

Heavy metals in surface sediments from Lake Batur, Bali, Indonesia: Spatial distribution, risk assessment, and source apportionment

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)

DOI: 10.17794/rgn.2026.1.7

Original scientific paper



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Abstract

This study aims to assess the environmental conditions of Lake Batur, Indonesia, a closed alkaline lake. In this study, the identification of heavy metals was carried out using 27 sediment and 13 water samples. The methods used in the study include magnetic susceptibility, geochemical, and multivariate analysis. The concentration of heavy metals in sediment samples follows the order Fe > Ti > Mn > V > Cu > Cr (wt%). The results of the pollution assessment (EF, Igeo, CF, and PLI) in sediment indicate that the lake sediment is currently polluted. The PLI shows that the Lake Batur sediment is in the high contamination category at all sample sites, especially because of the high enrichment of Cu and Cr. The use of metal (kepeng) in religious activities in temples near Lake Batur is believed to be the source of the Cu enrichment. The results of multivariate analysis and magnetic susceptibility reveal three groups of heavy metals in Lake Batur sediment based on their main sources: 1) Fe and Ti are dominated by lithogenic factors, 2) Cu and Cr are dominated by anthropogenic factors, and 3) Mn and V are influenced by a combination of lithogenic and anthropogenic factors. The heavy metal concentrations in water samples are as follows: Zn > Fe > Mn > As > Cu > Cr > Pb > Cd (ppb). Water samples show that heavy metal concentrations are still below the WHO's minimum drinking water threshold.

Keywords:

Lake Batur; heavy metals; lake assessment; magnetic susceptibility; geochemistry

1. Introduction

Lakes are important ecosystems for life as habitats for aquatic life and water sources for human activities. The increasing need for water must also be accompanied by good water quality. However, the decline in water quality due to heavy metal contamination in waters is one of the problems that are currently being faced (Huang et al., 2015; Dey et al., 2021). Heavy metals found in aquatic environments can come from natural processes (erosion, weathering, diagenesis, etc.) and anthropogenic sources (settlements, agriculture, tourism, industry, and religion) (Sun et al., 2013; Huang et al., 2015; Sukmawati et al., 2019; Aydi et al., 2022; Suandayani et al., 2023; Cai et al., 2023; Şener et al., 2023; Jawjit et al., 2024; Noya et al., 2024). Naturally, the concentration of heavy metals in aquatic environments are generally found in low concentrations, as these elements are present in trace amounts under unpolluted conditions

(Förstner and Wittmann, 2012). Heavy metal pollution in the lake water can affect the stability of the ecosystem for a long time (Ali et al., 2019). Increasing human activities around the waters can increase the concentration of heavy metals from anthropogenic sources and trigger pollution in the aquatic environment (Islam et al., 2015; Aydi et al., 2022; Şener et al., 2023; Saeed et al., 2024; Kieu and Quoc, 2024). Heavy metals that enter the waters can be deposited and accumulated in sediments, making bottom lakes an important indicator in monitoring pollutants (Şener et al., 2023). This makes it important to evaluate the condition of the waters to determine the distribution of heavy metals and the presence of pollution. Monitoring of lake conditions can be done by evaluating the level of trace element and heavy metal pollution in sediment and/or water using geostatistical and multivariate analysis (Mohan et al., 1969; Sun et al., 2013; Islam et al., 2015; Ranjan et al., 2016; Kumar et al., 2019; Aydi et al., 2021; Cai et al., 2023; Gopal et al., 2023; Şener et al., 2023; Noya et al., 2024; Matondang et al., 2025).

In addition to geochemical methods, environmental assessment can also be combined with rock magnetic methods such as magnetic susceptibility. This method is

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Received: 16 May 2025. Accepted: 27 August 2025.

Available online: 2 January 2026

non-destructive, inexpensive, and sensitive. Magnetic susceptibility measurements can be used as a proxy for heavy metal contamination levels and the distribution of contaminated areas. In some cases, increased amounts of magnetic minerals can indicate the presence of heavy metals in sediments and show a strong correlation (Chan et al., 2001; Chaparro et al., 2017; Yang et al., 2019; Wang et al., 2020; Sudarningsih et al., 2023; Noya et al., 2024; Matondang et al., 2025).

Lakes are widely used as water sources for agriculture, fisheries, and religious activities, especially for people on the island of Bali (Suryono et al., 2008; Wijaya et al., 2012; Suandayani et al., 2023). In the Lake Batur area, population activities are almost all over the area around the lake, both on land and in water, such as settlements, agricultural land, tourist attractions, and fish farms (Suryono et al., 2008; Wijaya et al., 2012). For the people around Mount Batur, Lake Batur is an important water source for daily activities because there is no river flow in the area. However, currently the water of Lake Batur is experiencing a decline in quality with a potential impact on the lake ecosystem and the surrounding community (Suryono et al., 2008). Several studies related to Lake Batur have been conducted to determine its hydrogeochemical conditions, water quality based on physicochemical parameters and the National Sanitation Foundation Water Quality Index (NSFWQI), and lake water sources (Polkowska et al., 2014; 2015; Sukmawati et al., 2019; Mustiatin et al., 2022). The condition of heavy metal pollution in Lake Batur is still unknown, especially based on the accumulation of metals in the lake's surface sediments.

The purpose of this study was to reveal the level of pollution of Lake Batur based on the concentration and enrichment levels of heavy metals in sediments and water using a combination of magnetic susceptibility, geochemical, and multivariate analysis methods. The results of the study are expected to be one of the considerations in managing Lake Batur.

2. Materials and Methods

2.1. Study area

Lake Batur is one of the caldera lakes located on the island of Bali, precisely in the city of Kintamani. Geographically, Lake Batur is located at latitude 08°15'30"S and longitude 115°24'30"E, at an altitude of 1,050 m above sea level, with a maximum depth of 88 m, and a water surface area of 16.05 km² (URL 1), where the lake is a closed system and has alkaline water characteristics (pH>8) (Wijaya et al., 2012; Polkowska et al., 2014; 2015; Sukmawati et al., 2019). According to Polkowska et al. (2014 and 2015), the water source of Lake Batur comes from rainwater, groundwater, and hot springs. The environment around the lake is dominated by basaltic to rhyolitic rocks basalt to rhyolite rocks originating

from the eruption of Batur stratovolcano 23,700 years ago included in the quaternary volcano (Wheller and Varne, 1986; Reubi and Nicholls, 2004; Mustiatin et al., 2022; Suryanata et al., 2024). A study by Wheller and Varne (1986) showed that the concentration of pre-caldera products of Batur is generally basaltic to andesitic (SiO₂ = 48% - 59%), caldera products are generally dacitic (SiO₂ = 60% - 62%), while post-caldera products are basaltic-andesitic (SiO₂ = 52% - 56%).

2.2. Sample collection, preparations, and measurements

This study used 27 lake sediment and 13 lake water samples (see Figure 1). Sediment samples were collected using a sediment grabber from the lake bottom in 2022 and 2023, while water samples were taken in 2023. Sediment samples were given a few drops of HNO₃ to help clean up organic contamination and dissolved metals from the sediment matrix (Salomons and Förstner, 1980; Siaka et al., 1998; Suandayani et al., 2023; Noya et al., 2024). For water samples, 100 ml of water was stored in an HDPE (high-density polyethylene) bottle and given HNO₃ to reduce acidity to a pH of around 2 and maintain metal conditions before analysis.

Sediment samples were first prepared by passing through a 325 mesh sieve to obtain a clay particle size (Yunginger et al., 2018). The filtered samples were then dried at room temperature. After drying, the samples were ground and ready for magnetic and geochemical susceptibility testing. For geochemical testing, samples were prepared in the form of flat solids. Sediment geochemical testing was conducted using the EDAX Orbis Micro-XRF at the Nanoscience and Nanotechnology Research Centre, Institut Teknologi Bandung (ITB), Indonesia. For magnetic susceptibility testing, the sample was placed inside a tube holder that is 2 cm in diameter and 2 cm in height. Magnetic susceptibility testing was conducted using the Bartington MS2B dual-frequency sensor at low frequency (0.47 kHz; χ_{LF}) and high frequency (4.7 kHz; χ_{HF}) and MS3 magnetic susceptibility meter at the Laboratory of Characterisation and Modeling of Rock Physical Properties, Faculty of Mining and Petroleum Engineering, ITB. The comparison between the magnetic susceptibility values at low and high frequencies can produce a magnetic susceptibility that depends on the frequency (χ_{FD} %) using Equation 1 (Dearing, 1994).

Water sample were prepared following standard procedure. Acidified samples were used for testing the concentration of trace metals in water by inductively coupled plasma-mass spectrometry (ICP-MS) after filtration using a 0.2 μ m syringe filter. Water geochemical analysis was conducted at the Hydrogeology and Hydrogeochemistry Laboratory, Faculty of Mining and Petroleum Engineering, ITB, Indonesia, using an ICP-MS Agilent 7800.

$$\chi_{FD} (\%) = 100 \times (\chi_{LF} - \chi_{HF}) / \chi_{HF} \quad (1)$$

2.3. Assessment of heavy metal pollution in lake sediment

In this study, several indices were used to assess the level of heavy metal pollution of Lake Batur sediment. It was included the enrichment factor (EF), the contamination factor (CF), the pollution load index (PLI), the geoaccumulation index (Igeo), and the degree of contamination (CD). The concentrations of heavy metals used in the assessment of the surface sediments of Lake Batur were the elements Ti, Fe, Mn, Cu, Cr, and V. The selection of these elements based on common anthropogenic elements found in human activities around the lake and refers to several previous studies by Sun et al. (2013), Yuan et al. (2014), Islam et al. (2015), Ranjan et al. (2016), Aydi et al. (2021), Dey et al. (2021), Yang et al. (2022), Cai et al. (2023), Gopal et al. (2023), and Şener et al. (2023).

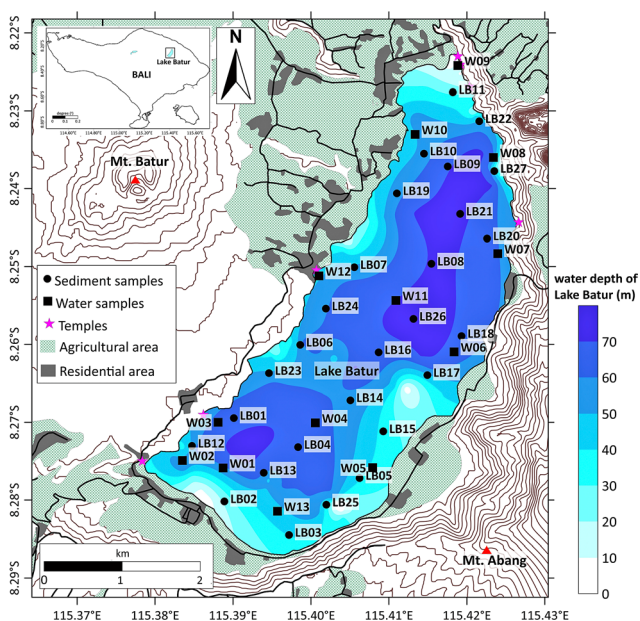


Figure 1. Locations of surface sediment sampling (black circle LB) and surface water sampling (black square WB) from Lake Batur. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

2.3.1. Enrichment factor (EF)

This factor can help in distinguishing metal sources between natural and human activities (Yongming et al., 2006; Gopal et al., 2023). The EF index is used to determine the level of anthropogenic contribution to heavy metal concentrations in sediments (Yongming et al., 2006; Islam et al., 2015; Şener et al., 2023). The EF index was proposed by Chester and Stoner (1973). In calculating EF, reference elements are usually used to normalise data, including Al, Fe, Mn, Li, and Rb (Ackerman, 1980; Islam et al., 2015; Aydi et al., 2022; Cai et al., 2023; Şener et al., 2023). In this calculation, Al is used as a reference element because of its high and con-

sistent abundance in the earth's crust, more stable geochemistry, and less influence by anthropogenic factors (Salomons dan Förstner, 1984; Xiang et al., 2019; Varol et al., 2020; Islam et al., 2015). The EF value is calculated using the following Equation 2 from Ergin et al. (1991).

In this study

$$EF = \frac{\left(\frac{C_n}{C_{Al}} \right)_{samples}}{\left(\frac{B_n}{B_{Al}} \right)_{crust \text{ or } background}} \quad (2)$$

Where (C_n/C_{Al}) is the ratio of heavy metal concentration in sediment samples with reference elements (in this study, Al) in sediment samples. While B_n/B_{Al} is the ratio of heavy metal concentration with reference elements (Al) in the background or crust. The background data used in this study came from Turekian and Wedepohl (1961) because their data is based on a broad compilation of shale analyses worldwide, making it more representative of marine and terrestrial sediments, and has been widely used for environmental assessment such as studies by Belhadj et al. (2017), Nowrouzi and Pourkhabbaz (2014), and Wang et al. (2025). Based on Zhang and Liu (2002) and Islam et al. (2015), EF values around 1 indicate that the metal source comes entirely from material in the earth's crust or natural weathering processes. While EF values > 1.5 indicate the influence of human activities (see Table 1).

2.3.2. Geoaccumulation index (Igeo)

The geoaccumulation index can detect the accumulation of heavy metals in sediments, especially those related to lithological formation and rock origin (Şener et al., 2023). Equation 3 for calculating Igeo was proposed by Müller (1969).

$$Igeo = \text{Log}_2 \left(\frac{C_n}{1.5C_{background}} \right) \quad (3)$$

Where C_n is the concentration of elements in the sample and $C_{background}$ is the concentration of elements in the background. The factor of 1.5 used in the equation is to minimize possible variations in element values in the background related to lithogenic effects (Ruiz, 2001; Islam et al., 2015; Şener et al., 2023). Sediment quality classification based on Igeo index is shown in Table 1.

2.3.3. Contamination factor (CF) and Pollution load index (PLI)

Contaminant factor (CF) can indicate the level of pollution based on trace metal contamination in sediment (Hakanson, 1980). The CF value is calculated from the ratio between the concentration of each element in the sample and the concentration in the background, such as the following Equation 4:

Table 1. Classification of the EF, Igeo, CF, and PLI for lake sediment.

EF	Enrichment classification by Yongming et al. (2006)	
	EF < 2	deficiency to minimal enrichment
	2 ≤ EF < 5	moderate enrichment
	5 ≤ EF < 20	significant enrichment
	20 ≤ EF < 40	very high enrichment
	EF > 40	extremely high enrichment
Igeo	Pollution class by Müller (1981)	
	Igeo ≤ 0	unpolluted
	0 < Igeo ≤ 1	unpolluted to moderately polluted
	1 < Igeo ≤ 2	moderately polluted
	2 < Igeo ≤ 3	moderately to heavily polluted
	3 < Igeo ≤ 4	heavily polluted
	4 < Igeo ≤ 5	heavily polluted to extremely polluted
Igeo ≥ 5	extremely polluted	
CF	Pollution class by Turekian and Wadepohl (1961); Loska et al. (1997)	
	< 1	low contamination
	1 ≤ CF < 3	moderate contamination
	3 ≤ CF < 6	considerable contamination
	CF ≥ 6	high contamination
PLI	Pollution class by Tomlinson et al. (1980)	
	PLI = 0	perfection or no pollutant
	PLI = 1	baseline levels of pollutants are present
	PLI > 1	progressive deterioration of estuarine quality

$$CF = \frac{C_n}{C_b} \quad (4)$$

Where C_n is the concentration of elements in the sample and C_b is the concentration of elements in the background. Next is the calculation of the pollutant load index (PLI) use **Equation 5**, proposed by **Tomlinson et al. (1980)** to determine the level of pollution based on all pollutants found at each sampling location based on the contamination factor value. Sediment quality classification based on CF and PLI is shown in **Table 1**.

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \dots \times CF_n} \quad (5)$$

2.4. Multivariate statistic analysis

In this study, multivariate statistical analysis was conducted for element concentration data in sediment, including Pearson correlation, principal component analysis (PCA), and hierarchical cluster analysis (HCA). Pearson correlation analysis was used to statistically determine the relationship between element concentration and other parameters. The determination of the component number PC is based on components that have eigenvalues ≥ 1 or called as Kaiser criteria (**Kai-**

ser, 1960). PCA and HCA analysis can be used to determine the source of elements contained in the sample. HCA analysis is used to group heavy metals in the sample based on their similarities (**Guo et al., 2018**). The multivariate statistical analysis was carried out using Minitab software seri 21.4.1.

3. Results and Discussion

3.1. Magnetic Susceptibility of ediment

The results of sediment sample testing showed an average magnetic susceptibility value of $147.39 \times 10^{-8} \text{ m}^3/\text{kg}$ (see **Table 2**). High magnetic susceptibility values were found at sites LB-09, LB-10, LB-11, LB-14, LB-15, LB-24, and LB-27, located in the northern and central areas of the lake. This indicates that the concentration of magnetic minerals in the northern part of the lake is higher than in the southern part (see **Figure 1** and **Table 2**). The $\% \chi_{FD}$ value in sediment samples was in the range of 0.65-7.31 indicates that superparamagnetic minerals do not dominate. The presence of a $\% \chi_{FD}$ value from a sediment sample < 2 can indicate the contribution of anthropogenic particles to the magnetic susceptibility value. Magnetic particles originating from pollutants have multidomain (MD) grains with $\% \chi_{FD} < 2$ (**Bouhsane and Bouhlassa, 2018; Ayoubi and Dehaghani, 2020**).

3.2. Heavy metal concentration in sediments and water

The concentration of heavy metals in the lake sediments from the test results using XRF testing is shown in **Table 2**. The average concentration of heavy metals in sediments is follow the order $\text{Fe} > \text{Ti} > \text{Mn} > \text{V} > \text{Cu} > \text{Cr}$. The concentration of these elements is influenced by geological conditions and human activities around the lake. The elements Fe, Mn, and Ti with high concentrations are in the northern area of the lake. In the northern part of the lake there are residential areas, agriculture, fish cages, and temples. In addition, the element Ti is also high in the eastern area of the lake. In this area there are settlements, agriculture, and fish cages. In the southern part, the element V with high concentrations. The elements Cr and Cu with high concentrations are in the central and southwest areas of the lake, and in the southwest area, there are temples and settlements.

The concentration of heavy metals in the surface water of the lake as a result of testing using ICP-MS and standard values from **WHO (2017)** are shown in **Table 3**. The heavy metals observed in the water samples of Lake Batur in this study were Mn, Zn, As, Pb, Cd, Cr, Fe, and Cu. Among the heavy metals observed, Zn had the highest average concentration (17.062 ppb), followed by Fe (22.432), Mn (6.813 ppb), As (2.147 ppb), Cu (1.766), Cr (0.642 ppb), Pb (0.275 ppb), and the lowest was Cd

Table 2. The heavy metal concentrations (wt%) in lake surface sediment samples.

Samples ID	χ_{LF}	% χ_{FD}	Ti	Fe	Mn	Cu	Cr	V
	($\times 10^{-8}$ m ³ /kg)		(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)
LB-01	31.180	7.312	0.238	3.927	0.110	0.035	0.030	0.150
LB-02	94.838	0.652	0.582	8.343	0.201	0.041	0.031	0.104
LB-03	95.886	3.669	0.536	7.659	0.224	0.038	0.023	0.095
LB-04	41.958	5.787	0.402	5.667	0.143	0.044	0.030	0.147
LB-05	116.506	4.851	0.729	8.611	0.184	0.045	0.024	0.102
LB-06	114.174	2.922	0.497	7.204	0.184	0.040	0.018	0.104
LB-07	75.020	3.858	0.419	6.682	0.163	0.040	0.024	0.096
LB-08	55.266	1.799	0.452	6.653	0.168	0.036	0.021	0.146
LB-09	310.766	2.691	1.125	11.859	0.302	0.050	0.021	0.040
LB-10	282.448	2.380	0.934	10.253	0.248	0.046	0.019	0.045
LB-11	355.356	2.869	1.278	11.416	0.265	0.046	0.015	0.048
LB-12	17.487	1.841	0.868	0.591	0.099	0.087	0.119	0.109
LB-13	71.468	2.431	0.462	7.156	0.180	0.046	0.027	0.132
LB-14	354.102	1.840	1.256	2.068	0.112	0.141	0.104	0.113
LB-15	219.517	2.620	1.235	2.676	0.081	0.078	0.076	0.028
LB-16	52.825	2.549	0.770	1.432	0.106	0.082	0.092	0.111
LB-17	137.210	2.390	0.677	7.857	0.174	0.039	0.035	0.085
LB-18	108.797	2.578	0.679	8.171	0.187	0.036	0.047	0.105
LB-19	138.869	3.213	0.640	8.288	0.186	0.041	0.041	0.093
LB-20	185.419	3.063	0.841	9.573	0.197	0.043	0.037	0.034
LB-21	201.043	2.890	0.862	10.107	0.246	0.045	0.043	0.054
LB-22	126.888	3.507	0.877	9.532	0.238	0.052	0.036	0.059
LB-23	35.699	3.285	0.273	4.977	0.140	0.040	0.048	0.141
LB-24	248.264	2.948	0.712	8.346	0.178	0.060	0.039	0.091
LB-25	75.161	3.344	0.538	6.855	0.162	0.041	0.036	0.125
LB-26	32.737	2.700	0.239	4.497	0.130	0.030	0.039	0.143
LB-27	400.603	3.224	1.135	11.732	0.272	0.048	0.016	0.029
min	17.487	0.652	0.238	0.591	0.081	0.030	0.015	0.028
max	400.603	7.312	1.278	11.859	0.302	0.141	0.119	0.150
mean	147.388	3.082	0.713	7.116	0.181	0.051	0.040	0.094

(0.072 ppb). The highest concentration of Zn, Mn, Pb, Cd, and Cr was at point WB-01 (65.061 ppb Zn, 10.730 ppb Mn, 1.257 ppb Pb, 0.572 Cd). This location is close to the pier, tourist area, settlements, agriculture, and floating cage fisheries, while for As, this point showed the second highest value. For the As concentration at all points of the lake water samples, it looks even, while Zn has the highest variation (see **Table 3**). Compared to the heavy metal standards in water for drinking water permitted by **WHO (2017)**, the eight heavy metals obtained in the samples still have concentrations below the standard (see **Table 3**). However, this does not mean that the lake water can be consumed without causing side effects, because in addition to the concentration of heavy metals, other parameters are also needed related to the characteristics of Lake Batur water to determine whether it is safe for consumption and daily activities or not.

3.3. Assessment of heavy metal in sediment of Lake Batur

Assessment of heavy metal pollution in surface sediments was conducted using EF, Igeo, CF, and PLI indexes. The enrichment factor values of all heavy metals indicate enrichment in the lake surface sediment samples. The distribution map of EF index and classification curve for each heavy metal can be seen in **Figures 2 and 3**. The order of the average EF index values from the largest is Cu (16.528), V (12.487), Cr (7.587), Mn (2.805), Ti (1.949), and Fe (1.866). Cu in sediment has an enrichment level of 6,243 to 80,138, which is significant to extremely high. V has an enrichment level of 1,007 to 36,572, which is no enrichment to very high. Cr has an enrichment level of 1,041 to 54,807, which is no enrichment to extremely high. Ti has an enrichment lev-

Table 3. The heavy metal concentrations (ppb) in lake surface water samples and WHO standard (ppb).

Sample ID	Mn	Zn	As	Pb	Cd	Cr	Fe	Cu
	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)
WB-01	10.730	65.061	2.254	1.257	0.572	1.350	39.405	1.489
WB-02	8.239	18.182	2.271	0.144	0.053	0.682	17.756	0.111
WB-03	7.757	12.223	2.196	0.329	0.034	0.655	17.192	0.077
WB-04	7.463	28.016	2.098	0.291	0.034	0.544	13.810	<0.000
WB-05	9.134	8.468	2.134	0.227	0.026	0.557	17.775	<0.000
WB-06	5.325	11.590	2.104	0.053	0.048	0.575	18.682	0.127
WB-07	4.876	9.207	2.131	0.037	0.025	0.620	20.628	<0.000
WB-08	3.704	9.809	2.145	0.050	0.018	0.583	49.365	<0.000
WB-09	3.490	13.519	2.102	0.737	0.026	0.489	27.454	2.109
WB-10	4.408	7.933	2.107	0.204	0.019	0.636	21.512	<0.000
WB-11	7.409	11.485	2.085	0.120	0.031	0.534	16.570	<0.000
WB-12	8.036	9.260	2.190	0.029	0.017	0.484	14.064	<0.000
WB-13	7.995	17.047	2.095	0.100	0.029	0.632	17.405	6.685
min	3.490	7.933	2.085	0.029	0.017	0.484	13.810	0.077
max	10.730	65.061	2.271	1.257	0.572	1.350	49.365	6.685
mean	6.813	17.062	2.147	0.275	0.072	0.642	22.432	1.766
WHO (2017)	400	(-)	10	10	3	50	(-)	2000

- (-) No health-based guideline value is proposed

el of 1,255 to 7,822, which is no enrichment to significant. Mn and Fe have enrichment levels ranging from no enrichment to moderate. Based on the EF values obtained greater than 1.5, Cu, Cr, V, and Mn have almost all sampling sites been affected by anthropogenic activities (Islam et al., 2015). Based on the data, sampling site LB-12 has the highest EF values for Cu, Cr, V, Ti, and Mn compared to other locations. Other locations with high enrichment for nearly all six heavy metals are LB-11, LB-23, and LB-26.

The spatial distribution map and classification curve of geoaccumulation factor (Igeo) are shown in Figures 4-5. The average of Igeo index is follow the order Cu (2.263), V (1.446), Cr (0.901), Mn (0.427), Ti (0.311), and Fe (0.303). The Igeo value in lake sediment shows the unpolluted to extremely polluted category (see Figure 5). The V in the sediment sample has an Igeo value of 0.448 to 2.316, which is included in the unpolluted to moderately heavily polluted category. The southern area of the lake has a higher Igeo V value than the northern area, with the highest value location at point LB-01 (see Figure 4). The Cu has an Igeo value of 1.338 to 6.288, included in moderately to extremely polluted category. The location with the highest Cu Igeo value is at site LB-14 (see Figures 4-5). The Cr has an Igeo value of 0.334 to 2.654, categorized as unpolluted to moderately to heavily polluted. The sample site with the highest Igeo is LB-12. The Mn, Fe, and Ti have Igeo values < 1 in all sample sites, included in the unpolluted to moderately polluted category.

The distribution map and classification curve of the contamination factor (CF) index of heavy metals in lake

sediments are shown in Figures 6-7. The order of the average CF index is as follows: Cu (11.276), V (7.205), Cr (4.490), Mn (2.126), Ti (1.550), and Fe (1.508). The V in the sediment sample has a CF index value of 2.154 to 11.538, which is included in the low to high pollution category. The southern part has a higher CF value than the northern part of lake, with the highest value at point LB-01 (see Figures 6-7). Cu has a CF index value of 6.667 to 31.333, which is included in the considerable to high pollution category for all sites with the highest site in LB-14 (see Figures 6-7). Fe, Ti, and Mn have a similar pattern for CF index and are categorized as low to moderate pollution (CF<3) (see Figure 7). The northern part has a higher CF for Fe than the southern part of lake (see Figure 6). The high CF for Ti is in the northern and central parts of the lake (sites LB-11, LB-14, and LB-15) (see Figure 6). Cr has a CF index of 1.778 to 13.222, categorized as low to high pollution. Locations with high CF for Cr are in the southwest part of the lake (LB-12) and the center of the lake (LB-14) (see Figure 6).

The spatial distribution map of the pollutant load index (PLI) from lake sediment is presented in Figure 8. The PLI index shows a range of values from 2.346 to 4.130 with an average value of 3.157. The largest PLI value is at site LB-14. The PLI index obtained that is >1 for all sites indicates the condition of the lake surface sediment is heavily contaminated and the condition of progressive deterioration of estuarine quality (see Table 1) (Tomlinson et al., 1980; Islam et al., 2015). Based on the CF and PLI distribution value, it can be estimated that the elements Cu, Cr, and V are the main contributors of pollution in the lake sediment. Based on the assess-

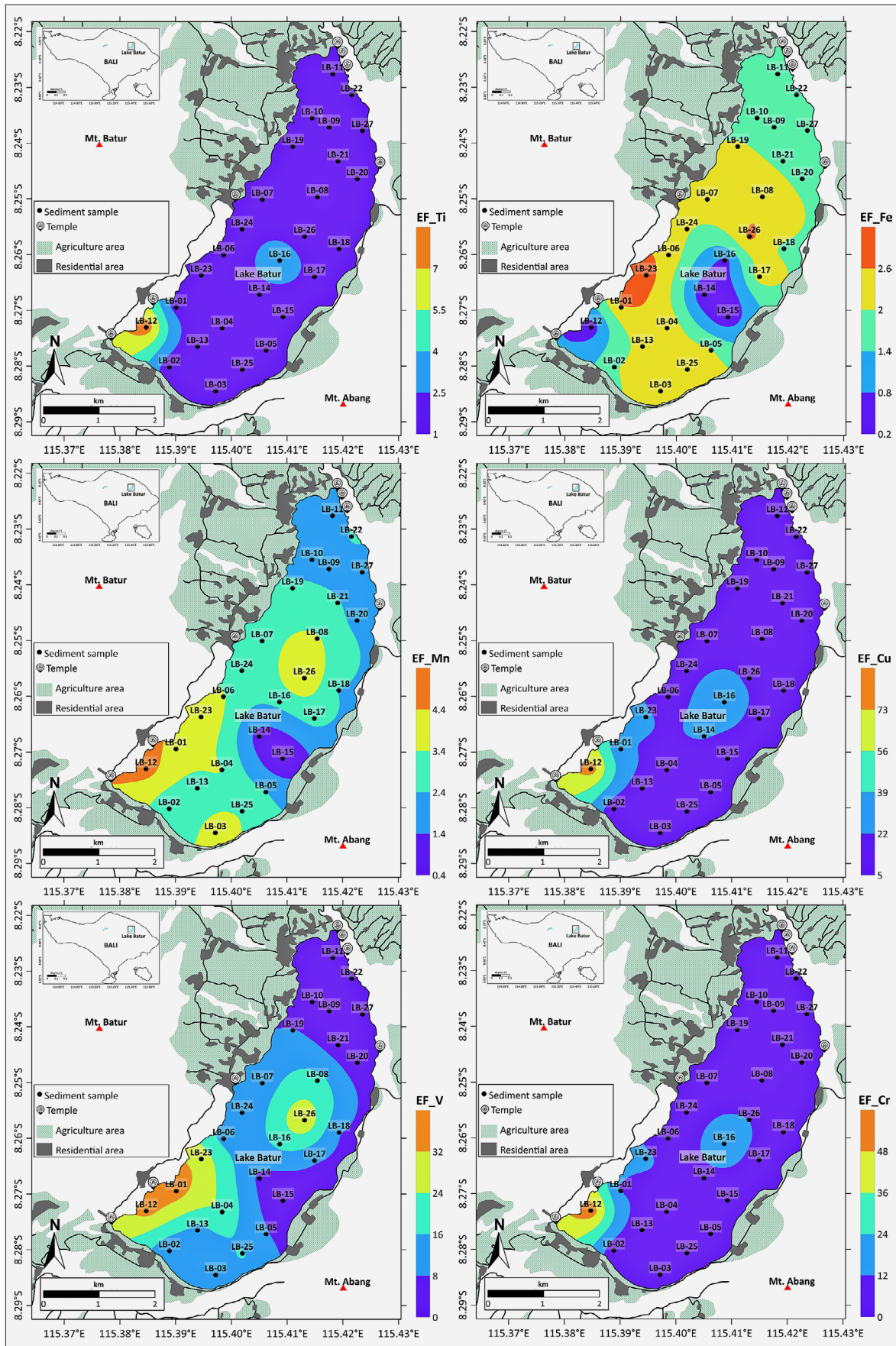


Figure 2. Spatial distribution of EF values for Ti, Fe, Mn, Cu, V, and Cr elements in Lake Batur sediments. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

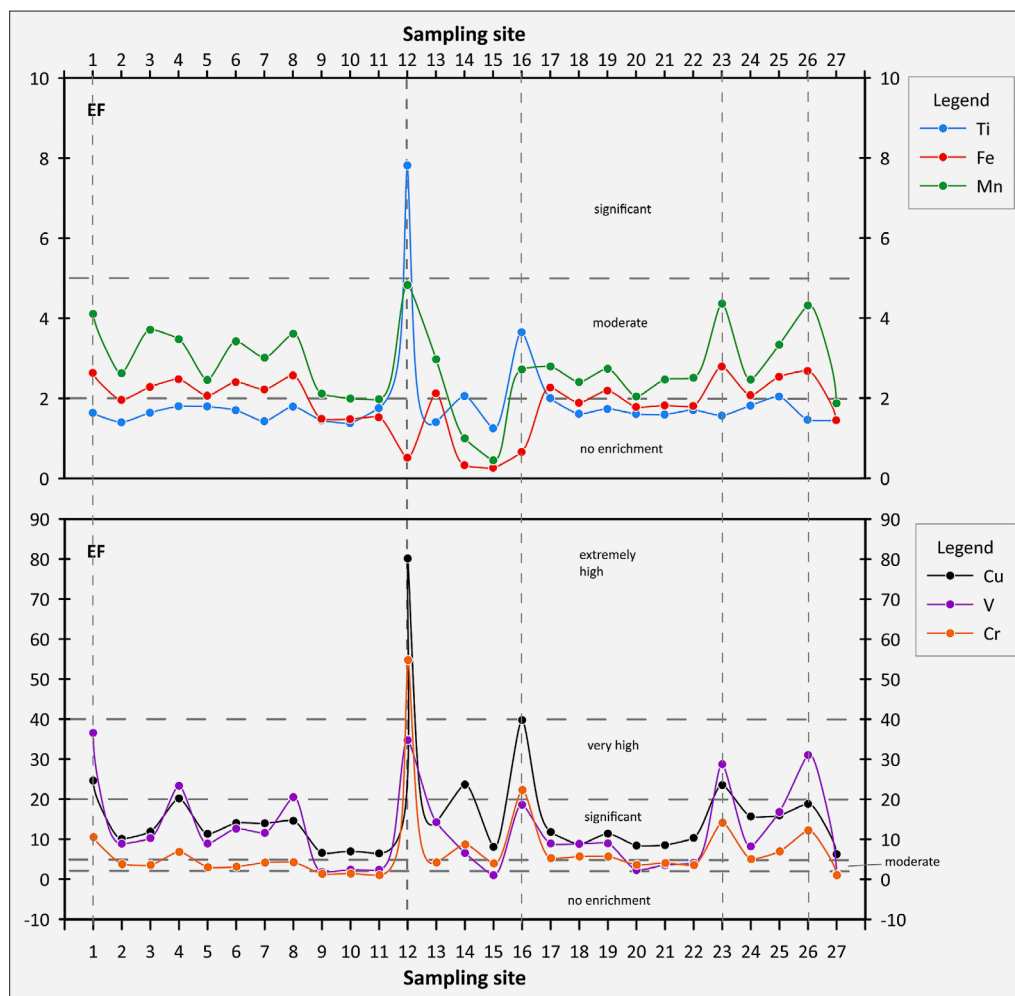


Figure 3. EF value curve and its classification for each sample site.

ment values EF, Igeo, CF, and PLI, it was found that sites LB-12 and LB-14 experienced much greater pollution than other sites. The assessment results also showed that Cu experienced the greatest enrichment and is the largest pollutant in the sediment of Lake Batur.

The site with the highest EF, LB-12, is located in the southwest of the lake (see Figure 2). Near this point, there is a settlement and Pancuran Solas Temple, one of the temples with a high level of religious activity by the Balinese Hindu community. The most famous activity carried out there is melukat, which involves the use of offerings, one of which is the metal kepeng, which is derived from Cu (Suandayani et al., 2023; Arwati, 1991). This activity is thought to be the largest source of Cu enrichment in Lake Batur sediments. Site LB-14 has the highest level of sediment contamination, located in the center of the lake; the cause of the high values is uncertain.

3.4. Identifying heavy metal sources in Lake Batur

The results of the Spearman correlation (see Table 4) showed a strong positive correlation between χ_{LF} with Ti ($r = 0.784$), Fe ($r = 0.694$), and Mn ($r = 0.619$) which

means that these elements are closely related to lithogenic input, while a negative correlation value indicates that the concentrations between elements do not affect each other. The negative correlation of χ_{LF} with Cr ($r = -0.245$) and V ($r = -0.814$) indicates that the elements are not lithogenic in origin. The negative correlation of χ_{FD} with all heavy metals indicates that the metals are not derived from superparamagnetic particles. The correlation between metals shows that Fe and Mn are strongly correlated ($r = 0.949$), indicating the possibility of originating from a single lithogenic source. Fe and Cr are negatively correlated ($r = 0.547$), indicating a different source of Cr from Fe, which may not be lithogenic. Ti and Cu are strongly positively correlated ($r = 0.767$), indicating the possibility of Cu also being influenced by lithogenic sources. Ti and V are strongly negatively correlated ($r = -0.737$), indicating different sources of V and Ti. Mn and Cr are negatively correlated ($r = 0.596$), indicating a different source of Cr. V has a negative correlation with all elements, indicating a different source of V from the others and possibly an anthropogenic origin.

For PCA analysis, based on Kaiser criteria there are 2 principal components (PCs) that meet the criteria. PC₁

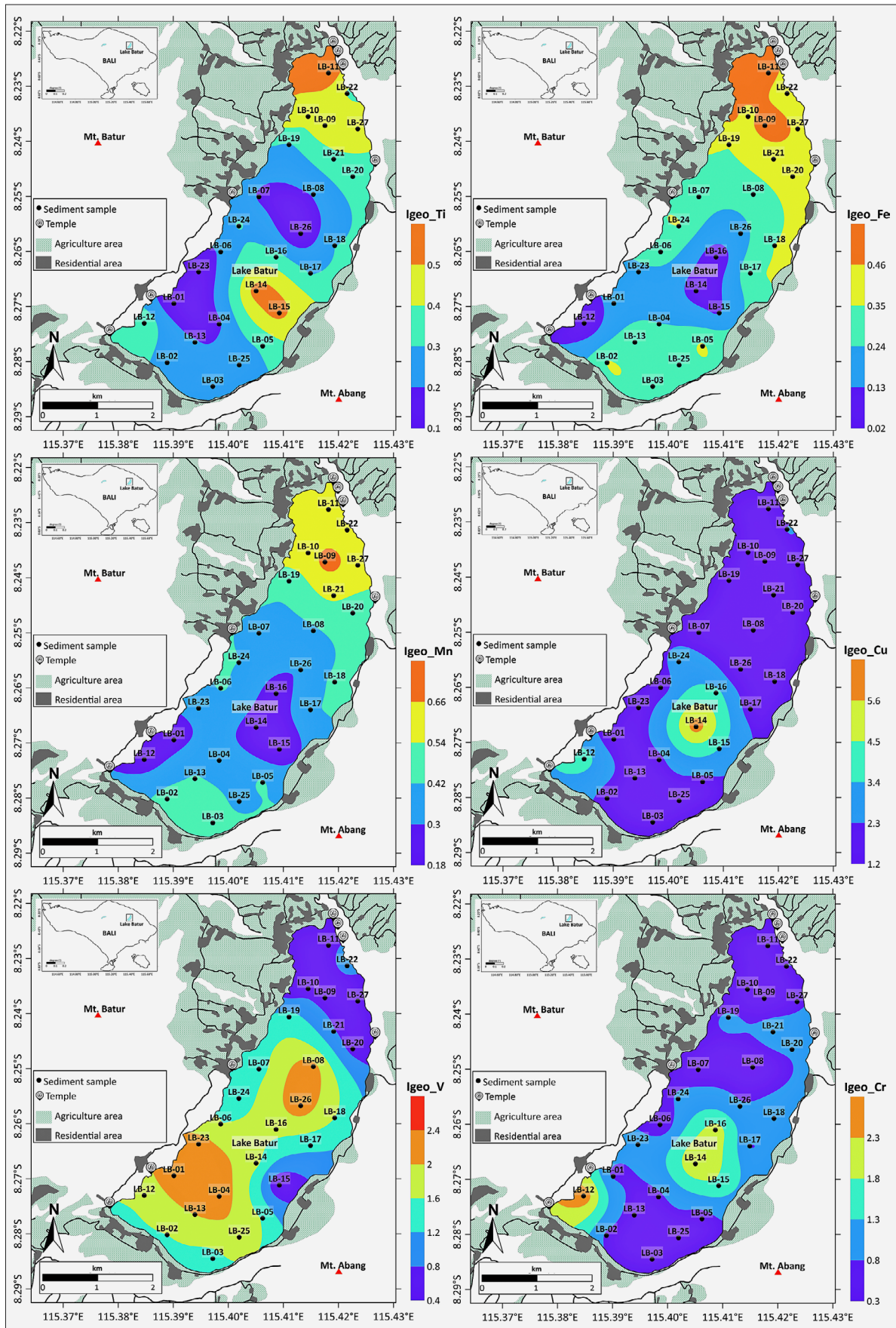


Figure 4. Spatial distribution of Igeo for Ti, Fe, Mn, Cu, V, and Cr elements in Lake Batur sediments. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

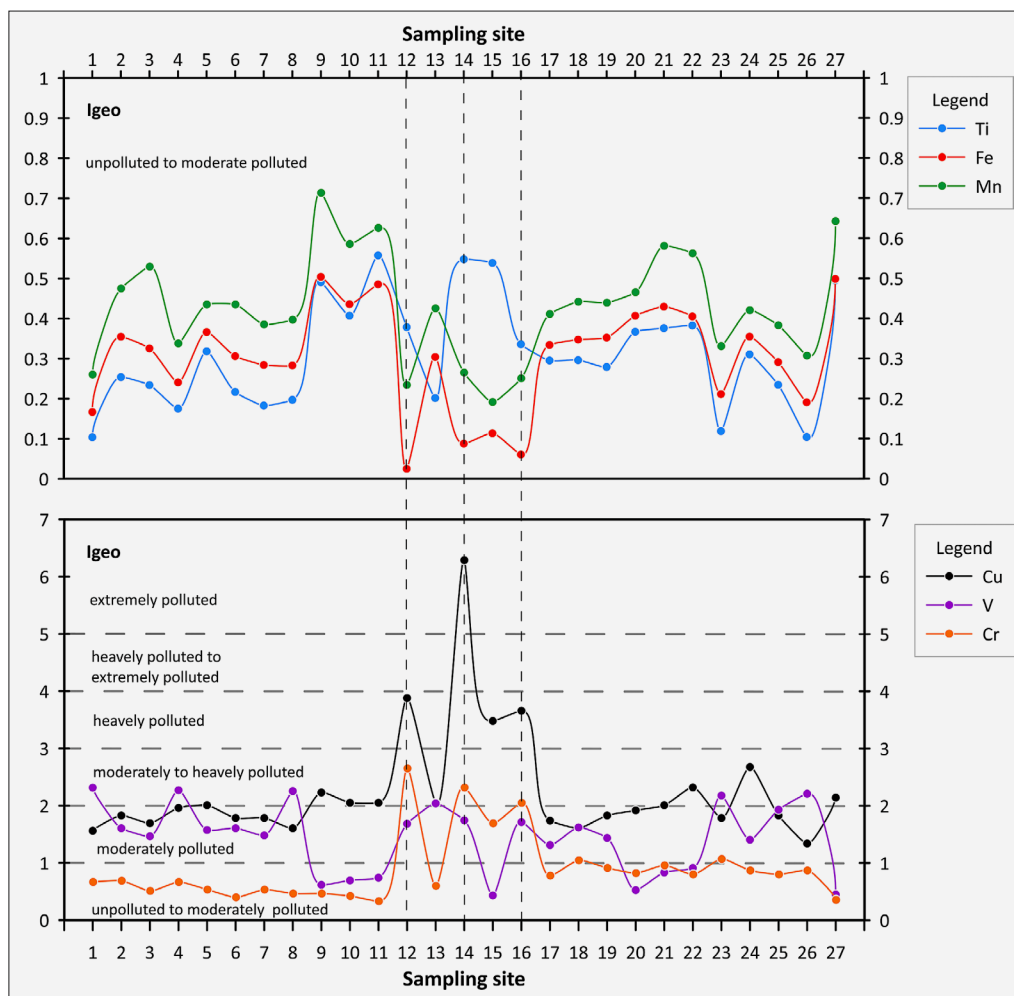


Figure 5. Igeo value curve and its classification for each sample site.

and PC_2 representing approximately 54.5% and 37.4% or around 91.9% of the total variance. The loading plot of the principal component in **Figure 9a** shows the presence of 4 groups of heavy metals, namely group 1 Fe and Mn, group 2 is Ti, group 3 is Cu and Cr, and group 4 is V. In the PCA plot, Fe and Mn are in the negative position on PC_1 , indicating a common source. Ti is in a strong positive position on PC_2 , Cu and Cr are in a strong positive position on PC_1 , and V is in the positive position on PC_1 . PC_1 indicates an anthropogenic metal source, and PC_2 indicates a lithogenic metal source. From the HCA analysis, 3 heavy metal clusters were obtained: cluster 1 is Ti, cluster 2 is Fe, and cluster 3 is Mn, Cu, Cr, and V (see **Figure 9b**).

Based on the multivariate analysis (Spearman correlation, PCA, and HCA) showing the presence groups of heavy metals, the source of heavy metals found in the lake surface sediment can be estimated. The results of the correlation analysis reveal a very strong correlation between iron (Fe) and manganese (Mn) ($r = 0.949$), suggesting a lithogenic source. The presence of Fe is influenced by natural processes such as rock weathering, with the primary source of Fe being the weathering of

the Earth's crust, which then becomes deposited in sediment (Riley and Chester, 1971; Ranjan et al., 2016). Additionally, titanium (Ti) shows a strong positive correlation with magnetic susceptibility (χ_{LF}) ($r = 0.784$), indicating a connection to magnetic minerals derived from the host rock. In contrast, vanadium (V) shows a strong negative correlation with χ_{LF} ($r = -0.814$) and Ti ($r = -0.737$), suggesting that this element does not originate from lithogenic sources, but is likely a result of anthropogenic input. PCA results support these findings, as lithogenic elements like Ti, Fe, and Mn load onto different components compared to heavy metals such as V and Cr. Notably, Ti has a high loading in the second component, indicating a distinct lithogenic source separate from the heavy metals. HCA depicted in the dendrogram shows that Cu, Cr, Mn, and V form a single cluster, implying a potential contribution from anthropogenic activities. Conversely, Fe and Ti tend to form separate clusters, further supporting the interpretation that they represent lithogenic input. Overall, the positive correlations of χ_{LF} with Ti, Fe, and Mn, alongside the negative correlations with V and Cr, highlight a clear distinction between natural (lithogenic) and anthropogenic sources in the sedimentary system of Lake Batur.

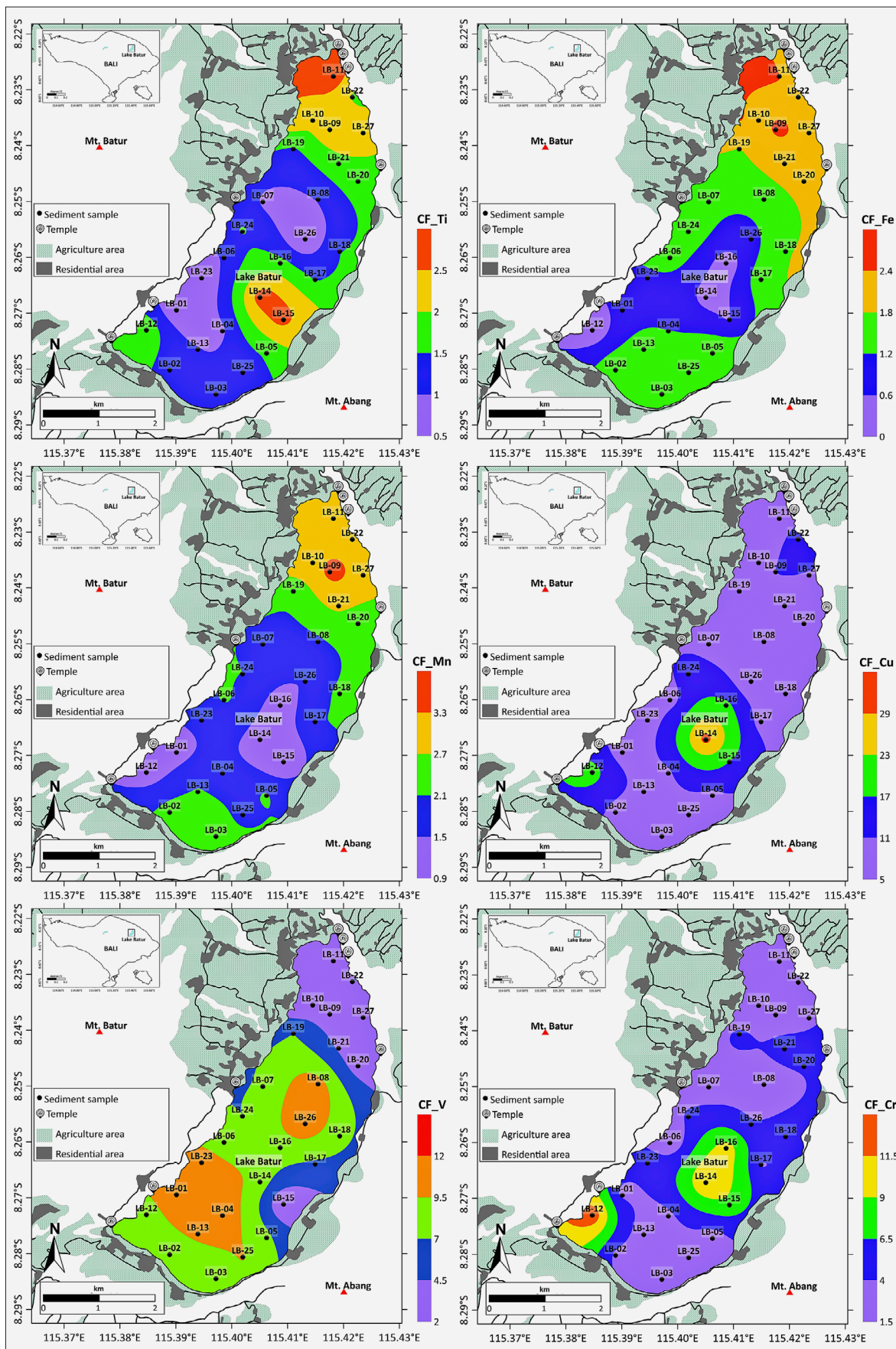


Figure 6. Spatial distribution of CF for Ti, Fe, Mn, Cu, V, and Cr elements in Lake Batur sediments. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

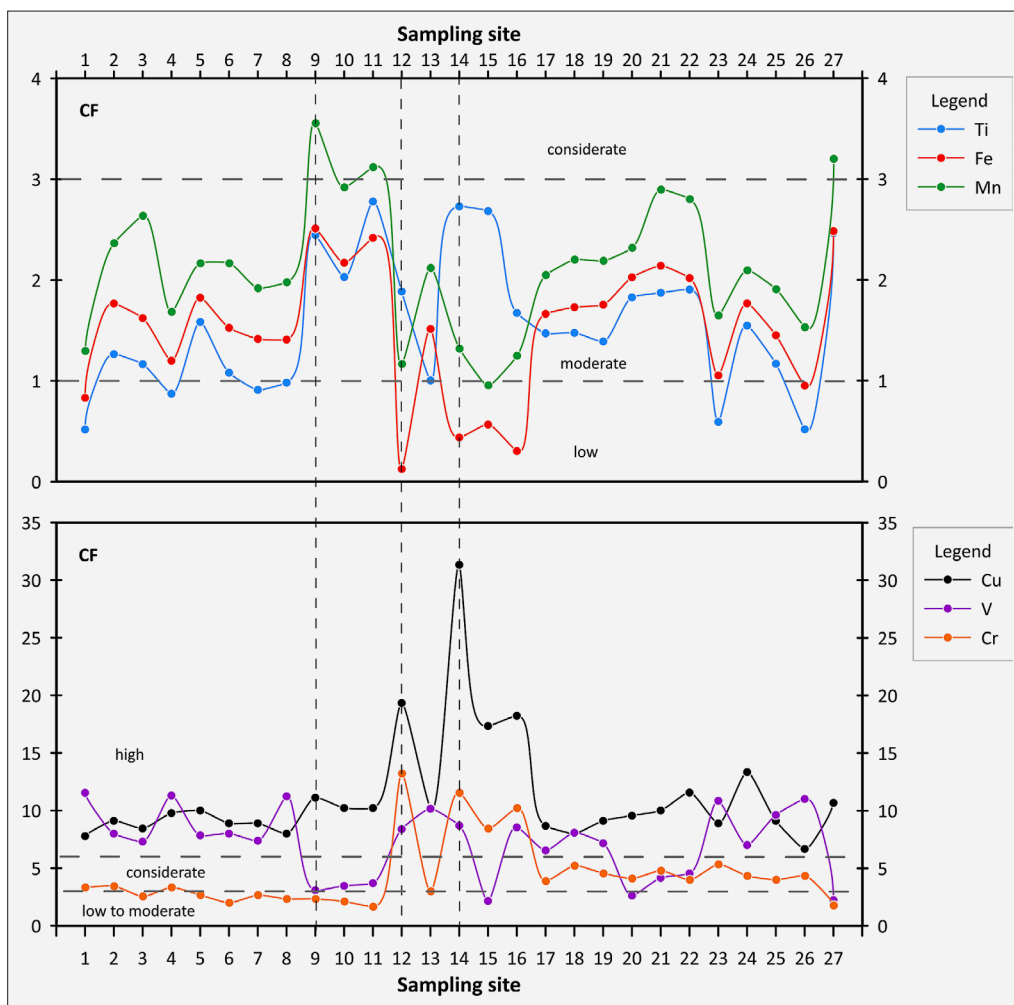


Figure 7. CF value curve and its classification for each sample site.

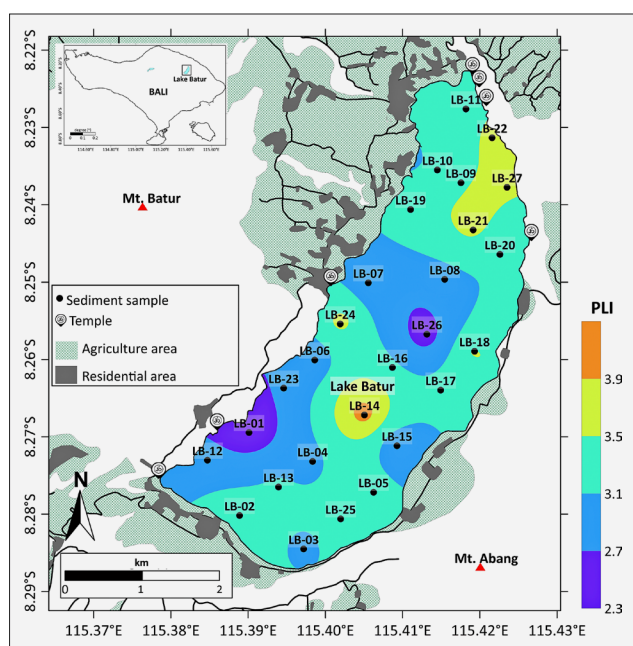
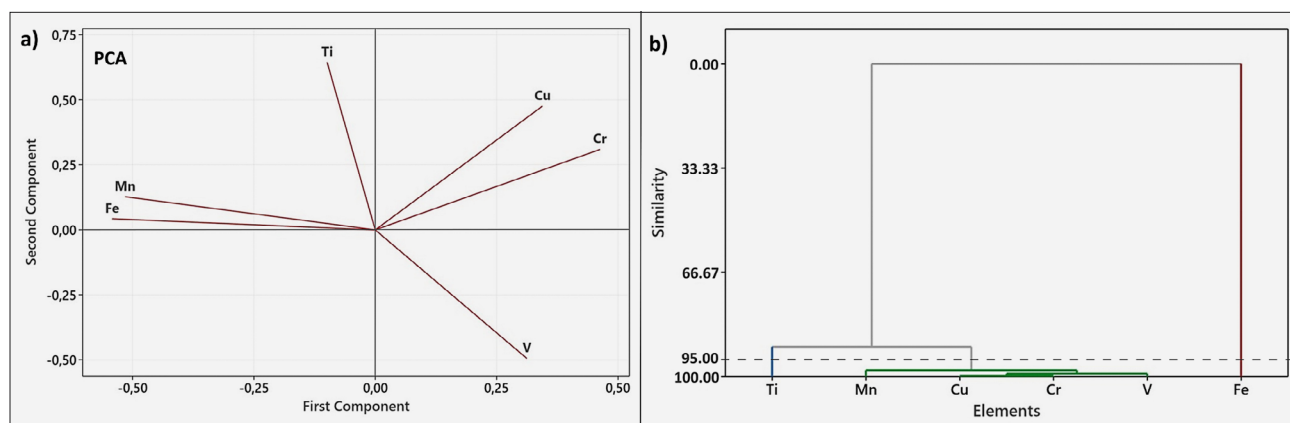


Figure 8. Spatial distribution of PLI in surface sediments of Lake Batur. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

Based on the EF index value, it is known that points LB-12, LB-14, and LB-16 have the highest enrichment levels for all observed heavy metal elements, especially Cu elements. Point LB-12 is located in the southwest of the lake (see Figure 2), near this point there are settlements and the Pancuran Solas Temple. Concentrations of trace metals such as Cu found in high concentration in the lake area that is close to the temple (Suandayani et al., 2023). The high Cu enrichment index is mainly found near the Pancuran Solas Temple, which is a temple with high religious activity. It is suspected that one of the main sources of Cu in the area is related to the melukat religious ceremony and prayer by the Balinese Hindu community. These activities use offerings, or canang, one of which contains kepeng (ancient copper coins), or the use of offerings in the form of pripihan (fish-shaped metals made of iron, copper, or precious metals), which are thrown into Lake Batur (Arwati, 1991; Suandayani et al., 2023). Burton (2002) identified eight elements: As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn as markers of lake sediment quality associated with anthropogenic contamination. Two of these elements, Cu and Cr, were found in Lake Batur sediments, strongly suggesting an anthropogenic source. The concentration of Cu and Cr can be impacted by a variety

Table 4. Spearman correlation of heavy metals with magnetic susceptibility in sediment samples of Lake Batur.

	χ_{LF}	% χ_{FD}	Ti	Fe	Mn	Cu	Cr
% χ_{FD}	-0.126						
Ti	0.784	-0.330					
Fe	0.694	0.109	0.419				
Mn	0.619	0.048	0.369	0.949			
Cu	0.449	-0.243	0.767	0.073	0.007		
Cr	-0.245	-0.207	0.065	-0.547	-0.596	0.251	
V	-0.814	-0.037	-0.737	-0.694	-0.611	-0.403	0.195

**Figure 9.** a) Plot first and second component of PCA. b) Dendrogram of cluster analysis.

of human activities near Lake Batur, including settlements, tourism, and religion (Sun et al., 2013; Suandayani et al., 2023; Gopal et al., 2023). The use of paint on boats and metal coatings, as well as ship maintenance in the port area, are examples of anthropogenic activities that are likely to be the cause of the high concentration of Cr in Lake Batur sediments (Gopal et al., 2023), because in Lake Batur the use of shipping is quite high for tourism and managing floating cage fisheries.

4. Conclusions

Assessment of heavy metal pollution of Fe, Ti, Mn, Cu, Cr, and V in lake surface sediments using the EF, Igeo, CF, and PLI indices shows that lake sediments are currently polluted by heavy metals, especially the high enrichment of Cu and Cr. According to PLI, the sediments from Lake Batur are classified as highly contaminated at every location. The results of magnetic susceptibility and multivariate analysis show that the sources of heavy metals in Lake Batur can be grouped into 3 categories, namely 1) Fe and Ti are dominated by lithogenic sources such as weathering of surrounding rocks, 2) Cu and Cr are dominated by anthropogenic sources, and 3) Mn and V are influenced by a combination of lithogenic and anthropogenic factors, with Mn being more lithogenic and V being more anthropogenic. The source of Cu enrichment comes from anthropogenic sources, especially religious activities in temples around Lake Batur. The use of paint and metal coatings on boats, as well as ship maintenance

in the port area, are examples of anthropogenic activities that are likely to be the cause of the high Cr in Lake Batur. For the concentration of heavy metals in water samples in decreasing order $Zn > Fe > Mn > As > Cu > Cr > Pb > Cd$. The concentration of all heavy metals in water samples is still below the standard given by WHO, unlike in sediments where there is a high concentration. This is likely related to the level of heavy metal sedimentation in Lake Batur so that some elements in the sediment have high concentrations. The quality of this polluted sediment can affect the condition of the lake ecosystem and the surrounding community. Therefore, proper monitoring and management are needed to maintain the condition of Lake Batur from declining quality.

Acknowledgement

We thank BKSDA (*Balai Konservasi Sumber Daya Alam* or Natural Resource Conservation Centre) of Bali, Indonesia for the permission to conduct field research at Batur Volcano Complex. This study was supported financially by the Asahi Glass Foundation 2023 to SB through a project entitled "Characterization of Lithogenic and Anthropogenic Minerals on Surface Sediments of Lake Batur, Bali, Based on Magnetic and Geochemical Parameters", with grant number FTTM.PN-5-20-2023.

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SAŽETAK

Teški metali u površinskim sedimentima jezera Batur, Bali, Indonezija: prostorna razdioba, procjena rizika i raspodjela izvora

Cilj je ovoga istraživanja procijeniti uvjete okoliša jezera Batur, Indonezija, zatvorenoga alkalnog jezera. U istraživanju je identifikacija teških metala provedena korištenjem 27 uzoraka sedimenta i 13 uzoraka vode. Metode korištene u studiji uključuju magnetnu osjetljivost, geokemijsku i multivarijantnu analizu. Koncentracija teških metala u uzorcima sedimenta slijedi redoslijed $Fe > Ti > Mn > V > Cu > Cr$ (wt%). Rezultati procjene onečišćenja (EF, Igeo, CF i PLI) u sedimentu upućuju na to da je jezerski sediment trenutačno onečišćen. PLI pokazuje da je sediment jezera Batur u kategoriji visoke kontaminacije na svim mjestima uzorkovanja, posebno zbog visokoga obogaćivanja bakra i kroma (Cu i Cr). Vjeruje se da je uporaba metala (kepeng) u vjerskim aktivnostima u hramovima u blizini jezera Batur izvor obogaćivanja bakra (Cu). Rezultati multivarijantne analize i magnetne osjetljivosti otkrivaju tri skupine teških metala u sedimentu jezera Batur na temelju njihovih glavnih izvora: 1) željezom i titanom (Fe i Ti) dominiraju litogeni čimbenici, 2) bakrom i kromom (Cu i Cr) dominiraju antropogeni čimbenici, 3) mangan i vanadij (Mn i V) pod utjecajem su kombinacije litogenih i antropogenih čimbenika. Koncentracije su teških metala u uzorcima vode sljedeće: $Zn > Fe > Mn > As > Cu > Cr > Pb > Cd$ (ppb). Uzorci vode pokazuju da su koncentracije teških metala još uvijek ispod minimalnoga praga za pitku vodu Svjetske zdravstvene organizacije (WHO).

Ključne riječi:

jezero Batur, teški metali, procjena jezera, magnetna osjetljivost, geokemija

Author's contribution

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All authors have read and agreed to the published version of the manuscript.