



Geochemistry and pollution status of surface sediments of Loktak Lake, Manipur, India

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Abstract

Surface sediments ($n = 29$) from Loktak Lake, the largest freshwater lake in northeastern India, were studied for geochemistry, mineralogy and the heavy metal pollution of the lake sediments was assessed. The XRD spectra of bulk sediments showed the dominance of quartz and clay fractions showed the dominance of illite and chlorite. The major oxides consist dominantly of SiO_2 , Al_2O_3 and FeO with low concentrations of K_2O , Na_2O and CaO . The depletion of CaO , Na_2O and K_2O compared to upper continental crust, post-Archean average shale and North-American shale composite indicated moderate to strong weathering, recycling of the source rock and their removal during transportation. The chemical index of alteration values (76.86–84.98) also suggested moderate to extreme chemical weathering of the Loktak Lake catchment lithologies. The mean concentrations (in mg/kg) of Zn (117 ± 23.45), Co (34 ± 13.67), Fe (7 ± 1.38 wt%), Cu (67 ± 12.87), Cr (282 ± 45.25) and Ni (194 ± 30.12) are about 2–4 times higher than that of the upper continental crust, except for Mn (425 ± 168.99 mg/kg) and Pb (17 ± 7.47 mg/kg). The heavy metal concentrations follow the trend of $\text{Fe} > \text{Mn} > \text{Cr} > \text{Ni} > \text{Zn} > \text{Cu} > \text{Co} > \text{Pb}$. The assessment of heavy metal pollution using enrichment factor, geo-accumulation index and modified degree of contamination suggested non-contamination to moderate contamination of sediments. According to sediment quality guidelines, the sediment-dwelling biota could be affected by the higher concentrations of Ni and Cr. The mean-effect range median-quotient suggests medium–high to high potential of the effects of heavy metal pollution. The uniformly higher concentration of heavy metals in general and Ni and Cr, in particular, indicated the dominance of natural (ophiolitic) sources with no or little, if any, anthropogenic influence.

Keywords Surface sediments · Geochemistry · Pollution assessment · Loktak lake

1 Introduction

Freshwater lakes are often contaminated with various pollutants since they are the receiving end of rivers, streams, run-offs and other waste discharges. Regardless of whether the origin is natural or anthropogenic, the pollutants, after entering the aquatic system, have a high affinity toward sediments. Sediments are heterogeneous assemblages of several sorbent phases such as organic

matter, oxides, sulfides, carbonates and clay or silt minerals [74]. Being the source and sink of pollutants derived from catchment weathering and anthropogenic activities such as untreated urban wastes, transport, industries and agricultural wastes [7], they are used to assess the health status of aquatic ecosystems in several studies [19, 73]. During chemical weathering and soil formation processes, labile feldspars are degraded from source rocks to secondary clay minerals and labile cations (Ca^{2+} , Na^+ , K^+ , Fe^{2+}

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and Mg^{2+}) are selectively leached relative to hydrolysate constituents (Al^{3+} and Ti^{4+}) [53]. Geochemical weathering alters rock mineral compositions depending on factors such as climate, biological activity, parent material, topography, duration of the weathering processes, rate of alteration, etc. [6, 49]. Quantitative estimation of the chemical weathering of silicates such as the chemical index of alteration (CIA) is widely used to interpret the weathering history of sediments [50, 53, 68]. It is a measurement of the proportion of secondary aluminum clay minerals to primary silicate minerals such as feldspars [50]. CIA value for average shale ranges from 70 to 75 reflecting values of muscovite, illite and smectite thus indicating a large proportion of clay minerals [10], while intensely weathered residual rocks forming kaolinite and gibbsite have CIA values approaching 100 [50]. The CIA value of 78.74 of Renuka Lake sediments indicated moderate weathering at the source [11]. Sediment texture, mineralogical composition and physico-chemical transport influence the distribution and accumulation of pollutants in sediments [74]. Most surface water sediments are derived from surface erosion and comprise a mineral component, which arises from the erosion of bedrock [18]. The chemical composition of sediments depends on its contents of quartz and clay fractions which is related to grain size, with Al_2O_3 increasing toward finer sediments (clays) and SiO_2 toward sands [10]. The knowledge of mineralogical compositions of a lake basin helps to understand the genesis of sediments, transport mechanisms and the nature and intensity of the weathering process within the watershed, etc. [34].

Among the pollutants, heavy metal is a worldwide problem that poses a potential threat to the aquatic ecosystem. They get accumulated into sediments through complex mechanisms of adsorption depending on the characteristics of adsorbed compounds and the sediment matrix [7]. Lake Hamahara of Japan has no industries in its catchment area and no known point sources for metal enrichment in the lake sediments and hence the metals are likely to be housed in the sediment matrix, with additional modifications depending on the sediment redox conditions, anthropogenic sources and surface soil erosion [3]. The deposited metals are released into the overlying water in response to chemical, biological and other physical disturbances [22]. Their non-biodegradable, persistent and irreversible characteristics play a critical role in different trophic levels of the food chain due to bioaccumulation and toxicity [72]. Heavy metals in aquatic systems are present as dissolved ions, complexes, suspended and colloid ions [2]. Upon entering the aquatic system, they have a high affinity to get adsorbed on the fine-grained sediments and consequently pose a threat to aquatic biota particularly the sediment-dwelling organisms [74]. The geochemical analysis of sediments such as enrichment

factor and geo-accumulation index are commonly used tools to assess heavy metal pollution [9, 27, 60, 72]. The pollution level in lake sediments is also addressed by comparing with sediment quality guidelines [7, 27, 52]. Therefore, with the increasing anthropogenic pressure on inland freshwaters, analysis of sediments is of utmost importance concerning their pollution status and in turn, evaluates the quality of the aquatic ecosystem [48].

Several studies on freshwater lake sediments focus on the environmental concerns of heavy metal contamination. Chakrapani [8] studied the sediment geochemistry of Himalayan Lakes such as Nainital, Bhimtal, Sattal and Naukuchiatal and found the influence of varying degrees of natural and anthropogenic activities on these lakes. Nasser Lake sediments of Egypt had low values of heavy metal pollution indices indicating low human activities in and around the lake [18]. Increased heavy metal pollution of Renuka Lake sediments was derived from human interference such as domestic effluents and untreated sewage discharge [11]. Manasbal Lake sediments had low to moderate pollution of heavy metals which were attributed to anthropogenic inputs such as agricultural run-off, domestic household sewage and land run-off [36]. Jeelani and Shah [28] reported on Zn, Cu and Pb pollution on the sediments of Dal Lake, whereas no pollution with Mn, Ni and Co suggesting the influence of both man-made and natural sources of heavy metal pollution. Being a major tourist destination, most of the lakeshore of Dal Lake is surrounded by developed land such as houses, hotels, restaurants and houseboats and the dominance of clay minerals and fine-grained nature of the sediments may be responsible for its higher heavy metal concentrations [28]. East Dongting Lake in China was reported to have concentrations of Cd, Pb, Cr and Ni exceeding the geochemical background values where Cd and Pb deriving from anthropogenic sources and Cr and Ni from natural sources [26]. The high organic carbon from the decomposed lake vegetation could be a sink of heavy metals in the lake sediments [26]. Anchar Lake sediments of Kashmir Valley had low to moderate contamination of Cu, Ni, Zn, Co and Cr which might be derived from agricultural inputs, domestic effluents and untreated sewage discharges [37].

Loktak Lake, located in the state of Manipur, is the largest shallow natural freshwater lake in northeastern India. It is an important wetland considering its socio-economic, cultural and ecological significance. It is one of the Ramsar sites (designated in 1990) that is listed in the Montreux Record (in 1993) indicating the degrading state of its ecological character. Factors such as hydrosol texture, characteristics, quantity and quality of input water often influence the distribution of heavy metals in lakes [15]. Large scale industries or power plants are absent in Manipur, but around 36 rivers and rivulets particularly the Nambul River

that passes through Imphal (capital city) carry a considerable quantity of untreated municipal and domestic wastes into the lake. Land-use land-cover pattern changes in the catchment also resulted in increased input of sediments and nutrients into Loktak Lake [71]. Moreover, the Ithai Barrage, constructed at its major outlet for hydro-electricity, minimizes the outflow of lake water thus, make the water relatively stagnant resulting in further increase of nutrients [41].

Earlier studies on Loktak Lake were confined to its water quality [42, 54], floating islands [32], pollen analysis of the sedimentary core [69], macrophytes and phytoplankton community [44, 59]. However, limited information on heavy metal abundances and pollution status of Loktak sediments are available [16, 45]. Therefore, we present here the results of our detailed study on the surface

sediments of Loktak Lake for heavy metals, major oxides and mineralogy and to assess the heavy metal pollution status of surface sediments. The paper is a first time report on mineralogy and major oxide compositions of the lake sediments that will provide baseline information for further studies for conservation and management of the lake.

2 Materials and methods

2.1 Study area

Loktak Lake (Fig. 1) of Bishnupur district is located ~48 km south of Imphal. It has a surface area of ~300 km² with water depth ranging from 0.5 to 4.6 m. Its location is between 93° 46' and 93° 55' E longitudes and from 24°

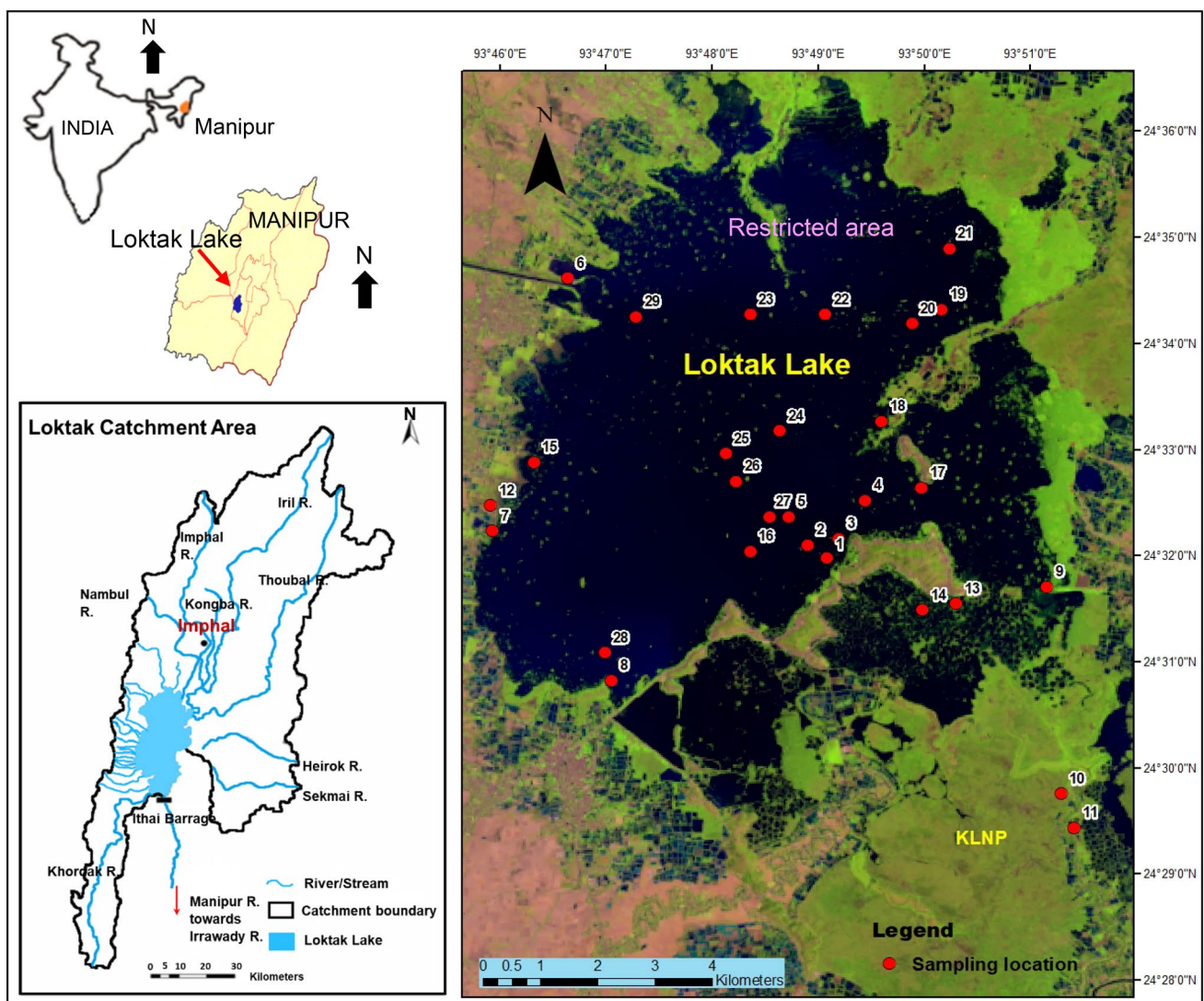


Fig. 1 Map of Loktak Lake showing sampling locations (modified after Singh and Sarkar 2013)

25° to 24° 42' N latitudes at an altitude of ~760 m above msl [71]. The lake is roughly oval-shaped with irregular boundaries prominent on its eastern side. Though its origin is unknown, the tectonic activity might have influenced its formation [63]. Isotopic data on the sediments indicated its existence from the middle of the last glacial period, i.e., ~25,000 years [46]. The lake receives a huge quantity of floodwater during the monsoon season, thus supplies water for drinking, hydroelectricity and irrigation. The lake serves as a habitat for rich biodiversity including migratory birds. A specific characteristic feature of the lake is the presence of several patches of floating heterogeneous mass of vegetation locally called phumdi. It consists of both live and dead biomass which are held together by a meshwork of rhizomes, crisscrossing roots and stems. It is of variable shapes and sizes, few inches to several feet thick and moves along with the wind. Coincident with the water draw down event during dry season, phumdi stays rooted on the shallower periphery of the lake. Its spread rises and falls during the year consistent with seasonal fluctuations in the lake water level [41]. It provides an important habitat for fish, migratory birds and other lake dwellers including fishermen. It also provides nutrients for the growth of various aquatic flora and fauna, thus helps in maintaining a balanced ecosystem of the lake habitat. The Keibul Lamjao National Park situated on the lake's southeastern part covering an area of ~40 km² is made up of the continuous mass of phumdi. The national park is a home of several species in addition to Sangai (*Rucervus eldii*), the deer species endemic to this park.

The direct and indirect catchment area of ~980 and ~7157 km², respectively, have a semi-tropical climate in the central Manipur/Imphal Valley and semi-temperate to temperate climate in the surrounding hills [61]. The mean annual rainfall of Manipur varies from 1500 to 1700 mm. During summer (May–June), the mean annual temperature is 24 °C, while that of winter (November–January) is 14 °C. The lake receives the maximum amount of water from the western catchment (52%), followed by direct precipitation (25%) and other linked channels (23%) [71]. The oval-shaped Manipur/Imphal Valley slopes gently to the south and the hills align in the north to south trending ridges. The Manipur Hills evolved as an accretionary prism due to the subduction of the Indian plate below the Myanmar plate [66]. The Rock Formations are of Tertiary—Cretaceous age consists dominantly of marine sediments (clay, silt and sand) of Eocene Disang Formation (minor mudstone, siltstone, sandstone and limestone) along with Oligocene Barail (carbonaceous shales), Miocene Surma (argillaceous sediments) and Tipam Formations (arenaceous sequence) in addition to minor amounts of igneous and metamorphic rocks [62]. Ultramafic igneous rocks of the ophiolitic serpentinites containing small amounts

of enstatite, chromite, amphiboles, and magnetite are intruded into the Disang Formation. The central Imphal Valley is covered with 200–300 m thick alluviums which overlay the Disang shales.

2.2 Sample collection and chemical analysis

The surface sediments ($n=29$) were collected from different sites of the lake during the year 2017. Sampling sites were located using a handheld GPS (Garmin, Model 72H). Surface samples (0–15 cm) each weighing ~500 g were grabbed and transferred into clean polybags with zip-lock for laboratory studies (Fig. 1). After air-dried at room temperature, megascopic observation of the samples such as color, texture and calcareousness (with few drops of 1 N HCl) were carried out. About 50 g of representative samples were powdered to ~200 mesh size. The soil pH of representative samples ($n=17$) was determined in a 1:2 ratio with distilled water. The sediment organic matter (OM) and the carbonate contents were based on loss on ignition (LOI) determined by weight loss measurement using the sequential heating method at 550 and 900 °C, respectively [56].

Based on the color and texture, 6 representative bulk sediment samples (sites 2, 6, 7, 9, 10 and 11) were selected for mineralogical studies by X-ray diffraction (XRD) using XPert PRO PANalytical diffractometer (Cu as an x-ray source with a Ni filter, intensity of 40 mA, voltage of 45 kV). The range of scan was from 5° to 60° 2 θ and the step size of 0.016° at a measuring time of one step/sec. Samples at sites 2, 7 and 10 were rerun after treated with ethylene glycol. For this, a film of 1.5 cm width sample spread on a glass slide was placed in a desiccator with 1-cm height ethylene glycol and kept overnight in an oven at 60 °C. Using X'Pert HighScore software, the XRD data were analyzed and d -spacing and 2 θ values were used for the identification of minerals using a mineral database [35]. For clay mineralogical studies, 4 representative samples at sites 13, 21, 22 and 28 were selected. ~20 g sample was treated with 100 ml of 25% acetic acid and kept overnight. The solution was washed with distilled water and then treated with 10% H₂O₂. After 2–3 times of washing, the sample solution was sonicated and transferred to an Atterberg-cylinder. The smear of clay fraction collected on a glass slide was run through XRD at diffraction peaks between 3° and 60° 2 θ . The samples were rerun after treated with ethylene glycol [67].

To study major element chemistry, 8 g of 17 representative sample powder pellets were prepared by using the hydraulic pellet press at 2500 psi. The pellet was exposed to wavelength dispersive x-ray fluorescence spectrometer (WD-XRF, S4 PIONEER) to detect ten major oxides (SiO₂, Al₂O₃, FeO, K₂O, MgO, TiO₂, CaO, Na₂O, P₂O₅ and MnO). The

accuracy was determined using certified reference materials such as PC3, Omnion monitor and GSP-2.

Heavy metal abundances in the surface sediments ($n = 29$) were determined by the open digestion technique following the B-solution procedure of the Shapiro and Brannock [58] method with some modifications. For this, a 0.5 g sample was taken in a Teflon crucible, treated with concentrated 10 ml HF, 5 ml HNO₃ and 3 ml HClO₄ and heated on a hot plate. In the second stage, 5 ml HF, 10 ml HNO₃ and 5 ml HClO₄ were added. Finally, 5 ml HNO₃ was added. An additional 5 ml HClO₄ was added in samples of high organic content for complete digestion. A freshly prepared 25 ml 1 N HCl was added and heated till the sample got into the solution. The solution was made up to 100 ml with distilled water and later analyzed by atomic absorption spectrophotometer (ThermoScientific, M series). Reference materials such as JLK-1, JSD1 and JSD2 (Geological Survey of Japan) were used to check the accuracy of the analysis. A procedural blank was prepared with each batch of digestion. Respective standard solutions for each metal, duplicate samples, procedural blanks and distilled water were rerun after every seven to ten samples to maintain accuracy.

2.3 Assessment of catchment area weathering

The chemical index of alteration (CIA) was defined by Nesbitt and Young [50]. It was calculated to evaluate the degree of weathering intensity in the catchment area of Loktak Lake. CIA was calculated using the following Eq. (1):

$$CIA = \left[\frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O} \right] \times 100 \quad (1)$$

For calculation of the CIA, the weight percent of major oxides is converted into molecular proportions by dividing the weight percent by their respective molecular weights.

2.4 Assessment of heavy metal contamination

To determine the degree of sediment pollution, pollution indices such as enrichment factor (EF), geo-accumulation index (I_{geo}) and modified degree of contamination (mC_d) were calculated. In this study, average UCC (upper continental crust) values of respective metals were taken as the geochemical background to calculate the pollution indices [43, 68].

2.4.1 Enrichment factor (EF)

The enrichment factor is used as an index to assess the level of contamination in sediments. To calculate EF, the metals are geochemically normalized to a conservative element such as Al, Fe or Si. Fe is commonly employed

to normalize metal contaminants [5, 7, 72]. Since Fe is relatively abundant in the study area and its abundance is generally influenced by natural sources, it was used as a reference element. The EF was calculated according to the following Eq. (2):

$$EF = (M/Fe)_{\text{sample}} / (M/Fe)_{\text{background}} \quad (2)$$

where $(M/Fe)_{\text{sample}}$ is the ratio of concentrations of metal and Fe of a sample, and $(M/Fe)_{\text{background}}$ is the ratio of concentrations of the metal and Fe of the background reference.

2.4.2 Geo-accumulation index (I_{geo})

The geo-accumulation index is a quantification of metal accumulation in sediments [47]. It was calculated using the following Eq. (3):

$$I_{geo} = \log_2 [C_n / 1.5B_n] \quad (3)$$

where C_n is the heavy metal concentration in mg/kg, 1.5 is the background matrix correction factor to minimize the effect of natural lithogenic variations/changes, and B_n is the geochemical background value.

2.4.3 Modified degree of contamination (mC_d)

Hakanson first developed the method for calculation of the degree of contamination (C_d) as the sum of contamination factors, C_f^i [25]. The method was based on seven heavy metals (Hg, Cd, As, Pb, Cu, Cr and Zn) and one organic pollutant, PCB, for a given lake. The formula and terminologies for contamination categories were also restricted to these pollutants. The method was later modified into a generalized formula as the sum of contamination factors of the metals analyzed divided by the number of metals, n [1]. The mC_d was calculated according to the following Eq. (4):

$$mC_d = \sum C_f^i / n \quad (4)$$

where C_f^i is the ratio between the measured concentration of heavy metal in a sample and the respective geochemical background value, $C_f^i = C_{\text{surface}}^i / C_{\text{reference}}^i$.

2.5 Sediment quality guidelines (SQGs)

High metal contents in aquatic sediments may cause adverse effects on biological components though the criteria for water quality are not exceeded [51]. If Loktak sediments are polluted with heavy metals, those metals may get into the water and reach the biota. Depending on the frequency of consumption of contaminated biota, metal toxicity may occur to nearby dwellers through the

food chain. Heavy metal concentrations in sediments are compared with that of SQGs of freshwater ecosystems to evaluate the sediment quality and the risk of heavy metal pollution on the sediment-dwelling organisms [39]. Two categories of the SQGs, i.e., effect range-low (ERL) and effect range-median (ERM) are widely used tools to determine sediment quality. They give baseline information about metal toxicity to aquatic ecosystems.

Mean-ERM-quotient (M-ERM-Q) is used to locate regions of potential hazard concerning sediment quality [27, 52, 70]. M-ERM-Q was calculated for heavy metals such as Zn, Cu, Pb, Ni and Cr by following the Eq. (5) given below [38]:

$$M - ERM - Q = \left(\sum_i^n C_i / ERM_i \right) / n \quad (5)$$

where C_i , ERM_i and n are the measured concentration of a metal in a sediment sample, ERM value of metal i and the number of metals, respectively.

3 Results and discussion

3.1 Salient characteristics of Loktak Lake sediments

The sediments of Loktak Lake show variable colors, i.e., medium to dark brown and light to dark gray. They are clayey to fine silty and the upper half a meter thick sediments in the lake are relatively unconsolidated. The majority of samples has a soapy feeling when dry. Since macrophytes are abundant in the lake, traces of plant materials were observed in the majority of samples. The dried sediments have oxidized patches or tinges. They are non-calcareous as they do not show effervescence with dilute HCl. They are acidic (pH=3.9–5.6). The acidic nature of Loktak sediments (pH=5.3) was reported earlier [40]. The organic matter content varies from 7.1 to 32.7 wt% with a mean of 20.21 ± 8.49 wt%. The majority of samples from the western periphery of the lake has relatively lower organic matter contents compared to the middle and the eastern periphery which may be due to relatively less prevalence of natural phumdi on the western side of the lake. The acidic pH and the high organic matter of sediments might result from the decomposition of abundant macrophytes particularly phumdi and their deposition on surface sediments. The soils in the Loktak catchment area are also characterized by low pH, organic carbon rich and high clay content [55]. Organic matter contents of Anchar Lake sediments are controlled by the type of bedrock geology in the catchment, climate, lake flora and fauna and anthropogenic influences along the catchments [37]. The acidic pH and the rich organic matter content of

Loktak sediments are comparable with that of Lake Chini of Malaysia. Sediments of Lake Chini had pH ranging from 4.8 to 5.5 and organic matter from 13 to 34.2% [14].

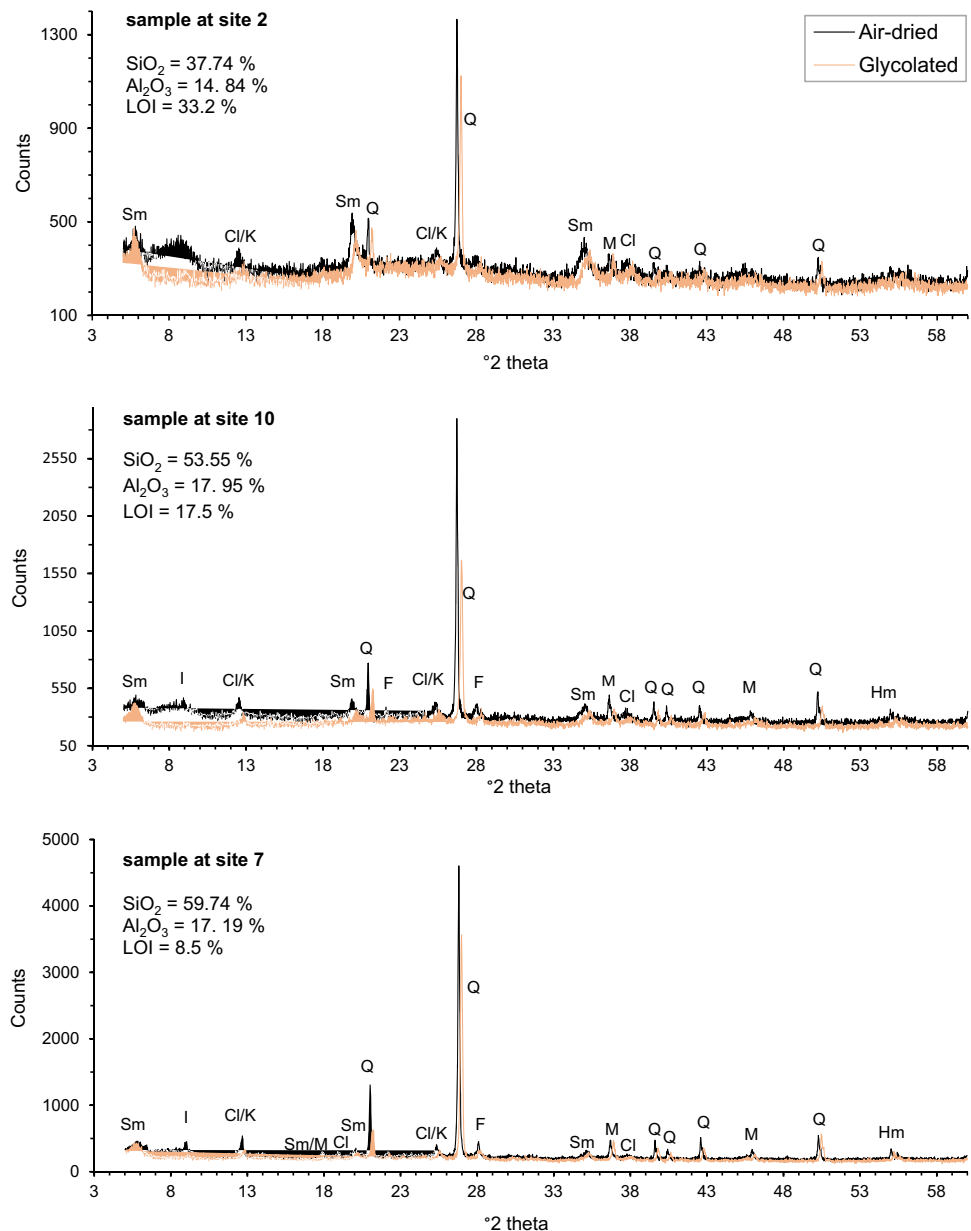
3.2 Mineralogy

The XRD spectra of bulk representative air-dried and glycolated sediments are given in Fig. 2. The samples consist dominantly of quartz (~4.23, 3.33, 2.45, 2.28, 1.98 and 1.81 Å), followed by smectite (~15, 4.45 and 2.56 Å), chlorite (~7.02 and 3.51 Å), kaolinite (~7.02 and 3.51 Å), feldspar (3.18 Å), mica (2.45 and 1.98 Å) and hematite (1.67 Å). After glycolation treatment, the peak of ~15 Å smectite became sharper and the peaks of ~9.90 Å illite disappeared. The minerals observed in the study are consistent with the geology of the catchment area. The XRD spectra of representative air-dried and glycolated clay fractions are given in Fig. 3. The clay fractions consist dominantly of chlorite (~14.35, 7.13, 4.73 and 3.55 Å) and illite (~10.18, 5.05, 3.34 and 2.85 Å), followed by kaolinite (~3.56 and 7.15 Å), smectite (~5.00 Å) and mica (~4.99 Å). Illite (~10.18 Å) peak reduced after glycolation.

3.3 Geochemistry

The major oxide compositions of 17 representative samples are given in Table 1. Supplementary data (Table S1) are also provided. The sediments consist dominantly of (in wt%) SiO_2 (37.74–59.74, mean = 47.92 ± 6.87), Al_2O_3 (14.84–20.8, mean = 18.08 ± 1.60) and FeO (6.15–11.17, mean = 8.38 ± 1.54) with low concentrations of K_2O (2.55 ± 0.34 wt%), Na_2O (0.58 ± 0.18 wt%) and CaO (0.25 ± 0.14 wt%). The FeO variability in the lake sediments may be due to the dilution effect of organic matter. LOI varies from 8.5 to 33.2 wt% (Table 1). The table also presents the comparison of concentrations of major oxides with that of UCC, post-Archean average shale (PAAS) and North American shale composite (NASC). Average MnO content is slightly higher than that of NASC, but lower than that of UCC and PAAS. Al_2O_3 and TiO_2 contents are higher than those of UCC and NASC, but slightly lower than that of PAAS. Compared with respective references, the concentrations of SiO_2 are relatively lower and that of FeO are relatively higher. High FeO contents in the sediments may be a source of Fe in the water and may affect the existing biota. The relatively higher concentrations of FeO and Al_2O_3 and lower content of SiO_2 indicate that the texture of lake sediments is skewed toward clay. The result is consistent with the observed clay nature of sediments. Compared with respective UCC and PAAS values, low concentrations of SiO_2 , MnO, CaO, MgO, Na_2O , K_2O and P_2O_5 and high concentrations of TiO_2 , FeO and Al_2O_3 in

Fig. 2 Representative XRD patterns of air-dried and glycolated surface sediments. Identified peaks are Sm = Smectite, I = Illite, F = Feldspar, Cl = Chlorite, K = Kaolinite, Q = Quartz, M = Mica, Hm = Hematite



lake surface sediments indicate a terrigenous influx of different source of sediment detritus and strong chemical weathering of the source rocks [49]. The Loktak sediments have lower contents of K_2O , MgO , CaO and Na_2O than corresponding UCC, PAAS and NASC. Ca, Na, K and Mg are mobile elements and their relatively lower concentrations indicate the high intensity of weathering of the sediments. The relatively higher FeO and lower SiO_2 contents in sediments suggest the involvement of mafic rock sources. P_2O_5 content is lower than that of UCC, slightly higher than that of NASC but similar to that of PAAS. The increased sewage input from Imphal city and chemical fertilizers from the surrounding agricultural

area might be the main external sources of phosphorus in the lake [13, 42].

3.4 Assessment of catchment area weathering

The calculated chemical index of alteration (CIA) of the 17 representative samples from Loktak Lake is given in Table 1 (Detailed data are given in the supplementary Table S1). CIA values of the average upper crust are 47, while that of intense weathering is 100. CIA value below 60 means low chemical weathering, between the range of 60 and 80 indicates moderate and above 80 suggests extreme chemical weathering. The calculated CIA indicates that 3

Fig. 3 XRD spectra of representative air-dried and glycolated clay fractions. Identified peaks are Sm = Smectite, I = Illite, Cl = Chlorite, M = Mica and K = Kaolinite

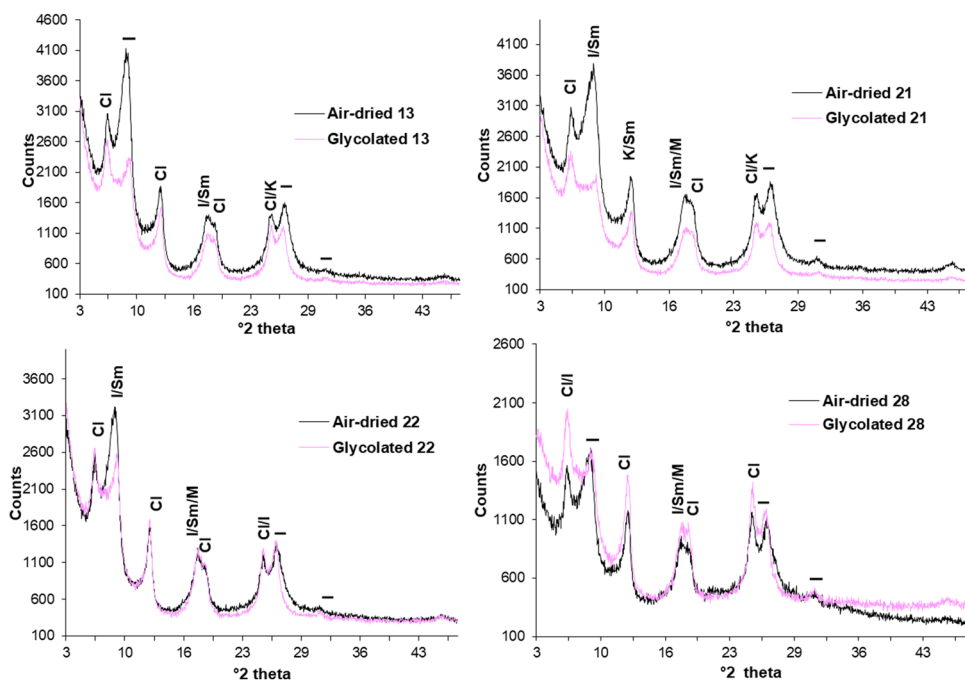


Table 1 Major oxide compositions ($n=17$, in wt%) of Loktak Lake sediments in comparison to sediments from references, calculated LOI and CIA

Major oxides	Present study		UCC ^a	PAAS ^a	NASC ^b
	Range	Mean \pm SD			
SiO ₂	37.74–59.74	47.92 \pm 6.87	66.0	62.80	64.80
Al ₂ O ₃	14.84–20.8	18.08 \pm 1.60	15.2	18.90	16.90
FeO	6.15–11.17	8.38 \pm 1.54	4.5	5.85	5.66
K ₂ O	2.01–3.24	2.55 \pm 0.34	3.4	3.70	3.97
MgO	1.28–2.46	1.94 \pm 0.30	2.2	2.20	2.86
TiO ₂	0.70–1.11	0.93 \pm 0.13	0.5	1.00	0.70
CaO	0.08–0.65	0.25 \pm 0.14	4.2	1.30	3.63
Na ₂ O	0.3–0.9	0.58 \pm 0.18	3.9	1.20	1.14
P ₂ O ₅	0.08–0.27	0.16 \pm 0.06	0.4	0.16	0.13
MnO	0.05–0.13	0.07 \pm 0.02	0.1	0.11	0.06
LOI	8.5–33.2	20.37 \pm 7.04	–	–	–
Total	97.23–105.64	101.24 \pm 2.51	–	–	–
CIA	76.86–84.98	81.37 \pm 1.92	–	–	–

^aTaylor and McLennan [68]; ^aMcLennan [43]; ^bGromet et al. [20]

samples (at sites 2, 10 and 29) have values ranging from 76.86 to 79.69 that show moderate chemical weathering. The rest 14 samples with CIA values ranging from 80.59 to 84.98 show extreme chemical weathering. The overall CIA values in the present study ranging from 76.86 to 84.98 with a mean of 81.37 ± 1.92 indicate moderate to extreme chemical weathering of lithologies of the catchment area. The CIA values are in a narrow range whose values are close to 80. The clayey and fine silty nature of sediments

also reveal the advanced stage of the catchment weathering. Since the past few years, Loktak Lake catchment is being eroded bringing a huge quantity of sediments into the lake due to shifting cultivation and deforestation in the higher altitude. Annually more than 650,000 metric tons of sediments are brought into Loktak from its catchment [71]. The frequent flood events in the central valley during the monsoon season might accelerate the weathering process. High CIA values (87–95) were also reported in Dal Lake reflecting extreme weathering [28] and CIA value of 71 in Nainital Lake sediments [8] and that ranging from 75.2 to 78.1 in Rewalsar Lake sediments [10] suggest moderate chemical weathering in their catchment areas.

Correlation coefficients are used to determine the relationships among major oxides. The Pearson’s correlation coefficients (r) among the major oxides, total LOI and CIA are given in Table 2. SiO₂ has a very strong ($r > 0.8$) positive correlation with Na₂O ($r = 0.919$; $p > 0.01$), negative correlation with LOI ($r = -0.906$; $p > 0.01$), strong ($r = 0.7-0.8$) positive correlation with TiO₂ ($r = 0.774$; $p > 0.01$), moderate ($r = 0.5-0.6$) positive correlation with MgO ($r = 0.532$; $p = 0.05$), negative correlations with K₂O ($r = -0.747$; $p > 0.01$) and FeO ($r = -0.631$; $p > 0.05$), respectively, and low positive correlation with Al₂O₃. Al₂O₃ has a very strong positive correlation with CIA ($r = 0.886$; $p > 0.01$) and good ($r = 0.6-0.7$) positive correlation with TiO₂ ($r = 0.648$; $p > 0.01$). The high Al₂O₃ content and high CIA value and their strong positive correlation corroborates the geology of the catchment area. FeO has moderate positive correlation with MnO and K₂O ($r = 0.571$ and $r = 0.533$; $p > 0.05$, respectively) and MnO has a strong positive correlation

Table 2 Correlations among major oxides, LOI and CIA of surface sediments of Loktak Lake

	SiO ₂	Al ₂ O ₃	FeO	K ₂ O	MgO	TiO ₂	CaO	Na ₂ O	P ₂ O ₅	MnO	LOI	CIA
SiO ₂	1											
Al ₂ O ₃	.344	1										
FeO	-.631**	-.246	1									
K ₂ O	-.747**	.122	.533*	1								
MgO	.532*	.405	-.197	-.149	1							
TiO ₂	.774**	.648**	-.352	-.304	.640**	1						
CaO	-.296	-.521*	.008	-.192	-.349	-.512*	1					
Na ₂ O	.919**	.302	-.455	-.530*	.649**	.808**	-.423	1				
P ₂ O ₅	-.097	-.433	.341	-.025	-.086	-.194	.436	.057	1			
MnO	-.309	-.564*	.571*	.017	-.132	-.433	.470	-.238	.713**	1		
LOI	-.906**	-.509*	.480	.504*	-.552*	-.910**	.566*	-.881**	.274	.468	1	
CIA	.384	.886**	-.269	-.040	.230	.586*	-.640**	.282	-.592*	-.585*	-.543*	1

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

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

with P₂O₅ ($r=0.713$; $p>0.01$). TiO₂ has a strong positive correlation with Na₂O ($r=0.808$; $p>0.01$), moderate positive correlation with CIA ($r=0.586$; $p>0.05$). LOI has moderate correlation only with CaO ($r=0.566$; $p>0.05$) and very strong negative correlations with TiO₂ ($r=-0.910$; $p>0.01$), SiO₂ ($r=-0.906$; $p>0.01$) and Na₂O ($r=-0.881$; $p>0.01$).

3.5 Heavy metal abundances

Heavy metal concentrations in sediments of Loktak Lake are presented in Table 3. The detailed data are presented in supplementary Table S2. The average concentrations of heavy metals are (in mg/kg) Zn = 117 ± 23.45, Cu = 67 ± 12.87, Pb = 17 ± 7.47, Ni = 194 ± 30.12, Mn = 425 ± 168.99, Cr = 282 ± 45.25, Co = 34 ± 13.67 and Fe = 7 ± 1.38 wt% and they follow an order of Fe > Mn > Cr > Ni > Zn > Cu > Co > Pb. The relative enrichment or depletion of metals in sediments infers changes in the source

in response to weathering, sedimentation and anthropogenic inputs [37]. Different factors lead to variations in the distribution and concentration of metals in sediments such as clay content, soil pH, organic matter, cation exchange capacity, iron and manganese oxides, etc. [17]. Fe concentration is generally high in lake sediments since it is one of the major elements in Earth’s crust. Its higher concentrations in Loktak sediments indicate the ultramafic nature of the parent rocks. Similarly, Mn content is also relatively high. Mn is naturally found associated with Fe. The sample at site 28 near the Moirang River inlet has relatively higher concentrations of the majority of metals since the river passes through several agricultural fields and the Moirang market just before joining the lake. Since Loktak Lake is the ending of many rivers, it acts as a sink of pollutants carried by the rivers. Solid wastes of more than 77.13 million tons and sewage of 33,148 m³ are generated daily by a population of about 0.28 million living in the

Table 3 Statistics of heavy metal concentrations (n = 29, in mg/L, OM and Fe in wt%) of Loktak sediments and their comparison with other sediments from references and SQGs

Elements	Present study		UCC ^a	PAAS ^a	NASC ^b	ERL ^c	ERM ^d
	Range	Mean ± SD					
Zn	94–218	117 ± 23.45	71	85	–	120	270
Cu	47–94	67 ± 12.87	25	50	–	70	390
Pb	8–41	17 ± 7.47	17	20	20	35	110
Ni	140–274	194 ± 30.12	44	55.00	58.00	30	50
Mn	208–895	425 ± 168.99	600	–	–	–	–
Cr	211–418	282 ± 45.25	83	110.00	125.00	80	145
Co	12–87	34 ± 13.67	17	23.0	25.7	–	–
Fe	4.53–9.82	6.55 ± 1.38	3.5	–	–	–	–
OM ^e	7.1–32.7	20.2 ± 8.49					

^aTaylor and McLennan [68]; ^aMcLennan [43]; ^bGromet et al. [20]; ^cEffect range-low and ^dEffect range median for freshwater ecosystem [39], ^eOrganic matter

catchment of the Nambul River [71]. Enhanced unsustainable agricultural activities such as shifting cultivation in the Loktak catchment area particularly in the hills, lead to land degradation resulting in increased soil erosion and lake sedimentation [24]. The lake area contributes 14% of the total state population and constitutes about 6.8% of the total land use pattern in Manipur [31]. Imphal, the capital city alone occupies 71% of the urban population of the catchment [24]. Several fish farms in the lake periphery also might have added pollutants. Moreover, direct input of untreated wastes, agricultural run-offs, and settlements in and around the lake adds pollution to the lake [65].

The average concentrations of heavy metal in Loktak sediments were compared with that of UCC, PAAS and NASC as given in Table 3. The average concentrations of heavy metals (except Mn) are higher than those in UCC, PAAS and NASC [20, 43, 68]. Cr concentrations are about 2–4 times higher than that of UCC. Cr tends to get distributed in mafic igneous rocks and are concentrated in various types of intrusions and deposits [29]. Peat exhibits a high sorption capacity for Cr that binds the metal mainly as an insoluble metal–organic complex [29]. Ni contents are about 3–6 times higher than that of UCC. Naturally, higher Ni concentrations are observed in sediments derived from serpentine rocks [30]. The relatively higher concentrations of Cr and Ni in Loktak sediments correspond with the geology of the catchment area. Abnormally rich Ni and Cr contents in Yercaud Lake sediments were considered to be derived from adjoining mafic rock exposures [19]. The majority of samples has Cu concentrations about 2–4 times higher than that of UCC. The concentration of Mn in 5 samples (at sites 3, 6, 9, 15 and 25) is higher than that of the respective UCC. Mn may be considered to be originated from natural sources since it is one of the abundant elements in the Earth's crust. Pb exists

rarely in nature and it can easily come from anthropogenic activities. Pb is generally an exhaust from motor vehicles and the increased number of cars and trucks in the catchment can be its atmospheric source. Earlier studies have mentioned the atmospheric fall out of Pb in the environment [21, 23]. Other sources of Pb might be inputs from paints, tourists' boats, etc. Its mean concentration is similar to that of UCC, whereas samples of 3 (at sites 6, 18 and 29) have slightly higher and 8 (5, 12, 13, 14, 15, 21, 22 and 28) have relatively higher concentrations. Except for Mn and Pb, the mean concentrations of Zn, Co, Fe, Cu, Cr and Ni are about 2–4 times that of the respective crustal average. The high concentration of heavy metals might have come from their high clay contents and the high organic matter. Lake Hamahara of Japan had metals enriched in the clays compared to the sands [3]. Khalil et al. [33] reported heavy metal distributions associated with organic matter content in Burullus Lake sediments. The enrichment of heavy metals in soils of Nansi Lake is due to the strong adsorption capacity of clay [22]. Because of the fine nature, clay provides the surface area for the adsorption and attraction of metal ions.

The heavy metal concentrations in Loktak sediments are compared with that of other freshwater lakes elsewhere (Table 4). Loktak Lake has higher concentrations of Pb, Ni and Fe, but lower concentrations of Mn and Zn than that of Chauli beel, an ox-bow lake along the Barak River in northeastern India. Loktak Lake has higher Ni concentrations than that of Dal Lake, whereas Dal Lake has higher concentrations of Mn, Zn and Cu, but with similar Pb and Co contents. Compared with Nainital Lake, Loktak Lake has relatively higher concentrations of Fe and Ni, lower contents of Zn and Pb, but with similar Cu and Co contents. Loktak Lake has higher concentrations of Ni and Co, lower contents of Cu, Pb and Zn than that of Manchar

Table 4 Comparison of heavy metal abundances (in mg/kg) of Loktak Lake sediments with those of other freshwater lakes of the world

Lakes	Zn	Cu	Pb	Ni	Mn	Cr	Co	Fe
Present study	117 ± 23.45	67 ± 12.87	17 ± 7.47	194 ± 30.12	425 ± 168.99	282 ± 45.25	34 ± 13.67	65,513.79 ± 13,763.9
Chauli Lake, India ^a	332.3–771.86	57.47–160	3.73–7.89	29.9–71.1	1309.5–2690.5	207.8–465.4	–	1485.04–2836.4
Dal Lake, India ^b	231–309	82–193	18–32	13–22	747–1178	–	12–27	–
Nainital, India ^c	381	88	99	61	–	–	25	65
Manchar Lake, Pakistan ^d	667.5	376.2	323	73.7	498	254	14.1	–
Poyang Lake, China ^e	104.17	35.17	32.63	30.47	–	91.39	12.84	–
Yercaud Lake, India ^f	168.9	574	30.0	146.9	372	384.8	108.4	107,395
Vembanad Lake, India ^g	184.5	30.9	32.6	48.7	461	107.5	18.6	54,000
Lake Nasser, Egypt ^h	35.4	21.8	10.9	27.6	280	30.8	–	12,418
Anchar Lake, India ⁱ	130.93	68.13	26.6	54.03	734.4	81	21.66	51,601
Rewalsar Lake, India ^j	353	42	39.4	44	387	75	–	19,374

^aDas and Choudhury [12]; ^bJeelani and Shah [28]; ^cChakrapani [8]; ^dArain et al. [2]; ^eXie et al. [72]; ^fGopal et al. [19]; ^gSelvam et al. [57]; ^hGoher et al. [18]; ⁱLone et al. [37]; ^jDas and Haake [10]

Lake, but with similar Mn and Cr contents. Loktak Lake has Ni and Cr concentrations higher than that of Poyang Lake, whereas Pb content is relatively lower. It is observed from the above comparisons that the concentrations of Fe, Ni and Cr are relatively higher in Loktak sediments. This may be because of the high rate of weathering processes of the catchment area that are part of the ultramafic rocks of the ophiolitic serpentinites of the eastern Himalayas. However, the higher concentration of Pb than that of UCC in 11 samples also indicates an increasing anthropogenic influence on the lake [42].

3.6 Assessment of heavy metal contamination

Quantification of heavy metal pollution in lake sediments helps to determine the pollution level and maintain the ecological health status of the aquatic environment. The following pollution indices are widely used geochemical approaches to assess heavy metal pollution in sediments.

3.6.1 Enrichment factor

Enrichment factor is generally used to evaluate the heavy metal enrichment by anthropogenic activities. The EF values suggested by Chen et al. [9] to interpret the different levels of metal pollution are $EF < 1$, no enrichment; $EF = 1-3$, minor enrichment; $EF = 3-5$, moderate enrichment; $EF = 5-10$, moderately severe enrichment; $EF = 10-25$, severe enrichment; $EF = 25-50$, very severe enrichment; $EF > 50$, extremely severe enrichment. When sedimentation occurs due to natural processes, the heavy metal concentrations have a linear relationship with the reference metal [5]. In regions having less anthropogenic influence, EF values close to unity suggest a crustal source, whereas values higher than 1.5 indicate a significant portion of the metals derived from non-crustal or non-natural sources [5]. Statistics of EF of the heavy metals in Loktak sediments are shown in Table 5 (Supplementary data are provided by Table S3). The EF of Cr ranges from 0.91 to 2.97. There is a minor enrichment of Cr in almost all the samples except the sample at site 25 from the middle of the lake with EF slightly below 1 showing no enrichment. The EF of Ni ranges from 1.43 to 4.32. The majority of samples has minor enrichment of Ni and samples at sites 13,

18, 21 and 28 have moderate enrichment with their EF values slightly above that of minor enrichment. Samples at sites 13 and 18 are close to Thanga and Karang Islands, respectively, and those at 21 and 28 are from the north-eastern portion and the Moirang River inlet, respectively. Minor enrichment of Pb is observed in 3 samples (at sites 12, 21 and 28), whereas no enrichment for the rest of the samples. There is a minor enrichment of Cu in almost all the samples, Co in 15 and Zn in 10 samples which are slightly above unity, whereas no enrichment of Mn for all the samples. No enrichment of Mn also occurred in the sediments of Yercaud Lake [19] and Lake Valencia [4]. With the high-organic matter content of Loktak sediments, Cu could form Cu-organic matter complexes. The average EF for Ni (2.46) is the highest, followed by Cr (1.90) and Cu (1.49) (Table 5). The average EF for all the metals ranges from 0.37 to 2.46 and their values follow an order of $Ni > Cr > Cu > Co > Zn > Pb > Mn$. Hence, the overall EF ranges from no enrichment to moderate enrichment with minor enrichment in the majority of the samples.

3.6.2 Geo-accumulation index

Geo-accumulation index values are categorized into 7 classes depending on numeral values of the index, each one representing different levels of pollution. The categories of I_{geo} are: < 0 = uncontaminated; $0-1$ = uncontaminated to moderately contaminated; $1-2$ = moderately contaminated; $2-3$ = moderately to strongly contaminated; $3-4$ = strongly contaminated; $4-5$ = strongly to extremely contaminated; > 5 = extremely contaminated [47]. The boxplot for the I_{geo} is shown in Fig. 4 (Supplementary data is provided by Table S3). According to the contamination categories, Loktak Lake sediments are moderately contaminated with Ni. Samples of 21 are moderately contaminated with Cr and the rest are uncontaminated to moderately contaminated. Samples of 10 are moderately contaminated with Cu (at sites 14, 15, 16, 17, 18, 19, 20, 21, 22 and 23) and the rest are uncontaminated to moderately contaminated category. There is no contamination with Mn and Pb except 5 samples (at sites 12, 13, 21, 22 and 28) have Pb in the uncontaminated to moderately contaminated category. The average I_{geo} values of Zn, Pb, Mn, Co and Fe are

Table 5 EF and mC_d

	EF							mC_d
	Zn	Cu	Pb	Ni	Mn	Cr	Co	
Min	0.52	0.85	0.23	1.43	0.19	0.91	0.50	1.82
Max	1.70	2.91	1.33	4.32	0.80	2.79	2.83	3.41
Mean	0.93	1.49	0.58	2.46	0.38	1.90	1.10	2.21
STDEV	0.29	0.44	0.30	0.63	0.15	0.49	0.51	0.28

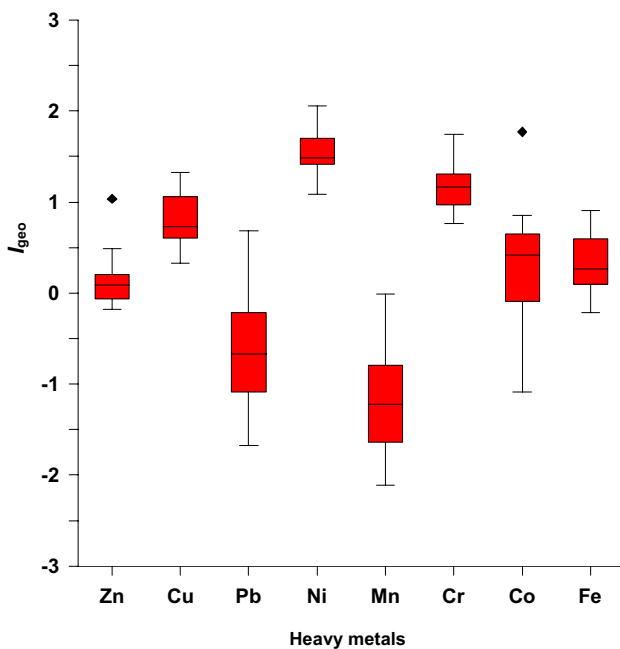


Fig. 4 Box-and-whisker plots for heavy metals and geo-accumulation index (I_{geo}) of Loktak sediments

below zero which means that as a whole the heavy metals are non-polluting. The average I_{geo} value is the highest for Ni (1.54) which is, followed by Cr (1.16) and Cu (0.81). The average I_{geo} values follow an order of Ni > Cr > Cu > Co > Fe > Zn > Pb > Mn. The overall I_{geo} values for the heavy metals range from non-contamination to moderate contamination. However, the high I_{geo} values of metals such as Ni and Cr are suggestive of the predominance of geogenic origin and no significant anthropogenic accumulation of heavy metals in the lake sediments.

3.6.3 Modified degree of contamination

The modified degree of contamination gives an overall contamination degree for a given sample [1]. The pollution status can be verified based on the gradations of contamination such as $mC_d < 1.5$ = nil to very low degree of contamination; $1.5 \leq mC_d < 2$ = low degree of contamination; $2 \leq mC_d < 4$ = moderate degree of contamination; $4 \leq mC_d < 8$ = high degree of contamination; $8 \leq mC_d < 16$ = very high degree of contamination; $16 \leq mC_d < 32$ = extremely high degree of contamination; $mC_d \geq 32$ = ultra-high degree of contamination. The statistics of mC_d of the Loktak sediments are shown in Table 5 (Supplementary data are provided by Table S3). The overall mC_d ranges from 1.82 to 3.41 with a mean of 2.21 ± 0.28 . According to contamination categories, the majority of samples have a moderate degree of contamination with low degree of contamination at sites 7, 8 and 27. The assessment of contamination by following the above methods, it is observed that pollution in the Loktak sediments is primarily due to natural sources along with secondary anthropogenic influences.

Correlation analysis is generally used to determine the potential common source of metals [23]. A high correlation suggests a similar source, whereas the low correlation means a more varied source of contamination. The Pearson’s correlation analysis among heavy metals and mC_d are given in Table 6. Zn has strong to moderate positive correlations with Co, mC_d , Cr, Pb and Ni ($r=0.779, r=0.766, r=0.616, r=0.510, p>0.01; r=0.406, p>0.05$, respectively), but low negative correlations with organic matter and Fe. Cu has a good correlation with Ni ($r=0.573; p>0.01$) and moderate negative correlation with Mn. Pb has good positive correlation with mC_d ($r=0.627; p>0.01$) and moderate positive correlations with Ni and Cr ($r=0.415, r=0.444; p>0.05$, respectively). There is a good correlation between Ni and Cr ($r=0.513; p=0.01$) and both are

Table 6 Correlations among heavy metal concentrations, OM and mC_d of sediments of Loktak Lake

	Zn	Cu	Pb	Ni	Mn	Cr	Co	Fe	OM	mC_d
Zn	1									
Cu	.025	1								
Pb	.510**	.331	1							
Ni	.406*	.573**	.415*	1						
Mn	.017	-.424*	-.208	-.212	1					
Cr	.616**	.096	.444*	.513**	.045	1				
Co	.779**	-.264	.333	.260	.251	.480**	1			
Fe	-.220	-.059	-.273	-.053	.343	-.163	-.036	1		
OM	-.266	.046	-.454*	-.166	.044	-.510**	-.282	.377*	1	
mC_d	.766**	.335	.627**	.761**	.086	.752**	.697**	.058	-.319	1

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

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

strongly correlated with mC_d ($r=0.761$ for Ni, $r=0.752$ for Cr; $p=0.01$). Co has significant positive correlation with mC_d ($r=0.697$; $p=0.01$). Organic matter has moderate positive correlation with Fe ($r=0.337$; $p>0.05$) and poor positive correlations with Cu and Mn. It has significant negative correlation with Cr ($r=-0.510$; $p>0.01$) and moderate negative correlation with Pb.

3.7 Sediment quality guidelines

The quality of lake sediments can be assessed by comparing their heavy metal contents with sediment quality guidelines (SQGs) to reveal the threshold metal contamination and their adverse effects on the sediment-dwelling organisms [39]. The heavy metal concentrations in Loktak sediments were compared with two categories of SQGs for freshwater ecosystems such as effect range-low (ERL) and effect range-median (ERM). Both the guidelines define three effect ranges, i.e., metal concentrations below the ERL value would unlikely give undesirable effects on the sediment-dwelling organisms whereas above the ERM value would likely contribute frequent undesirable effects and between the range of ERL and ERM contribute undesirable effects occasionally [5]. The concentration of Pb is lower than the ERL value (except the sample at site 28 from the Moirang River inlet that has higher Pb concentration than that of ERL), so its effect on the sediment-dwelling organisms will unlikely occur (Table 3). Samples at sites 2, 5, 11, 12, 21, 22 and 23 have Zn concentrations slightly above the ERL and samples at sites 1, 10 and 28 are relatively higher than that of ERL. Samples of 12 have Cu concentrations little above the ERL value and the rest are below the ERL value. The concentrations of Ni and Cr of all the samples are higher than that of respective ERMs suggesting the likely occurrence of toxic effects on the sediment-dwelling biota.

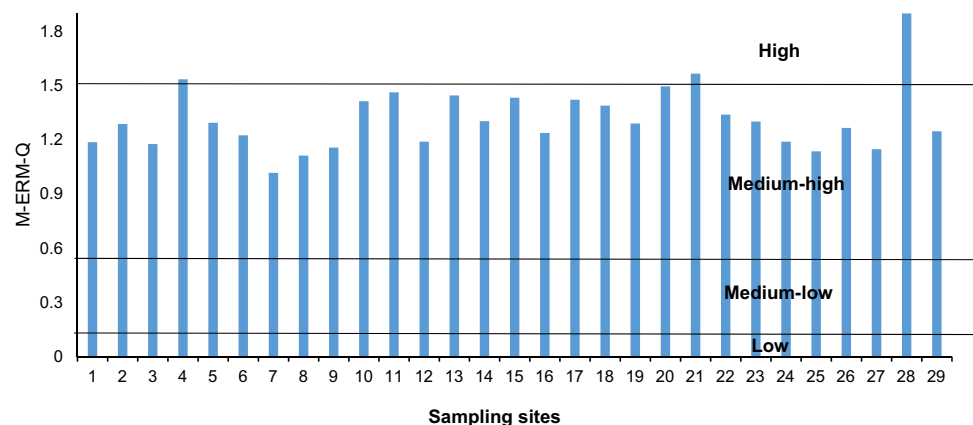
The mean-ERM-quotient (M-ERM-Q) of < 0.10 , $0.11 \leq \text{M-ERM-Q} < 0.50$, $0.51 \leq \text{M-ERM-Q} < 1.5$ and > 1.5

suggest 9%, 21%, 49% and 76%, respectively, of toxic probability [38]. The corresponding potentials of toxicity are low, medium–low, medium–high and high, respectively [70]. M-ERM-Q was calculated with 5 heavy metals such as Zn, Cu, Pb, Ni and Cr since SQGs have no recommended ERMs set for Fe, Mn and Co [39]. The calculated values range from 1.02 to 1.95 with a mean of 1.32 (Fig. 5) (Supplementary data are provided by Table S3). Samples of 2 (at sites 4 and 23 from nearby Thanga Island and northeastern portion of the lake, respectively) have values slightly above 1.5 and the sample at 28 from Moirang River inlet has M-ERM-Q value way above 1.5. They suggest 76% of toxic probability, while the rest have values within the range of 0.51 and 1.5 suggesting 49% of toxic probability. The result suggests that the majority of samples have a medium–high potential for heavy metal toxicity on the biotic population. It is mainly because of the high concentration of Ni and Cr in the lake sediments. The input of heavy metals into the lake needs to be monitored particularly Ni and Cr since their contaminations may impose biological risks as indicated by respective ERMs of the SQGs.

4 Conclusions

Studies on the mineralogy, major oxide compositions and the heavy metal pollution status of surface sediments of freshwater Loktak Lake were carried out. The sediments are non-calcareous and rich in organic matter (7.1–32.7 wt%). The XRD spectra of bulk sediments show the dominance of quartz, while smectite, kaolinite, mica, chlorite and hematite are also found. Clay fractions show the dominance of illite and chlorite and kaolinite, smectite and mica are also observed. The major oxides have relatively lower contents of SiO_2 , K_2O , MgO , CaO and Na_2O and a higher concentration of FeO than corresponding UCC, PAAS and NASC. The relatively higher FeO and lower SiO_2 contents in sediments suggest the

Fig. 5 Classification of samples based on M-ERM-Q



involvement of mafic rock sources. The low contents of labile elements such as Ca, Na and K indicate high intensity weathering of the catchment area. The high CIA (76.86–84.98) also indicates moderate to extreme chemical weathering of the lithologies in the catchment area. The higher concentrations of Al_2O_3 , high LOI and CIA values are consistent with the clay-rich nature of the sediments. Except for Mn and Pb, the mean concentrations of heavy metals are about 2–4 times higher than that of UCC and they follow the trend of $Fe > Mn > Cr > Ni > Zn > Cu > Co > Pb$.

The EF and I_{geo} indicated the heavy metal pollution of Loktak sediments ranging from non-pollution to moderate pollution. mC_d indicated the moderate degree of contamination in the majority of the Loktak sediments. The M-ERM-Q for heavy metals (Zn, Cu, Pb, Ni and Cr) suggested medium–high to high potential in their impacts on the biotic population. The relatively higher concentration of heavy metals in general and Ni and Cr, in particular, indicated an ophiolitic (ultramafic rocks) source with no or little, if any, anthropogenic influence. The remedial measures should include regular checking of waste disposal, monitoring of anthropogenic activities by communities in the direct and indirect catchment area and fertilizer application in agricultural fields located around Loktak Lake. There should be afforestation and reduced shifting cultivation in the catchment particularly in the hills and pre-treatment of effluents before reaching the lake.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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