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Environmental indices based geochemical assessment of riverine sediments in sustainability perspectives: A study of Chalakudy river, Southern Western Ghats, India during extreme rainfall events for building baseline qualitative databases

R. Resmi [ab], A. Krishnakumar [a], K. Anoop Krishnan [a], Rajesh Reghunath [c]

[a] National Centre for Earth Science Studies (NCESS), Ministry of Earth Science, Govt of India, Akkulam, Thiruvananthapuram-695011, Kerala, India

[b] Department of Environmental Sciences, University of Kerala, India

[c] Department of Geology, University of Kerala, Kariavattom, Thiruvananthapuram-695581, Kerala, India

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ABSTRACT

The increased heavy precipitation events associated with climate change can alter the geochemical status of sediments in tropical small catchment rivers, thereby affecting overall ecosystem health. The present study was carried out to understand the responses of sediment geochemistry in the Chalakudy River (CR) to heavy precipitation events, specifically focusing on contamination geochemistry. A total of 25 sediment samples were collected from upstream to downstream sections of the river during the 2019 extreme rainfall period and analyzed for trace element concentrations using X-ray fluorescence (XRF) techniques. The sediments in the Chalakudy river are generally acidic during heavy monsoon periods, and the conductivity values ranged from 18 to 1898 µS/cm. Based on the Degree of Contamination (DC) and Pollution Load Index (PLI), the sediments were found to be slightly polluted during the extreme rainfall period. Overall, contamination in the sediments was minimal and classified as low, except for an increase in barium content, which contributed to a slight elevation in pollution levels. These findings indicate that the increasing intensity and frequency of extreme precipitation events may pose long-term challenges to the sediment geochemical balance and thereby harmful for the aquatic systems. The study provides baseline data that is essential for future monitoring needs and contributes to sustainable river basin management under changing climate conditions.

CONTACT Author, Krishnakumar. A - drakrishnakumar@gmail.com
Supplemental data for this article can be accessed online at our website

1. Introduction

Tropical river basins are highly dynamic systems where sediment geochemistry reflects the interplay of weathering processes, hydrological conditions, and anthropogenic influences. Heavy metal contamination in river sediments of the Western Ghats has been linked to natural weathering of lithology and anthropogenic activities, including agricultural runoff, industrial discharges, and urbanization (Mohan et al., 2022). Elevated concentrations of heavy metals like cadmium, lead, and chromium can disrupt aquatic ecosystems and pose risks to human health (Shil et al., 2019). The Western Ghats, a critical hydrological region, is experiencing significant climatic shifts characterized by altered rainfall patterns and increasing intensity of extreme weather events (Gadgil, 2011).

These events often result in substantial runoff, which enhances the transport of sediments from upstream regions to floodplains and estuaries. The high-energy flows during extreme rainfall events mobilize soil particles, eroding riverbanks, and transporting pollutants adsorbed onto sediments. Increased runoff also elevates the delivery of contaminants such as heavy metals, nutrients, and organic pollutants into river systems, exacerbating the pollutant load (Seralathan et al., 1994). Heavy rainfall leads to sediment deposition in slower-moving parts of the river system, causing sedimentation rates to spike, particularly in reservoirs and estuarine zones (Dellapenna et al., 2020).

This impacts aquatic ecosystems by smothering benthic organisms, disrupting their habitats, and altering nutrient cycles (Eric et al., 2023). Furthermore, heavy metals bound to sediment particles, such as cadmium (Cd), lead (Pb), and mercury (Hg), can be released into the water column under specific conditions like pH changes or oxidation-reduction fluctuations caused by flooding (Rinklebe et al., 2016). Such events increase the bioavailability of these toxic metals, posing a direct threat to aquatic life and human health (Sojka et al., 2022).This study focuses on the distribution of heavy metals in the Chalakudy River, examining its variations from the relatively undisturbed upstream regions to the heavily disturbed downstream areas in response to heavy monsoons driven by climate change. Understanding these spatial variations in heavy metal concentrations is crucial for assessing ecological risks (Mohan et al., 2022), particularly in river basins like Chalakudy, which support sensitive freshwater ecosystems and high biodiversity. Additionally, this study provides insights into how climate change-induced hydrological alterations exacerbate pollutant dispersion and sediment quality degradation, further threatening aquatic habitats and water resources (Krishnakumar and Das, 2021). Studying sediment geochemistry is, therefore, crucial for understanding past environmental conditions, anticipating ecosystem responses to ongoing changes, and guiding sustainable resource management strategies in the context of a changing climate paradigm.

In August 2019, Kerala experienced a rainfall surplus of 123% compared to the long-term average, resulting in widespread flooding and extreme hydrological events (IMD, 2019). Such unprecedented rainfall surpluses, driven by climate change, pose significant challenges to the nature of river sediments and thereby its geochemistry, particularly in tropical river basins like the Chalakudy River. Hence, this study focuses on the geochemical responses and heavy metal variations in the Chalakudy River sediments during extreme monsoon events for using this database as a case study to understand the impact on sediment contamination and stability of other similar basins of the Western Ghats. The primary objective of this study is to investigate the geochemical responses of river sediments in the Chalakudy River Basin to heavy monsoon events induced by climate change. Specifically, it evaluates the elemental composition of heavy metals in river sediments using X-ray fluorescence (XRF) analysis during the intense precipitation period of 2019. Furthermore, the study assesses sediment contamination levels during this extreme rainfall event by applying established geochemical indices. Overall, the research aims to provide valuable insights into the geochemical behaviour of tropical river sediments under extreme hydrological conditions, thereby contributing to sustainable river basin management strategies of Sustainable Development Goals 'SDGs'13 (Climate action), 14 (Life Below Water), and 6 (Clean water and sanitation).

2. Study Area

The Chalakudy River, the fifth-longest river in Kerala, is a lifeline for the region, flowing through diverse landscapes and supporting multiple ecosystems and human activities. Spanning at a length of 145 km, it holds the distinction of being the longest river in Thrissur district of Kerala State (Fig.1). The river's total drainage area is approximately 1704 sq. km, of which 1404 sq. km lies in Kerala and the remaining 300 sq. km falls within the Coimbatore district of Tamil Nadu. Originating from the Anamalai hills and Nelliampathy ranges of the Western Ghats, the river flows westward through Palakkad, Thrissur, and Ernakulam districts. Fig. 2 shows the geology of the Chalakudy River Basin (CRB). The crystalline basement of metamorphic and igneous rocks, which shapes its unique geomorphological features such as waterfalls, cascades, rapids, meanders, stabilized channel-islands, terraces, and sandbars (Anish et al., 2021). There are intrusions of granite rock (acidic) mainly in the Parambikulam and Nelliyampathy plateaus (Maya and Seralathan, 2005). These features not only enhance the scenic beauty of the river but also play a crucial role in its hydrology and sediment dynamics.

The Chalakudy River Basin (CRB) is predominantly covered by dense evergreen reserve forests, which are among the most biodiverse and ecologically significant ecosystems in the Western Ghats. The extreme variation in rainfall pattern and distribution across different altitudes within the river basin has allowed niches for diverse vegetation types to evolve over time. Chalakudy River is one of the very few rivers in Kerala which is having relics of riparian vegetation in substantial level (Resmi et al., 2021). One third of the river's length is occupied by protected areas or forests that support wildlife. The Sholayar ranges hold a good percentage of Kerala's evergreen forests. The river is a lifeline for about ten lakh people, with both traditional and contemporary needs-fishing, irrigation, domestic use and so on.

3. Materials and Methods

3.1 Sampling and Analysis

The entire stretch of the Chalakudy River was covered with 25 representative sampling points, and sediment samples were collected during the heavy monsoon period in August 2019. The collected sediment samples were subjected to geochemical analysis to determine the concentration of key elements. Sampling locations are illustrated in Fig. 1. Each sample was air-dried, finely powdered, and passed through a 230-mesh sieve to obtain uniform particle size. A measured portion of the sieved sample was transferred to a pre-weighed, clean crucible and oven-dried at 110°C for one hour to eliminate residual moisture.

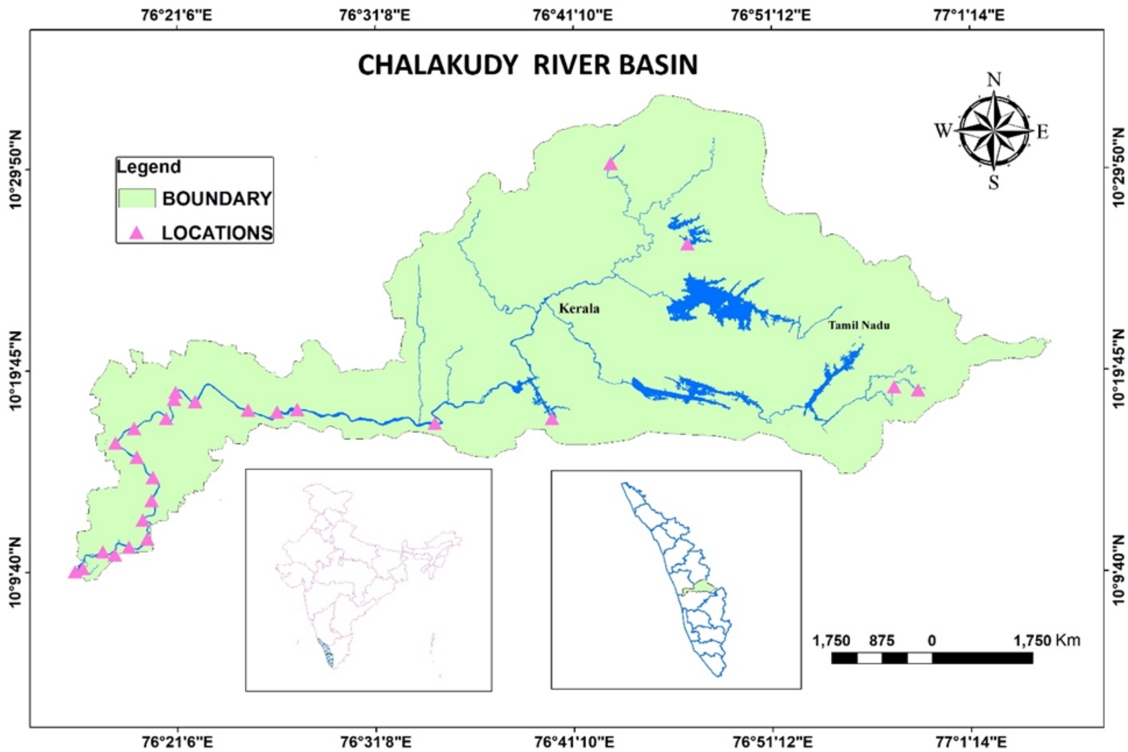

Fig.1. Sediment sampling locations in Chalakudy River

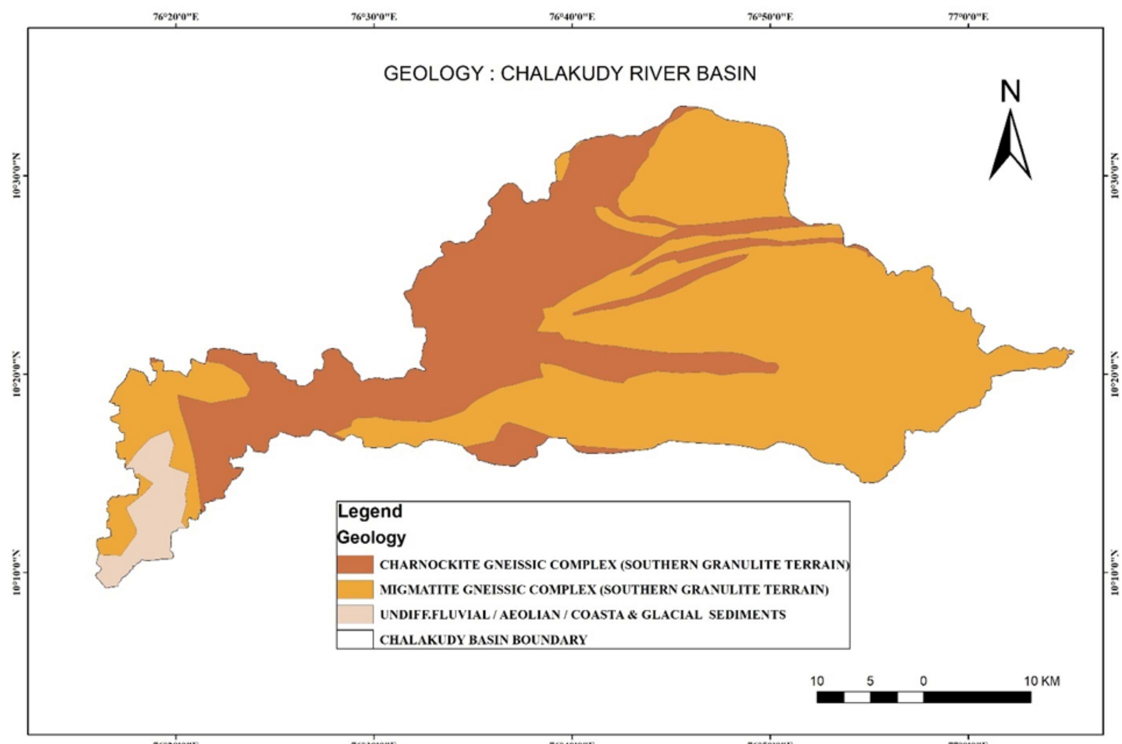

Fig.2 Geology of Chalakudy River Basin (CRB)

Subsequently, the samples were heated in a muffle furnace at 900°C for one hour to remove organic matter, carbonates, and interstitial water. For elemental analysis, the treated sediment was pelletized. Pellets were prepared by placing 1 gram of the powdered sample over a base layer of boric acid inside collapsible aluminium cups, which act as binders. The contents were then compressed using a hydraulic press at 20-tonne pressure to form pellets of 40 mm diameter suitable for spectrometric evaluation (Krishnakumar et al.,2024). The powdered pellets were then used for heavy metal concentration analysis (Karthikayini et al., 2023). A sequential wavelength-dispersive X-ray fluorescence (XRF) spectrometer (Bruker S4 Pioneer, 4 kW Rh X-ray tube) was utilized for the quantitative determination of potentially toxic elements in the sediment samples, including vanadium (V), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), strontium (Sr), rubidium (Rb), zirconium (Zr), barium (Ba), and cerium (Ce) (Krishnakumar et al., 2024).

3.2 Contamination Geochemistry

The heavy metal contamination in the sediment samples from the study area was evaluated using various indices, including the Contamination factor (CF), Degree of contamination (Cdeg), Pollution load index (PLI), Geo-accumulation index (Igeo), and Enrichment factor (EF).

3.2.1 Contamination Factor (CF) and Degree of Contamination (Cdeg)

The level of contamination of sediment by metal is expressed in terms of contamination factor (C) and is calculated using equation (1).

$$\textit{Contamination Factor, } (CF) = \frac{\text{C (heavy metals)}}{\text{C(background)}} \quad \text{............(1)}$$

where C (heavy metal) sample is the metal concentration in the polluted sediment and C(background) is the natural background value of the metal. In this study, the average shale value suggested by the World Shale Value table was used as the reference value. Table 1 represents the categories of Contamination factors used in this study.

Table 1 Categories of Contamination Factor (CF) (Hakanson, 1980; Varol, 2011)

CF Range	Contamination Level Description
CF<1	Indicates low contamination
1≤CF≤3	Suggests moderate level of contamination
3≤CF≤6	considerable contamination level
6≤CF	Indicates very high contamination

The contamination degree (Cdeg) of the environment is determined by the sum of the Contamination factors (CF) for all the elements analysed. This parameter is categorized into four classes, which are presented in Table 2.

Table 2 Categories of Degree of Contamination (Cdeg) (Hakanson, 1980; Varol, 2011)

Range	Class
Cdeg<8	low degree of contamination
8≤Cdeg≤16	moderate degree of contamination
16≤Cdeg<32	considerable degree of contamination
32≤Cdeg	very high degree of contamination

3.2.2 Pollution Load Index (PLI)

The Pollution Load Index (PLI) for each location was calculated using the method proposed by Tomlinson et al. (1980) using the following equation (2) and the categories of PLI is shown in Table 3.

$$\textit{Pollution Load Index, PLI} = (CF_1 * CF_2 * CF_3 * \ldots.* CF_n)^{1/n} \quad \text{......(2)}$$

Table 3 Categories of Pollution Load Index (PLI) (Tomlinson et al.,1980)

Range	Class
PLI<1	No Metal pollution
PLI>1	Metal pollution exists

3.2.3 Geoaccumulation Index (Igeo)

The index of accumulation enables the assessment of contamination by comparing the current levels of metal contamination and the baseline pre-industrial sediment concentrations in the sediments. It is often used to evaluate the extent of anthropogenic influence on sediment quality. It can be calculated using equation (3) proposed by Muller 1969.

$$\textit{Geoaccumulation Index, } I_{geo} = log_2 \frac{Cn}{1.5*Bn} \text{..........(3)}$$

Where Cn is the concentration of the given element in the sediment tested, and Bn is the average shale value described by the World Shale Average Table. The constant 1.5 factor is used because of the possible variation of the baseline data due to lithogenic effects. The following descriptive classification is given for the index of geo accumulation by Varol (2011).

Table 4 Categories of Geoaccumulation Index (Igeo) (Muller, 1969; Varol, 2011)

Range	Class	Classification
Igeo < 0	Class 0	Practically unpolluted
0 < Igeo ≤ 1	Class 1	Slightly polluted
1 < Igeo ≤2	Class 2	Moderately polluted
2 < Igeo ≤3	Class 3	Moderately severely polluted
3 < Igeo ≤4	Class 4	Severely polluted
4 < Igeo ≤5	Class 5	Severely extremely polluted
Igeo > 5	Class 6	Extremely polluted

3.2.4 Enrichment Factor (EF)

Enrichment Factor (EF) is a useful tool in determining the degree of anthropogenic heavy metal pollution (Das et al., 2019). The EF is computed using equation (4)

$$Enrichment\ Factor\ ,EF = \frac{\left(\frac{Metal}{Fe}\right)Sample}{\left(\frac{Metal}{Fe}\right)Background} \ldots\ldots\ldots\ldots (4)$$

where $\left(\frac{Metal}{Fe}\right) Sample$ is the ratio of the concentration of the test element to that of Fe and $\left(\frac{Metal}{Fe}\right) Background$ is the same ratio with respect to the reference sediment.

Table 5 Categories of Enrichment Factor (EF) (Sutherland, 2000)

Range	Class
EF<1	no enrichment
1≤EF<3	minor enrichment
3≤EF<5	moderate enrichment
5≤EF<10	moderately severe enrichment
10≤EF<25	severe enrichment
25≤EF<50	very severe enrichment
EF>50	extremely severe enrichment

4. Results and Discussion

4.1 Sediment pH

The variation of pH in the study area is shown in Fig.3.The pH ranges convey that the sediment in the corresponding areas is generally acidic. The average pH value is 5.84. The minimum pH value observed is 3.78, and the maximum pH value is 8.15. Most of the sediments are acidic in the CRB. Acidic conditions reduce sediment binding sites, increasing anionic contaminant mobility, while neutral to alkaline conditions enhance adsorption, limiting mobility and bioavailability. In the upper reaches of forested river sediments, this low pH is mainly due to the presence of humic acid, and some native species of plants are adapted to this condition.

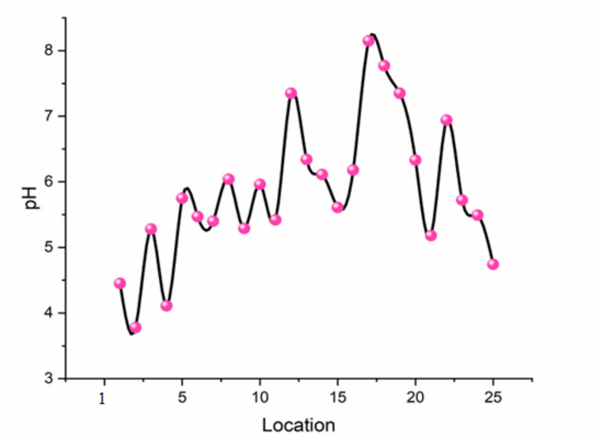

Fig.3 pH variation in surface sediments across sampling locations in the Chalakudy River

4.2. Heavy Metals (HMs)

Intense monsoonal precipitation significantly influences the mobilization, redistribution, and geochemical behavior of heavy metals in riverine environments, with profound implications for both water and sediment quality (Rahi et al., 2024). Globally, the persistence of heavy metal contamination remains a major environmental concern due to their non-biodegradable nature, participation in biogeochemical cycling, and the ecological hazards they present. Anthropogenic inputs from urban runoff, agrochemical residues, and industrial effluents introduce substantial quantities of heavy metals into fluvial systems.

These metals are subsequently transported through the water column, deposited into sediments, and potentially bioaccumulated and biomagnified within aquatic food webs, posing critical risks to benthic fauna, aquatic organisms, and human health (Eric et al., 2023). Sediments function as primary reservoirs for trace metals, and are widely regarded as effective indicators of long-term water pollution (Shil et al., 2019). However, the retention of heavy metals in sediments is not permanent; changes in physicochemical parameters or bioturbation can trigger their remobilization into the overlying water, reactivating their ecological threat.

Table 6 Statistical details of heavy metals in CR sediments, along with average shale values

HM	Mean	Shale Value	Standard Deviation	Skewness
V	199.8	130	36.5	0.3
Cr	153.6	90	68.7	0.89
Ni	68.7	50	20	0.23
Cu	118.4	45	44.4	0.73
Zn	145.1	95	44.1	2.73
Ga	21	19	2	0.87
Rb	145.6	140	61.4	1.99
Sr	352.3	170	196.1	2.1
Y	35.7	26	9.7	0.52
Zr	231.8	160	124.6	0.14
Ba	1504.2	580	446.5	-1.14
La	63	43	12.4	-0.58
Ce	205.7	82	46.5	-0.81

*HM: Heavy metal

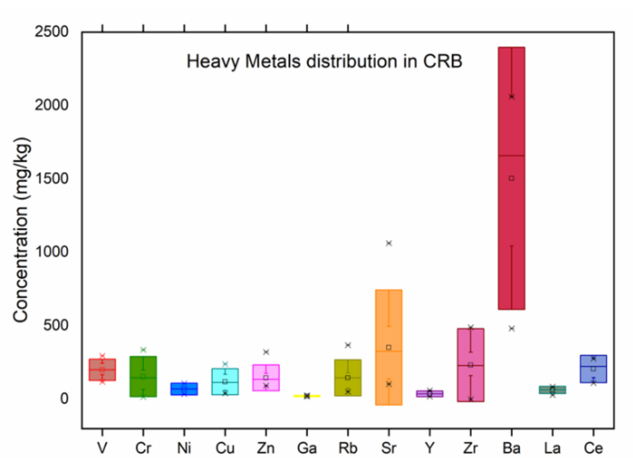

Fig.4 Box plot showing various heavy metal concentrations of sediments in the Chalakudy River

The mean heavy metal concentration of the sediment samples from the study area is shown in Table 6**.** The spatial distribution of heavy metals in the heavy monsoon period in CRB is shown in the Fig.4**.** From the figure, it is clear that the concentration of Ba in river sediments during the monsoon is comparatively higher than that of the other metals present in the area. The high concentration of barium in sediments could result from the natural weathering and erosion of rocks in the Western Ghats, which are rich in various types of rocks, especially granite and basalt, which can release barium into the river systems (Thomas et al.,2014). The Western Ghats experience intense monsoons, which contribute to the resuspension and transport of barium-rich sediments from upstream areas to downstream regions.

4.3 Contamination Geochemistry

The extent of heavy metal contamination in sediment samples from the study area was evaluated using multiple pollution indices, including the Contamination Factor (CF), Degree of Contamination (Cdeg), Pollution Load Index (PLI), Geo-accumulation Index (Igeo), and Enrichment Factor (EFc) (Mohan et al., 2022; Varol, 2011; Debanath et al., 2021). These geochemical indicators collectively offer a comprehensive understanding of the anthropogenic and natural influences on sediment quality. By quantifying the levels of trace metal accumulation, these indices help assess the magnitude of environmental stress on the sediment matrix, particularly under the influence of extreme hydro-meteorological events such as intense monsoonal flooding.

4.3.1 Contamination Factor (CF) and Degree of Contamination (C_{deg})

The contamination factor was found using equation (1), and from the values of contamination factors of elements from each location, the degree of contamination was calculated, and the results obtained are presented in Table 7. Figure 5 shows the distribution of contamination factors of each HMs in the monsoon period in the Chalakudy River. From the Degree of contamination (C_{deg}) results, a considerable degree of contamination is present during the heavy precipitation time in CR sediments. From Figure 6, the degree of contamination of sediment samples of the study area ranges from 17.42 to 25.20. The average value of the degree of contamination is 22.38. This means a considerable degree of contamination exists in the study area.

The increase in contamination may be due to the presence of an increase in barium content in sediments. This largely originates from the natural weathering of parent rocks in the Southern Western Ghats. Under acidic conditions, it becomes more bioavailable to aquatic systems, and elevated levels can be toxic to aquatic life and, if released into water, may pose risks to human health (Kravchenko et al., 2014). The moderate degree of contamination in sediments during heavy monsoons is attributed to enhanced runoff, erosion, and resuspension of sediments, which mobilize natural and anthropogenic pollutants (Seralathan et al.,1994).

Table 7 Ranges and mean of the Contamination factor (CF) in the study area, along with the degree of Contamination (C_{deg})

CF of HMs in CRB	Mean	Ranges
V	1.53	0.91-2.27
Cr	1.7	0.17-3.74
Ni	1.3	0.68-2.16
Cu	2.63	0.91-5.33
Zn	1.52	0.98-3.39
Ga	1.1	0.95-1.42
Rb	1.04	0.36-2.63
Sr	2.07	0.61-6.25
Y	1.37	0.69-2.35
Zr	1.44	0-3.06
Ba	2.59	0.83-3.55
La	1.46	0.67-1.98
Ce	2.5	1.34-3.37
Cdeg	22.38	17.42-25.20

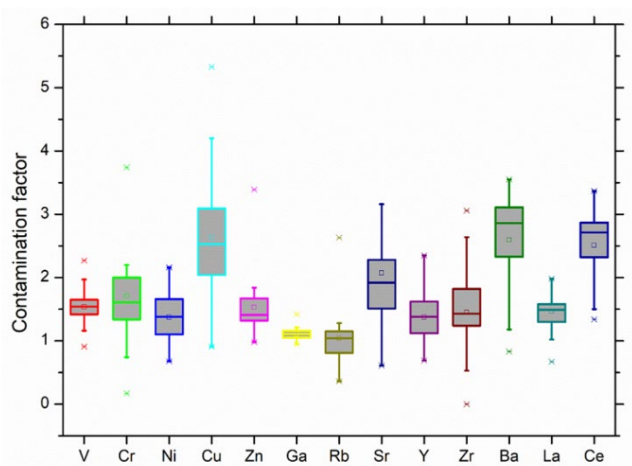

Fig.5 Box plot showing the ranges of contamination factor (CF) in the study area

4.3.2 Pollution Load Index (PLI)

Pollution Load Index of the samples were found out using the equation (2). From Figure 7, it is clear that monsoon sediments are observed for the Pollution Load Index (PLI) value above 1, indicating a level of contamination higher than the baseline or natural levels for the sediment (Das et al., 2019). In rivers of the Western Ghats, where monsoon rains are intense, the PLI during these periods can be elevated due to both natural processes (erosion of barium-rich rocks) and anthropogenic activities (pollution from agriculture and urban areas). In the Chalakudy River (CR) sediments, the PLI ranges from 1.2 to 1.8, which indicates slight pollution in the river sediments.

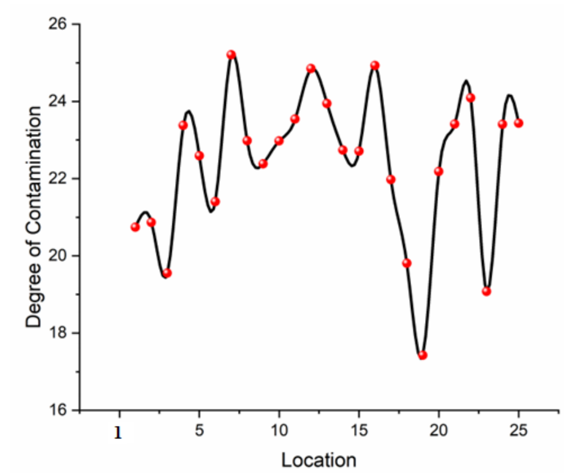

Fig.6 Degree of heavy metal contamination in sediments across sampling locations highland to lowland in the Chalakudy River

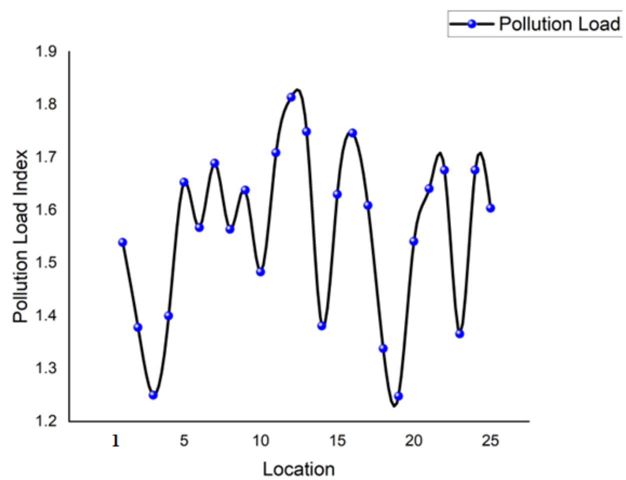

Fig.7 Spatial variation of Pollution Load Index (PLI) in Chalakudy River sediments

4.3.3 Geoaccumulation Index (Igeo)

The geoaccumulation index is found using equation (3), and the results are shown in Table 8. The results are tabulated below. Based on geoaccumulation index there is less or unpolluted sediments in Chalakudy River. The negative Igeo implies that individual metals may not have significant anthropogenic enrichment, and the contamination may primarily stem from natural sources or be influenced by dilution effects during heavy monsoons (Debnath et al.,2024). The geoaccumulation index distribution in each location is depicted in Fig.8. In the CR sediments, the Igeo values of metals vary across the locations, but all the metals are in the category of no enrichment (Class 0 Igeo<1) according to their Igeo values, as shown in Table 4.

4.3.4 Enrichment Factor (EF)

Enrichment Factor is found out using the equation (4). The results are shown in the Table 8.

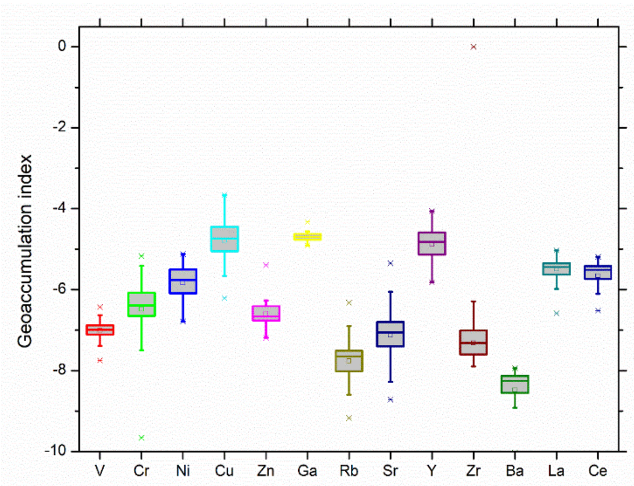

Fig.8. Boxplot showing the Geoaccumulation index w.r.t various heavy metals in the study area

Table 8 Estimated values of Enrichment factors in study area

EF	Mean	Ranges
V	2.45	0.24-4.19
Cr	2.54	1.03-3.89
Ni	2.13	1.29-5.49
Cu	4.65	1-4.68
Zn	2.52	0.33-6.9
Ga	1.86	0.55-26.46
Rb	1.82	0.95-3.49
Sr	4.18	0.55-26.46
Y	2.19	0.95-3.49
Zr	2.16	0-4.23
Ba	4.58	0.75-13.31
La	2.29	1.51-3.42
Ce	4.4	1.22-12.8

Based on the results obtained the majority of the study area is minor to major enrichment for heavy metals and some locations it is severely enriched with heavy metal. The enrichment factor (EF) for heavy metal pollution in the sediments indicates minor to moderate enrichment, suggesting that the contamination is influenced by both natural sources, such as lithological contributions, and anthropogenic activities, including agricultural runoff and urban discharges during the heavy monsoon period (Das Sharma et al., 2019; Debnath et al., 2024). The enrichment factor distribution of each metal in the Chalakudy river during the monsoon extreme time is depicted in the Fig.9.

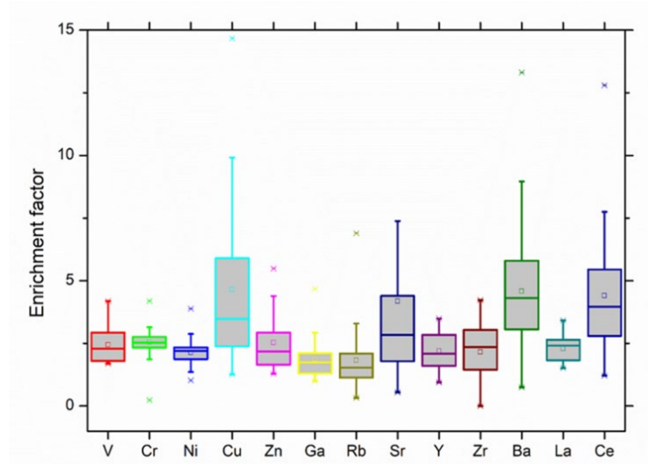

Fig.9. Box plot showing Enrichment factor distribution in sediments of the study area

5. Conclusions

This study highlights the geochemical responses of riverine sediments on heavy monsoon events intensified by climate change in the Chalakudy River Basin (CRB), during 2019, which caused flooding and severe economic losses. In this study, heavy metal contamination in riverine sediments of CRB has been studied, and the results indicate that extreme rainfall and increased runoff promote moderate levels of sediment contamination by enhancing erosion, transport, and resuspension of heavy metals. Although the geo-accumulation index suggests negligible contamination, the enrichment factor reveals slight to moderate enrichment, reflecting the combined influence of natural geological processes and anthropogenic activities. Rigorous tracking of sediment quality, is essential in understanding this pollution status and to take remedial measures for ensuring the ecological health and resilience of the river system in the face of future climate-related hydrological extremes. Since the Western Ghats River basins are prone to extreme climatic events as per -the warnings of UN this type of approaches are essential.

This study supports Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 14 (Life Below Water), highlighting the importance of monitoring environmental changes to safeguard aquatic resources and ensure sustainable river basin management. By addressing the impacts of climate change on sediment geochemistry and contamination, this study underscores the need for the protection of aquatic resources and effective management of river ecosystems.

The present study serves as a baseline data for understanding sediment geochemistry during periods of extreme precipitation, especially in the rivers of the Western Ghats, which are prone to the impacts of extreme events at shorter intervals. It should also serve as reference data for long-term monitoring and trend analysis, as well as for comparing sediment geochemistry during normal periods and future extreme events. This will help to evaluate mitigation strategies, track pollutant dispersion, and support policymaking for sustainable river basin management.

CRediT authorship contribution statement.

Resmi R: Conceptualization, sample collection, formal analysis, data curation, investigation, concept, writing original draft, validation, methodology, visualization. **A Krishnakumar:** conceptualization, formal analysis, data curation, supervision, validation, project administration, resources. **K Anoop Krishnan**: data curation, formal analysis, visualization. **Rajesh Reghunath**: Conceptualization, Data curation, validation, visualization

Declaration of competing interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this paper.

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