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Pollution Risk Assessment of Heavy Metals in Paradgaon Lake Sediments, Central India

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Abstract - The assessment of heavy metal contamination is pivotal in understanding environmental health and its impacts on aquatic ecosystems. This study aims to assess the concentration and distribution of heavy metals in the sediments of The Paradgaon Lake (PL) of Umrer Taluka, Maharashtra State, India, and to evaluate the level of pollution and ecological risks using various pollution indices. Six surface sediment samples (three each during pre and post monsoon seasons) along with five soil samples were collected from the PL and surrounding locations, respectively in the catchment of the PL. The air-dried powdered sediment samples were analyzed for the heavy metal concentrations using X-Ray Fluroscence (XRF) Spectrometry. The present study investigates the contamination of the heavy metals such as iron (Fe), aluminium (Al), manganese (Mn), zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), cobalt (Co), uranium (U), vanidium (V), and rubidium (Rb). The appraisal of sediment contamination was analyzed on the basis of enrichment factor (EF), Geo-accumulation Index (GI), Contamination Factor (CF), and Pollution Load Index (PLI). Additionally, ecological risk factor (Er) and potential ecological risk index (PERI) were calculated to comprehend the toxicity of heavy metals and the environmental response to all risk factors. The key metal contaminants in lake surface sediments include Fe, Al, Zn, Mn, Cr and Co. This study demonstrates that these heavy metals were generated from the common lithogenic source generated through weathering and erosion of the Deccan Trap Basalt (DTB) and associated soils in the catchment in addition to partial input from the adjoining coal mining. The heavy metals such as Zn, Cu, Cr, Ni, Pb, U, and Rb showed their higher concentrations during the premonsoon (PM) season as compared to the postmonsoon (PoM), while metals like Al, Fe, Mn, Co, and V have increased concentrations during the PoM season, indicating enhanced weathering and erosion in the different parts of the rocks (DTB) and associated soils contributing these metals during the monsoonal season in the catchment of the PL. The geoaccumulation index and contamination factor of the heavy metals in the PL showed moderate pollution level. These metals may be originated from anthropogenic sources such as agricultural runoff and coal mining in addition to natural geological processes. Overall, the study on Igeo, CF reflects moderate level of pollution, whereas the EF and Er clearly signifies the changes in land-use type and rainfall patterns on heavy metal accumulation in the present lake. The strong positive correlation between Mn and total organic carbon (TOC) points their biogenic source, while Pb has high positive correlation with total inorganic carbon (TIC) and moderately correlated with TOC indicating mainly anthropogenic origin of Pb with its input from coal mine and deposited in the soils of the catchment of the PL. The present findings also provide valuable insights of the environmental risk of heavy metals pollution in the Paradgaon Lake.

Keywords: heavy metal pollution, enrichment factor, geo-accumulation, contamination factor, Paradgaon Lake, Nagpur District

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INTRODUCTION

Lakes play a vital role in supporting human economic and social well-being by providing essential freshwater resources, enabling farmland irrigation, facilitating shipping, aiding in flood control, and promoting tourism (Liu *et al*., 2018). Over the past few decades, rapid urbanization, industrial expansion, and intensified agriculture have led to the accumulation and formation of contaminants in water systems causing significant damage to the ecological health of aquatic environments (Wang *et al*., 2021). Sediments in lakes provide invaluable information as they offer both a long and short-term perspective on the impact of anthropogenic activities on the surrounding environment and the lake itself (Kumar *et al*., 2019). Metals find their way into aquatic environments through a combination of natural and man-made sources. They can enter these ecosystems directly through discharges or indirectly through processes like dry and wet deposition and land runoff. The heavy metals are less soluble in lake water and remain suspended there for shorter period and further settles down on the lake floor in association with sediments for the longer time (Jain *et al*., 2008; Suresh *et al*., 2012). These metals gradually release into the water column over time, influenced by factors such as temperature, pH, and lake bottom activities (Kumar and Mahajan, 2023). This not only increases the metal content in the lake, but also degrades water quality, making it unsuitable for human consumption, especially for drinking and domestic purposes (Gaury *et al*., 2018; Kumar and Mahajan, 2023). Thus, the sediments present below the lake water primarily originate from surface erosion, and consist of two main components: a mineral part resulting from rock erosion and an organic part formed during soil development processes, including biological activity and decomposition. These sediments play a crucial role in trapping various pollutants such as trace metals as source which subsequently discharges into the overlying water, and can harm aquatic life (Wang *et al*., 2010). Analyzing water, sediments, and marine organisms helps estimate contamination levels of metals in the aquatic environment (Gohar *et al*., 2014). The accumulation of trace elements in lake sediments has been extensively used to understand the scale and source of anthropogenic inputs (Akin and Kirmizigül, 2017; Joju *et al*., 2024; Shah *et al*., 2021; Vasiliu *et al*., 2020; Yu *et al*., 2021). Total Organic Carbon (TOC) and heavy metals in surface sediments are vital indicators for assessing environmental contamination and understanding geochemical processes (Sangeetha *et al*., 2025). While TOC is a measure of the organic carbon content in sediments (Chakraborty *et al*., 2014). Heavy metals can be released into the environment from various sources like industrial discharges, mining, and natural weathering (Sanad *et al*., 2025).

The present work deals with the analysis of twelve heavy metals from pre and post monsoon surface sediments of The Paradgaon Lake (PL). It primarily focuses on heavy metal contamination in pre- (PM) and postmonsoon (PoM) surface sediments of the PL of Nagpur District, Maharashtra, Central India. The impact of anthropogenic activities especially enhanced agricultural practices and open cast coal mining on the PL has also been assessed in this study.

Studied Area

The surface sediment PL (latitude N 20°55’52”, longitude E79°13’22”) is located in Umrer Taluka, Nagpur District, within the state of Maharashtra, Central India (Figure 1). The PL is surrounded by both agricultural land and forest area (Figure 1b). The open cast coal mine of The Umrer Town is situated in the vicinity of the PL (Figure 1b). Thus, the agricultural practices and open cast coal mine could pose the possible impact on the water quality of the PL. The Nagpur District predominantly displays pediplain morphology due to the extensive presence of The Deccan Trap Basalt (DTB). The PL is surrounded by a pediplain landscape, reflecting the prevalence of the DTB in the region (Figure 1c).

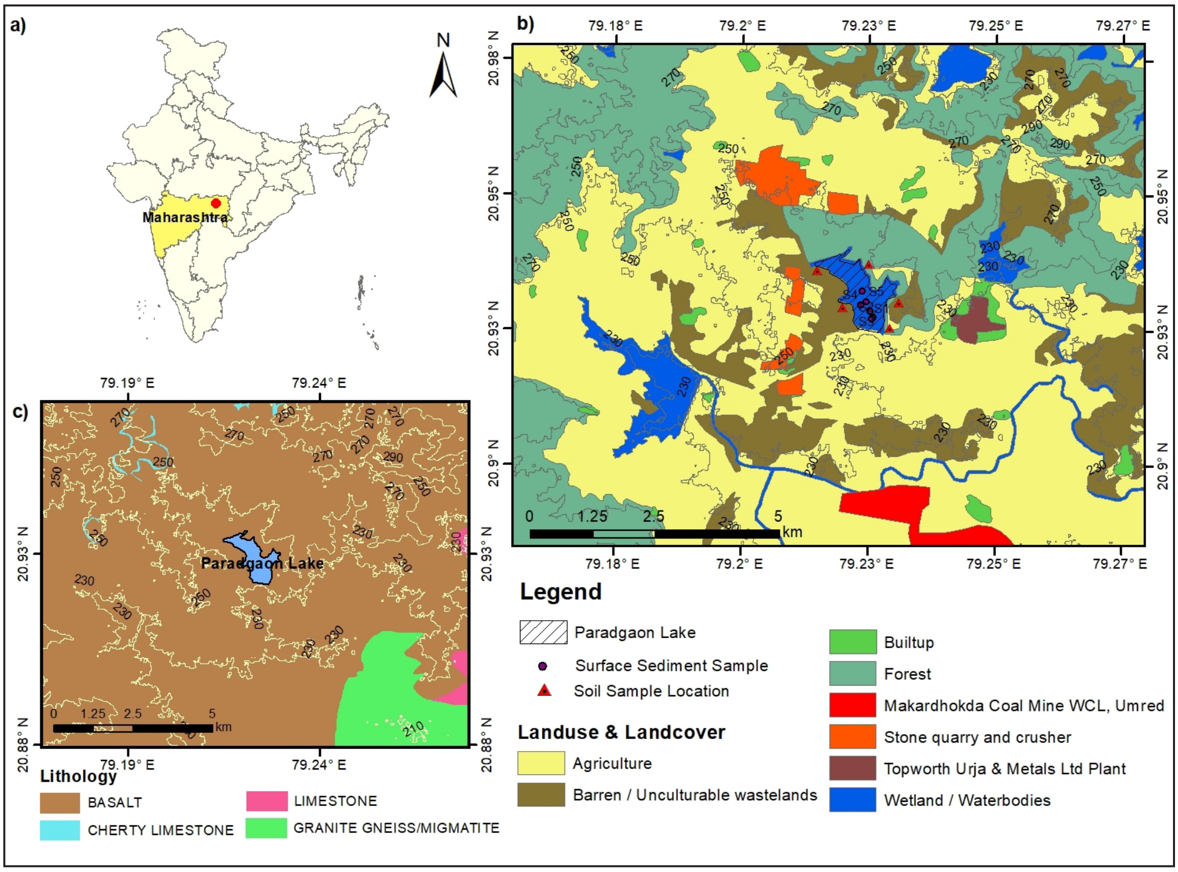

Figure 1. a) Map of India showing the state of Maharashtra with marked location of Nagpur District, b) Land-use landcover map around Paradgaon Lake (PL) showing marked locations of surface sediments and soil samples, c) Map showing geology around the PL.

Rainfall And Climate

The Nagpur District experiences a semiarid climatic conditions with the average temperature ranges from 14^{o}C to 27^{o}C, while the hottest month of May has an average temperature of 40^{o}C to 47^{o} C (gsda.maharashtra.gov.in/nagpur-district/). The Nagpur District receives rainfall from south-west monsoon with the average precipitation ranges from 800-900 mm in the western part of the district, while annual precipitation in the remaining area of the district varies from 1,000-1,200 mm (gsda.maharashtra.gov.in/nagpur-district/).

Geological/Stratigraphical Settings

The Umrer Taluka of The Nagpur District is geologically comprised a variety of rocks, including felsic volcanic tuff associated with the silicified zone, quartzo-feldspathic gneiss, schist, quartzite of Archean Eon, shale of The Vindhyan Supergroup, shale belonging to The Talchir Formation, sanstone, and shale intercalated with coal seam of The Barakar Formation, sansdstone, and clay of The Kamthi Formation, the intertrappeans associated with the DTB, limestone, and sandstone of The Lameta Group, and the youngest recent alluvium (DRM, 2000; Figure 1b). However, the DTB is mainly predominated around the lake, which also covers a significant portion of The Nagpur District and Maharashtra State (DRM, 2000).

METHODS AND MATERIALS

Methods

<u>Heavy Metal Contamination</u>

Various indices such as Heavy Metal Concentration, Enrichment Factor (EF), Contamination Factor (CF), Geo-accumulation Index (I-geo), Ecological Risk (Er), and Potetial Ecological

Risk Index (PERI) were calculated to assess their contamination in the PL.

Enrichment Factor (EF)

The study of source of elements in the atmosphere, marine water or rainfall, lake sediments, soil, mine waste, peat *etc.* can be discerned using the Enrichment Factor (EF) of heavy metals (Reimann and Caritat, 2005; Qingjie and Jun, 2008; Goher *et al.*, 2014). EF is a useful way to analyze geochemical patterns and make comparisons between different regions. EF is used to assess the level of contamination in the environment by comparing the abundance of specific elements in a sample to their occurrence in the background (Salomons and Förstner, 1984; Joju *et al.*, 2024). The Enrichment Factor (EF) was also utilized to establish the extent to which a particular element has been enriched due to anthropogenic activities (Equation 1).

EF is calculated using:

$EF^{EL} = (El/Al)_{sd} / (El/Al_{bg}$ ....(1)

where:

$(El/Al)_{sd}$ represents the ratio of geochemical element to aluminium in the sediments under investigation, while

$(El/Al)_{bg}$ denotes fraction of geochemical element to aluminium in surrounding background.

The correlation of a conservative trace metal with the concentrations of contaminant trace metals was done to normalize the pollutants (Lim *et al.*, 2006). Al is present as the most common conservative metal with its very meagre anthropogenic contributions in the surrounding environment, and therefore most often used for the normalization of trace metals (Sierra *et al.*, 2015). In the present study, aluminium (Al) was chosen as the reference element. This choice of reference element helps in assessing the enrichment of other elements in the sediment samples (Shah *et al.*, 2020). In this study, the calculation of enrichment factor was done using the average concentrations of geochemical elements of five subsurface soil samples (collected around the PL) collected from the pits dug away from the potential sources of main streams which carries weathered soils along with the metal contaminants to minimize the bias caused by anthropogenic influence for respective metals as local background values (pre-industrial reference level), and to avoid presumably continuous enrichment of heavy metals in soil from the source rock except for uranium where the upper continental crust (UCC) values (Taylor and McLennan, 1995) were used as the background concentration. The enrichment factor has been classified into five types for the appraisal of the level of pollution (Sutherland, 2000) such as low (< 2), moderate ($2 \leq EF < 5$), significant ($5 \leq EF < 20$), very high ($20 \leq EF < 40$), and extremely high ($EF > 40$).

Geo-accumulation Index (I_{geo})

The geo-accumulation index (Igeo) measures the level of metal pollution in sediments, and also helps to understand the lithogenic effects (Müller, 1969). In the present study, I_{geo} is used to recognize the heavy metal concentration in the PL sediments, and the background values were used from the average shale concentrations of these elements (Turekian and Wedepohl, 1961). I_{geo} (Müller, 1981) values were determined by applying the formula presented in the following Equation 2:

$I_{geo} = \log_2 cn/1.58\ bn$ .... (2)

where:

cn is the measured content of element, and

bn is the background average shale value of the element (Turekian and Wedepohl, 1961).

The variations in the background data caused by lithogenic effects have been corrected with the help of factor 1.5 (Müller, 1981; Joju *et al.* 2024; Nowrouzi and Pourkhabbaz 2014). I_{geo} index has been divided into seven classes (Müller, 1969; Buccolieri, 2006). These classes can be described as: a) unpolluted (< 0), b) unpolluted to moderately polluted (0-1), c) moderately polluted (1-2), d) moderately to highly polluted (2-3), e) highly polluted (3-4), f), highly to very highly polluted (4-5), and g) very highly polluted (> 5).

Contamination Factor (CF)

The heavy metal accumulation in sediments is significantly affected by the nature of the pollutant and the on-site physicochemical conditions that lead to its dissolution and build-up (Lone *et al.,* 2018). The extent of lake sediment pollution has previously been investigated by comparing it to the uncontaminated natural background values for a given constituent (Turekian and Wedepohl, 1961; Forstner and Müller, 1973; Macias *et al*., 2006). The Contamination Factor (CF) serves as a single parameter to assess sediment contamination and evaluate the environmental pollution in lakes. CF was determined using the following formula (Håkanson, 1980; Equation 3).

$$CF = C_{sample} / C_{background} \text{ .... } (3)$$

where 'C' represents concentration of the samples. This value is benchmarked against the globally accepted average shale value (Turekian and Wedepohl, 1961). This calculation helps in understanding the extent of contamination in the sediment sample relative to the earth crust (Shah *et al*., 2020). The CF has been classified into 04 classes (Häkanson, 1980) according to their concentrations and intensities, *i.e.* low contamination factor (< 1), moderate contamination factor (1< CF < 3), considerable contamination factor (3 < CF < 6), and very high contamination factor (CF > 6).

The Pollution Load Index (PLI)

The Pollution Load Index (PLI) quantifies the extent of pollution by analyzing metal concentrations in sediment samples collected at a site (Tomlinson *et al*., 1980). The calculation is based on the geometric mean of the CF (Tomlinson *et al*., 1980), formulated in Equation 4 below:

$$PLI = (CF1 * CF2 * CF3 * ... * CF_n)^{1/n} \text{ .... } (4)$$

where:
n equals number of elements.

This index allows for a comprehensive assessment of pollution levels by considering multiple contamination factors (Dhakate *et al*., 2020). The PLI computation can serve as a tool to develop an action plan of revival of wetlands. The PLI is divided into 03 classes (Tomlinson *et al*., 1980) *i.e.* PLI < 1: No pollution; PLI= 1: presence of pollutants moderate contamination factor (1< CF < 3), considerable contamination factor (3 < CF < 6), and very high contamination factor (CF > 6).

Ecological Risk Factor (Er)

The Ecological Risk Factor (Er) can be determined for an individual contaminant metal based on its specific toxicity response (Häkanson, 1980; Saha, 2022). The calculation is represented by the formula given in Equation 5:

$$Er = Tr * CFi \text{ .... } (5)$$

where 'Tr' signifies the toxic response of the metal which is referred from various studies (Zn, Cu, Cr, Pb: Häkanson, 1980; Co: Zhang and Liu, 2014; Ni: Pobi *et al*., 2019; Yi *et al*. 2020; Mn, Aguilera *et al*., 2022; U: V, Rb: Degbe *et al*., 2023), and 'CFi' represents the contamination factor associated with that particular metal (Dhakate *et al*., 2020).

The ecological risk (Er) is classified into five classes (Xu *et al.,* 2018). If Er value is less than 40 then the risk is low, whereas Er ranging between 40 and 80 signifies moderate risk. When Er value ranges from 80 to 160 the risk is considerable. The Er values from 160 to 320 indicates high risk, while Er value more than 320 reflects very high ecological risk (Xu *et al*., 2018).

Potential Ecological Risk Index (PERI)xa

PERI serves as a holistic measure for evaluating the ecological risk posed by heavy metals in soil (Aktaruzzaman *et al*., 2013; Jiao *et al*., 2015). It is determined by summing the ecological risk factors (Er) of individual metals while assessing the PERI (Häkanson, 1980; Joju *et al*., 2024), and can be expressed as Equation 6 below:

$$\mathrm{PERI} = \sum_{i=1}^{n=11} Er \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

The potential ecological risk index (PERI) is categorised into four classes (Class 1 to Class 2) on the basis of levels of risk (Dhakate *et al*., 2020). PERI <150 indicates low risk (Class 1), while PERI between 150 and 300 (Class 2) shows moderate risk. A PERI value between 300 and 600 (class 3) indicates a considerably high ecological risk. PERI exceeding 600 (Class 4), indicates that the sediments are categorized with significantly high risk (Dhakate *et al*. 2019).

Statistical Analysis

Various statistical parameters such as mean, minimum, maximum, standard deviation (SD) are computed after analysis. Pearson's correlation co-efficient analysis is conducted on metal concentrations in PL sediments for both PM and PoM seasons using Microsoft Excel (2010) to assess linear relationships and affinities between metal pairs.

Materials

Surface sediment samples were collected from 03 different locations during the PM (PLGPR-1, PLGPR-2, PLGPR-3) and PoM (PLGPO-1, PLGPO-2, PLGPO-3) seasons from the PL in May 2012 and January 2013, respectively along with five soil samples (PLSP1-1, PLSP2-1, PLSP3-1, PLSP4-1, PLSP5-1) around the PL on December 2013 for the present study (Figure 1b). The sediment and soil samples were oven-dried at approximately 80^{o} C. The dried samples were further powdered to -173 mesh size for its homogenization and proper chemical reaction of the particles and crucial good quality results. The X-ray Fluorescence (XRF) studies of these powdered samples were done for major and trace elements (Model: Philips Magi XPRO PW 2440) at The National Geophysical Research Institute (NGRI), Hyderabad. 22 International reference standards were used to confirm the accuracy of the XRF results following Krishna *et al*. (2007). While regional background study of the geochemical elements from soil profiles was done using XRF (Model: Brucker 58 Tiger) at Wadia Institute of Himalayan Geology (WIHG), Dehradun. The following international reference standards were used to calibrate the accuracy of the XRF: Shale: SCO-1, SDO-1, GXR-2, USGS, USA). Total organic carbon (TOC) and total inorganic carbon (TIC) from surface sediments of the lake were analyzed using TOC analyzer (Model: TOC-L, Make: Schimadzu) at PG Department of Geology, RTM Nagpur University, Nagpur. Accuracy of the results was confirmed using sucrose as a standard reference material.

RESULT AND ANALYSIS

The concentrations of twelve geochemical elements were studied from the PL surface sediments to assess the heavy metal pollution during pre- (PM) and postmonsoon (PoM) seasons (Table 1) and the spatial distribution of the selected enriched heavy metals (Fe, Al, Zn, Mn, Cr, and Co) during pre- and postmonsoon seasons is shown in Figure 2 (a-l). The average concentrations of the elemental content during premonsoon period is in the order as Fe>Al>-Mn>V>Cu>Cr>Zn>Rb>Ni>Co>Pb>U. The similar trend was also observed during the PoM period, except for Cu and Cr, where Cu concentration was more diluted as compared to Cr. However, the concentrations of eleven heavy metals from the five soil samples collected around the PL with their mean concentrations are provided in Table 2.

The total organic carbon (TOC) content in the PM sediments of the PL is moderate, and it varies between 29.174 and 33.713 % with mean (±SD) of 31.147 % (±1.9), whereas the total inorganic carbon (TIC) concentration is very low and ranges between 0.616 and 1.145 % with mean (±SD) of 0.875 (±0.216) (Figure 3a). The total organic carbon (TOC) content in the PoM sediments varies between 23.858 and 39.19 % with mean (±SD) of 30.616 % (±6.389), whereas the total

Table 1. Metal Concentrations of in Paradgaon Lake Surface Sediments in PM And PoM Seasons with Minimum, Maximum, Mean, and Standard Deviations (SD) Values

Element (mg/kg)	**PLGPR -1**	**PLGPR -2**	**PLGPR -3**	**Min.**	**Max.**	**Mean**	**± SD**	**PLGPO -1**	**PLGPO -2**	**PLGPO -3**	**Min.**	**Max.**	**Mean**	**± SD**
Fe	74100	79200	75500	74100	79200	76300	2151.485	81500	77800	77800	77800	81500	79000	1744.197
Mn	1300	1300	1400	1300	1400	1300	47.14045	1600	1400	2000	1400	2000	1700	249.4438
Zn	99.75	102.82	102.77	99.75	102.8	101.78	1.435572	103.91	100.86	98.66	98.66	103.91	100.9	2.152647
Cu	109.17	117.14	111.8	109.1	117.1	112.7	3.315844	112.92	104.54	103.4	103.4	112.92	106.95	4.244662
Cr	110.57	116.72	110.52	110.5	116.7	112.6	2.910994	116.01	114.89	102.61	102.61	116.01	111.17	6.07008
Ni	61.1	67.2	61.46	61.1	67.2	63.25	2.794582	64.52	59.81	54.4	54.4	64.52	59.37	4.134766
Pb	36.8	29.52	36.34	29.52	36.8	34.22	3.328703	30.99	37.52	30.9	30.99	37.52	33.14	3.099702
Co	34.72	38.85	34.94	34.72	38.85	36.17	1.897173	39.27	35.35	39.04	35.35	39.27	37.89	1.79615
U*	2.37	1.96	2.94	1.96	2.94	2.42	0.401857	1.8	2.06	2.01	1.8	2.06	1.96	0.112645
V	198.63	225.28	200.77	198.6	225.2	208.23	12.09013	224.44	210.79	238.79	210.79	238.79	224.67	11.43214
Rb	90.71	91.25	89.95	89.95	91.25	90.64	0.53325	90.99	89.09	77.1	77.1	90.99	85.73	6.149094
Al	67800	68500	67900	67800	68500	68100	309.121	68400	68700	67500	67500	68500	68200	509.902

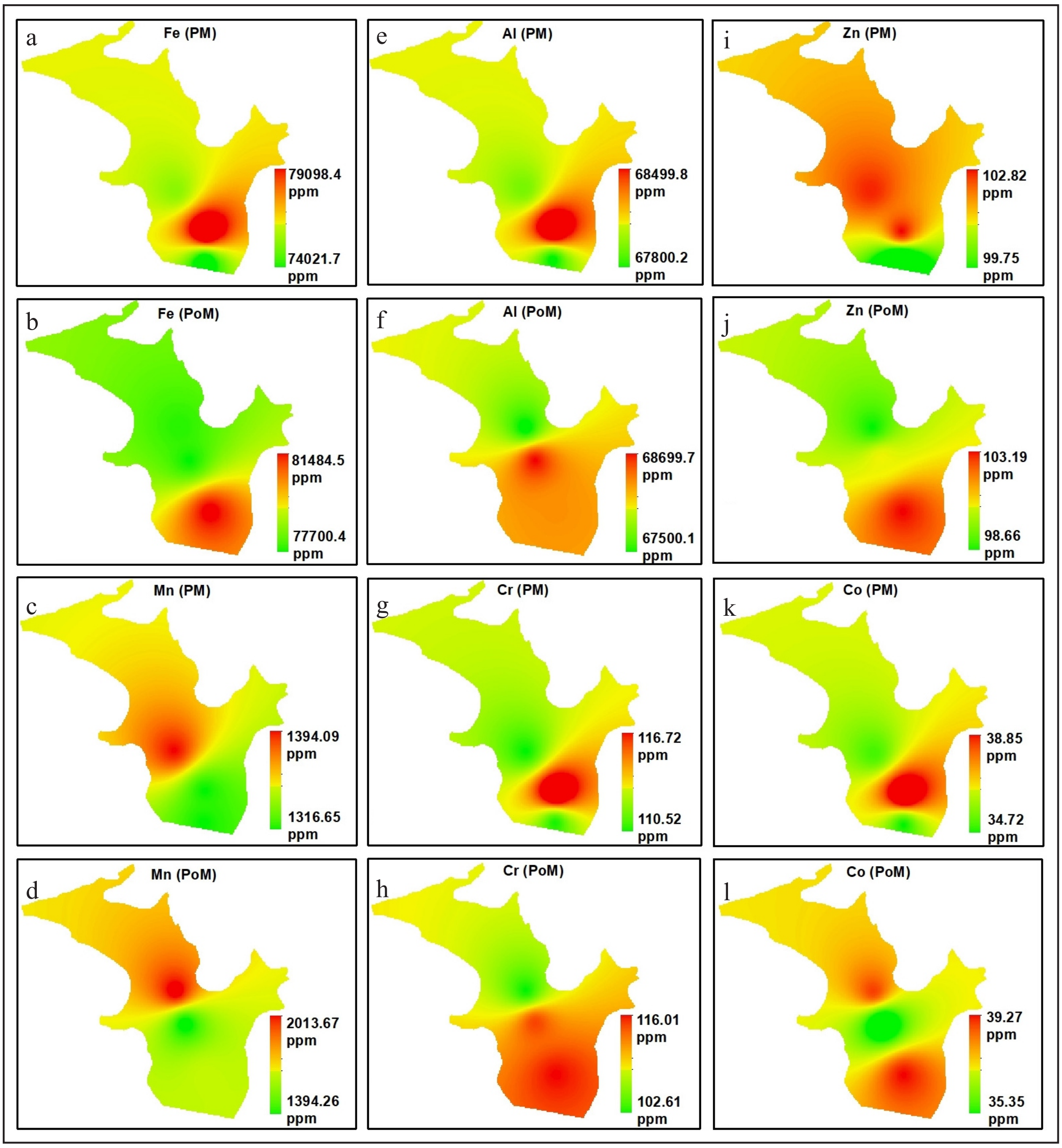

Figure 2. Distribution of significant heavy metals from surface sediments in the PL for PM and PoM seasons.

Table 2. Metal Concentrations in Subsurface Soil Samples Collected in The Catchment of PL with Mean Values

Element (mg/kg)	PLSP1-1	PLSP2-1	PLSP3-1	PLSP4-1	PLSP5-1	Mean
Fe	116100	106200	104100	122300	124500	114640
Mn	3500	1800	1700	1500	1400	1980
Zn	129	107	106	127	119	117.6
Cu	255	239	178	223	228	224.6
Cr	97	86	142	53	45	84.6
Ni	76	62	78	59	76	70.2
Pb	19	19	21	19	20	19.6
Co	69	48	47	54	52	54
U*	NA	NA	NA	NA	NA	NA
V	333	321	337	262	229	296.4
Rb	10	8	65	10	25	23.6
Al	90200	105800	89800	66100	67100	83800

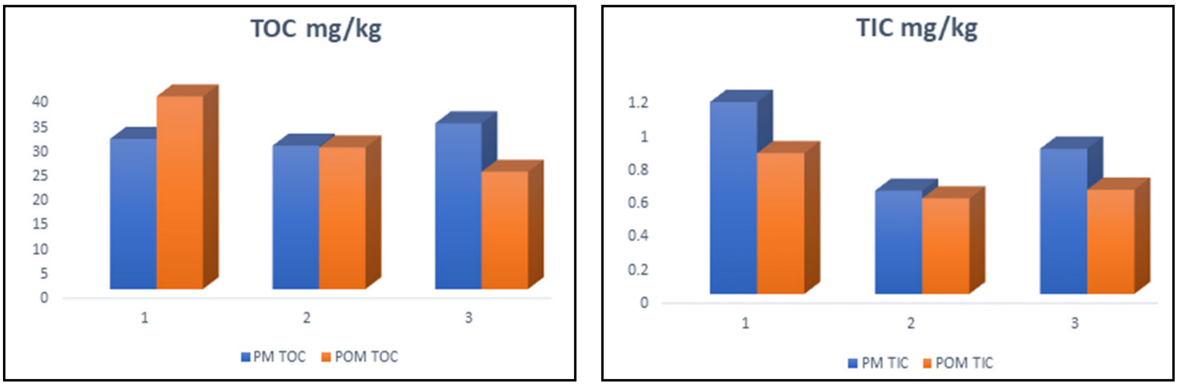

Figure 3. Concentrations of a) Total Organic Carbon (TOC mg/kg) and b) Total Inorganic Carbon (TIC mg/kg) in surface sediment samples in the PL during the PM and PoM seasons.

inorganic carbon (TIC) content is very low, and ranges between 0.57 and 0.84 % with mean (±SD) of 0.677 % (± 0.116) (Figure 3b).

Enrichment factor (EF) presents a simple method for assessing enrichment levels and quantifying the sediment contamination of various surface water bodies. The EF of metals for the PL during the PM and PoM seasons is provided in Figure 4a (Table 3a-b). The mean EF for metals during the PM season in decreasing order is Rb>Pb>Cr>Ni>Zn>U>V>Co>Fe>Mn>Cu, whereas the mean EF trend in the PoM season is Rb>Pb>Cr>Mn>Zn>Ni>V>Co>Fe>U>Cu. The implications of the geo-accumulation index (I_{geo}) for the PL (PM -PoM seasons) are depicted in Figure 4b (Table 3a-b). The CF values for the PL sediments are shown in Figure 4c (Table 3a-b). The mean PLI values for the PM and PoM sediments of the PL are 1.29 and 1.287, respectively (Table 3a-b). The E_r values of the PL sediments are illustrated in Figure 4d (Table 3a-b). The average concentration of E_r for metals in the PM and PoM sediments of the PL is U > Cu >Co > Pb > Ni >V >Cr > Fe > Mn > Zn > Rb and U > Cu > Co > Pb > Ni > V > Cr > Mn > Fe > Zn > Rb, respectively.

Pearson's Correlation Coefficients for heavy metals in PL sediments (PM and PoM seasons) are provided in linear matrix form (Table 4a-b). The high positive correlation exists between the heavy metals such as Al, Cu, Cr, Ni, Co, and V in the PM sediments of the PL, while Pb is not correlated with any of the metal content. Pb has high positive correlation with TIC and moderately correlated with TOC. U is strongly correlated with Mn and Pb, and Mn also correlates positively with TOC.

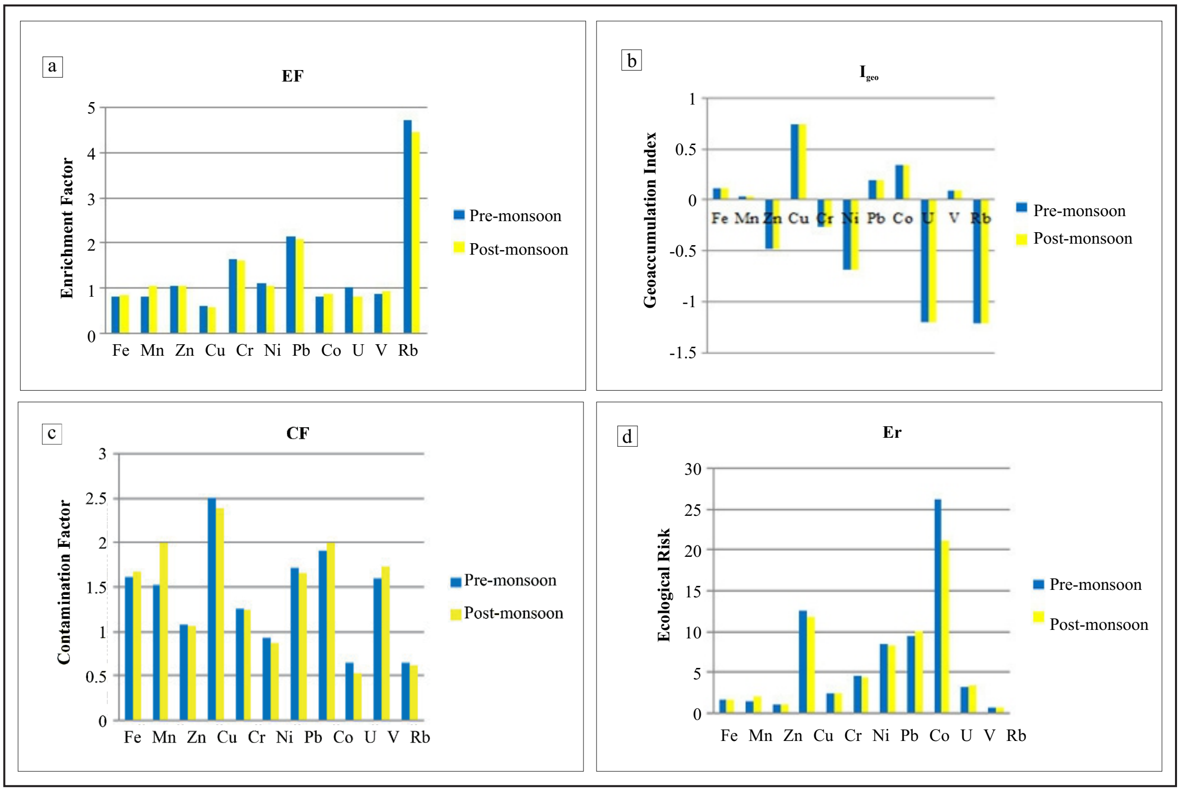

Figure 4. Comparative study of heavy metals in surface sediments of PL (PM and PoM seasons) for a) enrichment factor (EF), b) geo-accumulation index (I_{geo}), c) Contamination Factor (CF), and d) Ecological risk factor (Er).

Discussion

The sources of TOC in the PL are mainly originated from aquatic weeds, transported vegetal matters and in-situ grown algal matter both during the PM and PoM seasons. The sedimentary organic carbon in lake is mainly enriched from labile organic fractions of algal origin, while remaining organic matter in sediments may be derived from runoff containing terrestrial organic matter (Zhang *et al*. 2023; Vijayraj and Achyuthan, 2016).

The source, trait, and interrelations of metals generally remain the same when the correlation co-efficient of these metals is highly positive (Suresh *et al*., 2011). Hence, Al, Cu, Cr, Ni, Co, and V could have derived from the similar lithogenic source such as the DTB and associated soils in the catchment of the PL, while other metals could have different sources. Based on the correlation of Pb with TOC, U, and Mn, it can be inferred that these heavy metals were added through the anthropogenic activities such as coal mines in the soils of surrounding area of the PL, and ultimately deposited in the lake through weathering and erosion of soils of the region. The strong positive correlation between Mn and TOC indicates biogenic source. The leaching of Mn (fraction F3) generally takes place from lakes and soils, and it is closely associated with the dissolved organic carbon (Makri *et al*., 2021).

Iron (Fe), an important immobile element is commonly found together with Al in the earth crust (Chatterjee *et al*., 2007; Goher *et al*., 2014). The Deccan basalts of Western Ghats, India, have varying concentrations of the chalcophile elements such as Ni ad Cu (Banerjee and Mondal, 2021). The fractional crystallization of basalts tends to form Cu, Cr, Ni, and Co in the crtystal structure of different minerals associated with The Decan Trap Basalts (Jain and Gupta, 2013). The PL sediments (PoM) revealed strong to moderate correlation amongst metals like Al, Cu, Cr, Ni, Co, V, and Rb indicating similar lithogenic source such as the DTB and associated soils in the catchment, while strong correlation of Zn only with Fe may be related to inorganic carbon derived from

Table 3 a–b. Minimum, Maximum, And Mean Values of Enrichment Factor (EF), Geo-accumulation Index (I_{geo}), Contamination Factor (CF), Ecological Risk Factor (Er), Pollution Load Index (PLI), And Potential Ecological Risk Index (PERI) of Heavy Metals from Surface Sediments of PL for Pre (a: PM) And Postmonsoon (b: PoM) Seasons

a. Pre-monsoon

Sr. No.	Heavy Metal	Enrichment Factor			Index of Geoaccumulation			Contamination Factor			Ecological Risk		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	Fe	0.798907	0.845167	0.819	0.06572	0.16175	0.107	1.569915254	1.677966102	1.616	1.569915	1.677966	1.616
2	Mn	0.811507	0.865	0.807	0.028014	0.13493	0.028	1.529411765	1.647058824	1.529	1.529412	1.647059	1.529
3	Zn	1.048383	1.069606	1.065	-0.5146	-0.4708	-0.485	1.05	1.082315789	1.071	1.05	1.082316	1.071
4	Cu	0.60077	0.638041	0.617	0.6936	0.7953	0.7395	2.426	2.603111111	2.504	12.13	13.01556	12.522
5	Cr	1.614674	1.687829	1.637	-0.28865	-0.2099	-0.2617	1.228	1.296888889	1.251	2.456	2.593778	2.502
6	Ni	1.075768	1.171077	1.108	-0.7393	-0.602	-0.6894	0.898529412	0.988235294	0.93	4.492647	4.941176	4.65
7	Pb	1.86155	2.296916	2.148	-0.02327	0.29474	0.18988	1.476	1.84	1.711	7.38	9.2	8.55
8	Co	0.794695	0.880138	0.824	0.2848	0.44695	0.3438	1.827368421	2.044736842	1.903	9.136842	10.22368	9.51
9	U	*0.865192	*1.284526	*1.02039	-1.5016	-0.9167	-1.1975	0.52972973	0.794594595	0.654	21.18919	31.78378	26.16
10	V	0.828287	0.929818	0.864	0.02661	0.20825	0.0947	1.527923077	1.732923077	1.601	3.055846	3.465846	3.2
11	Rb	4.710896	4.730144	4.726	-1.2232	-1.2025	-1.2122	0.6425	0.651785714	0.647	0.6425	0.651786	0.64
			Pollution Load Index (PLI)					1.213	1.372	1.29			
						Potential Ecological Risk Index (PERI)					64.632	80.282	71.97

b. Post-monsoon

Sr. No.	Heavy Metal	Enrichment Factor			Index of Geoaccumulation			Contamination Factor			Ecological Risk		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	Fe	0.842527	0.867179	0.8467	0.13602	0.20305	0.107	1.648305085	1.726694915	1.6737	1.648305	1.726695	1.673
2	Mn	0.877815	1.232117	1.0549	0.13493	0.6495	0.028	1.647058824	2.352941176	2	1.647059	2.352941	2
3	Zn	1.041535	1.077798	1.0542	-0.5304	-0.4556	-0.485	1.038526316	1.093789474	1.06	1.038526	1.093789	1.062
4	Cu	0.571546	0.613265	0.5851	0.6153	0.7423	0.7395	2.297777778	2.509333333	2.376	11.48889	12.54667	11.883
5	Cr	1.505773	1.672678	1.6146	-0.3958	-0.2187	-0.2617	1.140111111	1.289	1.235	2.280222	2.578	2.4704
6	Ni	0.96206	1.1211	1.0391	-0.9069	-0.6608	-0.6894	0.8	0.948823529	0.873	4	4.744118	4.365
7	Pb	1.962934	2.335038	2.0775	0.04684	0.3227	0.18988	1.5495	1.876	1.657	7.7475	9.38	8.285
8	Co	0.812711	0.887063	0.8621	0.31075	0.4625	0.3438	1.860526316	2.066842105	1.994	9.302632	10.33421	9.971
9	U	*0.798095	*0.897422	*0.82522	-1.6245	-1.4298	-1.1975	0.486486486	0.556756757	0.529	19.45946	22.27027	21.188
10	V	0.882901	0.98271	0.9313	0.11233	0.29227	0.0947	1.621461538	1.836846154	1.728	3.242923	3.673692	3.456
11	Rb	4.055857	4.702935	4.4635	-1.4456	-1.2066	-1.2122	0.550714286	0.649928571	0.612	0.550714	0.649929	0.6123
			Pollution Load Index (PLI)					1.2	1.382	1.287			
						Potential Ecological Risk Index (PERI)					62.406	71.35	66.96

Table 4a. Pearson Correlation Co-efficients Among Heavy Metals in Premonsoon Samples (PM), PLI, PERI, TOC And TIC for The PL. Bold Numbers Shows Strong Positive Correlations of The Variables. PL: Paradgaon Lake; PLI: Pollution Load Index; PERI: Potential Ecological Risk Index; TOC: Total Organic Carbon; TIC: Total Inorganic Carbon; b. A TIC for the PL. Bold Numbers Shows Strong Positive Correlations of The Variables. PL: Paradgaon Lake; PLI: Pollution Load Index; PERI: Potential Ecological Risk Index (TOC: Total Organic Carbon; TIC: Total Inorganic Carbon)

Table 4a

	PLI	TOC	TIC	PERI	Fe	Al	Mn	Zn	Cu	Cr	Ni	Pb	Co	U	V	Rb
PLI	1															
TOC	0.983403	1														
TIC	0.436799	0.266337	1													
PERI	-0.49653	-0.3308	-0.99772	1												
Fe	-0.6731	-0.52775	-0.95928	0.976158	1											
Al	-0.76743	-0.63837	-0.91195	0.937567	0.990708	1										
Mn	0.885291	0.954972	-0.03163	-0.03591	-0.25197	-0.38125	1									
Zn	0.025699	0.206649	-0.88804	0.854974	0.722007	0.6212	0.487635	1								
Cu	-0.62687	-0.4751	-0.97469	0.987555	0.998148	0.9806	-0.19264	0.762759	1							
Cr	-0.8491	-0.73917	-0.84606	0.880114	0.962182	0.99029	-0.50606	0.506229	0.943829	1						
Ni	-0.81612	-0.69772	-0.87632	0.906842	0.976706	0.996815	-0.45376	0.556721	0.961843	0.998223	1					
Pb	0.813898	0.694973	0.878161	-0.90845	-0.97752	-0.99711	0.450345	-0.5599	-0.96288	-0.99799	-0.99999	1				
Co	-0.81914	-0.70148	-0.87378	0.904614	0.975564	0.996382	-0.45844	0.552347	0.960392	0.998522	0.999986	-0.99996	1			
U	0.998539	0.99177	0.387553	-0.4489	-0.63216	-0.73166	0.909126	0.07968	-0.58385	-0.81932	-0.7837	0.781313	-0.78695	1		
V	-0.80457	-0.68347	-0.88565	0.914972	0.980745	0.998193	-0.43611	0.572985	0.967049	0.996854	0.999806	-0.99987	0.999688	-0.77131	1	
Rb	-0.99835	-0.9922	-0.3844	0.445846	0.629509	0.729333	-0.91054	-0.08308	0.581077	0.81736	0.781575	-0.77918	0.784843	-0.99999	0.769129	1

Table 4a

	PLI	TOC	TIC	PERI	Fe	Al	Mn	Zn	Cu	Cr	Ni	Pb	Co	U	V	Rb
PLI	1															
TOC	-0.27199	1														
TIC	0.22632	0.875773	1													
PERI	-0.53017	-0.67172	-0.94588	1												
Fe	0.045773	0.94884	0.983391	-0.87127	1											
Al	-0.94707	0.56653	0.098367	0.229903	0.27735	1										
Mn	0.972301	-0.48938	-0.00762	-0.31731	-0.18898	-0.99587	1									
Zn	-0.37519	0.99405	0.817982	-0.58703	0.908801	0.652917	-0.58146	1								
Cu	-0.06403	0.977741	0.957562	-0.8122	0.993971	0.381021	-0.29551	0.949069	1							
Cr	-0.79923	0.795753	0.404551	-0.08588	0.563814	0.949875	-0.91757	0.856985	0.65097	1						
Ni	-0.4949	0.970798	0.734395	-0.47439	0.845384	0.747671	-0.6843	0.991153	0.898855	0.917802	1					
Pb	-0.89339	-0.18934	-0.63981	0.854588	-0.4897	0.701868	-0.76364	-0.08126	-0.39115	0.443997	0.051745	1				
Co	0.862751	0.251903	0.687767	-0.88612	0.544589	-0.65476	0.720672	0.144993	0.449347	-0.38564	0.012386	-0.99794	1			
U	-0.22604	-0.87591	-1	0.945784	-0.98344	-0.09866	0.007909	-0.81815	-0.95765	-0.40482	-0.73459	0.639588	-0.68755	1		
V	0.998187	-0.32942	0.167286	-0.47818	-0.01443	-0.96467	0.984606	-0.4303	-0.12398	-0.83395	-0.5463	-0.86473	0.830756	-0.167	1	
Rb	-0.7675	0.825639	0.450719	-0.13664	0.60525	0.932672	-0.89607	0.882181	0.688882	0.998696	0.936878	0.397666	-0.33802	-0.45098	-0.80469	1

weathering and erosion of soils caused by anthropogenic activities in addition to coal mining in the nearby areas of the PL. The intensive mining of coal contributes Zn as the major contaminant in soils mainly through coal gangue (Wang *et al*., 2022). The higher concentration of Zn in sediments is correlated with the increased particulate organic carbon derived through anthropogenic activity and may also results into elevated concentrations of Zn and Fe (Wardhani *et al*., 2022).

The EF for majority of the metals in the PL is below 2 (Sutherland, 2000) indicating their low enrichment except Rb and Pb with moderate enrichment for the PM and PoM seasons (Figure 4a; Figure 5a-e; Figure 6 a-e). The higher values of the EF for Rb and Pb could be due to natural factors and anthropogenic activities such as coal mining near the lake at Umrer Town.

I_{geo} values of many metals in the PL indicate unpolluted nature for both the seasons (Figure 2b; Müller, 1969). However, the lake sediments are moderately contaminated by the metals such as Cu, Co, Pb, Fe, and V indicating weak to moderate pollution (Figure 4b; Figure 5f-j; Figure 6f-j). The discharge of geogenic materials including the particulate matters from the opencast coal mine sites near the studied area could be the primary sources of these metals in the lake.

The CF values of metals such as Ni, U, and Rb in the PL sediments are less than 1 (Häkanson, 1980) indicating low contamination factor for the PM and PoM seasons (Figure 4c; Figure 5k-o; Figure 6k-o). The CF less than 1 also shows that there is no metal contamination by natural or human inputs (Raj and Jayaprakash, 2008). However, metals like Fe, Mn, Zn, Cu, Cr, Pb, Co, and

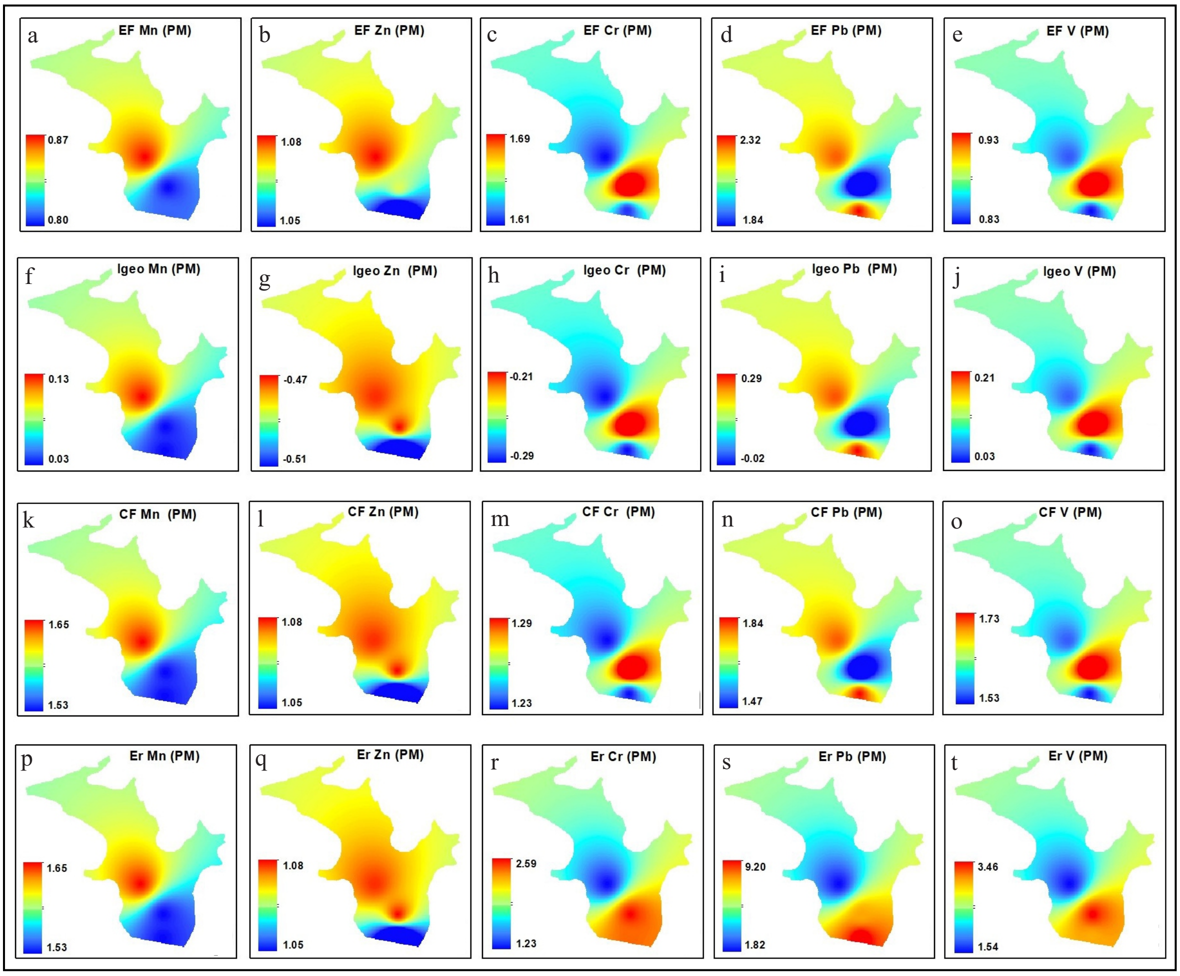

Figure 5. Distribution of a–e) enrichment factor (EF), f–j) geo-acumulation index (I_{geo}), k–o) Contamination Factor (CF) and p –t) Ecological risk factor (Er) for significant heavy metals (Mn, Zn, Cr, Pb, and V) from surface sediments of PL (PM season).

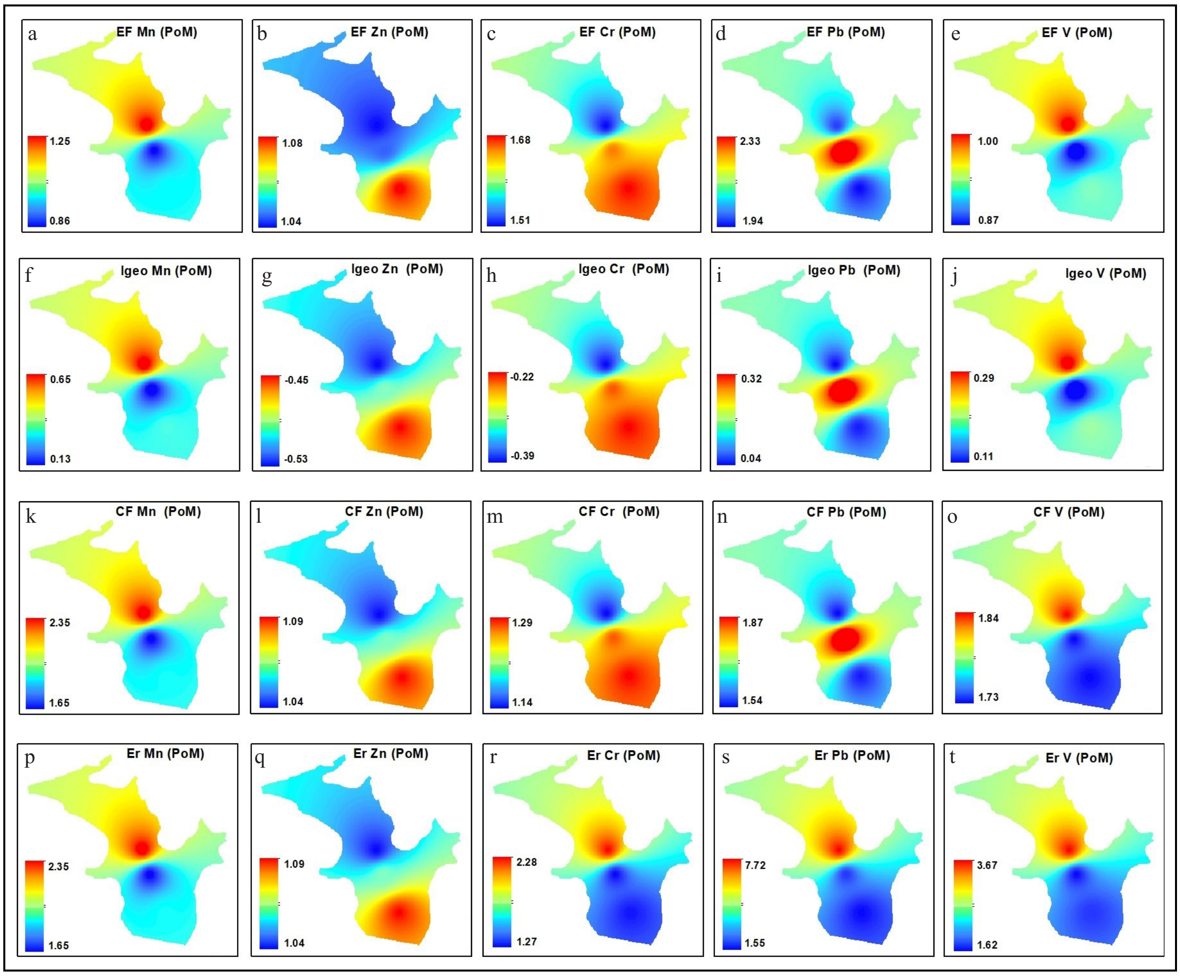

Figure 6. Distribution of a–e) enrichment factor (EF), f–j) geo-accumulation index (I_{geo}), k–o) Contamination. Factor (CF) and p−t) Ecological risk factor (Er) for significant heavy metals (Mn, Zn, Cr, Pb, and V) from surface sediments of PL (PoM season).

V have more than 1 CF values in both the seasons pointing moderate level of pollution in the PL sediments (Figure 4c; Figure 5k-o; Figure 6k-o).

The PLI may serve valuable input on the level of pollution in the region, which may be useful for policy makers to decide on the strategic planning (Harikumar and Nasir, 2010; Goher *et al*,, 2014). Thus, the sediments (PLI range 1-2) of both the seasons substantiate unpolluted nature of the PL as per the standard PLI index (Liu *et al*., 2018; Tomlinson *et al*., 1980).

The ecological assessment of metals recognizes the potential harmful impacts beyond the assessment of heavy metal concentrations. The heavy metals like U, Cu, Co, and Pb showed slighly higher values E_r index, but less than 40 (Xu *et al*., 2018) indicating their low ecological risk as individual metal (including the remaining heavy metals) for the PM and PoM seasons (Figure 4d; Figure 5p-t; Figure 6p-t). The possible source of excessive U, Pb, and CO could be the open cast coal mine in the region, while the other metals perhaps have the geogenic origin associated with anthropogenic soil erosion. The PERI assessment, derived from the ecological risk index (E_r) values of each metals (Figure 4d) in the PL sediments (PM and PoM), suggests a low potential ecological risk according to grade standards (Guo *et al*., 2010; Suresh *et al*., 2012).

CONCLUSIONS

This study demonstrates that heavy metals of the PL sediments such as Al, Cu, Cr, Ni, Co, and V were generated from common lithogenic source like the DTB and associated soils in the catchment area. The heavy metals such as Zn, Cu, Cr, Ni, Pb, U, and Rb showed their higher concentrations during the PM season as compared to the PoM, while metals like Al, Fe, Mn, Co, and V have higher concentrations during the PoM season indicating their accumulation in the PL from various part of the catchment area after the monsoonal rains. The geo-accumulation index and contamination factor of the heavy metals in the lake showed moderate pollution level. The result of EF and ecological risk analyses showed that economic development in the form of coal mining, changing land-use types, soils/parent materials, and amount of rainfall have considerable influence on heavy metal accumulation in the PL sediments. The ecological risk index revealed that among the eleven heavy metals, U posted the highest ecological risk during PM, and PoM seasons signify mainly its geogenic source in addition to some input from coal mining activities. The PERI revealed the low-potential ecological risk for the PL during both seasons. Similarly, the PLI indicated the unpolluted nature of the PL for both seasons. These findings provide crucial insights into the sediment quality of the PL. Pollution indices indicate that the PL sediments largely remain unpolluted, except for moderate contaminations of Cu, Co, Pb, Fe, and V. The ecological risk assessment showed that the heavy metals including U, Cu, Co, and Pb pose low potential risks. Consequently, remedial actions should be implemented, focusing on pollution control and management strategies for the region to prevent further the heavy metal pollution in the PL. This approach is essential for protecting aquatic systems, human health, and the future strategic planning for the lake water quality monitoring.

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