

Magnetic Susceptibility and Statistical Modeling for the Assessment of Toxic Heavy Metals in Surface Sediments of Ennore Port, East Coast of Tamil Nadu, India

D. Rajendiran

Shanmuga Industries Arts and Science College

N. Harikrishnan

harikrish.physics05@gmail.com

Sri Venkateswara College of Engineering

N. R. Sheela

Sri Venkateswara College of Engineering

K. Veeramuthu

Thiru Kolanjiappar Government Arts College

Research Article

Keywords: Sediments, Pollution Sources, Magnetic Susceptibility, Heavy Metals, Statistical Analysis

Posted Date: February 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8257448/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

The investigation of heavy metals in the Ennore ecosystem is crucial for assessing the magnitude and distribution of pollution in the region. In the present study, the concentrations of major and trace elements, including Mg, Al, Si, K, Ca, Ti, Fe, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd, Ba, La, and Pb, were determined in twenty-six sediment samples. The abundance of heavy metals in the sediments followed the decreasing order: Si > Al > Fe > Ca > Ti > K > Mg > Mn > Ba > V > Cr > Zn > La > Ni > Pb > Co > As > Cd > Cu. The average concentrations of all analyzed metals were found to be below the global crustal average. Owing to their strong affinity for forming metallic bonds with ferromagnetic materials, these metals significantly influence the magnetic properties of sediments, particularly magnetic susceptibility. Consequently, low-frequency (χ_{lf}), high-frequency (χ_{hf}), and frequency dependent (χ_{fd}) magnetic susceptibility measurements were carried out using an MS2B dual-frequency susceptibility meter. Furthermore, multivariate statistical techniques, including Pearson correlation, factor analysis, and cluster analysis, were employed to elucidate the relationships between heavy metal concentrations and magnetic susceptibility parameters, with the objective of evaluating anthropogenic influences on the sediments. The results demonstrate that magnetic susceptibility measurements provide a rapid, cost effective, non destructive, and reliable proxy for identifying and assessing sources of heavy metal contamination in sedimentary environments.

1.0. Introduction

Heavy metal contamination of sediments represents one of the most critical global environmental issues, posing substantial risks to ecosystems and human health. In recent years, the accumulation of heavy metals in coastal environments has intensified due to increasing anthropogenic activities, including industrial effluent discharge, tourism, and fishing operations (Dang et al., 2002). Sediments function as major sinks for heavy metals through the formation of stable complexes with organic matter, carbonates, and iron (Fe) and manganese (Mn) oxides (Duzzin et al., 1988). These metal fractions exhibit varying degrees of mobility, toxicity, and chemical reactivity, influencing their environmental behavior and bioavailability. Consequently, a comprehensive understanding of the geochemical speciation of metals is essential for accurately assessing sediment contamination and evaluating the potential ecological and human health risks associated with heavy metal exposure (Yalcin et al., 2016).

Magnetic susceptibility is a measure of the concentration of iron-bearing components in sediments and is widely used to characterize sediment types and quantify the abundance of iron-bearing minerals (Canbay, 2010). It represents a rapid, sensitive, and cost-effective analytical approach, providing an important parameter for applications in mineralogical and granulometric studies (Canbay, 2010). In recent years, magnetic susceptibility measurements have been extensively employed to identify and trace sources of heavy metal pollution. Techniques based on the magnetic properties of sediments have been widely adopted by environmental scientists and have demonstrated considerable success in pollution assessment studies. Numerous investigations have established magnetic susceptibility as a reliable indicator for identifying sources of heavy metal contamination (Thompson et al., 1986; Hay et al., 1997; Strzyszc et al., 1998; Durza, 1999; Lecoanet et al., 2001; Knab et al., 2001; Kapicka et al., 2003; Hanesch and Scholger, 2005; Lu et al., 2007). This relationship is primarily attributed to anthropogenic emissions, which commonly contain fine, strongly magnetic particles that are often enriched with heavy metals, particularly in soils and sediments of industrialized regions (Canbay, 2010).

Magnetic measurements have proven to be an effective tool for assessing the transport and distribution of pollutants through atmospheric and aquatic pathways (Scholger, 1998; Petrovský et al., 2000). The application of magnetic parameters as proxies for heavy-metal contamination is based on the close genetic and geochemical association between heavy metals and magnetic mineral phases. Numerous environmental magnetism studies have consistently reported strong correlations between heavy-metal concentrations and magnetic properties of soils and sediments (Hanesch et al., 2001; Jordanova et al., 2004; Schmidt et al., 2005; Spiteri et al., 2005).

Coastal populations are particularly vulnerable to heavy-metal exposure through direct contact with beach sediments and the inadvertent ingestion of seawater (Yalcin et al., 2016). The present study area includes several environmentally sensitive hotspots, such as tourist destinations, active fishing zones, and nearby industrial regions, which together increase the potential risk of metal contamination. In this context, the objectives of the present study are to: (i) quantify the concentrations of heavy metals and measure the magnetic susceptibility of surface sediments collected from Ennore Port along the east coast of Tamil Nadu; (ii) characterize the magnetic mineralogical properties of the sediments; (iii) evaluate the relationships between heavy-metal concentrations and magnetic susceptibility using multivariate statistical techniques; and (iv) identify the potential sources of heavy-metal pollution.

2.0. Geology of the Study Area

Ennore hosts the Ennore Port, officially designated as Kamarajar Port Limited, which functions as a key hub for regional trade and commercial activities. The port handles a diverse range of cargo, including containers, coal, petroleum products, and general merchandise. Strategically situated along the eastern coast of the Indian peninsula in the Bay of Bengal, Ennore Port lies approximately 2.5 km north of the Ennore Creek (Pandian et al., 2002). Owing to its intensive maritime operations, the port plays a pivotal role in supporting industrial growth and maritime trade within the Chennai metropolitan region and its adjoining areas.

The Ennore region and its environs accommodate numerous industrial establishments, such as thermal power stations, petroleum refineries, chemical processing units, and other manufacturing industries. While these activities significantly contribute to regional economic development, they also exert considerable pressure on the surrounding environment, leading to concerns related to pollution and ecological degradation of coastal systems. Similar to other rapidly industrializing and urbanizing coastal zones, Ennore experiences multiple environmental stresses, including contamination of air, water, and sediments, habitat alteration, and declining biodiversity. In response, various mitigation measures, environmental regulations, and conservation strategies have been initiated to manage and reduce these impacts.

Despite the extent of industrial development, Ennore retains substantial ecological importance, supported by coastal ecosystems such as mangroves, estuaries, and tidal flats. These habitats provide essential ecological services, including biodiversity support, shoreline protection, enhancement of water quality, and improved coastal resilience. Overall, Ennore represents a complex landscape characterized by the coexistence of industrial, commercial, and residential activities, coupled with significant environmental and socioeconomic challenges. Sustainable management and integrated planning are therefore essential to balance development with environmental protection. The geological characteristics of the study area are summarized in Table 1, while Fig. 1 illustrates the location map of the study area.

3.0. Materials and Methods

3.1. Sample Collection and Preparation

Figure 1 illustrates the locations of the sediment sampling sites, extending from 13°13'18.50" N, 80°20'10.10" E to 13°15'13.33" N, 80°20'17.43" E, as detailed in Table 1. A total of 26 sediment samples were obtained during the pre-monsoon period from three distinct environmental settings within the Ennore region, namely the sea (S), beach (B), and creek (C) zones along the east coast of Tamil Nadu. A Peterson grab sampler was used to carry out the sampling.

This study used a flame atomic absorption spectrometer (AAS; iCE 3000, Thermo Scientific, USA) to determine the concentrations of heavy metals. The principle of optical radiation absorption by free atoms in the gaseous phase was used to carry out both qualitative and quantitative analyses. Three to five standard solutions, prepared by appropriate dilution of a 1000 ppm certified stock solution, were used to establish calibration curves for each metal. Hollow cathode lamps corresponding to Pb, As, Hg, Cu, Zn, Cr, Ni, and Mn served as radiation sources, with an air-acetylene mixture being employed as fuel. The mean values were reported as the final concentrations after analyzing all samples and standards in replicates.

Table 1
Latitude and Longitude of the Study Area of Ennore,
East Coast of Tamilnadu, India

S. No	Sample	Latitude	Longitude
1	S1	13°14'46.02"	80°20'31.56"
2	S2	13°14'44.83"	80°20'48.04"
3	S3	13°14'44.09"	80°21'6.35"
4	S4	13°14'1.40"	80°20'20.71"
5	S5	13°14'1.32"	80°20'39.85"
6	S6	13°14'1.20"	80°20'56.76"
7	S7	13°13'18.50"	80°20'10.10"
8	S8	13°13'19.04"	80°20'29.96"
9	S9	13°13'19.54"	80°20'46.77"
10	B1	13°15'13.33"	80°20'17.43"
11	B2	13°14'49.77"	80°20'8.12"
12	B4	13°14'0.75"	80°19'46.26"
13	B5	13°15'12.59"	80°20'21.18"
14	B6	13°14'49.51"	80°20'10.55"
15	B7	13°14'0.79"	80°19'48.15"
16	B8	13°15'12.01"	80°20'25.27"
17	B9	13°14'49.51"	80°20'13.40"
18	C1	13°13'58.55"	80°19'38.62"
19	C2	13°13'50.50"	80°19'22.59"
20	C4	13°13'26.04"	80°18'53.16"
21	C5	13°13'9.64"	80°18'42.67"
22	C9	13°13'2.15"	80°18'52.99"
23	C10	13°13'59.38"	80°18'55.29"
24	C11	13°14'17.55"	80°18'56.60"
25	C12	13°14'35.42"	80°18'55.95"
26	C13	13°14'54.22"	80°18'51.95"

The Ennore coastal region was studied for the spatial variation of natural radionuclides from terrestrial to marine environments by collecting sediment samples. Sampling was carried out at three distinct zones: the nearshore marine region at a distance of 10 m parallel to the shoreline and at a water depth of 4 m (nine samples), the beach zone (eight samples), and the creek region (nine samples). After being collected, the samples were placed in clean polyethylene bags, labelled appropriately for their respective sampling locations, and transported to the laboratory. After air drying the samples in ambient conditions, coarse materials like shell fragments and stone debris were manually removed.

3.2. Atomic Absorption Spectrometry (AAS) Analysis

The flame atomic absorption spectrometer (AAS; ICE 3000, Thermo Scientific, USA) was used to determine the concentrations of heavy metals in this study. Qualitative and quantitative analyses were performed utilizing the principle of optical radiation absorption by free atoms in the gaseous phase. Three to five standard solutions prepared with appropriate dilution of a 1000 ppm certified stock solution were used to establish calibration curves for each metal. Hollow cathode lamps corresponding to Pb, As, Hg, Cu, Zn, Cr, Ni, and Mn served as radiation sources, with an air-acetylene mixture being employed as fuel. The mean values were reported as the final concentrations after analyzing all samples and standards in replicates.

3.3. Magnetic Susceptibility (χ) Measurements

To prevent any potential chemical changes and minimize the impact of moisture, the collected samples were air-dried at ambient temperature in the laboratory. Using established procedures (Zhang et al., 2011), extraneous materials like glass fragments, plant remains, refuse, and coarse lithic particles were removed from the dried samples after sieving through a 1 mm mesh. After processing, the samples were transferred to clean plastic containers and preserved for future analysis. The sieved material was packed into 10 ml plastic sample holders and analyzed at room temperature for magnetic susceptibility measurements. The use of an MS2B dual-frequency magnetic susceptibility meter, interfaced with a computer running Multisus2 software, resulted in measurements at both low (0.0465 kHz) and high (4.65 kHz) operating frequencies.

The sensitivity setting of 1.0 was used for all analyses. The mean value was calculated to ensure analytical reliability by taking five replicate measurements at each frequency for each sample. In natural sediment samples, the grain-size distribution is generally continuous and nearly uniform, making magnetic susceptibility a trustworthy indicator of relative variations in the concentration of pedogenic fine-grained magnetic minerals (Liu et al., 2005). The standard expression proposed by Dearing (1999) was used to determine frequency-dependent magnetic susceptibility (χ_{fd}).

$$\chi_{fd} (\%) = \left[\frac{\chi_{lf} - \chi_{hf}}{\chi_{lf}} \right] \times 100 \quad (1)$$

3.4. Multivariate Statistical Analysis

Multivariate statistical techniques namely Pearson's correlation analysis, factor analysis, and hierarchical cluster analysis were applied to examine the interrelationships between heavy metal concentrations and magnetic susceptibility parameters in sediment samples. These methods were employed to identify potential source contributions and to discriminate between lithogenic and anthropogenic inputs of heavy metals. All statistical analyses were performed using SPSS software (Statistical Package for the Social Sciences, version 16.0), and the statistical significance was evaluated at the predefined confidence level.

4.0. Results and Discussions

4.1. Heavy Metal Concentration in Sediments

The distribution of heavy metals in surface sediments of coastal environments such as Ennore is governed by a combination of anthropogenic and natural factors. Industrial operations, port and shipping activities, rapid urban expansion, and associated land-based inputs play a significant role in controlling metal accumulation in these sediments. Heavy metals enter the sedimentary system through multiple pathways, including industrial effluents, atmospheric fallout, urban surface runoff, and the weathering and transport of contaminated terrestrial materials. Systematic evaluation of metal concentrations in surface sediments is therefore essential for understanding sediment quality, identifying pollution sources, and assessing potential ecological and human health risks. The measured concentrations of the investigated elements in the sediment samples from the study area are summarized in Table 2. The concentration (mg kg^{-1}) varies as follows: 298 to 5987, 11478 to 37432, 115987 to 224978, 2985 to 9850, 3792 to 23176, 540 to 49434, 3597 to 56502, 22.37 to 691, 11.5 to 198.29, 69.10 to 1227.61, 1.40 to 19.95, 11.48 to 38.63, BDL to 3.60, 11.04 to 87.99, 1.8 to 9.9, 1.1 to 11.2, 142.3 to 426.8, BDL to 214.7 and BDL to 30.7 for Mg, Al, Si, K, Ca, Ti, Fe, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd, Ba, La and Pb respectively. Among the analyzed elements, aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), and silicon (Si) were identified as the dominant constituents in the sediment samples. The mean concentration of metals followed the descending order: $\text{Si} > \text{Al} > \text{Fe} > \text{Ca} > \text{Ti} > \text{K} > \text{Mg} > \text{Mn} > \text{Ba} > \text{V} > \text{Cr} > \text{Zn} > \text{La} > \text{Ni} > \text{Pb} > \text{Co} > \text{As} > \text{Cd} > \text{Cu}$ across the study area. Notably, sampling locations S2, S9, B4, B7, B9, C4, and C9 exhibited comparatively elevated levels of V, Cr, Co, Ni, and Zn relative to other sites. These enhanced concentrations can be attributed to intense anthropogenic influences, including harbor-related activities, industrial operations, urban effluent discharge, and dredging practices. The observed trends are consistent with reports from comparable coastal and industrialized environments documented in earlier studies (Nath et al., 1989; Millward and Moore, 1982; Santhiya et al., 2011).

Elevated concentrations of Ti, Fe, V, Cr, Mn, As, and Pb were observed at sampling locations S1, S2, S9, B2, B7, B8, B9, C4, C5, C9, and C11. These enrichments are likely associated with intensive anthropogenic activities linked to Ennore Port, which manages diverse cargo types such as coal, petroleum products, and general merchandise. Operational activities including dredging, vessel movement, and cargo loading and unloading can disrupt sediment strata and promote the resuspension and redistribution of metal contaminants, thereby enhancing their accumulation in bottom sediments. Occasional events, such as ballast water discharge, oil spill incidents, and accidental leakage of hazardous substances from ships, may further contribute to the input of heavy metals into the coastal environment.

Table 2
Heavy Metal Concentration of the Sediment Samples along the Study Area of Ennore, East Coast of Tamilnadu, Indi

Element	Mg	Al	Si	K	Ca	Ti	Fe	V	Cr	Mn	Co	Ni	Cu	Zn
Unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
S1	2822 ± 19.3	22895 ± 215.40	196697 ± 174.5	4568 ± 14.6	23176 ± 19.5	10689 ± 84.2	30771 ± 128.4	264.56 ± 17.6	113.33 ± 10.2	741.38 ± 44.1	12.95 ± 2.1	34.30 ± 1.6	1.69 ± 0.6	67.67 ± 6.5
S2	4851 ± 28.1	30132 ± 101.0	146205 ± 132.9	4950 ± 21.0	20679 ± 14.6	18739 ± 44.6	40889 ± 355.5	312.87 ± 20.6	145.77 ± 10.5	871.09 ± 49.5	16.35 ± 1.4	33.23 ± 2.6	3.60 ± 0.9	69.94 ± 5.9
S3	840.0 ± 8.1	21112 ± 111.5	178446 ± 267.4	2985 ± 11.4	10057 ± 74.1	2357 ± 9.4	12807 ± 110.9	98.94 ± 7.6	64.52 ± 4.1	249.11 ± 13.5	6.01 ± 0.9	13.21 ± 1.4	1.29 ± 0.1	29.78 ± 2.4
S4	1508 ± 17.0	12066 ± 98.01	130139 ± 124.9	5192 ± 8.54	13628 ± 55.9	3976 ± 12.7	13937 ± 124.6	78.38 ± 4.8	75.33 ± 1.6	264.74 ± 14.9	3.71 ± 0.1	27.59 ± 2.6	BDL	31.00 ± 3.1
S5	805.0 ± 7.1	24954 ± 156.2	179547 ± 155.5	7786 ± 14.9	14363 ± 99.7	731 ± 7.1	8298 ± 78.9	37.85 ± 1.9	41.85 ± 2.0	159.81 ± 8.7	9.10 ± 1.0	26.84 ± 1.9	2.46 ± 0.1	23.47 ± 2.9
S6	1842 ± 16.2	22728 ± 124.5	203630 ± 194.8	9850 ± 13.2	10586 ± 84.6	924 ± 6.8	6873 ± 66.5	23.12 ± 1.5	29.32 ± 1.1	138.35 ± 10.6	1.40 ± 0.8	19.67 ± 0.7	2.34 ± 0.3	39.023.7
S7	1935 ± 14.9	21075 ± 164.3	177947 ± 154.7	7047 ± 19.4	8403 ± 41.0	1683 ± 14.6	9120 ± 17.9	41.01 ± 3.1	67.16 ± 3.8	165.61 ± 14.6	6.42 ± 0.6	22.16 ± 1.1	1.98 ± 0.1	26.08 ± 2.1
S8	3355 ± 11.4	29875 ± 109.1	134994 ± 249.8	4059 ± 9.84	17169 ± 13.4	3769 ± 147.0	17881 ± 15.9	96.6 ± 4.6	102.3 ± 7.4	132.3 ± 9.7	7.54 ± 1.0	28.1 ± 2.6	BDL	39.8 ± 3.4
S9	4518 ± 35.2	25067 ± 100.6	139370 ± 176.2	5932 ± 24.6	10027 ± 97.5	8714 ± 74.6	24994 ± 21.4	191.9 ± 11.2	148.1 ± 13.4	108.1 ± 8.9	7.31 ± 0.9	31.4 ± 2.0	2.65 ± 0.2	46.0 ± 4.1
B1	895.0 ± 4.6	18546 ± 98.44	175149 ± 144.0	7615 ± 12.8	9643 ± 47.5	2139 ± 18.4	9534 ± 68.7	77.11 ± 6.2	41.38 ± 3.2	190.26 ± 9.1	7.38 ± 1.3	18.86 ± 1.1	1.05 ± 0.5	27.54 ± 2.2
B2	844.0 ± 7.1	11478 ± 87.02	204961 ± 185.7	6302 ± 10.3	7939 ± 68.1	2390 ± 11.6	8458 ± 74.1	48.9 ± 1.2	29.3 ± 1.6	177.1 ± 12.6	4.8 ± 0.8	12.8 ± 1.0	2.47 ± 0.2	21.0 ± 2.9
B4	1942 ± 11.0	19254 ± 144.3	194328 ± 165.9	4484 ± 8.65	7970 ± 44.2	49434 ± 141.6	56502 ± 447.6	691.0 ± 12.9	198.3 ± 11.6	1227.6 ± 98.6	19.95 ± 1.6	27.4 ± 1.6	1.09 ± 0.1	87.99 ± 7.4
B5	985.0 ± 6.5	20147 ± 121.3	201876 ± 199.5	6844 ± 18.7	3792 ± 17.9	1520 ± 107.6	3637 ± 288.6	22.4 ± 2.9	28.5 ± 1.9	72.1 ± 4.4	5.1 ± 0.6	19.2 ± 1.9	BDL	11.04 ± 1.0
B6	2447 ± 15.1	21654 ± 210.6	149657 ± 136.4	7369 ± 25.9	6806 ± 41.7	1116 ± 84.6	7520 ± 84.6	26.37 ± 1.9	28.2 ± 1.1	128.05 ± 10.6	2.88 ± 0.8	11.48 ± 1.0	BDL	19.16 ± 1.2
B7	1974 ± 3.9	14785 ± 144.6	115987 ± 98.60	5084 ± 17.4	17809 ± 147.2	13464 ± 119.5	22269 ± 199.6	198.71 ± 10.6	129.00 ± 10.4	798.16 ± 47.9	18.51 ± 1.1	38.63 ± 3.6	2.04 ± 0.2	63.31 ± 6.4
B8	889.0 ± 3.4	17362 ± 173.1	224978 ± 178.5	4478 ± 11.4	20176 ± 155.0	11589 ± 105.4	33441 ± 299.5	214.56 ± 17.6	113.33 ± 9.8	777.38 ± 68.4	16.95 ± 0.9	37.30 ± 2.9	1.9 ± 0.1	61.67 ± 5.8
B9	1748 ± 1.6	21568 ± 241.6	224879 ± 199.1	4350 ± 32.9	19679 ± 146.1	18539 ± 174.6	40189 ± 400.9	330.87 ± 12.5	144.77 ± 12.4	899.09 ± 74.6	17.35 ± 1.6	31.23 ± 2.4	3.60 ± 0.3	69.94 ± 5.7
C1	298.0 ± 4.4	13132 ± 128.7	209618 ± 199.5	7100 ± 10.8	4582 ± 10.3	540 ± 6.8	3597 ± 294.5	22.4 ± 0.8	11.5 ± 5.6	69.10 ± 5.9	2.10 ± 0.4	14.2 ± 1.6	BDL	12.0 ± 1.3
C2	1166 ± 6.1	18966 ± 176.1	191935 ± 270.6	7769 ± 21.7	7396 ± 14.2	1206 ± 11.9	5510 ± 51.6	24.37 ± 1.8	22.21 ± 1.9	112.05 ± 9.8	2.88 ± 0.6	14.48 ± 1.1	2.11 ± 0.2	18.16 ± 1.4
C4	5987 ± 1.1	30793 ± 298.4	163332 ± 145.9	5144 ± 15.4	20909 ± 147.0	14964 ± 164.2	36169 ± 311.0	224.71 ± 14.5	187.00 ± 15.8	748.16 ± 16.5	11.51 ± 1.1	31.63 ± 2.4	1.11 ± 0.1	61.31 ± 5.9

Element	Mg	Al	Si	K	Ca	Ti	Fe	V	Cr	Mn	Co	Ni	Cu	Zn
Unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
C5	2945 ± 2.4	26995 ± 256.3	134697 ± 122.2	4668 ± 9.87	20976 ± 133.7	11989 ± 113.7	34071 ± 314.9	211.56 ± 11.0	111.33 ± 9.4	741.38 ± 14.6	10.95 ± 1.6	34.30 ± 2.8	1.98 ± 0.1	64.67 ± 5.1
C9	4974 ± 6.4	37432 ± 341.2	151205 ± 149.6	4750 ± 14.9	21579 ± 211.2	18939 ± 163.5	40389 ± 394.6	309.87 ± 21.5	154.77 ± 9.7	871.09 ± 61.5	13.35 ± 1.1	31.23 ± 2.9	3.60 ± 0.4	61.94 ± 2.9
C10	879.0 ± 11	22112 ± 198.4	149446 ± 110.0	6185 ± 11.0	11957 ± 97.8	3157 ± 32.8	12807 ± 1118.4	61.94 ± 4.6	53.52 ± 3.5	241.11 ± 10.9	7.01 ± 0.6	24.21 ± 2.1	2.01 ± 0.3	29.78 ± 4.6
C11	1598 ± 5.7	18966 ± 166.6	127139 ± 99.21	5692 ± 19.5	11528 ± 54.6	3676 ± 29.4	12937 ± 99.7	98.38 ± 8.4	51.33 ± 2.8	261.74 ± 18.8	5.61 ± 0.7	22.59 ± 2.0	3.15 ± 0.4	28.00 ± 2.2
C12	802.0 ± 9.0	23454 ± 199.2	177547 ± 127.9	7986 ± 10.1	10963 ± 77.9	921 ± 7.9	8288 ± 74.6	30.85 ± 1.0	42.85 ± 1.6	147.81 ± 10.4	2.10 ± 0.6	24.84 ± 1.9	BDL	21.47 ± 2.7
C13	1801 ± 4.4	22828 ± 211.5	190630 ± 146.3	9050 ± 18.5	11986 ± 78.1	794 ± 6.6	6793 ± 51.2	27.12 ± 1.1	29.32 ± 1.1	122.35 ± 9.5	3.40 ± 0.9	22.67 ± 1.1	1.65 ± 0.2	39.02 ± 1.6
Average	2101	21899	172090	6047	13222	7998	19526	144.86	83.24	400.58	8.56	25.14	1.68	41.19
Maximum	5987	37432	224978	9850	23176	49434	56502	691.00	198.29	1227.61	19.95	38.63	3.60	87.99
Minimum	298	11478	115987	2985	3792	540	3597	22.37	11.5	69.10	1.40	11.48	BDL	11.04

Moreover, the rapid expansion of nearby industrial infrastructures such as thermal power plants, oil refineries, and manufacturing industries can introduce metal pollutants through wastewater effluents, atmospheric deposition, and improper industrial waste management practices. In addition, the release of untreated or partially treated municipal and industrial sewage represents a significant pathway for heavy metal loading in coastal waters and sediments (Dai et al., 2007; Cheng and Hu, 2010; Hosono et al., 2011; Mendiguchia et al., 2006; Basaran et al., 2009). Figure 2 illustrates the spatial distribution and concentration levels of heavy metals within the study area.

4.2. Distribution of Magnetic Susceptibility (χ) in Sediments

Table 3 summarizes the results of the magnetic measurements, including low-frequency χ_{lf} and high frequency χ_{hf} magnetic susceptibilities. The χ_{lf} values range from $1.2145 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ to $57.7217 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, with a mean value of $8.6295 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$. Variations in χ_{lf} are primarily controlled by local geological conditions, sedimentary processes, and the contribution of anthropogenic inputs. Previous studies have demonstrated that the magnetic susceptibility of natural, non-polluted sediments is governed by five key factors: parent material, climate, geomorphology, vegetation, and time (Dearing et al., 1996; Lu et al., 2007). The high frequency magnetic susceptibility (χ_{hf}) values range from $1.1039 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ to $55.7733 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, with an average of $7.5163 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, exhibiting a trend comparable to that observed for χ_{hf} .

Table 3

Sample ID with Low Frequency Susceptibility (χ_{lf}) ($\times 10^{-8} \text{m}^3 \text{kg}^{-1}$), High Frequency Susceptibility (χ_{hf}) ($\times 10^{-8} \text{m}^3 \text{kg}^{-1}$) and Frequency Dependent Susceptibility (χ_{fd}) %

S. No	Location ID	Low-Frequency Mass Depended Susceptibility (χ_{lf}) ($\times 10^{-8} \text{m}^3 \text{kg}^{-1}$)	High-Frequency Mass Depended Susceptibility (χ_{hf}) ($\times 10^{-8} \text{m}^3 \text{kg}^{-1}$)	Frequency Dependent Susceptibility (χ_{fd}) %
1	S1	7.8738	6.6578	15.4436
2	S2	1.5996	1.5890	0.6627
3	S3	35.0048	34.4855	1.4835
4	S4	11.9887	11.3836	5.0473
5	S5	21.7731	20.3737	6.4272
6	S6	1.8659	1.3986	25.0442
7	S7	14.9841	11.1779	25.4016
8	S8	9.2712	8.3332	10.1174
9	S9	3.9235	1.8192	53.6332
10	B1	1.6871	1.3696	18.8193
11	B2	9.9921	9.7706	2.2168
12	B4	1.2145	0.8134	33.0259
13	B5	4.7743	3.3419	30.0023
14	B6	6.8852	6.7885	1.4045
15	B7	3.0568	2.6605	12.9645
16	B8	4.7312	2.4737	47.7152
17	B9	3.9865	1.3659	65.7369
18	C1	1.9811	1.1339	42.7641
19	C2	57.7217	55.7733	3.3755
20	C4	2.0923	1.1719	43.9899
21	C5	1.9687	1.3115	33.3824
22	C9	2.0687	1.7778	14.0620
23	C10	1.9809	1.1039	44.2728
24	C11	7.3217	4.7733	34.8061
25	C12	2.2322	1.1792	47.1732
26	C13	2.3871	1.3968	41.4855
Average		8.6295	7.5163	25.4022

According to the classification proposed by Gautam et al., (2004), sediments are categorized as normal magnetic ($\chi_{lf} < 10 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$), moderately magnetic ($\chi_{lf} = 10 - 100 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$), and highly magnetic ($\chi_{lf} > 100 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$). Based on this classification, samples S1, S2, S6, S8, S9, B1, B2, B4, B5, B6, B7, B8, B9, C1, C4, C5, C9, C10, C11, C12, and C13 fall within the normal magnetic category, whereas samples S3, S4, S5, S7, and C2 are classified as moderately magnetic. None of the analyzed samples exhibit highly magnetic characteristics.

Approximately 80.7% of the sediment samples exhibited moderate magnetic properties, while 19.3% displayed normal levels, and none were found to be highly magnetic. This distribution indicates a notable presence of ferrimagnetic minerals within the sediments. The observed variation in low-frequency magnetic susceptibility (χ_{lf}) values suggests that the relatively high measurements cannot be solely explained by local geology. Therefore, the elevated magnetic susceptibility is likely influenced by anthropogenic inputs of diverse origins and other human activities. As illustrated in Figs. 3 and 4, χ_{lf} values are consistently higher than high-frequency susceptibility (χ_{hf}) values. At high frequencies, the relaxation time of superparamagnetic grains is shorter than the measurement duration, rendering their contribution negligible. In contrast, low-frequency measurements capture the susceptibility of all grains, including those with short relaxation times, such as fine super paramagnetic particles. Consequently, while the grain volume in the sediment remains constant, magnetic susceptibility is higher at low frequencies than at high frequencies (Kanu et al., 2013).

4.3. Frequency Dependent Susceptibility (χ_{fd})

Frequency dependent susceptibility (χ_{fd}) is widely used as an analytical tool to examine variations in the magnetic grain size distribution within sediment samples (Kanu et al., 2013).

when χ_{fd} values are low, the magnetic properties of the samples tend to be dominated by coarse multi domain (MD) particles rather than by superparamagnetic (SP) grains. According to Dearing's model for χ_{fd} (Dearing, 1999), sediments with χ_{fd} values between 0% and 2% are typically characterized by coarse MD grains. Sediments with χ_{fd} values ranging from 2% to 10% contain a mix of SP and single-domain (SD) grains, while those exceeding 10% are primarily composed of SP ferrimagnetic grains. In this study, all three types of magnetic assemblages were observed. Samples S2, S3, and B6, showing χ_{fd} values from 0% to 2%, are dominated by coarse MD grains.

On the other hand, samples S3, S4, S5, B2, B6, and C2, with χ_{fd} values between 2% and 10%, represent an intermediate group, indicating a blend of SP and SD grains. Finally, samples S1, S6, S7, S8, S9, B1, B4, B5, B7, B8, B9, C1, C4, C5, C9, C10, C11, C12, and C13, which exhibit χ_{fd} values greater than 10%, are dominated by SP ferrimagnetic grains. The spatial variation of χ_{fd} across the different sampling sites is presented in Fig. 5.

4.4. Pearson Correlation Analysis

The correlation between magnetic parameters and heavy metal contents indicated a clear association between ferrimagnetic oxides and heavy metals (Dong et al., 2014). In previous studies, the relationship between magnetic susceptibility and heavy metal concentrations has typically been evaluated using Pearson correlation analysis. In the present study, although the correlation between magnetic susceptibility and heavy metals was significant at the 1% level for all samples, the relationships between magnetic particles and pollutants remain complex and vary across different industrial processes (Bandaru et al., 2016). Notably, the correlation coefficients (r^2) between magnetic susceptibility and heavy metal concentrations in this study did not exceed 0.50, suggesting that the relationship diminishes in sediment samples with low magnetic susceptibility. The detailed correlation coefficients between heavy metals and magnetic susceptibility are presented in Table 4.

Table 4
Correlation Matrix between Heavy Metals and Magnetic Parameters in Sediment Samples along the Study Area of Ennore,

Correlations															
Variables	Mg	Al	Si	K	Ca	Ti	Fe	V	Cr	Mn	Co	Ni	Cu	Zn	As
Mg	1														
Al	0.756	1													
Si	-0.437	-0.271	1												
K	-0.330	-0.166	0.239	1											
Ca	0.570	0.530	-0.223	-0.533	1										
Ti	0.388	0.212	0.017	-0.519	0.339	1									
Fe	0.587	0.418	-0.060	-0.669	0.655	0.907	1								
V	0.422	0.253	0.016	-0.598	0.432	0.984	0.946	1							
Cr	0.710	0.459	-0.217	-0.682	0.647	0.832	0.938	0.867	1						
Mn	0.432	0.272	-0.003	-0.623	0.670	0.881	0.940	0.904	0.845	1					
Co	0.361	0.227	-0.021	-0.647	0.648	0.808	0.873	0.843	0.831	0.920	1				
Ni	0.502	0.372	-0.279	-0.480	0.828	0.504	0.707	0.561	0.759	0.694	0.757	1			
Cu	0.297	0.298	-0.016	-0.135	0.429	0.249	0.392	0.307	0.326	0.389	0.428	0.342	1		
Zn	0.558	0.374	-0.069	-0.574	0.731	0.842	0.944	0.887	0.896	0.930	0.878	0.784	0.423	1	
As	0.216	0.196	0.432	-0.139	0.166	0.631	0.588	0.660	0.505	0.504	0.501	0.303	0.282	0.567	1
Cd	0.018	-0.079	-0.252	0.146	-0.302	-0.217	-0.299	-0.251	-0.250	-0.285	-0.290	-0.416	-0.323	-0.335	-0.361
Ba	-0.463	-0.290	0.334	0.780	-0.729	-0.615	-0.810	-0.691	-0.772	-0.783	-0.755	-0.702	-0.445	-0.751	-0.206
La	0.226	0.083	0.061	-0.469	0.181	0.962	0.791	0.923	0.709	0.785	0.714	0.345	0.138	0.728	0.557
Pb	0.501	0.395	-0.056	-0.578	0.679	0.865	0.930	0.888	0.876	0.943	0.904	0.760	0.400	0.923	0.558
LF	-0.271	-0.155	0.112	0.024	-0.249	-0.291	-0.331	-0.288	-0.319	-0.309	-0.280	-0.408	0.022	-0.366	-0.315
HF	-0.264	-0.151	0.097	0.022	-0.249	-0.284	-0.329	-0.284	-0.321	-0.303	-0.284	-0.422	0.005	-0.363	-0.327
FD	-0.002	0.034	0.280	0.043	0.060	0.171	0.219	0.180	0.226	0.141	0.137	0.296	0.071	0.210	0.385
**. Correlation is significant at the 0.01 level (2-tailed).															
*. Correlation is significant at the 0.05 level (2-tailed).															

4.5. Factor Analysis

Principal Component Analysis (PCA) is an effective statistical tool for elucidating the relationships between magnetic minerals and heavy metals in sediments (Zhu et al., 2012; Wang et al., 2018).

Table 5
Rotated Factor Loadings of Heavy Metals and Magnetic Parameters in Sediments Samples along the Study Area of Ennore, East Coast of Tamilnadu, India

Variables	Factor 1	Factor 2
Mg	0.695	-0.114
Al	0.486	-0.047
Si	-0.494	0.869
K	-0.665	-0.103
Ca	0.641	0.099
Ti	0.806	0.482
Fe	0.894	0.438
V	0.831	0.494
Cr	0.910	0.266
Mn	0.823	0.464
Co	0.770	0.414
Ni	0.723	0.086
Cu	0.334	0.167
Zn	0.851	0.403
As	0.331	0.686
Cd	-0.138	-0.365
Ba	-0.828	-0.084
La	0.695	0.472
Pb	0.842	0.413
LF	-0.336	-0.061
HF	-0.326	-0.073
FD	0.052	0.351
% of variance explained	43.81	14.76
Extraction Method: Principal Component Analysis.		
Rotation Method: Varimax with Kaiser Normalization.		
a. Rotation converged in 3 iterations.		

As presented in Table 5, the analysis extracted three principal components, collectively explaining 58.57% of the total variance. The first principal component (PC1) accounted for 43.81% of the variance and exhibited strong loadings for Ti, Fe, V, Cr, Mn, Co, Ni, Zn, and Pb. The second principal component (PC2) explained 14.76% of the variance, primarily associated with FD%, Si, and As.

The analysis indicated that LF and HF components did not correlate with heavy metal concentrations. The observed spatial variations in heavy metal levels are likely influenced by a combination of natural geological processes and anthropogenic activities. Figure 6 illustrates the rotated factor loadings of heavy metals and magnetic parameters, highlighting these relationships.

4.6. Cluster Analysis

Cluster analysis is a multivariate technique used to classify variables into distinct groups based on similarities across a set of measured parameters, ensuring that closely related subjects are grouped together (Harikrishnan et al., 2018). In the present study, magnetic mineral and heavy metal variables were grouped into two clusters using the average linkage method (Chandrasekaran et al., 2021). The clustering results are illustrated in the dendrogram shown in Fig. 7. Cluster I is primarily associated with the concentrations of heavy metals and magnetic minerals, whereas Cluster II is dominated solely by Si. These results indicate that the distribution of magnetic minerals in the study area is strongly influenced by the presence of heavy metals.

5.0. Conclusion

Sediments from the Ennore region along the east coast of Tamil Nadu, India underwent systematic analysis to determine the concentrations of heavy metals and magnetic susceptibility measurements (χ_{lf} , χ_{hf} , χ_{fd}). The detected heavy metals were found in the following descending order: Mn > Ba > V > Cr >

Zn > La > Ni > Pb > Co > As > Cd > Cu > Al > Fe > Ca > Ti > K > Mg. Magnetic susceptibility analysis indicated that the average low-frequency (χ_{lf}) and high frequency (χ_{hf}) susceptibilities were $8.6295 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and $7.5163 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, respectively. It should be noted that sample C2 had a higher χ_{lf} ($52.7217 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) and χ_{hf} ($55.7733 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$), which indicates that there is a slight dominance of ferromagnetic minerals in the sediments. The frequency dependent susceptibility ($\chi_{lf}\%$) further indicates the presence of super paramagnetic or single domain magnetic minerals. The heavy metals found in the sediments were primarily derived from anthropogenic activities, such as the discharge of treated or untreated sewage, industrial effluents, and harbor or shipping related operations. Overall, this study demonstrates that magnetic susceptibility serves as an effective tool for identifying hotspots of heavy metal contamination and tracing their pollution sources.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

Declaration

The authors declare that no funding or financial support was received from any agency, institution, or organization for the conduct of this research, preparation of the manuscript, or publication of the article.

Author Contribution

Rajendiran Dhanapal: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization, Harikrishnan Nallaiyan: Writing – review & editing, Resources, Methodology, Conceptualization, Sheela N R: Resources, Methodology, Conceptualization, Veeramuthu Kasinathan: Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization, Project administration.

Acknowledgement

The authors express their gratitude to the Coastal Environmental Engineering Division (CEE) of the National Institute of Ocean Technology (NIOT), NIOT Campus, Pallikaranai, Chennai – 600100, Tamil Nadu, India, for their valuable collaboration, insights, and contributions.

Data Availability

The data that support the findings of this study are openly available.

References

1. Bandaru, V.L., Gawali, P.B., Hanamgond, P.T., and Kannan, D., 2016. Heavy metal monitoring of beach sands through environmental magnetism technique: a case study from Vengurla and Aravali beaches of Sindhudurg district, Maharashtra, India. *Environ. Earth Sci.* 75, 678. <https://doi.org/10.1007/S12665-016-5477-9>.
2. Basaran, A.K., Aksu, M., Egemen, O., 2009. Impacts of the fish farms on the water column nutrient concentrations and accumulation of heavy metals in the sediments in the eastern Aegean Sea (Turkey). *Environ. Monit. Assess.* 162, 439–451. DOI: 10.1007/s10661-009-0808-x.
3. Canbay, M., 2010. Investigation of the relation between heavy metal contamination of soil and its magnetic susceptibility, *Int. J. Physical Sciences*, 5(5), 393–400. <https://doi.org/10.5897/IJPS.9000331>.
4. Chandrasekaran, A., Senthil Kumar, C.K., Sathish, V., 2021. Effect of minerals and heavy metals in sand samples of Ponnai River, Tamil Nadu, India. *Sci Rep.* 11, 23199. DOI: 10.1038/s41598-021-02717-x.
5. Cheng, H., Hu, Y., 2010. Lead (Pb) isotopic finger printing and its applications in lead pollution studies in China: a review. *Environ Pollut.* 158, 1134–1146. DOI: 10.1016/j.envpol.2009.12.028.
6. Dai, J., Song, J., Li, X., Yuan, H., Li, N., Zheng, G., 2007. Environmental changes reflected by sedimentary geochemistry in recent hundred years of Jiaozhou Bay, North China. *Environ. Pollut.* 145, 656–667. DOI: 10.1016/j.envpol.2006.10.005.
7. Dang, Z., Liu, C., Haigh, M.J. 2002. Mobility of Heavy Metals Associated with the Natural Weathering of Coal Mine Soils, *Environ. Pollut.* 118, 419–426. DOI: 10.1016/s0269-7491(01)00285-8.
8. Dearing, J.A., 1999. *Environmental Magnetic Susceptibility, Using the Bartington MS2 System.* second. England: Chi Publishing.
9. Dearing, J.A., Hay, K.L., Baban, S.M.J., Huddleston, A.S., Wellington, E.M.H., Loveland, P.J., 1996. Magnetic susceptibility of soil: an evaluation of conflicting theories using a national data set. *Geophysical Journal International.* 127, 728–734. DOI: 10.1111/j.1365-246X.1996.tb04051.x.

10. Dong, C., Zhang, W., Ma, H., Feng, H., Lu, H., Dong, Y., and Yu, L. (2014). A magnetic record of heavy metal pollution in the Yangtze River subaqueous delta. *Sci. Total Environ.* 476–477, 368–377. DOI: 10.1016/j.scitotenv.2014.01.020.
11. Durza, O., 1999. Heavy metals contamination and magnetic susceptibility in soils around metallurgical plant, *Phys. Chem. Earth Part A solid Earth Geod.* 24(6), 541–543. [https://doi.org/10.1016/S1464-1895\(99\)00069-1](https://doi.org/10.1016/S1464-1895(99)00069-1).
12. Duzzin, B., Pavoni, B., Donazolo, R., 1988. Macro invertebrate communities and sediments as pollution indicators for heavy metals in the River Adige Italy, *Water Res.* 22, 1353–1363. 10.1016/0043-1354(88)90091-7.
13. Hari Krishnan, N., Chandrasekaran, A., Ravisankar, R., Alagarsamy, R., 2018. Statistical assessment to magnetic susceptibility and heavy metal data for characterizing the coastal sediment of East coast of Tamilnadu, India. *Applied Radiation and Isotopes.* 135, 177–183. DOI: 10.1016/j.apradiso.2018.01.030.
14. Hanesch, M., Scholger, R., 2005. The influence of soil type on the magnetic susceptibility measured throughout soil profiles, *Geophys. J. Int.* 161, 50–56. <https://doi.org/10.1111/j.1365-246X.2005.02577.x>.
15. Hanesch, M., Scholger, R., Dekkers, M.J., 2001. The application of fuzzy c-means cluster analysis and non-linear mapping to a soil data set for the detection of polluted sites, *Phys. Chem. Earth*, 26, 885–891. DOI:10.1016/S1464-1895(01)00137-5.
16. Hay, K.L., Dearing, J.A., Baban, S.M.J., Loveland, P.A., 1997. Preliminary attempt to identify atmospherically-derived pollution particles in English top soils from magnetic susceptibility measurements, *Physics and Chemistry of the Earth*, 22, 207–210. [https://doi.org/10.1016/S0079-1946\(97\)00104-3](https://doi.org/10.1016/S0079-1946(97)00104-3).
17. Hosono, T., Su, C.C., Delinom, R., Umezawa, Y., Toyota, T., Kaneko, S., Taniguchi, M., 2011. Decline in heavy metal contamination in marine sediments in Jakarta Bay, Indonesia due to increasing environmental regulations. *Estuar. Coast. Shelf Sci.* 92, 297–306. DOI:10.1016/j.ecss.2011.01.010.
18. Jordanova, D., Hoffmann, V. Thomas Fehr, K., 2004. Mineral magnetic characterization of anthropogenic magnetic phases in the Danube river sediments (Bulgarian part), *Earth Planet. Sci. Lett.*, 221, 71–89. DOI:10.1016/S0012-821X(04)00074-3.
19. Kanu, M.O., Meludu, O.C., Oniku, A.S., 2013. A preliminary Assessment of soil pollution in some parts of Jalingo Metropolis, Nigeria using magnetic susceptibility method. *Jordan. J. Earth Environ. Sci.*, 5(2), 53–61. <https://search.emarefa.net/detail/BIM-349938>.
20. Kapika, A., Jordanova, N., Petrovský, E., Podrazský, V., 2003. Magnetic study of weakly contaminated forest soils, *Water Air Soil Pollut.* 148, 31–44. DOI:10.1023/A:1025429928763.
21. Knab, M., Appel, E., Hoffmann, V., 2001. Separation of the anthropogenic portion of heavy metal contents along a highway by means of magnetic susceptibility and fuzzy c-means cluster analysis, *Eur. J. Environ. Eng. Geophys.* 6, 125–140.
22. Lecoanet, H., Lévêque, F., Ambrosi, J., 2001. Magnetic properties of salt marsh soils contaminated by iron industry emissions (southeast France), *J. Appl. Geophys.* 48, 67–81. DOI:10.1016/S0926-9851(01)00080-5.
23. Liu, Q.S., Maher, B.A., Yu, Y., Deng, C.I., Zhu, R.X., Zhao, X.X., 2005. Quantifying Grain Size Distribution of Pedogenic Magnetite Particles in Chinese Loess and its Significance for Pedogenesis, *J. Geophys. Res.* 110, B11102. DOI: 10.1029/2005JB003726.
24. Lu, S.G., Bai, S.Q., Xue, Q.F., 2007. Magnetic properties as indicators of heavy metals pollution in urban top soils: a case study from the city of Luoyang, China, *Geophys. J. Int.* 171, 568–580. <https://doi.org/10.1111/j.1365-246X.2007.03545.x>.
25. Mendiguchia, C., Moreno, C., Manuel-Vez, M.P., Garcia-Vargas, M., 2006. Preliminary investigation on the enrichment of heavy metals in marine sediments originated from intensive aquaculture effluents. *Aquaculture.* 254, 317–325. DOI:10.1016/j.aquaculture.2005.10.049.
26. Millward, G.E., Moore, R.M. 1982. The adsorption of Cu, Mn and Zn by iron oxyhydroxides in model estuarine solutions. *Water Research*, 16, 981–985. [https://doi.org/10.1016/0043-1354\(82\)90032-X](https://doi.org/10.1016/0043-1354(82)90032-X).
27. Nath, B.N., Rao, V.P., Becker, K.P., 1989. Geo chemical evidence of terrigenous influence in deep-sea sediments up to 80S in the Central Indian Basin. *Mar Geol* 87, 301–313. <http://dris.nio.org/dris/handle/2264/7200>.
28. Pandian, P.K., Ramesh, S., Murthy, M.V., Ramachandran, S., Thayumanavan, S., 2004. Shoreline changes and near shore processes along Ennore coast, east coast of South India. *Journal of Coastal Research.* 20(3), 828–845. <https://www.jstor.org/stable/4299341>.
29. Petrovsky, E., Kapicka, A., Jordanova, N., Knab, M., Hoffmann, V., 2000. Low-field magnetic susceptibility: a proxy method of estimating increased pollution of different environmental systems, *Environ. Geol.* 39, 312–318. DOI:10.1007/s002540050010.
30. Santhiya, G., Lakshumanana, C., Jonathan, M.P., Roy, P.D., Navarrete-Lopez, M., Srinivasalu, S., Uma-Maheswarie, B., Krishnakumar, P. 2011. Metal enrichment in beach sediments from Chennai Metropolis, SE coast of India. *Marine Pollution Bulletin*, 62, 2537–2542. <https://doi.org/10.1016/j.marpolbul.2011.08.019>.
31. Schmidt, A., Yarnold, R., Hill, M. & Ashmore, M., 2005. Magnetic susceptibility as proxy for heavy metal pollution: A site study, *J. Geochem. Explor.*, 85, 109–117. DOI:10.1016/j.gexplo.2004.12.001.
32. Scholger, R., 1998. Heavy metal pollution monitoring by magnetic susceptibility measurements applied to sediments of the river Mur (Styria, Austria), *Eur. J. Environ. Eng. Geophys.* 3, 25–37.
33. Spiteri, C., Kalinski, V., Rosler, W., Hoffmann, V., Appel, E. MAGPROX team., 2005. Magnetic screening of a pollution hotspot in the Lausitz area, Eastern Germany: correlation analysis between magnetic proxies and heavy metal contamination in soils, *Environ. Geol.* 49, 1–9. DOI:10.1007/s00254-005-1271-9.
34. Strzyszczyk, Z., Magiera, T., 1998. Magnetic susceptibility and heavy metals contamination in soils of Southern Poland, *Phys. Chem. Earth*, 23 (9–10), 1127–1131. 10.1016/S0079-1946(98)00140-2.
35. Thompson, R., Oldfield, F., 1986. *Environment Magnetism*. Allen and Unwin, London. Venkatachalapathy, R., Veerasingam, S., Basavaiah, N., Ramkumar, T., Deenadayalan, K., 2011. Environmental magnetic and geological characteristics of Chennai coastal sediments, Bay of Bengal, India. *J. Earth. Syst. Sci.*, 120 (5), 885–895. DOI:10.1007/s12040-011-0108-z.

36. Wang, G., Liu, Y., Chen, J., Ren, F., Chen, Y., Ye, F., and Zhang, W., 2018. Magnetic evidence for heavy metal pollution of topsoil in Shanghai, China. *Front. Earth Sci.* 12, 125–133. DOI: 10.1016/j.marpolbul.2011.01.030.

37. Yalcina, F., Nyamsarib, D.G., Paksub, E., Yalcinb, M.G., 2016. Statistical Assessment of Heavy Metal Distribution and Contamination of Beach Sands of Antalya-Turkey: an Approach to the Multivariate Analysis Techniques, *Filomat*, 30 (4), 945–952. DOI:10.2298/FIL1604945Y.

38. Zhang, C., Qiao, Q., Piper, J.D.A., Huang, B., 2011. Assessment of heavy metal pollution from a Fe-smelting plant in urba river sediments using environmental magnetic and geochemical methods. *Environ. Pollut.* 159, 3057–3070. DOI: 10.1016/j.envpol.2011.04.006.

39. Zhu, Z., Han, Z., Bi, X., and Yang, W. (2012). The relationship between magnetic parameters and heavy metal contents of indoor dust in e-waste recycling impacted area, Southeast China. *Sci. Total Environ.* 433, 302–308. DOI: 10.1016/j.scitotenv.2012.06.067.

Figures

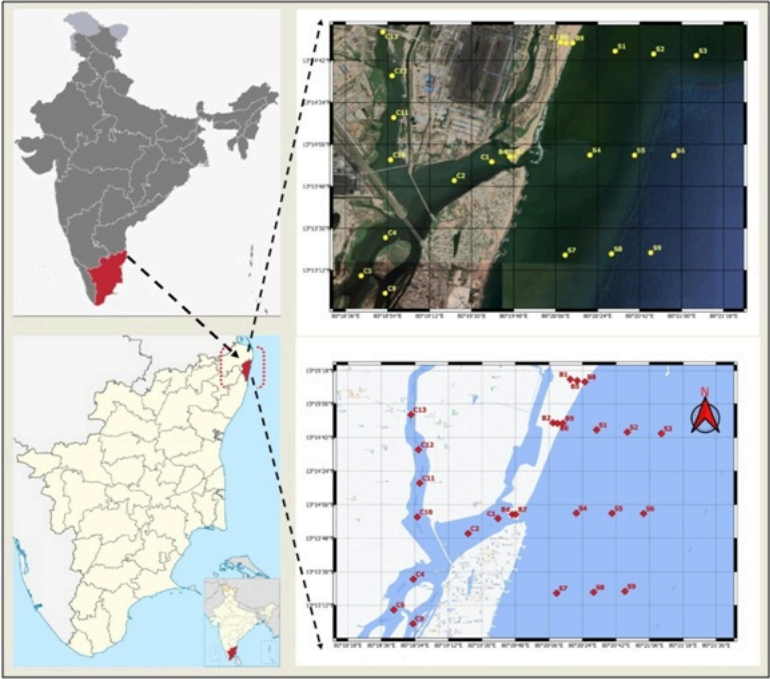


Figure 1

Location Map of the Study Area

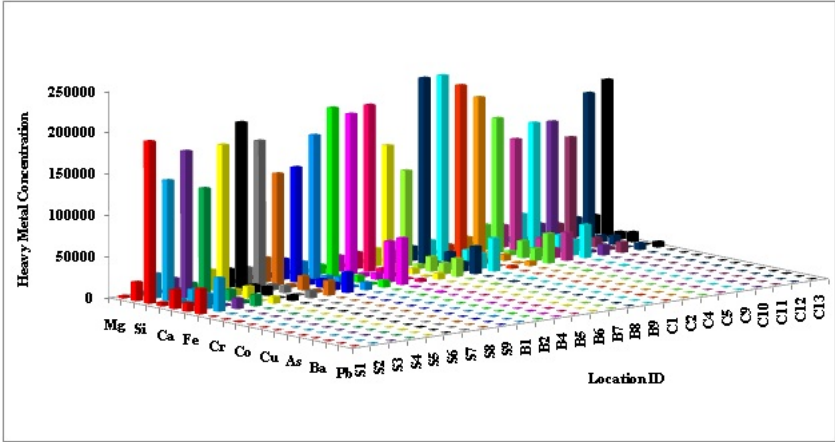


Figure 2

Heavy Metal Concentration Levels of Sediments in the Study Area

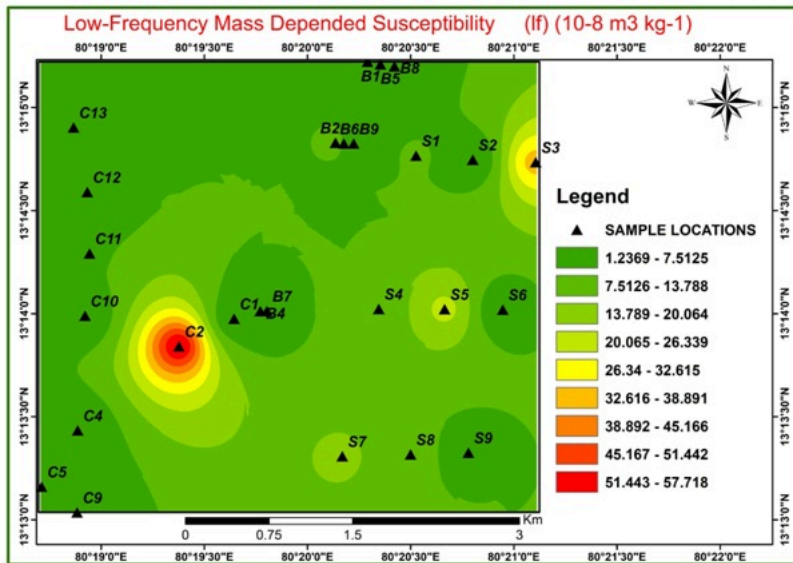


Figure 3

Location Vs Low Frequency Susceptibility ($10^{-8} \text{ m}^3 \text{ kg}^{-1}$)

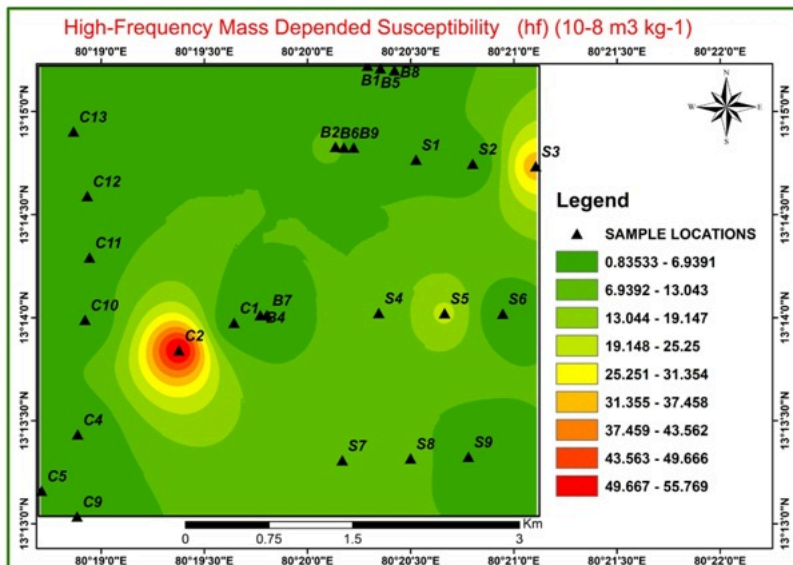


Figure 4

Location Vs High Frequency Susceptibility ($10^{-8} \text{ m}^3 \text{ kg}^{-1}$)

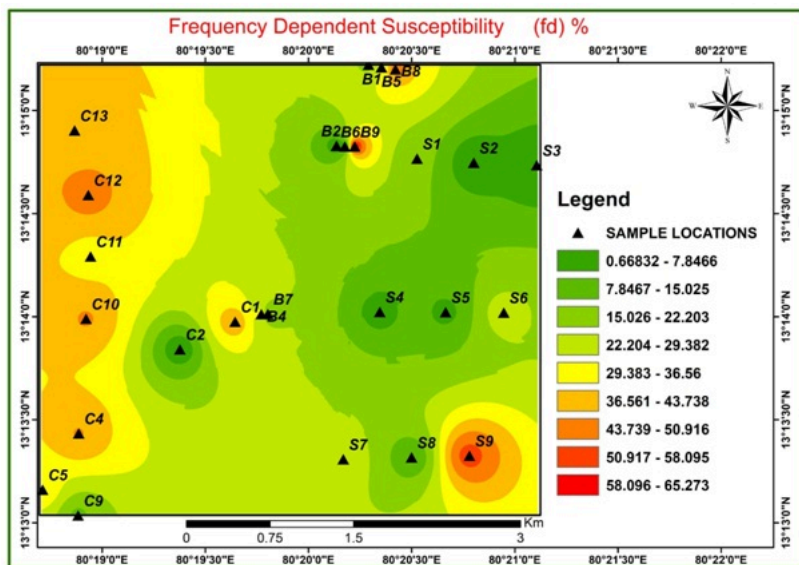


Figure 5

Location Vs Frequency Dependent Susceptibility (FD) %

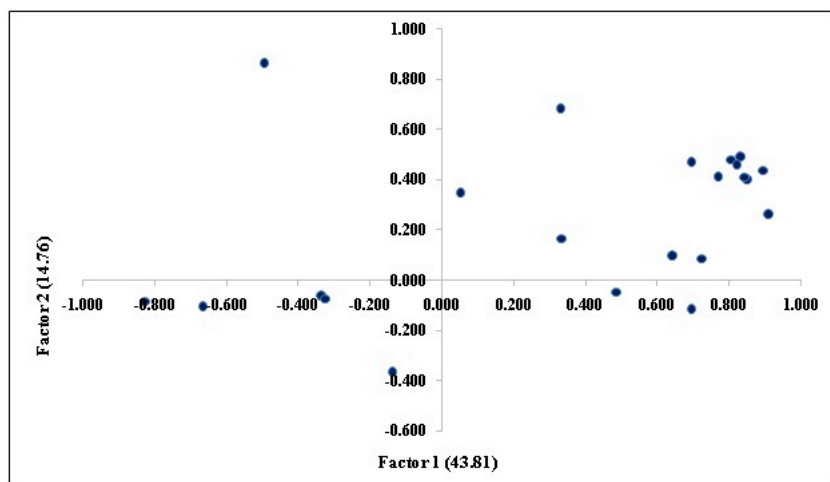


Figure 6

Rotated Factor Analysis of Heavy Metals and Magnetic Parameters

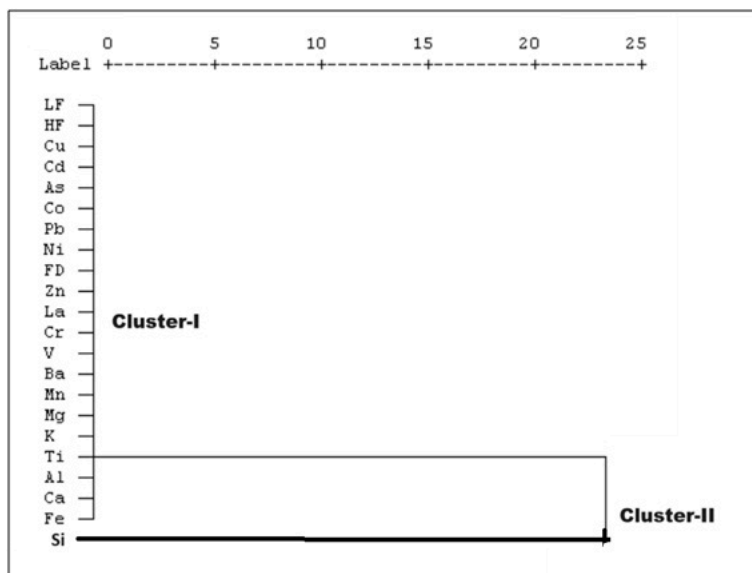


Figure 7

Dendrogram Shows the Cluster Analysis of Heavy Metals and Magnetic Parameters

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [RajaMHHighlights.docx](#)
- [RajaMHDeclarationofcompetinginterest.docx](#)
- [RajaMHCRediTauthorshipcontributionstatement.docx](#)