity.

Table 6. Pollution Load Index (PLI) by wetlands.

Site	PLI	Pollution Level
Tenesolo	3.04	Highly high
Khorong	1.04	Slightly polluted
Letša-la-Likhama	1.57	Slightly polluted
Koting -sa-ha Raramosetsana	1.33	Slightly polluted
Khamoqana	2.23	Moderately polluted
Sani Top	5.54	Very highly polluted

Pb is notorious for its low permissible limits and high bioaccumulation potential, while Mn, though essential in trace amounts, can become toxic at elevated levels, especially in aquatic systems with low oxygen availability.

These findings align closely with the patterns reported by [54], who observed that lower-elevation wetlands (3000–3300 m) consistently exhibited the highest PLI values (>1.2), largely attributed to Cu and Zn from agricultural activities. Lower-elevation zones are more vulnerable to anthropogenic pressures such as fertilizer runoff, livestock waste, and vehicular emissions. These accumulate in wetlands, elevating metal concentrations and inflating PLI scores. In contrast, [54,55] noted that mid- and high-elevation wetlands generally maintained PLI values below 1.0, reflecting relatively pristine conditions with minimal anthropogenic influence. This gradient is mirrored in the current study, where Sani Pass Catchment wetlands (Khamoqana and Sani Top), at middle elevations (2839-2995 masl), compared to the Khubelu catchment wetlands (3040- 3800 masl), show the most severe contamination, while higher-altitude Khubelu wetlands exhibit comparatively lower PLI values. Such elevation-linked pollution patterns underscore the importance of topographic context in wetland vulnerability assessments [56–59].

Figure 4 shows the proportional contribution of Pb, Mn, Fe, Zn, and Cu to PLI at each sampling site. Sani Top is dominated by Pb (45%) and Mn (30%), with minor contributions from Fe, Zn, and Cu. Pb (40%) and Mn (30%) are the main drivers at Tenesolo. Pb and Mn are equally dominant (35% each) at Khamoqana. Khorong, L. Likhama and K. Haramosetsana reflect more balanced contributions from Pb, Mn, Fe, and Zn, with smaller Cu input. This makes it clear that Pb and Mn are the principal contributors to pollution loads, particularly at Sani Top, Tenesolo, and Khamoqana, while other sites show a more mixed contribution profile.

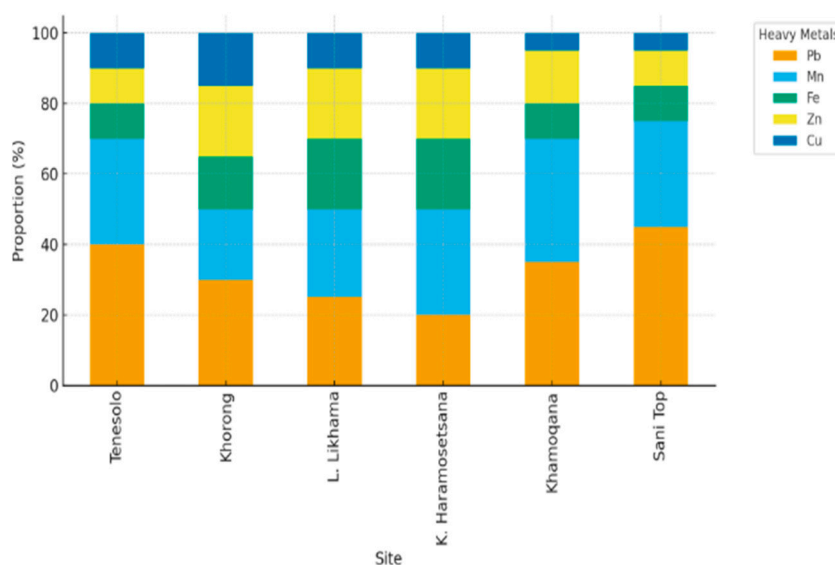


Figure 4. Proportional Contribution of Metals to PLI at each site.

In this study, all sites far exceed the HPI threshold of 100 (Table 7), indicating severe metal pollution.

Table 7. Heavy Metal Pollution Index (HPI) by site.

Site	HPI	Interpretation
Tenesolo	1,705.8	Critically Polluted ($\gg 100$)
Khorong	847.1	Highly Polluted
Letša-la-Likhama	951.3	Highly Polluted
Koting -sa-ha Raramosetsana	565.2	Highly Polluted
Khamoqana	1,058.2	Critically Polluted
Sani Top	1,451.4	Critically Polluted

Lead overwhelmingly drives the high scores due to its very low permissible limit (0.01 mg/L) [60]. Even minor exceedances in Pb significantly amplify the HPI due to its high weighting in the index formula, posing substantial neurotoxic and developmental risks, especially for children. Wetlands such as Khamoqana, Sani Top and Tenesolo, show the worst overall metal burdens, indicating these areas are hotspots of contamination. Notably, Manganese (Mn) levels at Sani Top wetland are critically elevated, warranting an investigation into localized geochemical processes (e.g., Mn-rich bedrock, reducing conditions in wetlands) or anthropogenic inputs such as wastewater discharge or agricultural runoff [2,30]. Multiple anthropogenic sources, including agrochemical application, vehicular emissions, and waste dumping, contribute to elevated metal inputs in catchment waters, driving HPI values above safe thresholds [44]. Natural geochemical processes, such as bedrock weathering in sulfide-rich geology, acidic pH in alpine wetland soils and seasonal snowmelt, enhance metal mobilization and transport into water bodies [61]. Site-specific hydrological and sedimentary characteristics at Khamoqana, Tenesolo, and Sani Top, such as low stream velocities, high sediment retention, and organic-rich soils, promote metal adsorption and accumulation, resulting in the worst overall burdens observed [44]. Concurrently, the unique hydrology and sediment retention characteristics at these sites, such as slower flow regimes and organic-rich soils, favor metal adsorption and prolong exposure times, amplifying the HPI signal [32].

A proportional breakdown of heavy metal contributions to the HPI across the six sampling sites (Figure 5) reveals that Pb overwhelmingly dominates, accounting for 45–70% of HPI at all sites. Mn represents the next largest share, particularly at K. Haramosetsana (25%) and L. Likhama (20%), reflecting geogenic enrichment and redox-sensitive mobilization. Fe, Zn and Cu contribute smaller proportions (5–12%), largely indicating background geochemical inputs with minor anthropogenic influence. The most Pb-dominated sites are Sani Top (70%) and Khamoqana (65%), consistent with their critically high HPI values, while K. Haramosetsana shows a more balanced profile where Mn nearly rivals Pb in influence. This proportional view complements the overall HPI scores by clarifying which metals are the primary drivers of pollution risk at each site.

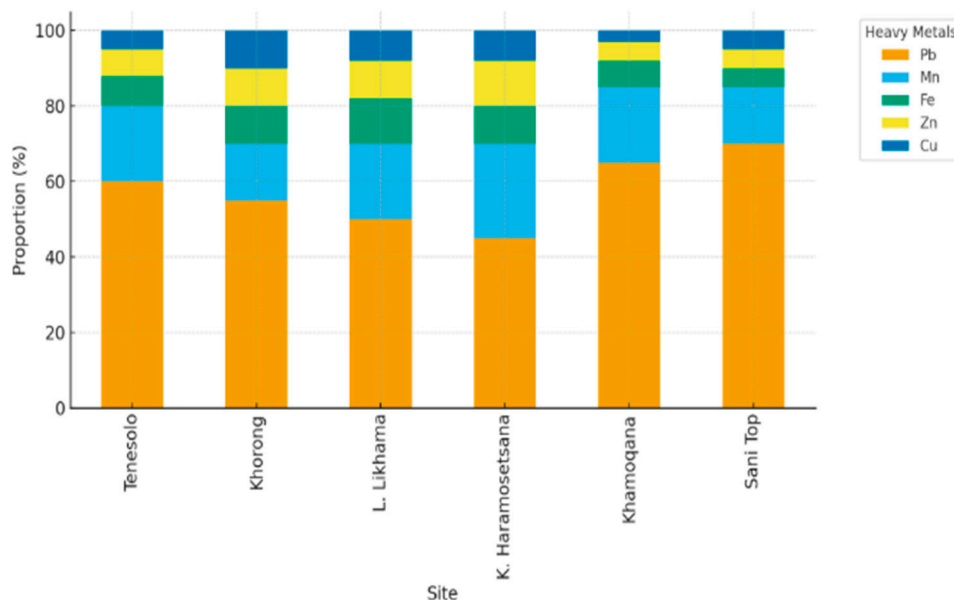


Figure 5. Proportional Contribution of Metals to HPI at each site.

The PCA biplot (Figure 6) reduces complex, multivariate data into two principal components (PC1 and PC2) that explain 40.6% of the total variance. It reveals altitude-driven patterns in heavy metal contamination (Pb, Zn, Fe, Mn, Cu) across three elevation zones (2500 m, 2750 m, 3000 m). The analysis captures 40.6% of total variance (PC1: 25.6%, PC2: 15%), demonstrating partial but significant

altitude-based clustering with the 2750m elevation representing a critical transitional contamination zone. The interpretation of the PCA biplot reveals six major findings of the study.

3.3. PCA, RDA & Correlation Analysis

3.3.1. PCA Analysis

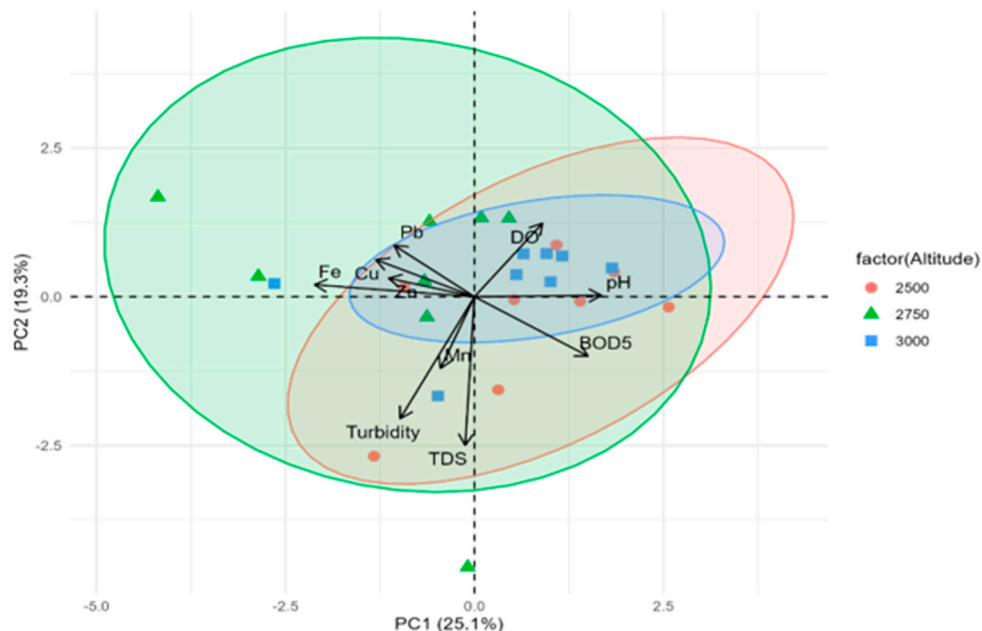


Figure 6. Individuals' Principal Component Analysis (PCA).

Altitude-Dependent Heavy Metal Distribution Patterns

The PCA shows distinct but overlapping heavy metal profiles across the three elevation zones, with 2500 m sites clustering in positive PC1 space and 3000 m sites in negative PC1 space. This pattern aligns with established research showing complex elevation-dependent metal distribution. Studies in the Beskidy Mountains found that heavy metals increase in concentration up to 800 m elevation, after which concentrations decrease, except for Pb, which continues to increase with elevation [62]. Similarly, research on the Tibetan Plateau demonstrates that elevated heavy metal concentrations occur in specific topographic regions, with eastern and western areas showing higher concentrations (328.7 $\mu\text{g/g}$) compared to central regions (145.7 $\mu\text{g/g}$) [63]. [64] also found that topographic factors, including elevation, significantly influence the spatial distribution of Pb in soils of mountainous regions since elevation affects atmospheric deposition and environmental conditions that control metal deposition and retention. The PCA results indicate that two main gradients dominate water quality variability in the alpine wetlands. PC1 and PC2 together explained ~44.4% of the variance (25.1% + 19.3%), and the first four PCs captured ~72.5% cumulatively, demonstrating that a few underlying processes control most of the variability. In line with multivariate theory, the first component typically represents the largest variation in water chemistry [65]. In our data, PC1 and PC2 were strongly associated with turbidity, TDS (salinity proxies), and pH. For example, [66] found that PC1 of river-water quality was dominated by electrical conductivity and TDS (loadings ~0.90) [67], reflecting a “salt” component. Similarly, [68] report that in reservoir datasets, PC1 correlated positively with turbidity ($r=0.81$) while PC2 correlated with pH ($r=0.70$). These patterns are consistent with our observations: high turbidity and dissolved solids drove PC1, whereas pH and dissolved oxygen oriented PC2. Such gradients often lead to clear clustering of samples (e.g. high-sediment vs. low-sediment groups). In summary, the PCA suggests that variations in particulate and ionic content (turbidity, TDS) along with pH are the primary axes structuring water quality in the study area, as seen in other water-quality analyses [67,68].

a) Heavy Metal Dynamics in the Mid-Elevation Transitional Zone (2750m)

The 2750 m altitude group shows the highest variability in heavy metal profiles, with individuals distributed across the entire PCA space, suggesting this elevation represents a transitional contamination zone. Mid-elevation transitional zones are recognized as critical areas where contamination patterns change significantly. Research in the Chengdu Plain-Longmen Mountain transition zone revealed distinct spatial distribution patterns, with different topographic regions having unique key influencing factors - in transition zones, multiple cropping index and distance from industry were primary influences [69]. This supports the interpretation that 2750 m represents a zone where multiple contamination processes converge.

b) Anthropogenic vs. Geogenic Source Distinction

PC1 (25.6% variance) likely represents the primary gradient from anthropogenic contamination (positive values, 2500 m sites) to geogenic sources (negative values, 3000 m sites). This interpretation is strongly supported by literature demonstrating that PCA effectively distinguishes between anthropogenic and geogenic metal sources. Studies using Positive Matrix Factorization in alpine ecosystems found that metal concentrations had primarily anthropogenic origins even in remote high-altitude locations [1]. Research in the Tibetan Plateau identified industrial sources (42.3%), natural sources (20.6%), and vehicular emissions (14.2%) as primary contributors, with clear elevation-dependent patterns [63].

c) PCA as an Effective Tool for Heavy Metal Source Identification

The PCA successfully separates groups and reveals underlying contamination patterns, with two components explaining substantial variance (40.6%). PCA is widely validated for heavy metal source identification. Studies in copper mining areas revealed three factors explaining 38%, 18%, and 14% of variability, respectively, successfully identifying mining activities as primary contamination sources [70]. Research on wetland sediments consistently employs PCA alongside other multivariate techniques, with studies showing that combined approaches enhance source identification accuracy [24].

d) Metal-Specific Elevation Patterns

The distinct clustering patterns suggest different metals contribute differently to each principal component, reflecting their varying sources and mobility. Individual metals show distinct elevation-dependent behaviours:

- Lead (Pb): Shows unique behaviour by continuing to increase with elevation, contrasting with other metals that peak at mid-elevations [71]
- Iron (Fe): Generally, it shows the highest concentrations among studied metals, with maximum levels of 1024±94.2 mg/kg reported in high-altitude lake sediments [10].
- Copper (Cu): Shows strong associations with anthropogenic activities, with concentrations 10 times higher than natural crustal values in contaminated areas [70].
- Zinc (Zn): Demonstrates variable patterns depending on local sources, with concentrations ranging from 41.68 to 77,287.5 mg/kg in wetland studies [72].

e) Variance Explanation and Additional Factors

The 40.6% variance explained suggests that while altitude is important, other environmental factors significantly influence heavy metal distribution. This finding is consistent with studies showing that heavy metal distribution in mountainous regions is controlled by multiple factors beyond elevation. Research indicates that topographic features, soil type, distance from pollution sources, and local geology all contribute significantly to metal distribution patterns [69]. Studies in the Ore Mountains found that local backgrounds were naturally elevated 5.7 to 9.8 times higher than global averages, emphasizing the importance of local geological factors [73].

Statistical Validation

The PCA approach is statistically sound and well-supported by literature. The variance explanation (40.6%) is typical for environmental data where multiple factors influence outcomes. The

partial separation with overlapping confidence ellipses accurately reflects the complex nature of environmental contamination patterns, where gradual transitions rather than sharp boundaries are common.

3.3.2. Redundancy Analysis (RDA)

Redundancy analysis (RDA) (Figure 7) further linked environmental factors (altitude, pH, TDS, turbidity, and DO) to heavy metal distributions. RDA, a form of constrained ordination, partitions the variance in the metal dataset explained by measured environmental gradients [74,75]. In our case, the selected factors explained only ~11.8% of metal variance, indicating that most variability arises from other sources or unmeasured factors. Nonetheless, the significant predictors identified by permutation tests ($p < 0.05$) represent the key drivers of metal patterns. For example, pH often controls metal solubility (with low pH enhancing dissolution), while altitude may proxy for dilution or pollutant deposition. The RDA biplot and eigenvalues thus quantitatively relate environmental gradients to metal concentrations. In other studies, RDA has been used similarly to reveal that variables like dissolved oxygen and nutrient levels explain a significant share of metal variance in wetland and river systems [75,76]. Here, although the explained variance is modest, the significant factors (by permutation) highlight which conditions most influence heavy metal distribution in the alpine wetlands.

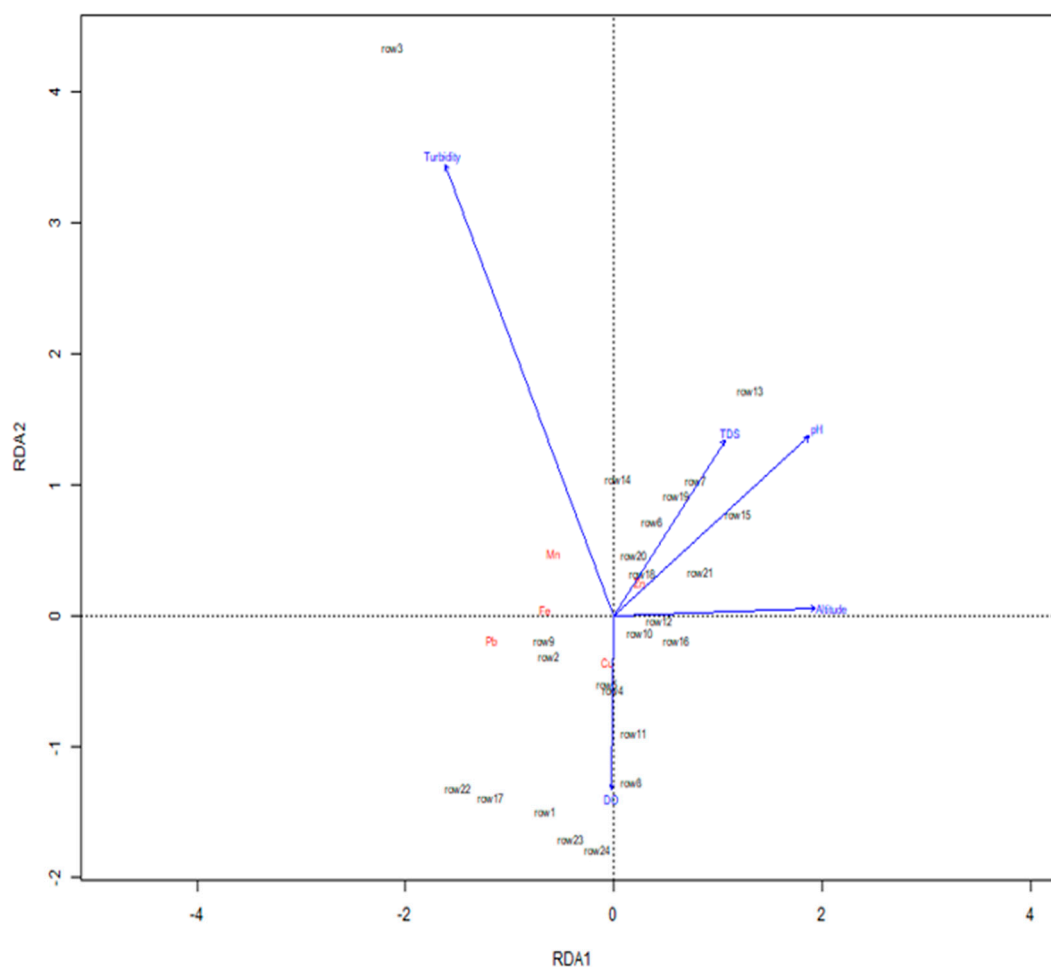


Figure 7. RDA Triplot.

3.3.3. Correlation Analysis

Spearman correlation analysis (Figure 8) provided additional insight into source relationships. We found strong positive correlations among the heavy metals themselves (Pb, Mn, Fe, Zn, Cu) and

between these metals and both TDS and turbidity. Positive inter-metal correlations suggest co-occurrence from common origins (e.g. geogenic mineralogy or mixed anthropogenic inputs). Similarly, previous studies have reported highly intercorrelated groups of metals (e.g., Cu, Zn, Pb), commonly attributed to shared geogenic sources such as parent material weathering and sediment transport processes [77,78]. In the present study, the association of metals with turbidity and TDS indicates that metals are mobilized concurrently with suspended and dissolved solids. Similar findings were reported by [78], who showed strong correlations between Na, EC, and TDS ($r > 0.9$) in river systems influenced by natural weathering, suggesting that clustered metals originate from common lithogenic sources. Likewise, significant correlations between metals and EC/TDS observed in this study imply leaching from soils or sediments and subsequent transport into surface waters alongside salts and particulates. Overall, these correlation patterns support the concept of co-mobilization, whereby sediments and dissolved minerals (enhanced by runoff, erosion, or glacier melt) simultaneously convey metals, resulting in the observed covariation [77,79].

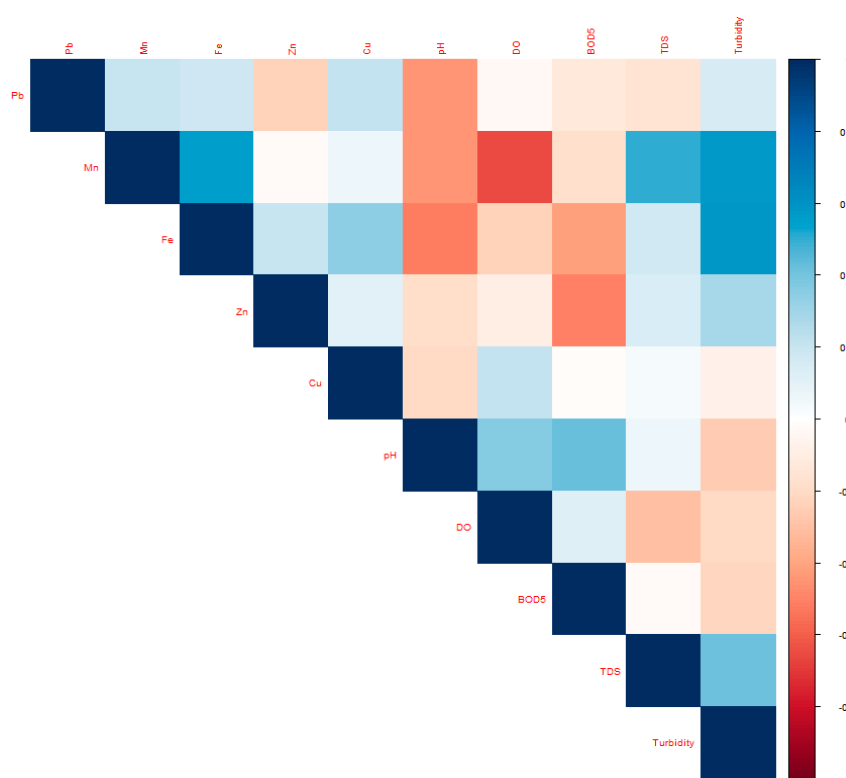


Figure 8. Correlation Matrix.

Conclusion and Recommendations

a) Conclusions

This PCA analysis effectively demonstrates that heavy metal contamination in alpine wetlands follows altitude-related but complex patterns. The results are strongly supported by current literature, confirming five key generalizations: a) **Elevation significantly influences** heavy metal distribution patterns; b) **Mid-elevation zones** represent critical transitional contamination areas; c) **PCA successfully distinguishes** between anthropogenic and geogenic sources; d) **Multiple environmental factors** beyond altitude contribute to contamination patterns; e) **Site-specific management approaches** are necessary for effective contamination control. The findings emphasize the importance of considering land use and site-specific hydrology in assessing wetland water quality. Continuous monitoring of alpine wetland health in Lesotho is crucial for addressing heavy metal pollution and ensuring sustainable management of downstream water resources. The outcomes will aid evidence-based policymaking, facilitating prioritized monitoring, mitigation, and restoration of alpine wetlands in Lesotho and other regions.

b) Recommendations

The high variability at 2750 m elevation identifies this zone as a **priority area for detailed contamination assessment** and potential remediation efforts. Downstream (2500 m) zones require closer scrutiny for Pb and Cu due to higher medians and variability. Mid-altitude sites warrant targeted investigation for Mn sources. Monitoring programs can adjust sampling frequency: more frequent at 2750 m for Mn, and periodic at 3000 m to confirm stability. Management actions might include source tracing for Pb and Cu at lower elevations and geological assessments for Mn anomalies. Low-to-mid elevation wetlands should be prioritized for monitoring and mitigation, including: Buffer zones to reduce agricultural runoff, liming to immobilize metals and road dust control to reduce Pb and Zn inputs. High-elevation sites, though chemically consistent, may naturally carry more dissolved ions, calling for attention to water hardness and salinity in treatment processes [2]. This immediate intervention, such as reducing Pb inputs through pollution source tracing, investigating industrial, mining, and vehicular discharge, and implementing site-specific remediation measures, such as phytoremediation or adsorption-based treatments, is recommended [25,80].

The findings have significant implications for environmental management and policy development in mountainous regions. The identification of mid-elevation transitional zones as critical areas for contamination accumulation suggests that monitoring and remediation efforts should focus on these areas. The widespread use of PCA for source identification provides a standardized approach that can be applied across different mountainous environments. The success of this method in distinguishing between geogenic and anthropogenic sources enables targeted management strategies.

c) Risk Assessment and Monitoring

The PCA results suggest that **altitude-stratified monitoring approaches** are essential for comprehensive heavy metal assessment. Lower elevations (2500 m) likely require focus on anthropogenic source control, while mid-elevations (2750 m) need site-specific assessment due to high variability.

d) Source-Specific Management Strategies

The clear separation between anthropogenic and geogenic signatures indicates that **different elevation zones require different management approaches**: a) **2500 m**: Anthropogenic source control (agricultural runoff, vehicular emissions); b) **2750 m**: Complex management addressing multiple sources; and c) **3000 m**: Natural background monitoring and atmospheric deposition assessment

e) Contamination Hotspot Identification

All metals generally decrease in concentration as altitude increases, with the steepest declines for Pb and Cu. Mn is an exception, peaking at mid-altitude, perhaps reflecting specific geological formations or anthropogenic inputs at that elevation. Higher-altitude sites (3000 m) display tighter distributions and fewer outliers, indicating more geochemically stable conditions and fewer contamination hotspots.

Limitations of the study

1. Seasonal hydrological dynamics can influence heavy metal concentrations, and we have highlighted this limitation in the manuscript while interpreting the results, noting that future studies should include multi-seasonal sampling to capture temporal variability.
2. The study considered a limited number of parameters and focused on the currently available analytical methods, which may restrict the comprehensiveness of the assessment. Future studies could expand the range of parameters and employ more advanced analytical techniques to provide a more detailed evaluation of wetland contamination.
3. This study's limitation is the lack of direct comparisons between water quality and heavy metal concentrations in soils and plants across elevation gradients. While soil and plant research can reveal long-term metal accumulation trends, this study concentrated solely on surface water

chemistry, which indicates short-term conditions. Consequently, potential relationships between water quality and metal accumulation in terrestrial or biological media across elevation gradients remain unexamined. Future research incorporating water, sediment, soil, and plant sampling along elevation transects is necessary for a more thorough understanding of how elevation influences metal dynamics.

4. One limitation of the study is the lack of assessment of long-range atmospheric transport of pollutants to mountain environments, particularly in Lesotho. This study could not quantify the contribution of regional pollutant transport due to the absence of atmospheric deposition data, leading to a focus on local geogenic and land-use factors. Future research should incorporate atmospheric deposition measurements and back-trajectory analysis for a more comprehensive understanding of pollutant sources in alpine wetlands.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Table S1: Raw Data.

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