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Heavy metal toxicity and its human health assessment: A preliminary study from the Perumal Lake sediments, Tamil Nadu, India

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ABSTRACT

The current investigation manifests the heavy metal toxicity and its human health assessment to appraise the environmental deterioration of the sediments within the Perumal Lake, Tamil Nadu, India. Five surface samples were collected from the Perumal Lake in 2023, which undergoes the selective perception of the granulometric analysis, implying supremacy of the clay content and limited sand and silt contents. The organic matter indicates the higher input of waste disposal, and the $CaCO_3$ illustrates the existence of shell fragments in the lake environments. Noteworthy results of the heavy metal concentration as arranged in the devaluation order as Zn > Cu > Fe > Cr > Ni > Mn > Pb > Co > Cd. Followed by the heavy metal concentration, the environmental contamination indices such as I_{geo} denote that except for Cd metal, other heavy metals indicate moderate to extreme pollution status. The Enrichment Factor (Ef) illustrates Fe, Co, Cd, Zn, Cu, Ni, and Pb, highlighting no metal enrichment. In contrast, Mn and Cr reveal low metal enrichments, and the Cf reveals all the heavy metals, which argues for low to high contamination ranges. The C_d and the $_mC_d$ are categorized as very high, and PERI underscores the low-risk category. The Hazard Index (HI) of the non-carcinogenic category and carcinogenic demonstrates that children and adults are primarily at risk of ingestion. At the same time, the dermal pathway indicates low jeopardy to children and adults and no risk to humans. The Heavy Metal Toxicity Load (HMTL) poses the sample location three registers a significant accumulation of toxic contagion proposed to remove from the sediments. Realm of heavy metal toxicity and its human health assessment underscores for researchers in environmental quality determination, and the strategies discussed such as phytoremediation, in-situ capping, and biotechnological techniques, may be helpful in evaluation and implement remediation methods of pollution in aquatic environments.

KEYWORDS: Environmental indices, Non-carcinogenic, Carcinogenic assessment, Hazard Index, Lake sediments.

INTRODUCTION

Encyclopedically, the heavy metals in the aquatic environments were derived from the weathering of geogenic materials and anthropogenic inputs (Armstrong-Altrin et al., 2021 and 2022; Singh et al., 2022). Nonetheless, the heightened contamination of the heavy metals in the lake environs reveals tremendous inputs of anthropogenic sources (Gao et al., 2016; Zhang et al., 2018). Nuanced observation illustrates the sediments were palpable as an imperative parameter for transporting heavy metals from the river to the lake environment. Elaborate studies handled by the Tamil Nadu Pollution Control Board show that almost 80% of the water is drained into the rivers as polluted industrial waste. As a result, elevated polluted inputs limelight, environmental deterioration, and human hazards. An immense accumulation of heavy metals in the sediments specifies the aquatic environment is polluted. Heavy metal toxicity in sediments and lake water unveils the hazardous impacts on humans, fishes, vertebrates, and invertebrates. This could lead to bioaccumulation and persistence in the aquatic environments, posing non-carcinogenic and carcinogenic risks to human beings once they intrude into the food web (Ouyang et al., 2018; Ali and Khan, 2018). The assertive clustering of heavy metals in sediments debilitated by approaching water mixed with the food cycle, argues for health issues for the habitants who regularly consume in the surrounding environments (Qing et al., 2015). Admittance of the heavy metals into the lake environs expedites the fine and clay particles in the sediments, constraining the heavy metals to assemble undesirable biological effects (Bibi et al., 2007). Peculiar researchers who studied heavy metal toxicity conceded grains in the sediments play a vital role in the variation in the heavy metal concentrations, and intriguingly, the heavy metals heightened with a concurrent decrease in the dimension of the grains in the aquatic environments (Tansel and Rafiuddin, 2016). Heavy metal enrichments in the provenance unveiled adequate dissemination typically through motorcycle exhausts, mining, boat and ship transportation, industrialization, fertilizers, pesticides, atmospheric airborne deposits and paints, and rapid urbanization activities (Islam et al., 2017).

A geochemical study of heavy metals such as Fe, Mn, Cu, Cr, Co, Ni, Zn, Cd, and Pb unveiled a framework for evaluating the sediments' origin, fate, and metals inputs (Arakel and Hongjun, 1992). Anthropogenic metals employ an intricate interplay of the heavy metals and the sediments disclosed with the fine particles. Fe-Mn oxides' interplay with the organic matter implies the ion exchange process, complexation, and chemical adsorption, which demonstrate environmental deterioration compared with natural sources (Palma et al., 2015). A comprehensive study of the heavy metal concentration data alone cannot offer nuanced data on sediment toxicity and the quality of adverse environmental pollution. A variety of environmental pollution indices, such as Geoaccumulation index, Enrichment factor, Contamination factor, Degree of contamination, and Potential Ecological Risk Index, have been developed and employed to study the toxicity aspects of aquatic environments (Gupta et al., 2014; Sivakumar et al., 2016).

Bonnail et al. (2019), while studying the Ganga River sediments to address the enrichment of heavy metals such as Cs, Co, Hg, Ni, Pb, and Zn content, and this could be a result of higher anthropogenic and natural activities illustrates the hazards circumstance for environments and the human beings. Nuanced observation implies that hospital effluents are an essential contributor to the heavy metal accumulation in the encompassing aquatic environment in the Cauvery river (Devarajan et al., 2015). Suresh et al. (2012) studied the Veeranam lake sediments to address the Cadium (Cd) metal concentration, which infers a higher ecological risk, leading to adverse health risks and environmental contamination impacts. Ramanathan et al. (1999) investigated the Pichavaram mangroves to establish heavy metal dissemination. However, the study elaborated that the metal concentration of the sediments suggests the environment is unpolluted by the chemical incursions. Lake sediments of Pykara reported heavy metals such as Co, Cr, Cd, Ni, Zn, Cu, Pb, and As argues the elevated pollution status of the aquatic environs (Singh and Vasudevan, 2023). The record of dual exposure routes, such as the Carcinogenic and Non-carcinogenic categories, illustrates rigorous exploration of Human health risk assessment. This could be due to ingestion, inhalation, and dermal pathways. Regarding health hazards, the International Agency for Research on Cancer (IARC, 2012) demonstrates that the inhabitants' exposure to heavy metals such as Cd, Cr, Pb, and As represents carcinogens. In contrast, Cu, Zn, Fe, Ni, Mn, and Co admit the non-carcinogenic risks.

Rapid industrialization and urbanization possess the accessibility of heavy metals in the socio-environment, along with imprudent annihilation practices, illustrating the potent contamination of aquatic regions, which are responsible for human health hazards and other organisms. In recent decades, monitoring the water bodies has been considered as important to ensure and safeguard the environment from heavy metal pollution. In this scrutiny, careful examination of broad evaluation aims to address the environmental pollution and human health assessment in the sediments of Perumal lake, Tamil Nadu. Heavy metal toxicity has various appraisal indexes such as I_{geo}, EF, CF, C_d, and mC_d, and PERI to monitor the environmental contaminations. Based on these indices, we evaluated the level of heavy metal contamination in the Perumal Lake sediments. The outcome of this research will provide a baseline information on the quality and health hazards to the local community.

STUDY AREA

The present study examines the Perumal Lake in the Cuddalore district, Tamil Nadu, India. The Perumal Lake is considered a unanimous prominent tank in the Cuddalore district of Tamil Nadu. The study area covers a total surface area of 13.24 sq. km between the latitudes 11° 30' to 11°45' N and longitudes 79°30' to 79°47' E and placed in the SOI Toposheets no. 58 M/10 (Fig. 1).

Mean Sea Level (MSL) of the lake is situated at an altitude of 80 feet in the Neyveli tertiary uplands. The dynamic flow of the rivers, such as the Gadilam and Ponnaiyar rivers in the north and the Vellar and Coleroon rivers in the south, drains to the lake. An insightful understanding argues the rivers flow from west to

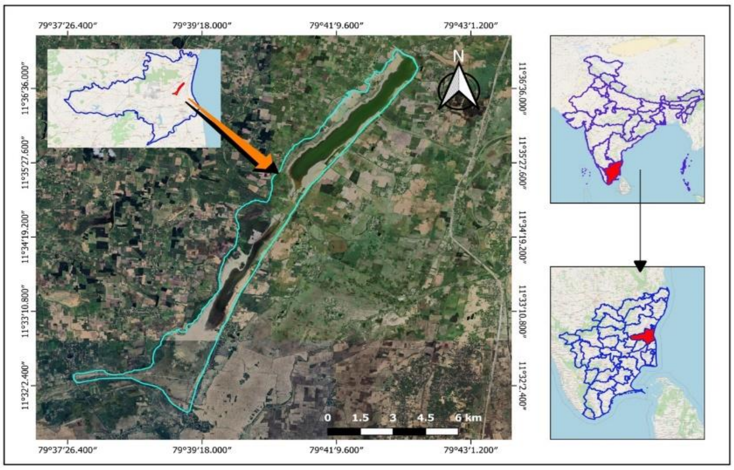

Figure 1 Dimension of the present investigation demonstrates in Google Earth View to demarcate the shape of the Perumal Lake

east in a sub-parallel pattern in the interplay between the lakes. The land pattern of the study unveils the geological age represented from the Mio-Pliocene to recent sediments. Furthermore, the morphometric characteristic of the lake underscores invaluable insights of length and width covers as 11.5 km and 2.07 km with a mean depth of about 3.10 m. The average rainfall of the Cuddalore districts exhibits 1,116.32 mm.

MATERIALS AND METHODS

In March 2023, a total of five surface sediment samples were collected during the summer season in the Perumal Lake at a depth of 0 to 10 cm using a Van Veen Surface Sampler (Fig. 2). The geo-coordinates of the respective samples were recognized by the GPS (Garmin, eTrex) (Table 1). To avoid the contaminations, the collected sediments were perfectly packed within the pre-cleaned zip lock plastic bags and transported to the laboratory for preliminary process.

To remove the humid content from the sediments, the samples were dried in a hot air oven at 60°C. The Garmin GPS Map 178 (Chartoplotter / Sounder) has identified the lake's morphometric parameter. The physicochemical characteristics of sediments iclude granulometric analysis, organic matter, calcium carbonate, and heavy metals. 100g of sediment samples were taken from the bulk samples using the cone and quartering method to determine the grain size characteristics. The sediment samples were dissolved with Hydrogen peroxide (H_2O_2) to remove the Organic matter from the sediments (Gee and Bauder, 1986). Afterward, the sediments were distinguished using sieve shaking methods (using ASTM sieves ranging from 2mm to 0.063mm for 15 minutes) and particle size analysis. The fractioned sediments were retained in the sieve stacks to identify the phi value of the sediments to reckon the appropriate sand, silt, and clay percentage using the ternary textural classification of hydrodynamic subdivisions (Flemming, 2000). Insightful analysis has underscores to appraise the organic matter and calcium carbonate of the sediments employed in the muffle furnace at the temperature of 550°C for 4 hours, followed by burning at 925°C for 2 hours (Bacardit and Camarero, 2010).

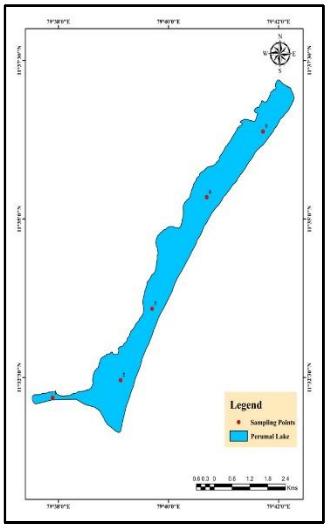

Figure 2 Location map of the surface sediments obtained from the present investigating area

TABLE 1. Coordinates of sample locations, textural characteristics, organic matter, and calcium carbonate content in the Perumal Lake surface sediments

S. No	Latitude	Longitude	Sand	Silt	Clay	Organic Matter (%)	Calcium Carbonate (%)
1	11°32'11.02"	79°37'53.65"	2.7	4.3	93	3.12	0.69
2	11°32'27.50"	79°39'7.79"	1.8	1.2	97	2.48	0.66
3	11°33'35.09"	79°39'42.07"	4.6	2.4	93	1.67	0.58
4	11°35'20.61"	79°40'41.62"	4.2	0.8	95	2.08	0.77
5	11°36'22.73"	79°41'43.09"	0.7	3.2	96.1	2.88	0.89
Min			0.7	0.8	93	1.67	0.58
Max			4.6	4.3	97	3.12	0.89
Avg			2.76	2.43	94.9	0.02	0.72

The sediments were pulverized in the agate mortar and stored in a glass bottle at 4°C until the chemical analysis section was carried out (Türkmen and Akbulut, 2015). To estimate the metal fractions in the sediments, the samples' clones of 0.05g were mixed with the 10 ml of associated acid as a 7:3:1 ratio of HF, HNO_3, and $HClO_4$ for the dilution. After digestion of the sediments, the retained solution is computed with the 250ml of double distilled water and stored in polythene bottles for Inductive Coupled Plasma – Mass Spectrometry (ICP-MS) analysis were carried out at National Geophysical Research Institute (NGRI), Hyderabad, India in Perkin Elmer SCIEX ELAN @ DRC-II to demonstrate the heavy metal content of Fe, Mn, Cu, Co, Zn, Cr, Ni, Pb, and Cd (Al-Qadasy, 2017).

ECOLOGICAL RISK ASSESSMENT METHODS

GEOACCUMULATION INDEX (I_{geo})

The I_{geo} implies an extent of heavy metal contamination in the studies sediments respecting the average shale concentration of the metals (Guo et al., 2015). The algorithm to enumerate the I_{geo} is adopted as (Muller, 1969)

$$I_{geo} = \frac{Log_2\, C_n}{1.5\, B_n} \qquad \text{Eq. (A.1)}$$

C_n represents the concentration of the sediments, 1.5 is the factor value adopted as presumed lithogenic variation (Taylor, 1964), and Bn represents the Background value of the metals proposed by Turekian and

Wedepohl (1961). The Igeo is classified as seven on the basic pollution level in the sediments. The classification states as 0-unpolluted, 0-1 states unpolluted to moderately polluted, 1 – 2 represents moderately polluted, 2 – 3 indicates moderately polluted to strongly polluted, 3 – 4 infers strongly polluted, 4 – 5 stands for strongly polluted to highly polluted, and > 5 shows extremely polluted.

CONTAMINATION FACTOR (CF)

The pivotal role played by the heavy metals intruding into the sediments due to the human effects is evaluated by the Cf (Ahmed et al., 2016). The CF is accessed based on the equation,

$$CF = \frac{C_n}{B_n} \qquad \text{Eq. (A.2)}$$

Where C_n indicates the concentration of the metals accessed from the sediments, B_n poses the Background value of the heavy metals. The Contamination factor of the sediments is categorized into four classes such as $CF < 1$ represents low contamination factor, $1 \leq CF \leq 3$ states moderate contamination factor, $3 \leq CF \leq 6$ shows considerable contamination factor, and $CF > 6$ means very high contamination factor (Taylor, 1964).

ENRICHMENT FACTOR (EF)

Nuance assessment poses the intense heightened of heavy metals and it explains the degree of anthropogenic inputs in the aquatic environments, which is studied by the enrichment factor indices (Sakan et al., 2009). The formula to compute the EF is denoted as,

$$EF = \frac{\left({}^{C_n}/_{C_{fe}}\right)}{\left({}^{B_n}/_{B_{Fe}}\right)} \qquad \text{Eq. (A.3)}$$

In this study, Fe was adopted as the reference element for the standardization as a result of the association of Fe with fine-grained sediments and metal fractionation and behavior are examined as similar to abounding heavy metals, followed by Fe, which is mainly derived from the geogenic process in most of the environments tends to be uniform (Bhuiyan et al., 2010). The formula states that C_{fe} represents Fe concentration in the sediments, and B_{fe} indicates Background geochemical concentration. The enrichment factors are classified in the following order: $EF < 2$ shows low metal enrichment, $2 \leq EF \leq 5$ presents moderate enrichment, $5 \leq EF \leq 20$ displays high enrichment, $20 \leq EF \leq 40$ accounts for very high contamination, and followed by $EF > 40$ infers extremely high contamination (Pekey, 2006).

DEGREE OF CONTAMINATION

The C_d examined the synergy of the CF for the analogous samples. To derive the C_d assessment as a consequence of the equation stated as

$$C_d = \sum_{i=1}^{n=1} Cf \qquad \text{Eq. (A.4)}$$

In this case, C_d is posed as the contamination degree, n is noted as number of elements in samples, and CF reflects the contamination factor of the sediments. The C_d is classified into 4 categories: $C_d < 6$, which is designated a low contamination degree; $6 \leq Cd < 12$ represents a moderate contamination degree; $12 \leq C_d < 24$ stands for a considerable contamination degree; and $C_d \geq 24$ indicates a very high contamination degree.

The ${}_mC_d$ demonstrates the omnipresent contamination suggests the synergy response to multi-metals / organic matter in the sediments. The Formulae to attain the ${}_mC_d$ are determined by,

$$mC_d = \frac{\sum_{i=1}^{n=1} Cf}{n} \qquad \text{Eq. (A.5)}$$

This could deal with the parameters such as n affirms the no. of elements and CF states Contamination Factor. Noxious classification of ${}_mC_d$ categorized as ${}_mC_d < 1.5$ represents nil to very low, $1.5 \leq {}_mC_d < 2$ denotes low degree, $2 \leq mCd < 4$ infers moderate degree, $4 \leq {}_mC_d < 8$ shows high degree, $8 \leq {}_mC_d < 16$ stands for very high, $16 \leq {}_mC_d < 32$ indicates extremely high, and ${}_mC_d \leq 32$ means ultra-high (Abrahim and Parker, 2008).

POTENTIAL ECOLOGICAL RISK INDEX (PERI)

The synergy of the PERI desires to pervasively estimate the severity of the metal contamination in sediments by contemplating the toxicity of the metals and ecological antiphon of the environment (Weber et al., 2013). The formulae examine the PERI as

$$E_r^i = T_r^i \times C_B^i \qquad \text{Eq. (A.6)}$$
$$RI = \sum_{i=1}^{m} E_r^i \qquad \text{Eq. (A.7)}$$

Where the RI is the ubiquitous of the potential individual heavy elements, E_r^i represents the potential risk of individual heavy elements, T_r^i infers toxicity response factor for metals Pb=Cu=Ni=5, Zn=1, Cr=1, and C_B^i indicates the Background level of the heavy metal concentrations.

HEALTH RISK ASSESSMENT

The comprehensive study of the health risks in sediments from India falls into the carcinogenic and non-carcinogenic prospects of

Table 2. Units used for the calculation of non-carcinogenic and carcinogenic risk human health risk assessments (Source: Alghamdi et al., 2018 and Vinod Kumar et al., 2020)

IR	Ingestion Rate	0.2 g/d for child and 0.1 g/d for adult
ER	Exposure Frequency	365 d / yr for both adult and children
ED	Exposure duration	6 yr for child and 30 yr for adult
SA	Skin Surface area existing	1600 cm^2 / event for child and 4350 cm^2 / event for adult
AF	Sediments to skin adherence Factor	0.2 mg/cm^2 for child and 0.7 mg / cm^2 for adult
ABS	Absorption Factor	0.001 for child and 0.01 for adult
CR	Conversion Factor	10^{-6} (Kg/mg)
BW	Body weight	15 kg for child and 70 Kg for adult
AT	Average Time	2190 days for child and 10,950 days for adult
RfD_i	Reference dose for ingestion pathway	Fe (0.3), Cu (0.04), Co (0.0003), Mn (0.014), Cd (0.5), Zn (0.3), Ni (0.002), Pb (0.0035), As (0.3), and Cr (1.5) mg/kg/day
RfD_d	Reference dose for dermal pathway	Fe (4.50E-02), Cu (12), Co (0.06), Mn (1.84E-03), Cd (0.005), Zn (60), Ni (5.4), Pb (0.42), As (0.123), and Cr (0.015)

habitats through two vulnerability routes: the average daily dose (ADD) of ingestion and dermal contact. The human risk underscores the nuanced observation of exposure, tolerance level, lifestyle, body weight, and individual habits (Swarnalatha et al., 2015). The health risk assessment profound insights were carried out on children and adults. The ADD (ingestion and Dermal Pathways) were meticulously observed with the formulae adopted as

$$ADD_i = \left(M \times IR \times ER \times ED /_{BW \times AT}\right) \times 10^{-6} \quad \text{Eq. (A.8)}$$

$$ADD_d = \left(M \times SA \times AF \times ABS \times ER \times ED /_{BW \times AT}\right) \times 10^{-6} \quad \text{Eq. (A.9)}$$

Where, M is the metal concentration of Fe, Mn, Cu, Cr, Zn, Pb, Ni, and Co in the sediments. The other abbreviations can be explained in Table 2. The Non-carcinogenic risk of the heavy metals study was conducted in the sediments to decode the HQ (Hazard Quotient) and HI (Hazard Index) (USEPA 2015). To assess the Hazard Quotient, the peculiar heavy metal in the sediments and the HI enumerate the comprehensive synergy of the HQ,

$$HQ = \left(\frac{ADD_{ing}}{RfD_{ing}}\right) \quad \text{Eq. (A.10)}$$

$$HQ = \left(\frac{ADD_{derm}}{RfD_{derm}}\right) \quad \text{Eq. (A.11)}$$

$$HI = HQ_{ing} + HQ_{derm} \quad \text{Eq. (A.12)}$$

Where ADD is the Average Daily Dose, RfD states the Reference dose of the metals.

LCR enumerates the carcinogenic risk that plays a pivotal role in any cancer disease whose entire life is liable to carcinogenic vulnerability (Li et al., 2014). The LCR is calculated using the formula adopted by Kusin et al. (2018):

$$LCR = \left(ADD_{ing} \times SF\right) + \left(ADD_{derm} \times SF\right) \quad \text{Eq. (A.13)}$$

Where SF is denoted as Slope Factor, SF affirms that heavy metals cause cancer to human beings.

HEAVY METAL TOXICITY LEVEL (HMTL)

Saha and Paul (2018) proposed that heavy metal toxicity load analysis yields profound insights into the environment's heavy metal accumulation. However, the study deals into the HMTL and detachably removes a percentage of elevated heavy metals in the environment. The algorithm to evaluate the HMTL reveals the quantification assessments as,

$$HMTL_I = C_i \times HIS \quad \text{Eq. (A.14)}$$

where Ci is the concentration of the metal i in sediments and HIS is the hazard intensity score obtained from (ATSDR 2019).

RESULTS AND DISCUSSION

PHYSIOCHEMICAL CHARACTERISTICS OF THE LAKE SEDIMENTS

The synergy of the textural parameters and heavy metal concentration analysis yields profound insights into heavy metal toxicity, ecological risk assessment indices, Human health Hazards, and Heavy Metal Toxicity Load intricacies. The comprehensive research systematically delves into the heavy metal toxicity and human health assessments of Perumal lake sediments. Sediment's physiochemical properties, including granulometric analysis, organic matter, and calcium carbonate content, reveals significant trends. The sediment composition is characterized by a sand-silt-clay ratio, with sand ranging from 0.7 to 4.6 % (average 2.76), silt from 0.8 to 4.3 % (average 2.43), and clay from 93 to 97 % (average 95). Ternary classification of textural characteristics suggests predominant clay matrices in the surface sediments, indicating relatively high clay content. The ternary classification of the hydrodynamic textural characteristics urges the surface sediments mostly implanted in the E-VI category, which implies predominantly clay matrixes (Fig. 3). These noteworthy findings could affirm that the sediments comprised relatively soarer content of clay sediments.

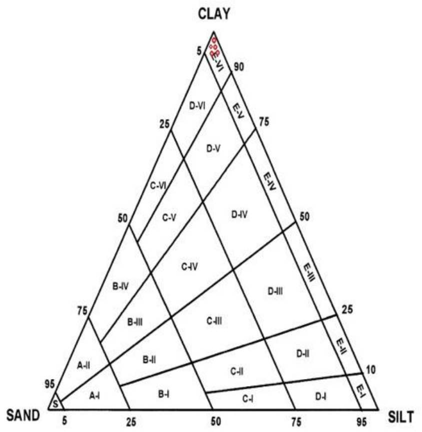

Figure 3 Ternary diagram of hydrodynamic nomenclature of the surface sediments of the present investigating area

Moreover, the presence of organic matter (OM) in sediments ranges from 1.67 to 3.12% (average 2.43%), while calcium carbonate ($CaCO_3$) levels indicate values from 0.58 to 0.89% (average 0.72%). The abundance of clay sediments suggests that lake water is highly unstable and susceptible to wave erosion (Wildi et al., 2004). Additionally, the presence of organic matter in sediments points to the discharge of agricultural runoff and untreated urban and industrial waste from the surrounding areas (Goher et al., 2014). The profound interplay of these $CaCO_3$ not only defines the weathering of calcareous rock (limestone or metamorphosed limestone rocks) but also accentuates the exquisite intricacies of the calcareous microorganisms, offering an elevation of the anthropogenic inputs to the sediments (Saravanan et al., 2018).

Table 3 Comprehensive data on heavy metal concentration (in ppm) of the individual samples of the Perumal Lake

S.No	Fe	Mn	Cr	Cu	Co	Ni	Zn	Pb	Cd
1	203	148	90.3	329	4.95	210	630	85.1	5.1
2	248	152	53.2	143	6.69	101	311	65.1	4.9
3	271	144	582	551	15.5	334	296	46.9	4.7
4	428	152	562	468	22.4	282	250	60.2	4.9
5	271	144	47.5	174	7.5	112	148	48.6	4.6
Min	203	144	47.5	143	5.0	101	148	46.9	4.6
Max	428	152	582	551	22.4	334	630	85.1	5.1
Average	293	148	281	337	12.1	210	345	62.6	4.8

LAKE MORPHOMETRIC CHARACTERISTICS

According to Håkanson (1981), the morphometric parameters encompass the lake's area, length, width, and depth. Meticulous observation of the morphometric characteristics implies the area is 13.24 sq. km, Maximum length states 11.54 km, maximum width indicates 2.07 km, and followed by mean depth implies 3.1 m of the lake.

DISSEMINATION OF HEAVY METAL CONCENTRATION AND ITS IMPLICATIONS

The spatial diffusion of heavy metal concentration urges profound insights of sediments from lake are Fe (203 – 428 ppm), Mn (144 – 152), Cr (47.49 to 581 ppm), Cu (143 – 551 ppm), Co (4.95 – 22.42 ppm), Ni (101 – 334 ppm), Zn (148 – 629.6 ppm), Pb (46.9 – 85.1 ppm), and Cd (4.6 – 5.1 ppm), respectively (Table 3). As per the original research presumptions, the Perumal lake sediments implies the heavy metal concentration were predominately formulated in the recession form as Zn > Cu > Fe > Cr > Ni > Mn > Pb > Co > Cd. As arbitrary to the average shale sedimentary concentration, the heavy metals such as Cr, Cu, Co, Ni, Zn, Pb, and Cd are enumerated as heightened value, whereas the Fe and Mn metals represent the minimal concentration, respectively (Turekian and Wedepohl, 1961). From the presumption urges, Fe, Mn, and Co metals were amplified in sample location 4, Cr, Cu, and Ni metals significantly enriched in sample location 3, and followed by Zn, Pb, and Cd elevated their concentration in the sample location 1 (Fig. 4). Textural analysis helps to figure out the influences on the heavy metal concentration of the Lake sediments. The realm of the clay sediments reveals the larger surface area to absorb the heavy metal scavenging phases such as Fe/Mn hydrolysates (Bradl, 2004).

A comprehensive analysis of the preceding studies enumerates the elevated Fe and Mn metal concentrations in the lake sediments to trivially ensure metal on the earth's crust (Singh and Vasudevan, 2023). Suresh et al. (2012) analyzed the heavy metal concentration of Veeranam lake sediments i.e. Cd (0.81 $\mu g\ g^{-1}$), Cu (94.12 $\mu g\ g^{-1}$), Pb (30.06 $\mu g\ g^{-1}$), Ni (63.61 $\mu g\ g^{-1}$), Zn (180.08 $\mu g\ g^{-1}$), and Cr (88.20 $\mu g\ g^{-1}$). Some other studies examine that Fe, Mn, Cu, Cr, Co, Ni, Pb, and Zn concentrations are higher than the Average Shale Sedimentary Concentration (Arulpoomalai Ayyanar, 2020). The magnitude of the heavy metal contagion in the sediments states as a sink drains from various sources

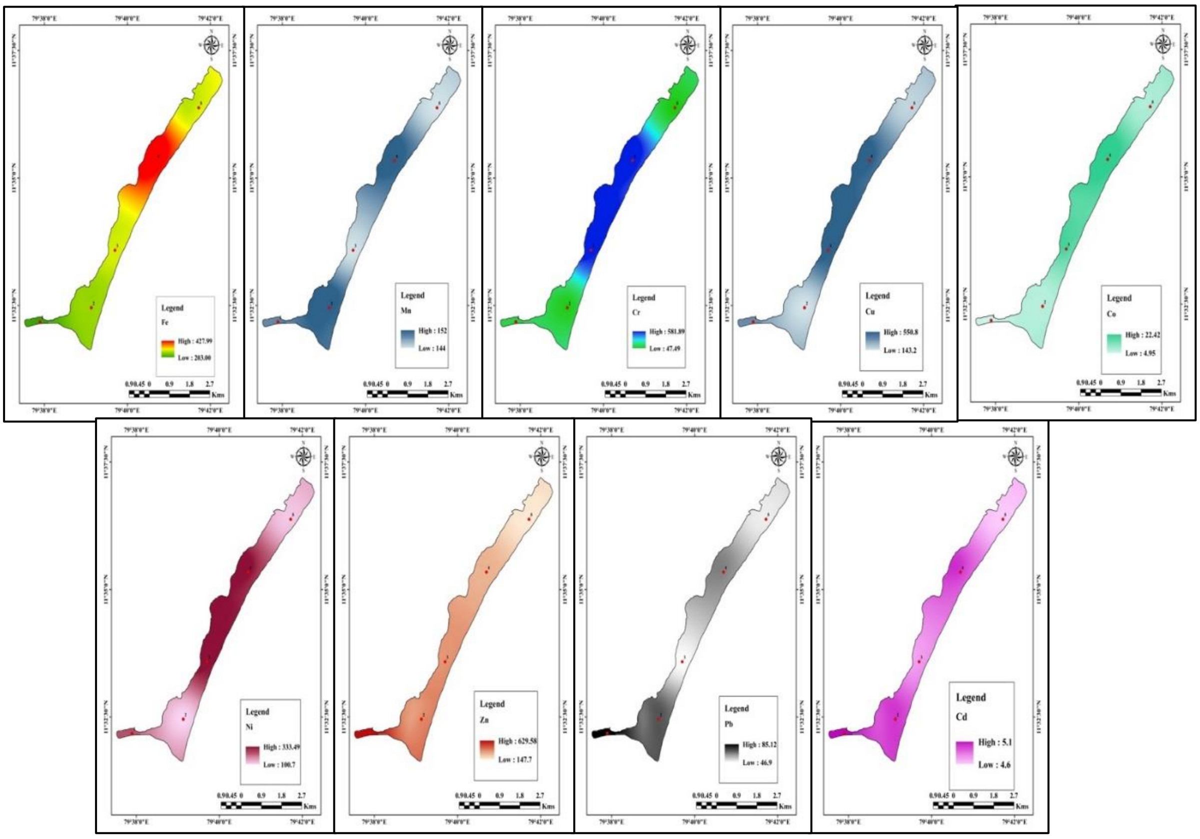

Figure 4 Heavy Metal Concentration of the surface sediments argues to inspect the metal enrichments in the sample location of the present investigating area.

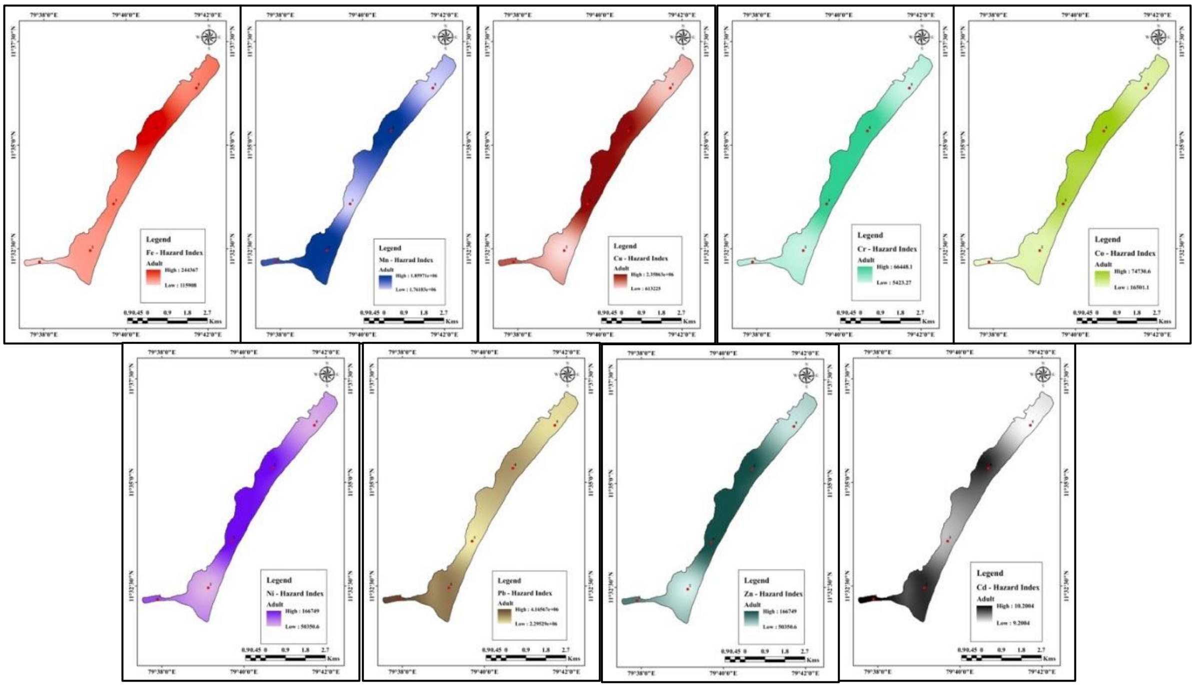

Figure 5 Human Health Assessment poses Hazard index of the heavy metals in the surface sediments inspect the non-carcinogenic jeopardy for the adults of the present investigating area.

such as bioaccumulation and biomagnification, which are deleterious to the environment (Bastami et al., 2014).

PEARSON CORRELATION

The statistical analysis of the Pearson correlation strategic approach allows us to generate a robust and realistic analysis regarding heavy

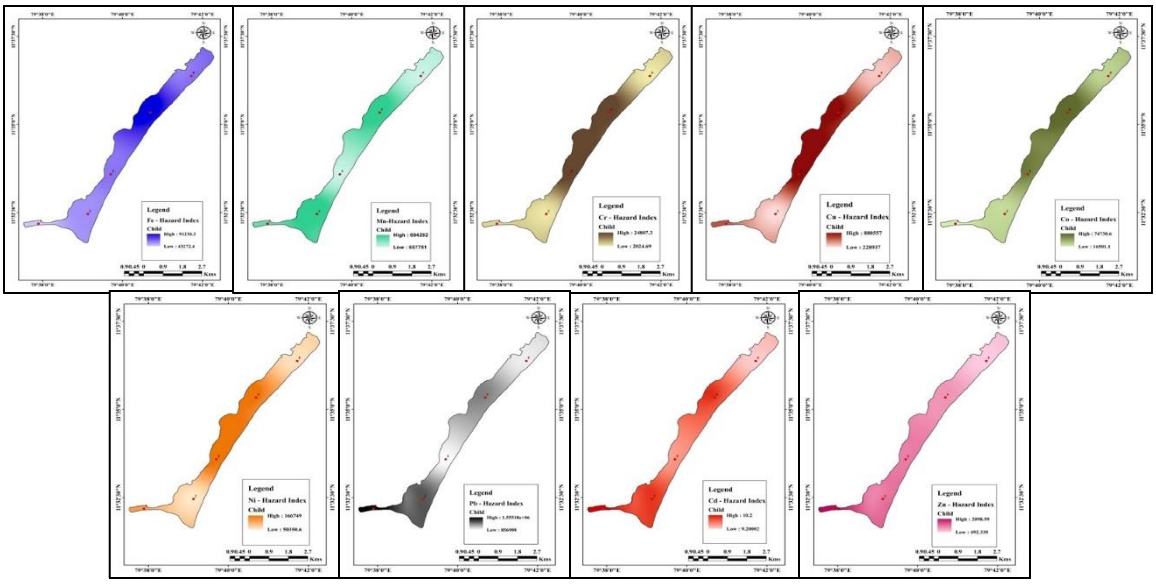

Figure 6 Human Health Assessment poses Hazard index of the heavy metals in the surface sediments inspect the non-carcinogenic jeopardy for the child of the present investigating area.

metal concentration, textural characteristics, and OM and $CaCO_3$ of the sediments, affording insight of utmost relevance. The Pearson correlation is presented in Table 4.

Fe metal exhibits significant correlations with Chromium (Cr) and Cobalt (Co) and moderate correlations with Copper (Cu) and sand content while showing negative correlations with Zinc (Zn), Lead (Pb), Cadmium (Cd), silt, and OM. Manganese (Mn) concentration notably correlates with Pb, Cd, and clay but lacks correlations with Cr, Cu, Ni, silt, and $CaCO_3$. Chromium content is significantly associated with Cu, Co, Ni, and sand but negatively correlated with other metals. Copper concentration strongly correlates with Co, Ni, and sand but negatively correlates with other metals. Similarly, Co concentration correlates with Ni and sand, with negative associations with other metals. Nickel concentration is adversely correlated with sand and negatively associated with other parameters. Zinc content is significantly correlated with Pb, Cd, and sand but negatively correlated with clay and $CaCO_3$. Lead content significantly correlates with Cd and OM but is negatively associated with sand, clay, and $CaCO_3$. Cadmium exhibits weak associations with other metals, while sand is negatively associated with silt, clay, OM, and $CaCO_3$. Silt content is positively associated with OM, Clay is positively associated with $CaCO_3$, and OM is correlated with $CaCO_3$. These Pb metals, predominantly related to organic matter, play a vital role in the toxicity index. To state that the Cu, Ni, Zn, and Cr were observed indicates the same sources and transport pathways of these contagions (Haller et al., 2009; Pote et al., 2008). Heavy metals such as Cr, Cu, Ni, Zn, Pb, and Co possess the influences of extensive anthropogenic activities, including the heavy discharge of untreated urban and industrial effluents into the lakes (Sivalingam et al., 2020).

ENVIRONMENTAL TOXICITY INDICES OF THE LAKE SEDIMENTS

To predict the I_{geo} of the heavy metals in the sediments unveils that Fe, Mn, and Co were elevated at sample location 4, which presumes in the moderately to extremely polluted category, and Cr, Cu, Ni signifies the strongly polluted categories, which peculiarly at the sample location 3, and followed by Zn, Pb, and Cd accounted significantly in the sample location 1. In contrast, the Zn and Pb urge moderately to highly polluted zones. However, Cd was observed as unpolluted. In the Perumal Lake, the Zn and Pb enrichments demonstrate the discharges of industrial disposal and fertilizers to the sediments (Yang et al., 2018). Besides, the Cu, Co, and Ni metals pose the metal melting factory emission may be the reason for the enrichment (Wang et al., 2018).

Consequently, Mn and Fe contaminations are contributed to the sake of sewage sludge and boat repairing processes due to the unpolluted action of the Cd, which does not play a vital role in the sediments (Soliman et al., 2019). The EF of the lake sediments is notably suggested as no metal enrichment, except Cu and Zn, which are classified as low metal enrichments. On sample location, the study urges the Cr and Cu to be elevated in the locations 3 and 4. In contrast, Ni and Zn increased in locations 1, 2, and 3, confess the low metal enrichment to moderate enrichment (Fig. 6). The EF affirms the origin of these heavy metals in the Perumal Lake sediments, which is mainly related to the geogenic background and deposited due to natural weathering process (runoff and erosion) (Zhang and Liu, 2002).

Table 4. Pearson correlation analysis for the heavy metal concentrations, textural parameters, OM and $CaCO_3$ of the Perumal Lake sediments

Parameters	Fe	Mn	Cr	Cu	Co	Ni	Zn	Pb	Cd	Sand	Silt	Clay	OM	$CaCO_3$
Fe	1.000													
Mn	0.394	1.000												
Cr	0.666	-0.013	1.000											
Cu	0.427	-0.159	0.929	1.000										
Co	0.909	0.210	0.917	0.746	1.000									
Ni	0.400	-0.153	0.918	0.999	0.726	1.000								
Zn	-0.525	0.161	-0.213	0.103	-0.402	0.137	1.000							
Pb	-0.358	0.482	-0.413	-0.190	-0.424	-0.162	0.892	1.000						
Cd	-0.145	0.641	-0.149	0.024	-0.161	0.052	0.854	0.949	1.000					
Sand	0.450	0.107	0.920	0.952	0.757	0.956	0.169	-0.070	0.197	1.000				
Silt	-0.720	-0.627	-0.453	-0.121	-0.647	-0.106	0.553	0.365	0.120	-0.311	1.000			
Clay	0.166	0.401	-0.469	-0.762	-0.168	-0.779	-0.592	-0.227	-0.273	-0.655	-0.515	1.000		
OM	-0.521	0.004	-0.876	-0.709	-0.774	-0.699	0.418	0.614	0.349	-0.763	0.644	0.177	1.000	
CaCO3	0.285	-0.085	-0.370	-0.467	-0.060	-0.495	-0.448	-0.157	-0.322	-0.620	0.105	0.476	0.513	1.000

A proximate inquiry of the CF shows that the Fe and Mn metals accounted for low contamination factors. Cr, Cu, Co, Ni, Zn, and Pb indicate considerable contamination factors. Consequently, Cd exhibits high contamination factor in the lake sediments. Notable findings indicate that the considerable contamination of Cr, Cu, Co, Ni, Zn, and Pb in the sediments could be attributable to anthropogenic and geogenic sources. This could exhibit the anthropogenic influences of the sediments due to point pollution sources and non-point pollution sources linked to vehicle sources, agricultural runoff, sewage and waste discharges, electroplating, and clothing industries. The accumulation of Pb from the contamination factor inferences reveals vehicle emission deposits from the nearby roadways (Yang and Rose, 2005; Gupta et al., 2013; Njenga et al., 2009).

Research suggests that the abnormal enrichment of Cd in sediments is due to the disposal of batteries, electroplating, pigments, and metal manufacturing (Jain et al., 2010). Furthermore, the sources of Zn in the sediments are due to the wear and tear of tires and break lining (Singh and Kumar, 2017), followed by Cu enrichments poses the metal plating, antifouling, and brake lining wears (Duodu et al., 2016). The ambiguous result of the C_d and $_mC_d$ examines the accretion of heavy metals and urges a very high contamination degree and a high degree of contamination in the sediments, as shown in Table 5. Based on the comprehensive forecast of the PERI was calculated for each sampling location, 1 (11.36), 2 (6.24), 3 (14.34), 4 (13.34), and 5 (4.43) urges a low risk (PERI < 150) to the local biological communities.

HEALTH RISK ASSESSMENT OF HEAVY METALS IN SEDIMENTS

The conspicuous observation of heavy metals embellishment urges the non-carcinogenic and carcinogenic threat analysis in surface sediments to affirm the ingestion and dermal pathway for adults and children, listed in Tables 6 and 7. The valuable insight of the average daily dose computed in mg/kg/day unit was forecast for the heavy metals, such as Fe, Mn, Cr, Cu, Co, Ni, Zn, Pb, and Cd. The result found that the examined ADD_{ing} value of the heavy metals is potentially adverse than the RfD_{ing} delves the ingestion route probably causes harmful effects on humans in the environment. The intriguing findings underscore the nuanced interplay of ADD_{ing} value for heavy metals such as Fe, Mn, Cr, Cu, Co, Ni, Zn, Pb, and Cd values, unveiling the ADD_{derm} route's influential characteristics for adults and children. Remarkably, an insightful examination of ADD illuminates an oral intake through the accidental contact of the sediments in the hand-to-mouth aspects.

The Non-carcinogenic health risks coupled with exposure to heavy metals such as Fe, Mn, Cr, Cu, Co, Ni, Zn, Pb, and Cd for the adult and child contemporary in the surrounding lakes (Table 5). To address these non-carcinogenic risks, we evaluated the Hazard Quotient of ingestion (HQing) and Hazard Quotient of dermal (HQderm) to affirm the health risks to the habitants. The HQ value is less than 1.0, denoted as safe conditions, and has no harmful effects, whereas the HQ value greater than 1.0 indicates harmful effects (Qu et al., 2012; USEPA, 2015).

It is worth noting that this assessment shows the HQ_{ing} of the heavy metals such as Fe, Mn, Cr, Cu, Co, Ni, Zn, Pb, and Cd values predominately higher than 1.0, it would be harmful to the adult and child. In contrast, the HQ_{derm} showed no detrimental effects on human health due to less than 1.0. Rigorous investigation implies the heavy metals in the sediments due to the rapid urbanization, growing population, industrialization, and agricultural inputs (Alghamdi et al., 2018).

Consequently, the HI of the sediments plays a pivotal role in enumerating the high-end

Table 5. Environmental toxicity Indices such as I_{geo}, EF, CR, C_d and mC_d, and PERI for the Perumal Lake sediments

	Geoaccumulation index				Enrichment factor				Contamination Factor			
	Min	Max	Avg	Results	Min	Max	Avg	Results	Min	Max	Avg	Results
Fe	6.81	7.13	6.95	Extremely polluted					0.00	0.01	0.01	Low contamination Factor
Mn	4.91	4.94	4.92	Highly Polluted	-0.64	-0.27	-0.45	No metal enrichment	0.17	0.18	0.17	Low contamination Factor
Cr	3.45	4.54	3.97	Strongly polluted	-0.82	1.15	-0.14	No metal enrichment	0.53	6.47	3.12	Considerable contamination Factor
Cu	3.63	4.22	3.94	Strongly polluted	-0.42	1.03	0.19	No metal enrichment	3.18	12.24	7.49	High Contamination Factor
Co	1.80	2.45	2.10	Moderately polluted	-0.98	-0.94	-0.96	No metal enrichment	0.26	1.18	0.63	Low contamination Factor
Ni	3.66	4.18	3.92	Strongly polluted	-0.59	0.23	-0.25	No metal enrichment	1.48	4.90	3.09	Considerable contamination Factor
Zn	3.97	4.60	4.27	Highly Polluted	-0.45	2.10	0.32	No metal enrichment	1.55	6.63	3.63	Considerable contamination Factor
Pb	2.80	3.05	2.91	Moderately polluted	-0.86	-0.58	-0.77	No metal enrichment	2.35	4.26	3.13	Considerable contamination Factor
Cd	0.04	0.01	0.01	Un polluted	0.99	0.97	0.98	No metal enrichment	15.33	17.00	16.14	High Contamination Factor

	Cd	mCd	PERI
Min	25.92	2.88	4.43
Max	45.73	5.08	14.34
Avg	36.54	4.06	9.78
Results	Very High Contamination Degree	High degree contamination	Low Risk

Table 6 Pervasive Study of the Non-Carcinogenic for the Adult and Child in the study area

	ADULT					CHILD				
	ADDi	ADDd	HQi	HQd	HI	ADDi	ADDd	HQi	HQd	HI
Fe	48680.42	0.000123627	162268.05	0.002747267	162268.05	18174.02	6.06293E-06	60580.07	0.000134732	60580.07
Mn	25350.81	0.00006438	1810772.45	0.03498913	1810772.48	9464.30	3.15733E-06	676021.71	0.001715942	676021.72
Cr	45715.05	0.000116096	30476.70	0.007739752	30476.71	17066.95	5.69361E-06	11377.97	0.000379574	11377.97
Cu	57049.61	0.000144881	1426240.24	1.20734E-05	1426240.24	21298.52	7.10528E-06	532463.02	5.92107E-07	532463.02
Co	1952.36	4.95813E-06	37993.33	8.26355E-05	37993.33	728.88	2.43157E-07	37993.33	4.05262E-06	37993.33
Ni	35552.80	9.02886E-05	103780.00	1.67201E-05	103780.00	13273.05	4.42795E-06	103780.00	8.1999E-07	103780.00
Zn	55987.62	0.000142184	1089.53	2.36974E-06	1089.53	20902.04	6.97301E-06	1089.53	1.16217E-07	1089.53
Pb	10478.11	2.66098E-05	2993745.20	6.33567E-05	2993745.20	3911.83	1.305E-06	1117664.87	3.10715E-06	1117664.87
Cd	829.04	2.1054E-06	9.68	0.00042108	9.68	309.51	1.03253E-07	9.68	2.06507E-05	9.68

Table 7 Pervasive study of the Carcinogenic for the Adult and Child of the present study

	ADULT						CHILD			
	ADDi	SFi	ADDd	SFd	LCR	ADDi	SFi	ADDd	SFd	LCR
Cr	45715.05	22857.527	0.000116096	0.002321926	0.02285753	17066.95	8533.477	5.694E-06	0.000113872	0.0085335
Cu	57049.61	96984.336	0.000144881	0.006157447	0.096984342	21298.52	36207.49	7.105E-06	0.000301974	0.0362075
Ni	35552.8	20913.414	9.02886E-05	0.003837266	0.020913418	13273.05	7807.675	4.428E-06	0.000188188	0.0078077
Pb	10478.11	89.06392	2.66098E-05		8.90639E-05	3911.827	33.25053	1.305E-06		3.325E-05

Table 8 Heavy metal Toxicity Load to get rid of the percentage of toxic heavy metal accumulation in the study area

S.No	Cr	HMTL-Cr	Removal	Cu	HMTL-Cu	Removal	Ni	HMTL-Ni	Removal	Zn	HMTL-Zn	Removal
1	90.33	75786.87	6.77%	328.9	264764.5	19.75%	210.2	208728.6	20.25%	629.6	574824.8	38.52%
2	53.22	44651.58	3.99%	143.2	115276	8.60%	100.7	99995.1	9.70%	310.7	283669.1	19.01%
3	581.9	488214.1	43.61%	550.8	443394	33.08%	333.5	331165.5	32.14%	296.4	270613.2	18.14%
4	561.5	471098.5	42.08%	468.4	377062	28.13%	281.8	279827.4	27.15%	249.9	228158.7	15.29%
5	47.49	39844.11	3.56%	174	140070	10.45%	111.6	110818.8	10.75%	147.7	134850.1	9.04%
HIS	893			805			993			913		
Permissible Load	80370			36225			67524			86735		
Permissible Limit (mg/kg)	90			45			68			95		

risk of heavy metals attributed based on the summation of HQ_{ing} and HQ_{derm} of the sediments. The HI value attributes, as the value is less than 1.0 and greater than 1.0, imply no risk and high risk to adults and children (Qing et al., 2015). This could lead to the result observed for HI of adult and child states that the sediments were highly considerable as risk categories indicate chronic non-carcinogenic effects play a significant role of oral exposure through the food contagion consumed from sediments as presented in Tables 6 and 7.

LCR represents a value is lesser than 1×10^{-6} and denotes no risk/effects to humans, whereas an LCR greater than 1×10^{-6} urges a high risk of cancer to human beings and followed by a range of 1×10^{-6} to 1×10^{-4} illustrates that it undergoes tolerable risk of heavy metals to habitants (USEPA, 2011; Karunanidhi et al., 2022). In these present inferences, the LCR value for heavy metals such as Cr, Cu, Ni, and Pb illustrates the sediments of the Perumal Lake accounting as the values are inferior to 1×10^{-6} registered as unworthy sediments to cause cancer to adult and child in the surrounding regions (Table 7). On pioneering innovation research illuminates the assorted heavy metals in sediments emerges as the premise for several cancers. Cr and Ni were associated with diseases such as lung, paranasal sinuses, and nasal cavity cancer (Cancer-Causing Substances in the Environment – NCI).

HEAVY METAL TOXICITY LOAD

Employing the heavy metal toxicity load evaluation demonstrates the glut of heavy metals load in the Lake environments. It unveils a noteworthy picture for adequate removal of metal loads taken in monitoring the environments. The HMTL examines the heavy metal values, permissible limits, and percentage removal of toxic loads (Table 8). The allowable limit of heavy metals toxicity is accounted for by hazard intensity scores (HIS) proposed by ATSDR (2019). The HMTL value of sediments resulted in the average shale concentration of sediments (Turekian and Wedepohl, 1961). The meticulous observation of the percentage of HMTL removal of the heavy metals such as Cr (3.56% - 43.61%; avg. 20%), Cu (8.60 – 33.08%; avg. 20.24%), Ni (9.70 – 32.14%; avg. 20.26%), and Zn (4 – 38.52%, avg. 21.08%), respectively (Table 8). In the study area, sample location 3 registers a significant accumulation of toxic contagion proposed to be removed from the sediments, except Zn, which is higher in location 1.

CONCLUSION

An extensive investigation into heavy metal concentrations in Perumal Lake sediment, Cuddalore district, Tamil Nadu, yields significant insights. Key findings include the prevalence of clay content in surface sediments, with minimal contributions from organic matter (OM) and calcium carbonate ($CaCO_3$) in heavy metal association. Metal gradation follows Zn > Cu > Fe > Cr > Ni > Mn > Pb > Co > Cd, with low Fe and Mn values, possibly due to limited geogenic input. Anthropogenic sources, including urban and industrial effluents, agricultural runoff, and vehicle emissions, contribute significantly to Cu, Cr, Co, Ni, Zn, and Pb accumulation through unprocessed urban and industrial effluents, agricultural runoff and vehicles emission may leads to aquatic toxicity.

The correlation analysis suggests that heavy metals do not bind significantly with textural, OM, and $CaCO_3$ components, thus limiting their impact on sediment dispersion. Anthropogenic influences, such as agrochemicals, vehicle emissions, untreated waste discharge, and rapid urbanization, contribute extensively to heavy metal accumulation in sediments. Exploration of environmental toxicity indices, including I_{geo}, EF, CF, Cd, mCd, and PERI, reveals moderate to extreme pollution levels for most heavy metals except for Cd.

Non-carcinogenic assessments reveal potential risks to children and adults from ingesting sediments, while dermal exposure poses no significant risk. Combined HQ values underscore the chronic non-carcinogenic effects of oral exposure to foods sourced from the lake surroundings, particularly affecting adults and children. Furthermore, the assessment of LCR for heavy metals suggesting that the sediments pose negligible risk of causing cancer to adults and children in the surrounding areas. Notably, this finding underscores the effectiveness of potential remediation techniques in addressing heavy metal toxicity in sediments. Various remediation strategies, including phytoremediation, in-situ capping, and biotechnological approaches, offer promising avenues for mitigating heavy metal contamination.

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CONFLICT OF INTEREST

The authors declare that they have no known competing interests.

ABBREVIATION

I_{geo} - Geoaccumulation Index; Ef – Enrichment Factor; Cf – Contamination Factor; C_d and the $_mC_d$ – Degree of Contamination and Modified Degree of Contamination; PERI - Potential Ecological Risk Index; ADD - Average Daily Dose; HI – Hazard Index; LCR -Lifetime Carcinogenic Risk; HMTL - Heavy Metal Toxicity Load; HQ - Hazard Quotation

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