



## Water quality and health risk assessment of trace elements contamination in Ghodaghodi Lake, Sudurpaschim Province, Nepal

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### Abstract

The contamination of trace elements (TEs) in freshwater sources has become an alarming issue globally. This study evaluates the contamination level of TEs, their spatial distributions, and the health risks in the Ghodaghodi Lake complex, Nepal. Altogether, ten water samples were collected, and As, Ba, Cd, Co, Cr, Cs, Cu, Li, Mn, Ni, Pb, Rb, Sc, Sr, Ti, Tl, V, Y, and Zn were determined by inductively coupled plasma mass spectrometry. The results revealed that Sr, Zn, Cu, As, Sc, and Rb were dominated TEs, contributing to the contamination. The principal component analysis and correlation matrices demonstrated both the geogenic and anthropic origin of the TEs in the lake. The water quality index (WQI=10.08) and hazard indices <1 exhibited that the TEs pose a low risk to human health and, hence the water of the lake was suitable for drinking purposes. However, exposure risk assessment results suggested that children are relatively more vulnerable compared to adults. The outcome of this study will provide new insights to local people and the concerned authorities for the sustainable management of Ramsar listed Ghodaghodi Lake complex.

**Keywords:** Ghodaghodi Lake, health risk assessment, Nepal, trace elements, water quality

### Introduction

Freshwater resources are indispensable for all living organisms including human beings (Huang et al., 2009). The freshwater lakes are the major sources of drinking water and maintain the ecological balance that supports many life forms. However, the contamination of these resources is one of the major threats to public and ecological health worldwide (Pant et al., 2020a). Among the various contaminants, trace elements (TEs) are the most toxic and persistent that can impact the aquatic ecosystems through the process of bio-accumulation and bio-magnification (Shah et al., 2012; Xie et al., 2016). In addition, the TEs are transported to the standing (lentic) water bodies through streams, rock weathering, erosion and precipitation. The ongoing retreat of mountain glaciers under the changing scenarios of global climate, extensive land use/cover changes, excessive use of agro-fertilizers and pesticides, industrial and urban sewage discharge, and commercial and domestic sewages are some of the major sources of toxic TEs to the freshwater lakes. Meanwhile, lakes are less dynamic and readily contaminated by the toxic TEs, and thus, are a matter of concern to public health hazards thereafter getting scienti-

fic attention. The major TEs contamination in lake water bodies, including Arsenic (As), Barium (Ba), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Cesium (Cs), Copper (Cu), Lithium (Li), Manganese (Mn), Nickel (Ni), Lead (Pb), Rubidium (Rb), Scandium (Sc), Strontium (Sr), Titanium (Ti), Thallium (Tl), Vanadium (V), Yttrium (Y), and Zinc (Zn), has become an alarming issue in many developing countries over the past few decades and Nepal is not the exception (Jehan et al., 2020; Pant et al., 2021a). Some of these elements are carcinogenic (e.g., As, Pb, Cr, and Cd) and directly affect human health and damage the organs like the liver, kidney, digestive, nervous, and blood circulation systems (Huang et al., 2009). Additionally, some of the health effects caused by these elements include peripheral neuropathy, skin, lung and bladder cancer, tubular dysfunction, neurodevelopment effects, cardiovascular diseases, hypertension, infertility, and adverse pregnancy (WHO, 2011).

Explicitly, Pb damages the peripheral nervous system, whereas As affects the central nervous system and they are

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responsible for the loss of weight, loss of appetite, and gastrointestinal disorders. Similarly, Ba can cause vomiting, abdominal pain, difficulties in breathing, irregularity in blood circulation, and muscle weakness (Li & Zhang, 2010). Owing to the potential risk of the TEs mentioned above, various multivariate statistical approaches such as correlation matrix (CM), cluster analysis (CA), and factor/principal component analysis (FA/PCA) are widely used to assess the sources, concentrations, and potential risks posed by the elements to human and ecological health in recent years (Dong et al., 2015; Pant et al., 2018).

Freshwater is one of the prime resources in the Himalayan region which are not only the means of livelihoods support but also a key indicator for ecological sustainability in the entire region (Dong et al., 2015). However, some recent studies have reported that these indispensable resources are being contaminated by various pollutants including TEs (Adhikari et al., 2020; Bishwakarma et al., 2019; Pal et al., 2021; Pant et al., 2020b). In addition, in the central Himalayas, particularly in Nepal, the freshwater lakes are situated at different ecological regions such as the Koshi Tappu Ramsar area in Sunsari (< 100 masl) and Tilicho Lake in Manang (>4900 masl) are under pressure due to various natural and anthropic factors. The lakes located in the high Himalayas have experienced limited direct anthropic stresses; however, these are susceptible to the impacts of climate change, long-range transport of pollutants, and geogenic weathering. However, there are a limited number of scientific studies available on the lake water hydrochemistry from Nepal Himalayas. For instance, Sharma et al. (2015) studied mercury (Hg) contaminations in the two Ramsar listed lakes i.e., the Phewa Lake and the Gosainkunda Lake. They found potential threats of the TEs to these lakes from geogenic, anthropic, and long-range transport of the pollutants. On the other hand, the lakes and other freshwater ecosystems located in the Terai and Hilly regions are experienced high anthropic pressure such as agricultural runoff, domestic and urban wastes (Niraula, 2012; Rupakheti et al., 2017). However, there are very few published literature on the TEs from the lowland region of Nepal.

Ghodaghodi lake complex is one of the Ramsar listed lakes situated in the low-land Terai region of Sudurpaschim Province, Nepal. It is a natural freshwater ecosystem, which is inter-connected with swamps, marshes, and meadows. Despite providing various ecosystem services, the lake faces threats from anthropic activities and natural flash floods especially during the rainy season. In addition, religious and touristic activities also add the chemical pollutants into the lake (Bhatta et al. 2019). This lake has not received enough scientific attention regarding chemical contaminations including TEs and associated human health impacts. Thus, the main objective of this study is to determine the surface water quality of the lake and explore the sources of dissolved TEs including associated health risks. The study could provide an insight on

the contaminations of TEs and their potential health risks and contribute to develop appropriate policy measures associated with the water quality management in the Himalayas.

## Materials and Methods

### Study area

The Ghodaghodi Lake complex (28°41'03"N and 80°56'43"E) is situated at an elevation of 205 masl, a Ramsar listed lake. It is located in the Kailali district of Sudurpaschim Province, Nepal. The lake complex covers an area of 2563 ha with 14 large and small oxbow lakes associated with marshes, swamps, streams, and springs (Fig. 1). The lake is rich in aquatic macrophytes, fishes, birds, reptiles, and mammals (Lamsal et al., 2014). The persisting anthropic activities like excessive harvesting, poaching, habitat destruction, population pressure, forest fragmentation, siltation, excessive use of fertilizer and pesticide seepage have threatened the existing ecological conditions in the lake (Acharya et al., 2020; Pant et al., 2021c; Tripathee et al., 2016; Xiao et al., 2014).

The Ghodaghodi Lake basin has a tropical monsoon type of climate with distinct seasonality. The mean annual rainfall ranges from 1630 mm to 1705 mm. About 80 % of the total annual rainfall occurs during the monsoon season from June to September in the lake basin. The average monthly maximum temperature ranges from 21 °C to 38 °C and a minimum of 6 °C to 25 °C (Bhatta et al., 2019).

### Sample collection and lab analysis

For this study, a total of 10 representative water samples were collected from different sites of the Ghodaghodi Lake (Fig. 1). The samples were collected in the winter season (January) in 2018 at a depth of about 10 to 15 cm. Acid-washed 20 mL ultra-clean high-density polyethylene (HDPE) bottles with a screw cap were used to collect water samples. The samples were filtered through a 0.45 µm polypropylene membrane filter and kept in the refrigerator at 4°C until further analysis. To avoid the adsorption of TEs on the walls of the bottles, water samples were acidified to pH < 2 by using supra pure nitric acid. A total of 19 TEs (As, Ba, Cd, Co, Cr, Cs, Cu, Li, Mn, Ni, Pb, Rb, Sc, Sr, Ti, Tl, V, Y, and Zn) were analyzed using inductively coupled plasma-mass spectrometry (ICP-MS, X-7 Thermo 141 Elemental) at Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITP-CAS), Beijing, China. The accuracy of the analytical protocol was ascertained by performing the triplicate measurements of the externally certified reference solution, showing the analytical precision < 5% (Pant et al., 2020b).

### Human and Health Risk Assessment

#### *Water Quality Index (WQI)*

The WQI is one of the useful tools that represent the overall water quality at a certain place and time based on TEs concentrations (Wu et al., 2018). The weightings (Wi) are allotted according to the relative significance of water quality parameters in the overall quality of drinking water (US-EPA,



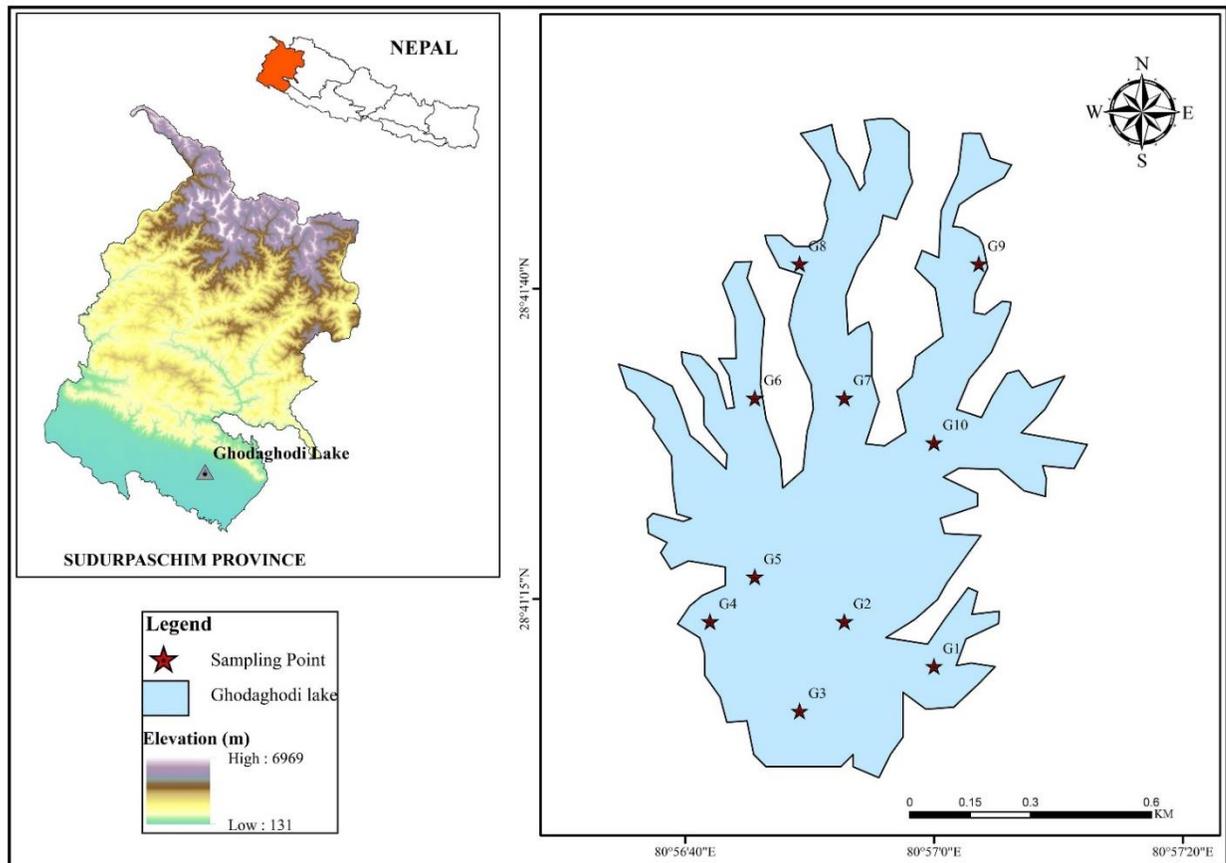
1989; Li and Zhang, 2010; Pant et al., 2021b). The water quality parameters with given  $W_i$  were used in WQI calculation, and the lowest ranking was given for Zn, as it possessing insignificant health effects, whereas the highest ranking was provided for Pb, Cd, and Cr (Xiao et al., 2014). In this study, the WQI for only ten elements were calculated due to the unavailability of other elements' drinking water standards. WQI was obtained from the relation:

$$WQI = \sum [W_i \times (C_i/S_i) \times 100]$$

Where,  
 $W_i = w_i / \sum w_i$   
 $w_i$  is the weight of each TE,  
 $\sum w_i$  = sum of the weightings of all the TEs,

$C_i$  = concentration of each TE in each water sample,  
 $S_i$  = World Health Organization Guidelines for drinking water for each TE.

For this study, WHO drinking water quality guidelines were taken as reference for each TE, and their weights ( $W_i$ ) were assigned using the values from Tripathee et al. (2016). The computed WQI values were classified into five different categories (Acharya et al., 2020): excellent ( $WQI < 50$ ), good ( $WQI = 50 - 100$ ), poor ( $WQI = 100 - 200$ ), very poor ( $WQI = 200 - 300$ ), and unsuitable for drinking purpose ( $WQI > 300$ ).



**Figure 1** Sampling locations in the Ghodaghodi Lake, Sudurpaschim Province, Nepal

**Health Risk Assessment**

Health risk assessment models are used to quantify the potential risk of TEs to people (Wu et al., 2009). The toxicity caused by the TEs present in the lake in terms of hazard quotient (HQ) is obtained from the relation:

$$HQ = \frac{ADD}{RfD}$$

Where, HQ is the numerical estimation of the toxicity potential imposed by a single TE within a single route of exposure, ADD is the average daily dose (Tripathee et al.,

2016), and RfD = reference dose of the contaminant for non-carcinogenic risk (mg/kg/day) obtained from (US EPA, 2010).

Then hazard index (HI) was calculated to indicate its overall non-carcinogenic risk (Li and Zhang, 2010), for which the non-carcinogenic HQs through ingestion and dermal adsorption pathways for each TE were summed and presented as:

$$HI_{ing/derm} = HQ_{ing/derm}$$

The human population has exposure to the TEs present in water bodies via ingestion, inhalation, and dermal absorption; however, direct ingestion and dermal absorption are the most common ways. So, the exposure dose for these two main pathways was calculated as follows:

$$ADD_{ingestion} = \frac{Cw \times IR \times EF \times ED}{BW \times AT}$$

$$ADD_{dermal} = \frac{Cw \times SA \times Kp \times ET \times EF \times ED \times 10^{-3}}{BW \times AT}$$

Where,

$ADD_{ingestion}$  = average daily dose from ingestion ( $\mu\text{g}/\text{kg}/\text{day}$ ),  $ADD_{dermal}$  = average daily dose from dermal ( $\mu\text{g}/\text{kg}/\text{day}$ ),  $Cw$  = average concentration of TEs in water ( $\mu\text{g}/\text{L}$ ),  $IR$  = ingestion rate, 2 and 0.64 L/day for adults and children, respectively,  $EF$  = exposure frequency (350 days/year assuming that the local people spend remaining 15 days away from the site),  $ED$  = exposure duration (30 years and 6 years for adults and children, respectively),  $BW$  = average body weight (assumed that the bodyweight is 70 kg and 15 kg for adults and children, respectively),  $AT$  = average time (in days), ( $ED \times 365$  days),  $SA$  = exposed skin area, (18,000  $\text{cm}^2$  for adults and 6,600  $\text{cm}^2$  for children),  $Kp$  = skin permeability coefficient in water ( $\text{cm}/\text{h}$ ),  $ET$  = exposure time spent in bathing and shower (0.58 and 1 h/day for adults and children, respectively). These values were obtained from the reference of Tripathy et al., (2016).

The local people widely use the water from the Ghodaghodi Lake complex for drinking and other domestic purposes. Importantly, the lake is one of the most important religious sites and thousands of pilgrims consider the lake water as a holy one and use it as *Jal* (holy water). Meanwhile, the shallow ground water is widely used for drinking purposes in the vicinity of the lake area where the lake water acts as a recharge zone for about 75,000 people from 13,174 households in the lakeshade (Lamsal et al., 2014).

### Statistical analyses

The multivariate statistical techniques were used for evaluation and interpretation of the TEs concentration and to identify the major sources of TEs in the lake. Hierarchical agglomerative cluster analysis (CA) was applied to assess the variability of the TEs and grouping of similar sampling sites based on TEs concentration. Additionally, in order to assess the potential association, Spearman's rank correlation

coefficient was applied. For the identification of major sources of TEs, PCA with varimax rotation was performed (Pant et al., 2020b).

## Results and Discussion

### General hydrochemistry of TEs

The statistical summary of dissolved TEs in the surface water of Ghodaghodi Lake is presented in Table 1. Based on the mean concentration of the TEs present in the lake water, three major categories were identified: (i) concentrations  $>10 \mu\text{g}/\text{L}$  (Sr and Ba), (ii) concentrations between 1 - 10  $\mu\text{g}/\text{L}$  (Sc, Cu, As, Rb and Zn), and (iii) concentrations  $< 1 \mu\text{g}/\text{L}$  (Li, Ti, V, Cr, Mn, Co, Ni, Y, Cd, Cs, Tl, and Pb) (Fig. 2 and Table 1). The higher concentrations of Sr and Ba were detected in the lake, which could be attributed to the underlying geology and lake sediments. In addition, the results confirmed from the fact that Sr and Ba both belong to group IIA of the periodic table and thus contributed from the same sources. Furthermore, the concentration of the 3d elements such as Sc, Cu, and Zn associated with other TEs such as Rb and As were found with their moderate concentrations. While Li, Ti, V, Cr, Mn, Co, Ni, Y, Cd, Cs, Tl, and Pb in the lake water samples have relatively lower concentrations, indicating the low anthropic contamination in the lake. The measured TEs were compared with the drinking water guidelines established by the WHO and US EPA (Table 1). The concentrations of all TEs in the present study were within the permissible limit of standard guidelines and mostly less than the global average of freshwater ecosystems (Gaillardet et al., 2014).

Some of the elements showed relatively higher standard deviation in this study (Table 1). The elements such as Rb; and Ba and Sr are the crustal elements (alkali and alkaline earth metals) and they have naturally high concentrations in the lake basin whereas the lake water is impacted by the activities of visitors specially the pilgrims so the concentration of Cu and Zn could be fluctuated. So, higher standard deviation of those elements could be due to the geogenic and anthropic factors.

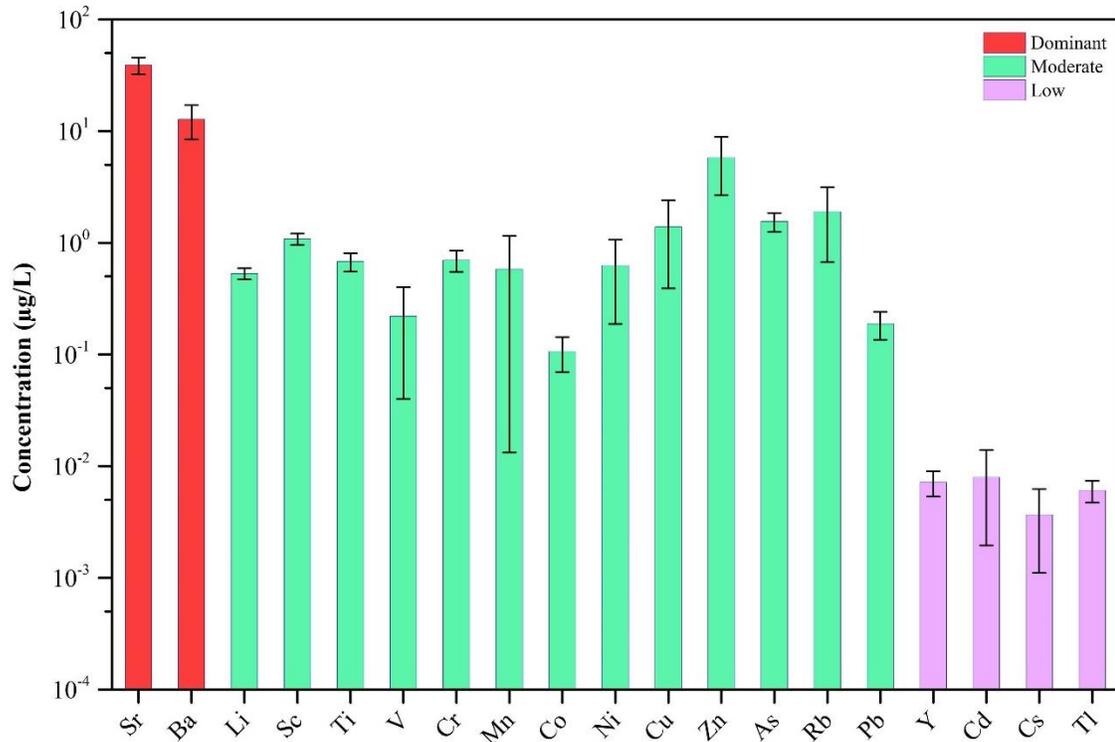
### Correlation matrices (CM)

The CM can be applied to indicate the origin, controlling mechanisms and transport of the TEs. It also shows potential associations among various TEs (Pant et al., 2020b). Spearman's rank correlation coefficient showed that Ti-Sc; Co-Sc-Ti; Ni-Cr; As-Ti-Mn; Sr-Sc-Ti-Co-Cu; Cd-Cu; Ba-Sc-Ti-Co-Ni-Sr; Pb-Ba have a strong positive correlation ( $p < 0.01$ ), indicating that the TEs have similar sources (Table 2). The strong correlation ( $r > 0.75$ ) indicates similar sources including geologic, pedogenic, and anthropic processes (Li and Zhang 2010b). Similarly, Cu-Sc-Ti; Tl-Li; Cs-Cd; Pb-Co; Pb-Sr exhibited moderate positive correlation ( $r = 0.5 - 0.75$ ;  $p < 0.05$ ; Table 2) in the lake indicating that these elements were derived from mixed but similar sources whereas Pb has a moderate negative correlation with Zn ( $p < 0.05$ ) exhibiting their different origin. Also, In Table 2, some TEs were found significant negative correlation, it indicates that they may have



different sources of origin. Most of the aforementioned association highlighted that the TEs concentration is primarily derived from natural geogenic and pedogenic sources with the minor signature of anthropic contribution. Prior studies on

the southern slope of central Himalayan freshwater lakes have also suggested mostly similar associations of the TEs (Bhatta et al., 2020; Thapa & Saund, 2013).



**Figure 2** Mean concentrations of trace elements (TEs) in the Ghodaghodi Lake, Sudurpaschim Province, Nepal

### Cluster analysis (CA)

The dendrogram resulting from ward's method showed three major clusters that were Cluster 1 (sites 3, 7, 8, 9, and 10), Cluster 2 (sites 1, 2, 4, and 5), and Cluster 3 (site 6) (Fig. 3). Cluster 1 was relatively less contaminated with the dominance of Ba as a crustal element. However, Cluster 2 was characterized by the dominance of Ni, Zn, and Rb elements indicating major anthropic activities such as chemical fertilizers, pesticides, and pilgrims' activities in the lake complex. Moreover, Cluster 3 showed the characteristic features of pedogenic contamination of Mn and As, primarily derived from the process of soil formation in the lake complex. In addition, the ongoing developmental activities such as road construction may also be responsible for the elevated concentration of As and Mn in the lake. Thus, from the CA, it can be determined that the lake Ghodaghodi is relatively less polluted by anthropic sources where the geogenic and pedogenic activities are the major sources of TEs.

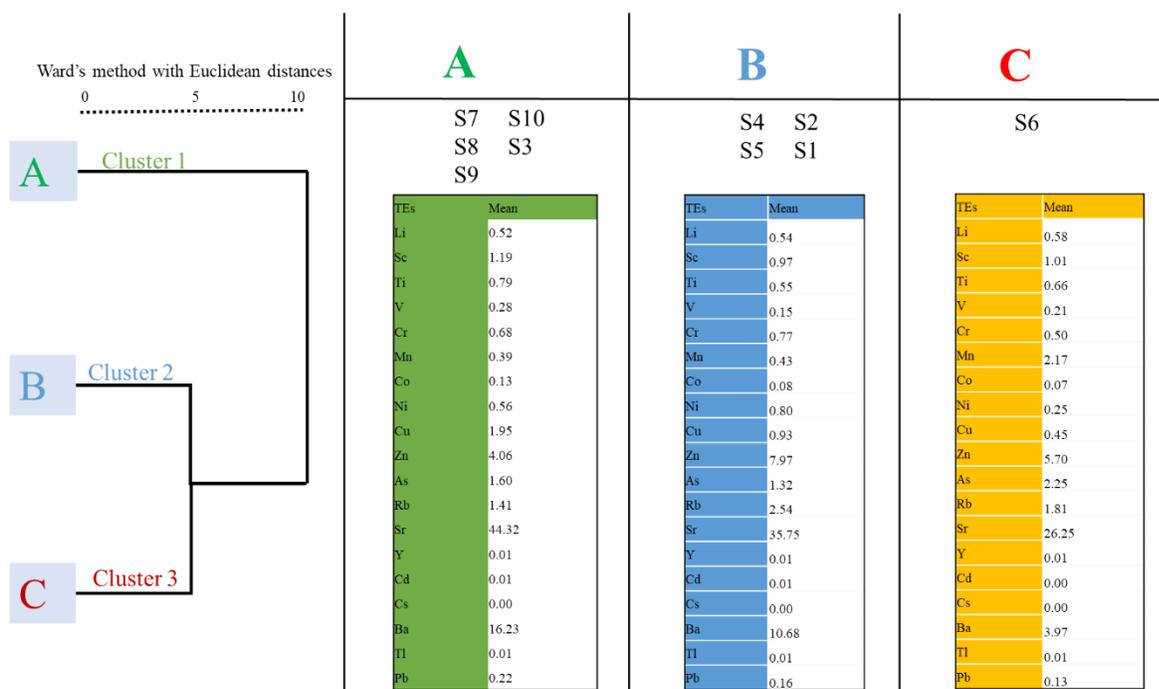
### Principal component analysis (PCA)

The PCA is the linear combination of the original variables and explains the variance of a large set of original variables using a smaller set of newly independent variables. In this

study, the cumulative variance with 93.10 % and values >1 successfully identified the four principal components (PCs) via PCA of the varimax rotation process (Fig. 4, Table 3). Meanwhile, the components loadings with > 0.75, and 0.50 - 0.75, respectively, were discussed as strong and moderate associations of the TEs (Pant et al., 2020b). PC1 explained that 38.87 % of the total variance had strong positive loadings on Ba, Co, Cu, Sc, Sr, and Ti. Furthermore, it exhibited moderate positive loadings on Pb, and negative loadings on Y. Sr and Ba are group IIA elements and found in the earth crust, and thus the other elements associated with this group are also contributed primarily from the geogenic source. PC2 explained 27.94 % of total variance with strong positive loadings on Zn, Rb, Cd, and Cs and moderate positive loadings on Cr and Ni. Elements of this group included IA and IIB, and they are associated with the mixed sources of origin. We ascribed that these elements are influenced by the signature of anthropic inputs such as chemical fertilizers and religious activities around the lake. PC3 explained 13.68 % of total variance with strong positive loadings on Li and Tl and moderate positive loadings on Cr. Furthermore, this group has strong negative loadings on V and moderate negative loadings on Co. The characteristics of this group ascribed that the elements were mainly contributed from natural sources.

**Table 1** Concentration of the trace elements (TEs) in the Ghodaghodi Lake (unit in  $\mu\text{g/L}$ )

Elements	Min	Max	Mean	SD	Drinking-Water Guidelines	
					WHO	US EPA
Li	0.46	0.64	0.53	0.06	-	-
Sc	0.85	1.25	1.08	0.13	-	-
Ti	0.48	0.86	0.68	0.13	-	-
V	0.00	0.48	0.22	0.18	-	-
Cr	0.50	1.00	0.70	0.15	50	100
Mn	0.32	2.17	0.58	0.57	400	-
Co	0.07	0.17	0.11	0.04	50	-
Ni	0.14	1.72	0.63	0.44	70	-
Cu	0.36	3.20	1.39	1.00	2000	1300
Zn	3.14	13.65	5.79	3.13	3000	5000
As	1.21	2.25	1.55	0.30	10	10
Rb	0.33	4.76	1.90	1.23	-	-
Sr	26.25	49.72	39.09	6.58	-	-
Y	0.00	0.01	0.01	0.00	-	-
Cd	0.00	0.02	0.01	0.01	3	5
Cs	0.00	0.01	0.00	0.00	-	-
Ba	3.97	18.86	12.78	4.30	700	-
Tl	0.00	0.01	0.01	0.00	-	-
Pb	0.10	0.25	0.19	0.05	10	10

**Figure 3** Dendrogram showing the clustering of sampling locations based on trace elements (TEs) in the Ghodaghodi Lake, Sudurpaschim Province, Nepal

**Table 2** Correlation matrices of the trace elements (TEs) in Ghodaghodi Lake, Sudurpaschim Province, Nepal

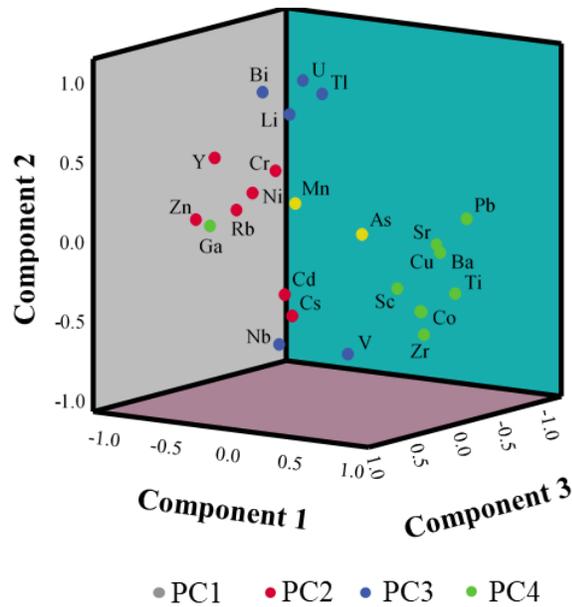
Elements	Li	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Cd	Cs	Ba	Tl	Pb
Li	1.00																		
Sc	-0.43	1.00																	
Ti	-0.43	<b>0.95**</b>	1.00																
V	-0.57	0.28	0.35	1.00															
Cr	0.59	-0.15	-0.37	-0.53	1.00														
Mn	0.16	0.29	0.51	0.15	-0.42	1.00													
Co	-0.61	<b>0.90**</b>	<b>0.89**</b>	0.30	-0.20	0.16	1.00												
Ni	0.60	-0.08	-0.18	-0.38	<b>0.83**</b>	-0.24	-0.08	1.00											
Cu	-0.07	<b>0.66*</b>	<b>0.69*</b>	0.27	0.07	0.45	0.63	0.23	1.00										
Zn	0.47	-0.40	-0.53	-0.16	0.42	-0.07	-0.63	0.02	-0.12	1.00									
As	0.07	0.62	<b>0.75*</b>	0.29	-0.38	<b>0.84**</b>	0.38	-0.23	0.52	-0.13	1.00								
Rb	0.53	-0.24	-0.27	-0.10	0.39	0.21	-0.38	0.20	0.38	<b>0.77**</b>	0.08	1.00							
Sr	-0.21	<b>0.81**</b>	<b>0.79**</b>	0.13	0.12	0.24	<b>0.87**</b>	0.28	<b>0.86**</b>	-0.44	0.41	-0.03	1.00						
Y	0.52	-0.52	-0.52	-0.29	0.41	-0.18	-0.47	0.52	-0.52	-0.06	-0.29	-0.17	-0.41	1.00					
Cd	-0.07	0.38	0.31	0.43	0.25	0.09	0.35	0.26	<b>0.82**</b>	0.25	0.17	0.55	0.60	-0.50	1.00				
Cs	-0.34	0.34	0.27	0.57	-0.04	-0.19	0.31	0.08	0.57	0.04	0.04	0.27	0.34	-0.51	<b>0.73*</b>	1.00			
Ba	-0.32	<b>0.77**</b>	<b>0.78**</b>	0.13	-0.02	0.19	<b>0.89**</b>	0.15	<b>0.75*</b>	-0.59	0.35	-0.16	<b>0.96**</b>	-0.41	0.45	0.27	1.00		
Tl	<b>0.65*</b>	-0.57	-0.42	-0.34	0.19	0.19	-0.51	0.38	-0.19	0.04	-0.11	0.11	-0.19	0.51	-0.16	-0.52	-0.19	1.00	
Pb	-0.35	0.47	0.58	0.03	-0.26	0.22	<b>0.71*</b>	-0.13	0.43	<b>-0.66*</b>	0.24	-0.23	<b>0.68*</b>	-0.29	0.08	-0.04	<b>0.84**</b>	-0.08	1.00

\* Correlation is significant at the 0.05 level (2-tailed).

\*\* Correlation is significant at the 0.01 level (2-tailed).

PC4 showed 12.61% of the total variance with strong positive loadings on Mn and As, and moderate negative loadings on Cr and Y. The grouping of these elements indicated that they were mainly originated from pedogenic processes. The PCA analysis demonstrated a minor anthropic signature for the contribution of TEs, and

elemental composition was mostly governed by natural factors in the Ghodaghodi Lake. However, increasing anthropic activities around the lake could be one of the significant factors contaminating the water of the lake in the future.



**Figure 4** Factor loading plot of the PCA for trace elements (TEs) in the Ghodaghodi Lake, Sudurpaschim, Nepal

**Table 3** Rotated component matrix of the trace elements (TEs) composition in the Ghodaghodi Lake, Sudurpaschim Province, Nepal

	PC1	PC2	PC3	PC4
Li	-0.08	0.34	<b>0.91</b>	0.21
Sc	<b>0.86</b>	0.10	-0.18	0.16
Ti	<b>0.88</b>	-0.22	-0.24	0.32
V	0.29	0.24	-0.77	0.25
Cr	0.01	0.57	0.59	-0.53
Mn	-0.37	-0.12	0.16	<b>0.90</b>
Co	<b>0.78</b>	0.02	-0.57	0.03
Ni	-0.12	0.69	0.41	-0.39
Cu	<b>0.83</b>	0.45	-0.13	0.12
Zn	-0.49	<b>0.80</b>	0.21	-0.17
As	0.17	-0.13	0.12	<b>0.96</b>
Rb	-0.15	<b>0.90</b>	0.28	0.00
Sr	<b>0.92</b>	0.04	0.08	-0.38
Y	-0.57	0.46	0.45	-0.51
Cd	0.27	<b>0.93</b>	-0.18	-0.14
Cs	0.29	<b>0.88</b>	-0.33	-0.04
Ba	<b>0.91</b>	-0.02	-0.01	-0.42
Tl	-0.10	-0.01	<b>0.85</b>	0.40
Pb	0.74	-0.49	-0.09	-0.12
Eigenvalue	7.38	5.31	2.60	2.40
Variance (%)	38.87	27.94	13.68	12.61
Cumulative (%)	38.87	66.81	80.49	93.10

**Water quality index (WQI)**

The WQI of the Ghodaghodi Lake based on the measured TEs is presented in Table 4. As the WHO guideline values for other elements were unavailable, only ten TEs were used to calculate the WQI of Ghodaghodi Lake. In this study, the total weight ( $\sum W_i$ ) of TEs was 32. In comparison with the previous studies of freshwater lakes of Nepal, Himalaya, the total weight assigned for this study is relatively low (Rupakheti et al., 2017). The WQI for Ghodaghodi Lake was observed to be 10.08 that belonged in the excellent category ( $WQI < 50$ ). It also indicates that the lake water is potable and could be

used for drinking purposes from the perspective of measured elements. Importantly, the results are solely based on TEs and other important analysis such as microbial activities are not included in this study. The WQI of the lake was relatively lower as compared to the other Himalayan lakes such as Phewa (159.2) and Gosainkunda (11.5) (Rupakheti et al., 2017). It indicated that Lake Ghodaghodi is relatively pristine compared to the aforementioned lakes; however, the weight assigned and incorporation of Hg could also be responsible for the different results of the WQI in the earlier studies.

**Table 4** Water Quality Index (WQI) of the Ghodaghodi Lake, Sudurpaschim Province, Nepal

Elements	Weight of elements	W <sub>i</sub>	C <sub>i</sub>	S <sub>i</sub>	C <sub>i</sub> /S <sub>i</sub>
Cd	5.000	0.156	0.010	3	0.003
Cr	5.000	0.156	0.700	50	0.014
Cu	2.000	0.063	1.390	2000	0.0006
Pb	5.000	0.156	0.190	10	0.019
Mn	5.000	0.156	0.580	400	0.001
As	5.000	0.156	1.550	50	0.031
Zn	1.000	0.031	5.790	3000	0.001
Ni	1.000	0.031	0.630	70	0.009
Co	1.000	0.031	0.110	50	0.002
Ba	2.000	0.063	12.780	700	0.018
Total	32.000	1.000			0.100
					<b>WQI=10.08</b>

**Hazard risk assessment (HRA)**

The estimated HQ values of the measured TEs through ingestion and dermal absorption pathway for both adults and children are listed in Table 5. The HQ values  $> 1$  indicated that the residents are exposed to health risks from using the lake water, whereas  $HQ < 1$  indicated minimal risk (Dai et al., 2016). In this study, the HQ ingestion and HQ dermal values for all elements were  $< 1$ , which indicated the minimal health effects on humans for both adults and children. As compared to adults, higher HQ<sub>ingestion</sub> and HQ<sub>dermal</sub> values for children were observed, suggesting that children are more sensitive when exposed to TEs in water, as similar to the previous study (Li & Zhang, 2010). So, the children should be given special attention and should be less exposed to these TEs. Overall, the HI for As, Co, and Cr was higher compared to other elements for both adults and children, which may contribute more risk to human health. Zn presented little health threat to

residents despite its high concentration in the water as it has low toxicity. Co indicated a high risk to human health despite its low concentration in the water due to its very low reference dose (RfD). Adverse effects for Co included allergic dermatitis, and other TEs might affect the nervous, hemopoietic, cardiovascular, and endocrine systems (Fang et al., 2014). From these risk evaluations, it could be suggested that currently there is a low risk due to TEs to the inhabitants in the vicinity of the lakes. However, the sources of the TEs, their concentrations and potential health risks including long-range transport of the pollutants are assessed in the few lakes in the region (Pant et al., 2020a; Pant et al., 2021b; Rupakheti et al., 2017; Sharma et al., 2014; Tripathi et al., 2016). Thus, this study could be useful for the government authorities, decision-makers and other concerned stakeholders for the sustainable management of the Ramsar listed lakes in the Himalaya.

**Table 5** Hazard Quotient for adults and children for each trace element (TEs) in the Ghodaghodi Lake, Nepal

TEs	C <sub>w</sub>	RfD <sub>Ingestion</sub>	RfD <sub>Dermal</sub>	Adult		Children			
				HQ <sub>Ingestion</sub>	HQ <sub>Dermal</sub>	HI	HQ <sub>Ingestion</sub>	HQ <sub>Dermal</sub>	HI
As	1.55	0.3	0.123	$1.48 \times 10^{-1}$	$1.88 \times 10^{-3}$	$1.49 \times 10^{-1}$	$2.20 \times 10^{-1}$	$5.54 \times 10^{-3}$	$2.26 \times 10^{-1}$
Ba	0.01	200	14	$1.43 \times 10^{-6}$	$1.07 \times 10^{-7}$	$1.54 \times 10^{-6}$	$2.13 \times 10^{-6}$	$3.14 \times 10^{-7}$	$2.45 \times 10^{-6}$
Cd	0.01	0.5	0.025	$5.71 \times 10^{-4}$	$5.97 \times 10^{-5}$	$6.31 \times 10^{-4}$	$8.53 \times 10^{-4}$	$1.76 \times 10^{-4}$	$1.03 \times 10^{-3}$
Co	0.11	0.3	0.06	$1.05 \times 10^{-2}$	$1.09 \times 10^{-4}$	$1.06 \times 10^{-2}$	$1.56 \times 10^{-2}$	$3.23 \times 10^{-4}$	$1.60 \times 10^{-2}$
Cr	0.70	3	0.075	$6.67 \times 10^{-3}$	$1.39 \times 10^{-3}$	$8.06 \times 10^{-3}$	$9.96 \times 10^{-3}$	$4.11 \times 10^{-3}$	$1.41 \times 10^{-2}$
Cu	1.39	40	8	$9.93 \times 10^{-4}$	$2.59 \times 10^{-5}$	$1.02 \times 10^{-3}$	$1.48 \times 10^{-3}$	$7.65 \times 10^{-5}$	$1.56 \times 10^{-3}$
Mn	0.58	24	0.96	$6.90 \times 10^{-4}$	$9.01 \times 10^{-5}$	$7.81 \times 10^{-4}$	$1.03 \times 10^{-3}$	$2.66 \times 10^{-4}$	$1.30 \times 10^{-3}$
Ni	0.63	20	0.8	$9.00 \times 10^{-4}$	$2.35 \times 10^{-5}$	$9.24 \times 10^{-4}$	$1.34 \times 10^{-3}$	$6.93 \times 10^{-5}$	$1.41 \times 10^{-3}$
Pb	0.19	1.4	0.42	$3.88 \times 10^{-3}$	$6.75 \times 10^{-6}$	$3.88 \times 10^{-3}$	$5.79 \times 10^{-3}$	$1.99 \times 10^{-5}$	$5.81 \times 10^{-3}$
Zn	5.79	300	60	$5.51 \times 10^{-4}$	$8.64 \times 10^{-6}$	$5.60 \times 10^{-4}$	$8.23 \times 10^{-4}$	$2.55 \times 10^{-5}$	$8.49 \times 10^{-4}$

## Conclusion

This study was conducted to investigate the sources and potential health risks of the trace elements (TEs) of the Ghodaghodi Lake complex in Sudurpaschim Province, Nepal. Based on the mean concentrations of the TEs in the lake there are three major groups: (i) Sr and Ba (concentrations >10 µg/L); (ii) Sc, Cu, As, Rb, and Zn (concentrations between 1-10 µg/L); and (iii) Li, Ti, V, Cr, Mn, Co, Ni, Y, Cd, Cs, Tl and Pb (concentrations of <1 µg/L). The concentrations of all the TEs are under the permissible level compared with the drinking water guidelines established by WHO and US EPA. The distribution of TEs exhibited that Sr, Ba, Zn, Cu, As, Sc, and Rb; and Cs, Y, Tl, Cd, and Co are the major and minor contributors, respectively originating from geogenic, pedogenic, and anthropic sources.

The water quality index < 50 (WQI=10.08) suggested that the water is suitable for drinking purposes on the basis of measured TEs. The health risk assessment concluded that there is minimal chance of causing a health risk to humans, which is consistent with the WQI. Furthermore, the relatively high hazard quotient value indicated that children could have a high risk as compared to adults due to the TEs contamination in water. Therefore, special attention should be given to reduce the risk in the future. Overall, this study suggested that the water quality of the Ghodaghodi Lake in terms of TEs is quite good; however, appropriate measures should be adopted to maintain the better water quality in the future. Thus, this study could be useful for the government authorities and decision-makers for the sustainable management of the Ramsar listed lake. Finally, future studies focusing on spatiotemporal variations and long-range transport of pollutants could give further insights into the water quality of the lake in the Himalayas.

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