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Research article

Magnetic susceptibility and heavy metal contents in sediments of Riam Kiwa, Riam Kanan and Martapura rivers, Kalimantan Selatan province, Indonesia

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ABSTRACT

Kalimantan Selatan is proud of the Martapura River's natural and cultural history. Martapura tributaries include Riam Kanan and Kiwa. The Martapura River is essential because it provides clean water and a livelihood for riverside residents. Human-caused river pollution grows with population density (also known as anthropogenic pollutants). This study characterizes surface sediment magnetic characteristics and heavy metal contents along the Riam Kanan, Riam Kiwa, and Martapura rivers. The purpose of this research is to evaluate the magnetic signal with respect to heavy metal contents found in surface sediments taken from rivers and to confirm the use of the rock magnetism method in environmental studies in the study area. Surface sediment samples were gathered and tested for magnetic, heavy metal, and mineralogical content. According to the findings, the pseudo-single domain (PSD) magnetite mineral predominates among the magnetic minerals that can be found in the surface sediments of the rivers Riam Kanan, Riam Kiwa, and Martapura. This substantially greater grain size may be due to magnetic particles produced by erosion along the river banks. The mass-specific magnetic susceptibility of surface sediments ranges from 103.11 to 1403.64 $\times 10^{-8}$ m^3/kg, with an average value of 355.67 $\times 10^{-8}$ m^3/kg due to the peatland environment. Magnetic susceptibility strongly negatively correlates with heavy contents like Cu, Zn, and Hg, according to Pearson correlation analysis. Due to this correlation, magnetic susceptibility may indicate heavy metal pollution in certain rivers. This current study demonstrates the novelty of the relationship between magnetic susceptibility and the contents of heavy metals in surface sediments from rivers in peatland and tropical environments by illustrating how the relationship affects the magnetic susceptibility of the sediments.

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1. Introduction

River sediment is the result of a process of sedimentation in the river environment originating from the weathering of bedrock and from erosion, organic matter, particles, or anthropogenic compounds (waste generated from human activities) [1]. The big problem that arises in river sediments, especially in developing countries, is the presence of substances that are harmful to the environment (pollutants). Anthropogenic pollutants are the dominant source of pollutants in river sediments, such as those from land use activities (urban and rural) around the river, industrial waste disposal, household waste, mining waste, or agricultural waste [2]. Sediment is a significant medium for clarifying and identifying the origin and dynamics of a heavy metal partition rather than analyzing the water column above it [3], so that sediment is an important indicator for viewing river pollution caused by heavy metals [4,5].

To monitor heavy metals in sediments and soil, magnetic methods are often used because these methods are efficient, fast, and non-destructive [6–12]. In several studies showing the presence of heavy metals in sediments and soils, which can be identified through an increase in the overall quantity of magnetic minerals [5,13–18]. This research was to investigate the sediment flow of rivers in the South Kalimantan region in terms of magnetic mineralogy and to determine the relationship between increased concentrations of anthropogenic magnetic particles, concentrations of Fe, Zn, Cu, Mn, and Hg, the sources of pollution, and pollution assessment. The five elements selected in this study, referring to studies that have been carried out by several researchers regarding the content of heavy metals in water and river sediments, found the presence of Fe, Mn, and Cu (exceeding the standards of Indonesian Government Regulation Number 22 of 2021) [19]. Hg content is found in Riam Kanan River water [20]. The South Kalimantan Environment Agency reported that three heavy metals polluted rivers in South Kalimantan and had exceeded the threshold, namely Hg, Fe, and Zn [21]. Therefore, this study investigates Fe, Mn, Cu, Zn, and Hg metals in river sediments. In addition, the researchers wanted to study in greater detail the magnetic mineralogy of the sediment flow of the rivers. We try to show that simple and quick magnetic measurements taken in situ can, under certain conditions, show how heavy metals were added by humans.

Magnetic studies on river environments in Indonesia are still very rarely conducted. So far, the presence of heavy metals and variations in the concentration of magnetic minerals in suspended sediments in the volcanic environment along the Citarum River have been reported by Sudarningsih et al. [22]. Other studies include magnetic studies of estuary iron sand in Papua [23], as well as an estuary study in Aceh [24]. Meanwhile, Mariyanto et al. [25] have reported the correlation between heavy metals and magnetic susceptibilities in sediments from the Brantas River in East Java, while Yunginger et al. [26] have reported a similar study on lake sediments in Gorontalo. The study of magnetism in the river environment located in the peat area, especially for the territory of Indonesia, has never been done, and this is interesting, considering that this research will be very different from the previous rivers. This research is very important as a preliminary study that is very useful to find out the magnetic characteristics of sediments in areas with peat backgrounds, given the vast amount of peatlands owned by Indonesia, which is 20.6 million hectares [27]. The current work is helpful in determining whether or not there is a correlation between magnetic characteristics and the level of heavy metals in the sediments found in the river. This research also shows the presence of iron minerals, which are chemically active as heavy metal scavengers, in river sediments, which has not been studied much. Fe ions are frequently substituted by other cations in pure or non-stoichiometric magnetite or hematite phases. These cations are substituted for the Fe2+ and/or Fe3+ ions in the ferrite structure

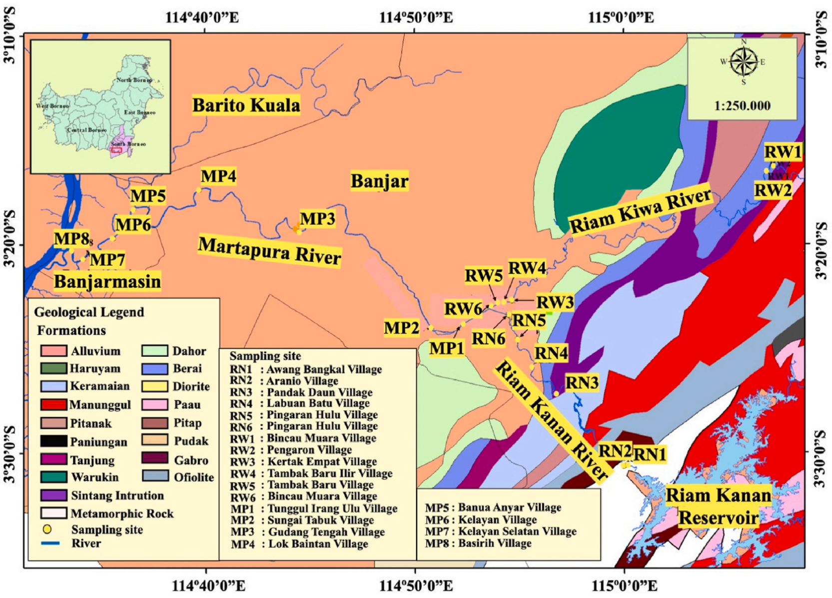

Fig. 1. The sampling sites along the Martapura, Riam Kanan and Riam Kiwa Rivers (yellow dots) and the Geological map of the study area (modified from Sikumbang and Heryanto [31]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of magnetite or hematite. Extensive research has established that highly magnetic iron oxide has a propensity to bind metals [28]. This data is critical for investigating the potential of magnetic measurement as a proxy indicator of heavy metal pollution in rivers in a tropical peatland environment, particularly in the Riam Kanan, Riam Kiwa, and Martapura rivers, and for estimating the degree to which sediments in these rivers are contaminated using the geoaccumulation index.

2. Materials and methods

This research area is located in a tropical climate. Rainfall is highest from November to April (rainy season), and lowest from May to October (dry season) [29]. The highest annual rainfall amount is 4457.32 mm, and the lowest is 1849.33 mm for 2020. There has been an increase in the amount of rainfall since 2000–2020 of around 500 mm [30].

The Martapura River, a tributary of the Barito River, is a natural and cultural heritage as well as a symbol of pride in Banjarmasin. Mount Bobaris and Meratus supply water to Martapura and Banjarmasin cities via the Riam Kanan and Riam Kiwa rivers. According to the geological map of Banjarmasin sheet, Kalimantan [31], rocks in the area of the mountains of Bobaris and Meratus are ultramafic rocks consisting of basal, gabbro, dunnite, peridotite, pyroxenite, and plagiogranite (Fig. 1). The watershed area of the Martapura river is 453.88 km^2, while the length of the Martapura river itself, including all of its tributaries, is around 36.566 km. The depth of the Martapura River ranges from 4 to 5 m, and its width is 85–95 m [32]. The Martapura River reaches 9.5% of the area of Banjarmasin City and splits right in the middle of Banjarmasin City [33]. The Banjarmasin mainland is formed on alluvial plains and peat deposits as part of the Barito Basin [34].

Communities in this area use the Martapura River as a source of drinking water, irrigation, agriculture, construction, and transportation. Both sides of the river are agricultural, residential, and industrial land. Residential and industrial waste is discharged directly into the river. With excessive use of fertilizers and pesticides, the waste will also enter the river. Along the river, there are also several places used for fish cages. Excessive fish feed will also settle in this river. In addition, in the lower reaches of this river there are industrial areas, ports, and a confluence with the Barito River. Industrial waste that is directly discharged into the river and the results of corrosion from abandoned ships will affect the sediment of this river. Besides busy transportation both on land and in rivers, which also contributes to toxic waste due to vehicle emissions into river sediments.

The Riam Kanan River is part of the Riam Kanan sub-watershed, which flows from Aranio District to Astambul District. These sub-watersheds have a total area of 164,768 ha, a length of 70 km, a depth ±15 m, and an average width of 50 m. These Riam Kanan sub-watersheds also pass through the Karang Intan sub-district [20]. The Riam Kiwa sub-watershed is a tributary of the Martapura river, which has a river length of ±24.4 km and a depth ±1.86 m from Sungai Tabuk Village, Simpang Empat District, to Pingaran Ulu Village, Astambul District. Along these two rivers, there are dwellings, agricultural land, and fish cages at several points [35]. Residential waste and fish cages will enter the river directly. Residential waste and residual fertilizers and pesticides will enter this river. These two rivers are on either side of a busy thoroughfare. Vehicle emissions are toxic materials that will settle in river sediments.

Fig. 1 also shows 20 surface sediment sampling points consisting of 8 samples from the Martapura (MP) river (Bincau Banjar Regency to Basirih Banjarmasin City in southern Kalimantan), 6 sediment samples from the Riam Kanan River (RK), which is the outlet river of the Riam Kanan dam, and 6 sediment samples from the Riam Kiwa River (RW), which is a river originating from several districts in this area. The names of the sampling sites with latitude, longitude, and descriptions of the sampling areas are given in Fig. 1 and the land use map at the research location can be seen in Fig. 2. Sources of heavy metals in this research area come from both natural

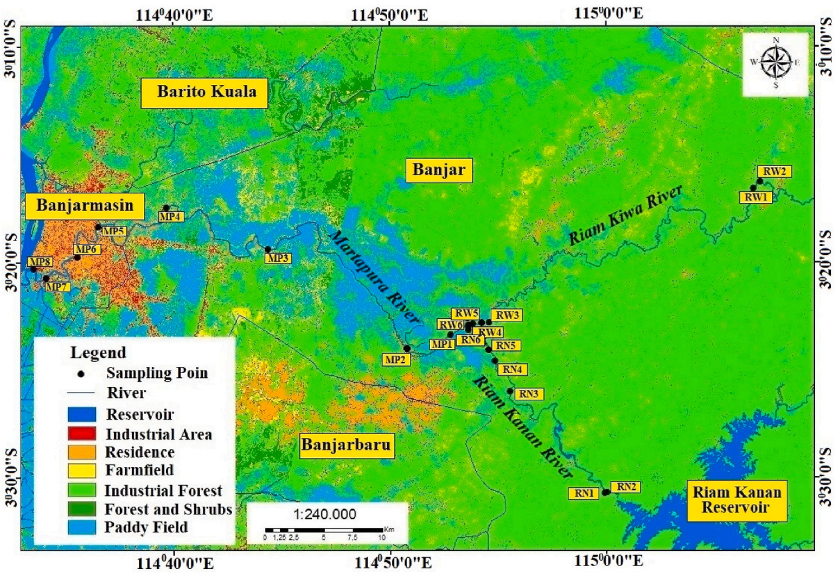

Fig. 2. Map of land use along Riam Kanan, Riam Kiwa and Martapura River.

and anthropogenic processes. Natural processes come from the weathering of bedrock, namely igneous rocks. Anthropogenic sources come from agricultural activities, fish cages, household waste, vehicle emissions, and industrial activities.

Sampling points were chosen to provide both background area coverage and anthropogenic input values. To facilitate data processing and to better assess the spatial distribution of the analyzed parameters, three different rivers were identified based on rock formation, geographic and hydrographic criteria consisting of the Martapura River with sampling points MP1, MP2, MP3, MP4, MP5, MP6, MP7, and MP8. This location is affected primarily by settlements, industry, agricultural activities including fish cages, estuarine vehicle emissions and peat areas. Riam Kanan River with sampling points RK1, RK2, RK3, RK4, RK5, and RK6. This location is affected by weathering of bedrock i.e. ultrabasic and frozen, vehicle emissions, fish cages and settlements. Riam Kiwa River with sampling points RW1, RW2, RW3, RW4, RW5, and RW 6. These locations are affected by settlements, peatlands and vehicle emissions.

Sample locations were recorded (latitude and longitude positions) using a handheld Global Positioning System unit. All rivers in this study area never experience drought throughout the year. Samples were taken in the dry season. Referring to the sampling technique described by Wang et al. [36], a sediment grabber was used to collect samples of the surface sediment. Approximately 2 kg of sediment samples were placed in a plastic container. Each location point is taken into one bag and labelled according to the name of the river and the order in which it was taken. No. 1 is the first sample from the most upstream part of the river, and the last number is the sample number at the most downstream sampling point of each river. The sample is then taken to the laboratory for preparation.

The procedure developed by Mariyanto et al. [25] was followed closely while the samples were being prepared in the laboratory. For a homogeneous sediment grain size, the sample was sieved with a 325-mesh sieve and air-dried at room temperature. The primary pathway for the redistribution of nutrients and pollutants across aquatic systems is fine-grained sediments [37]. After drying, 10 g of sample were put into a plastic bag to measure the heavy metal content in the Indonesian Geological Survey Center laboratory using atomic absorption spectroscopy (AAS) analysis using an AA280FS (Varian Inc., Palo Alto, CA, USA) instrument. The dried sample was also placed in a cylindrical plastic holder with a size of 25.4 mm in diameter and 22 mm in height (10 cm^3 in volume). This sample will be used for magnetic susceptibility measurements using the Bartington MS2B susceptibility meter (Bartington Instrument Ltd., Oxford, UK). The results of this measurement are the values of low-frequency magnetic susceptibility (χ_{LF}), high-frequency magnetic susceptibility (χ_{HF}), and frequency-dependent magnetic susceptibility (χ_{FD}). Some of the other samples were extracted using a magnet following the procedure of Novala et al. [38]. XRD SmartLab (Rigaku, Japan) equipment identified magnetic materials in extracted samples, determined magnetic mineral domains using the 1.2 H/CF/HT VSM instrument (Oxford Instrument, Oxford, UK), and determined magnetic mineral structure and morphology using SEM-EDS and a JED-2300 T energy-dispersive X-ray spectrometer. The following is the formula suggested by Müller [30] that should be used to calculate the geoaccumulation index (I_{geo}): $I_{geo} = Log_2\left(\frac{C_n}{1.5B_n}\right)$; The element's observed concentration at the sampling location is denoted by the symbol C_n, while the geochemical background value is denoted by the symbol B_n. Both values are derived from argillaceous sedimentary fossils (shale mean). Referring to Abrahim & Parker [39], that particular aspect of this study is the contrast in the enrichment ratio obtained when using continental shale reference

Table 1
The bulk sediment samples were analyzed for their heavy metal contents, which included the elements Fe, Mn, Zn, Cu, and Hg, as well as their low frequency magnetic susceptibility (χ_{LF}), high frequency magnetic susceptibility (χ_{HF}), and frequency dependent magnetic susceptibility (χ_{FD}).

Sample	Heavy Metal concentration (mg/kg)					χ_{LF}	χ_{HF}	χ_{FD}
	Fe $\times 10^3$	Zn $\times 10^2$	Mn $\times 10^2$	Cu	Hg	($\times 10^{-8}$ m^3/kg)	($\times 10^{-8}$ m^3/kg)	(%)
RN1	70.40	1.27	15.97	72.00	0.08	385.87	349.99	2.47
RN2	70.20	1.18	11.03	57.00	0.06	601.31	592.13	1.53
RN3	63.70	0.91	7.91	61.00	0.03	856.55	852.89	0.43
RN4	49.70	0.66	5.96	28.00	0.15	103.11	100.63	2.41
RN5	52.20	0.60	9.12	38.00	0.01	1403.64	1398.81	0.34
RN6	86.80	1.04	10.01	36.00	0.01	409.93	404.93	1.22
RW1	52.20	0.96	9.50	61.00	0.05	304.54	301.82	0.89
RW2	54.60	1.00	13.85	75.00	0.08	226.14	222.54	1.59
RW3	56.60	0.98	13.85	85.00	0.10	218.75	217.69	0.48
RW4	54.40	0.85	10.68	50.00	0.03	393.45	392.93	0.13
RW5	47.80	1.10	12.00	72.00	0.06	227.72	226.13	0.70
RW6	33.60	0.65	15.65	29.00	0.01	304.08	303.05	0.34
*MP1	58.60	0.93	12.99	51.00	0.11	361.86	359.98	0.52
*MP2	48.00	0.79	10.26	40.00	0.09	293.00	291.47	0.52
*MP3	68.00	1.06	21.42	75.00	0.12	195.97	193.93	1.04
*MP4	63.10	1.03	17.86	82.00	0.12	191.97	190.79	0.61
*MP5	58.60	1.47	8.15	68.00	0.21	155.97	153.85	1.36
*MP6	64.80	1.31	9.91	72.00	0.15	152.47	151.08	0.91
*MP7	67.30	1.61	7.97	67.00	0.17	134.61	131.91	2.00
*MP8	50.90	1.10	4.94	43.00	0.12	197.11	196.13	0.52
Mean	50.57	1.02	1.14	58.10	0.09	355.67	351.63	1.00
Min	33.60	0.60	4.94	28.00	0.01	103.11	100.63	0.13
Max	86.80	1.61	21.42	85.00	0.21	1403.64	1398.81	2.47

* [31].

values compared to the uncontaminated natural background obtained from the studied area. In many cases, the latter method is the best approach, because background values or a local baseline for this research area are not yet available.

3. Results

3.1. Magnetic characterization

The results of both the magnetic susceptibility measurements and the geochemical analysis are presented in Table 1. Low-frequency magnetic susceptibility (χ_{LF}), high-frequency magnetic susceptibility (χ_{HF}), and frequency-dependent magnetic susceptibility (χ_{FD}) are the outcomes of measurements of magnetic susceptibility. The magnetic susceptibility values of sediment samples from the rivers Riam Kanan (RN), Riam Kiwa (RW), and Martapura (MP) differ, as shown by the magnetic susceptibility values of the samples in Table 1. Riam Kanan River has magnetic susceptibility values ranging from 103.11 to 1403.64 ($\times 10^{-8}$ m^3/kg); Riam Kiwa River has magnetic susceptibility values ranging from 218.75 to 393.45 ($\times 10^{-8}$ m^3/kg); and Martapura River has magnetic susceptibility values ranging from 131.91 to 304.08 ($\times 10^{-8}$ m^3/kg). The findings of the analysis suggest that there are variations in the values that are found at each of the sampling points. According to the information presented in Table 1, the RN5 point is the one that possesses the highest susceptibility value (χ_{LF}) and has significantly increased in comparison to the RN4 point. The value of (χ_{FD}) meantime, shifts dramatically from point RN4 to point RN5.

The average heavy metal content in sediment samples, from highest to lowest, was Fe (50.57 $\times 10^3$ mg/kg) > Mn (1.14 $\times 10^2$ mg/kg) > Zn (1.02 $\times 10^2$ mg/kg) > Cu (58.10 mg/kg) > Hg (0.09 mg/kg). Mass-based magnetic susceptibility (χ_{LF}) values range from 103.11 to 1403.64 $\times 10^{-8}$ m^3/kg (on average of 355.67 $\times 10^{-8}$ m^3/kg). The value of frequency-dependent magnetic susceptibility (χ_{FD}) varies from 0.13 to 2.47%.

The findings of an XRD examination carried out on several typical samples of the sediments that were collected are presented in Fig. 3. The purpose of the XRD analysis is to identify the kinds of magnetic minerals that are present in the sample. It can be seen from the peak points on the diffractogram curve that the most prevalent magnetic mineral in the sample is magnetite (Fe_3O_4). This conclusion is reached based on the data.

A hysteresis curve is generated for the sediment sample after a measurement using a VSM. This curve can be thought of as having

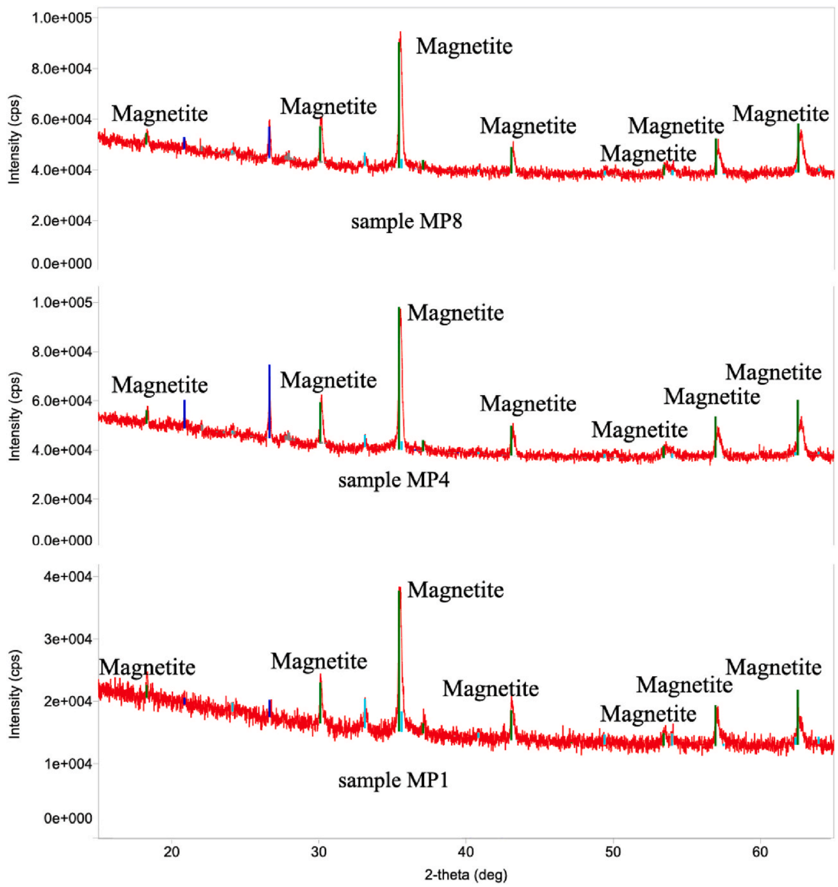

Fig. 3. The diffractogram is dominated by the peaks for the mineral magnetite (Fe3O4) in three extracted representative sediment samples.

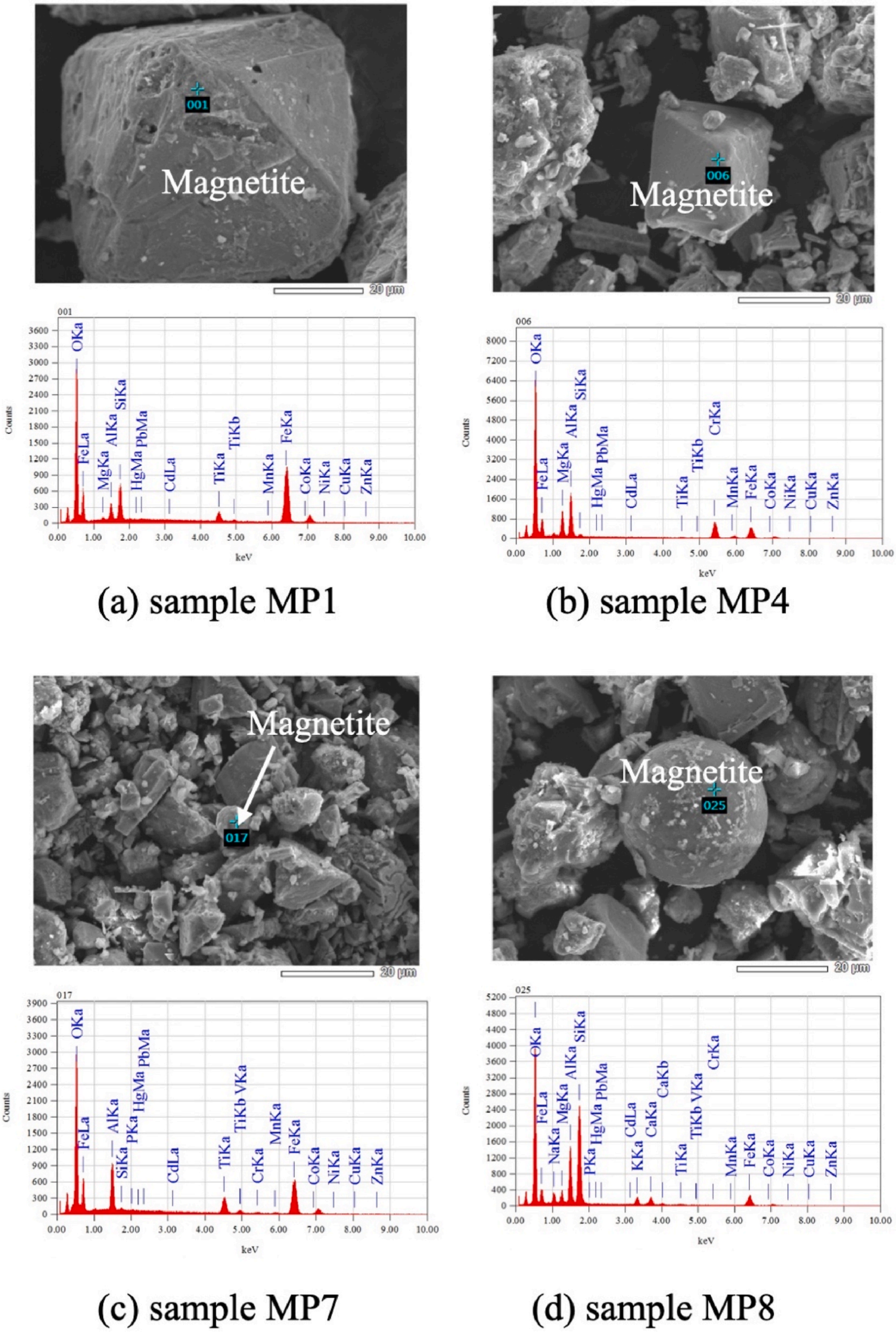

Fig. 4. The results of SEM–EDS analysis representative sediment samples from Martapura river.

two distinct parts: a curve that is going up and a curve that is going down. The curve that is going up is the result of VSM measurements that were performed with an increasing applied magnetic field (*H*), and the curve that is going down is the opposite of that. The hysteresis curve that was generated from the VSM measurement results can be seen in Fig. 5 (a–c). In the beginning, the result of the VSM measurement is a dashed curve, which represents a combination of paramagnetic and ferrimagnetic properties. A solid curve is obtained through analysis and subsequent correction brought about by the paramagnetic component.

Fig. 5 shows the results of VSM measurements for the extracted sediment samples in the form of hysteresis curves (5a and 5b). This curve can be thought of as having two parts: an upward curve that depicts an increase in the magnetic field (*H*), and a downward curve that depicts a decrease in the magnetic field. The dotted line is the result of the initial VSM measurement, indicating a mixture of paramagnetic and ferrimagnetic materials. The full line curve is the result of a correction by the paramagnet component. Fig. 4 (a–d) depicts the SEM–EDS analysis results. Magnetite mineral SEM picture with associated energy spectra.

3.2. Assessment of the geoaccumulation index

Fig. 6 shows the analysis of the geoaccumulation index. The geoaccumulation index shows that the Riam Kanan River is indicated to be unpolluted to moderately polluted at the RN1 point by Mn and Cu, the same as point RN6 by Fe. The Riam Kiwa River is unpolluted to moderately polluted at points RW2 and RW3 by Mn and Cu; RW5 by Cu; and RW6 by Mn. Martapura River is unpolluted to moderately polluted in MP1 due to Mn, MP3 and MP4 due to Mn and Cu, MP5 due to Zn and Cu, MP6 due to Cu, and MP7 due to Zn. As

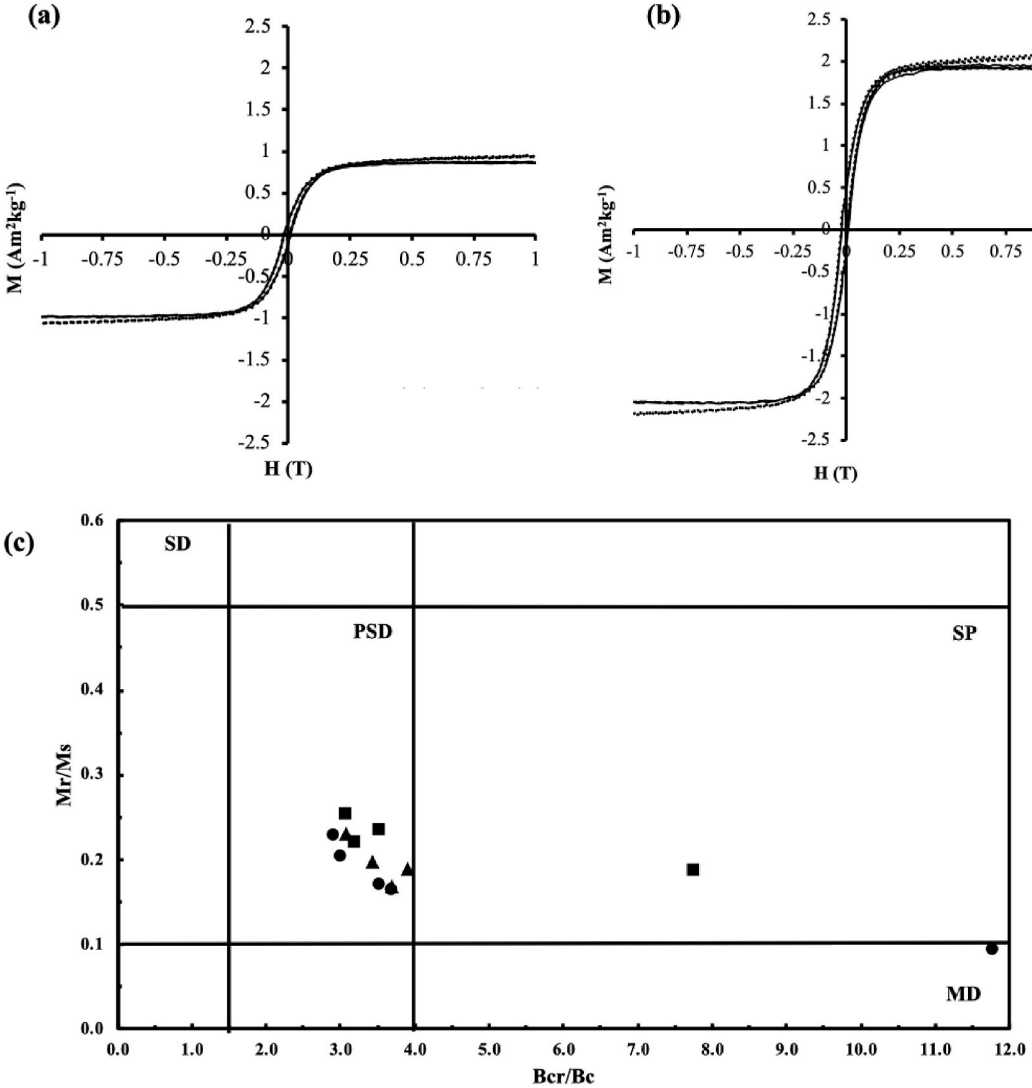

Fig. 5. Magnetic hysteresis curves before the correction for the paramagnetic contribution (represented by the dotted line) and after the correction (represented by the dotted line) for the samples (MP1(a) and MP4(b). Properties of hysteresis exhibited by the representative sediment samples (square = Riam Kiwa; triangle = Riam Kanan; round = Martapura)(c).

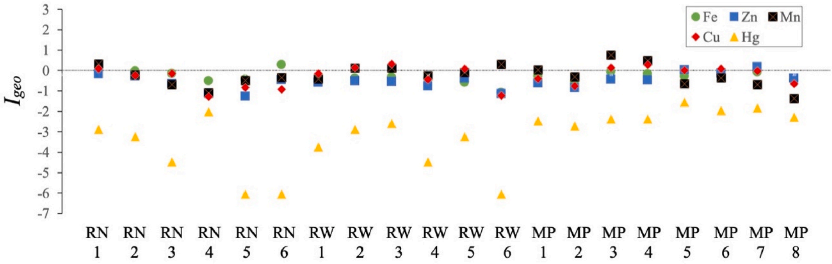

Fig. 6. The indexes of heavy metal in the river sediment samples were contaminated as a result of geoaccumulation.

compared to the results of multiple measurements in rivers located in non-volcanic and volcanic locations, the average concentration of Fe in the samples from these three rivers is relatively low. However, based on the geoaccumulation index, there are rivers that are polluted with Fe and fall into the "slightly polluted" category. The Zn geoaccumulation index value increased from point RW2 to point RW3 in the lightly polluted category. Likewise, the Cu geoaccumulation index value increased from MP3 to MP4 in the lightly polluted category. The geoaccumulation index shows that all river sediments, at some point, are polluted by Mn and Cu and fall into the category of lightly polluted, but they are not polluted by Hg.

3.3. Correlation between the magnetism parameters and heavy metals

Table 2 shows the correlation coefficient between the magnetism parameters and the content of heavy metals and other heavy metals themselves in river sediment samples. This coefficient reveals the strength of the association between these parameters and heavy metal contents, magnetic parameters with heavy metal contents, and magnetic parameters themselves. In addition to this, it provides an indication of the degree to which magnetic parameters are strongly related to one another. In the Riam Kiwa river, the Pearson correlation coefficient between χ_{LF} and heavy metal concentrations varies between $R = -0.70$ (for Cu) and $R = -0.75$ (for Hg), whereas in the Martapura river, the correlation coefficients are $R = -0.81$ (for Zn) and $R = -0.70$ (for Hg). The Pearson correlation coefficient between χ_{FD} and heavy metal concentrations in the Riam Kanan River varies between $R = 0.84$ (for Hg). Certain heavy metal concentrations are significantly correlated with both χ_{LF} and χ_{FD}. For the Martapura River, the highest negative correlation exists between the heavy metal contents of Hg and χ_{LF}; in contrast, Hg shows the largest positive correlation with χ_{FD} for the Riam Kanan river.

Table 2
Pearson correlation (R) between magnetic characteristics and heavy metal contents. Strong (>0.6) correlation R is bold.

	Fe	Zn	Mn	Cu	Hg	χ_{LF}	χ_{FD}
Sample: RN rowhead							
Fe	1.00						
Zn	**0.75***	1.00					
Mn	0.49	**0.80***	1.00				
Cu	0.28	**0.75***	**0.74***	1.00			
Hg	−0.44	−0.08	−0.15	−0.13	1.00		
χ_{LF}	0.60	0.17	−0.21	−0.46	0.07	1.00	
χ_{FD}	0.03	0.37	0.34	0.08	**0.84***	0.27	1.00
Sample: RW rowhead							
Fe	1.00						
Zn	0.69	1.00					
Mn	−0.51	−0.42	1.00				
Cu	**0.79***	**0.89***	−0.15	1.00			
Hg	0.69	**0.76***	0.07	**0.97****	1.00		
χ_{LF}	−0.13	−0.58	−0.43	**−0.70***	**−0.75***	1.00	
χ_{FD}	0.29	0.53	−0.20	0.45	0.43	−0.51	1.00
Sample: MP rowhead							
Fe	1.00						
Zn	0.53	1.00					
Mn	0.49	0.45	1.00				
Cu	**0.86***	0.44	0.56	1.00			
Hg	0.39	**0.91****	−0.36	0.44	1.00		
χ_{LF}	−0.54	**−0.81***	0.15	−0.63	**−0.70***	1.00	
χ_{FD}	0.42	0.59	0.07	0.48	0.21	0.62	1.00

*p-value <0.1.
**p-value <0.01.

4. Discussion

4.1. Magnetic susceptibility and magnetic minerals in sediment samples

When compared to sediments from other sources, the low-frequency magnetic susceptibility value of sediments that come from the Riam Kanan, Riam Kiwa, and Martapura rivers has a significantly higher value compared to that of Chaparro et al. [18] and Dong et al. [40]. However, when compared with the sediments of the Citarum River [22] and the Brantas River [25], the third river sediment in the study had a lower low-frequency magnetic susceptibility value.

The difference in susceptibility values for each river sediment sample can be explained as follows: RN samples are sediment samples formed by the weathering of bedrock, specifically peridotite, with susceptibility values ranging from 200 to 1000 $\times 10^{-8}$ m^3/kg [41]. However, because there are also many fish cages in this area, the sediment susceptibility value tends to decrease at point RN4 due to the large amount of organic matter, which is a non-magnetic material that precipitates in the sediment [42].

The increased susceptibility value at the RN5 point is thought to originate from the metal enrichment factor. Because this area is a transition from the previous point, this can be indicated by the χ_{LF} and χ_{FD} values at the RN5 point, which increased sharply from the previous point (RN4) (Table 1) [24]. The Riam Kiwa River is in an alluvial area. Based on the research of Dlouha et al. [43], the average magnetic susceptibility value in alluvium soil ranges from 362.4$\times$ 10^{-8} m^3/kg, and this corresponds to the average magnetic susceptibility (χ_{LF}) value of the Riam Kiwa river sediments. The susceptibility value of sediment samples from the Riam Kanan and Riam Kiwa Rivers has a variable value from upstream to downstream, while the Martapura River's sediments have a decreasing susceptibility value as one moves downstream. The trend of decreasing magnetic susceptibility values in sediment samples from the Martapura River is thought to be due to the fact that the Martapura River is located in a peatland area. Soils on peatlands have low susceptibility values, ranging from 1.1–136.5 $\times 10^{-8}$ m^3/kg [44].

Reviews show that peatland environments have low magnetic susceptibility [45–47]. When the peat materials flow into the river, they have the potential to influence the magnetic mineral content of the sediment. The fact that the sediments from the Martapura river are found in a peatland environment explains why they have a low magnetic susceptibility. As part of the calculation for the association factor, the quantity of lithogenic magnetic minerals must be determined. There is a strong possibility that magnetic qualities originate from a mixture of lithogenic and anthropogenic magnetic material [48]. According to the findings of previous research, χ_{FD} has been put to use in order to identify the presence of superparamagnetic particles [49]. The value of χ_{FD} in the sediments of the Martapura river ranges from 0.13 to 2.47%, which indicates that the sediments contain an admixture of coarse non-superparamagnetic grains and low superparamagnetic grains [50].

The results of the XRD analysis of the sediment samples that were extracted demonstrate that the peaks associated with magnetite (Fe_3O_4) dominate the diffractogram (Fig. 3). Based on these findings, it appears that the magnetite mineral predominates in the surface sediment samples collected at this location. This was also clarified by the SEM-EDS results, which showed that magnetite minerals were present in the samples (Fig. 4(a–d)).

The results of a VSM analysis can be used to decide about the magnetic mineral domain. Various examples of magnetic domains have been interpreted on the basis of hysteresis curves [51], and the curves of hysteresis for the extracted samples show a predominance of the PSD grain characteristics (Fig. 5c). In addition, Franke et al. [10], Zhang et al. [12], and Sudarningsih et al. [22] found evidence of magnetic minerals that were predominately PSD grains in the river sediments in other locations.

4.2. Heavy metal content

The average content of heavy metals in the sediment samples of this study, when compared with the heavy metal content in sediments from other rivers, can be reported as follows: the Fe content has less Fe content when compared to the Fe content in sediments from the Krueng River, Aceh, Indonesia [24]; Brantas River, east Java, Indonesia [25]; Citarum River, west Java, Indonesia [22]; and Vaigai River, Tamilnadu, India [52]. The high Fe content of the sediments in these rivers is due to their being in a volcanic area, which has a very high Fe content; the bedrock is very high. The average Zn content in this study's sediment samples was also lower when compared to sediments from the Krueng River, Aceh, Indonesia [24]; Citarum River, West Java, Indonesia [22]; Zijiang River, Hunan, China [53]; Xiangjiang River, Hunan, China [54]; Vaigai River, Tamilnadu, India [52]; Mefou River sediments, West-Africa [55]; Gardon of Ales River, France [56]; and Gorges River, Australia [57]. The Mn content of the sediment samples in this study was higher than that of the Zijiang River in Hunan, China [53], the Halda River in Bangladesh [58], and the Chenab River in Pakistan [59]. The Hg content in the study area was higher than in the Gardon of Ales River sediments in France [56], but lower than in the Awetu watershed in southwestern Ethiopia [60], and the Bortala River in Xinjiang, China [61]. The difference in heavy metal content occurs due to lithogenic and anthropogenic factors. The high content of heavy metals in river sediments in China is generally caused by anthropogenic factors, including industrial activities, mining, smelting activity, agricultural activities, dense settlements, and vehicle emissions. The high Hg levels in river sediments in southwestern Ethiopia are suspected to be due to the influence of agricultural activities, electronic waste, and car washing.

4.3. Assessment of environmental risk

We investigated the state of the heavy metal concentrations in the surface sediments from the Riam Kanan, Riam Kiwa, and Martapura rivers by comparing the heavy metal concentrations to the sediment quality guideline that was published by the Wisconsin Department of Natural Resources in 2003 [62]. It gives an explanation of the possibilities at those different levels of sediments that are contaminated with heavy metals, which range from low to high and are designated by the numbers 1, 2, 3, 4, and 5. These three levels of status are distinguished by three different concentrations of the effects at various values, which range from minimum to maximum. These values are referred to as the threshold effect concentration (TEC), the midpoint effect concentration (MEC), and the probable effect concentration, respectively. The values that fall within each status level's acceptable range are as follows: TEC for level 1, between TEC and MEC for level 2, between MEC and PEC for level 3, and >PEC for level 4. The average levels of heavy contents, specifically Fe, found in sediment samples taken from the Riam Kanan, Riam Kiwa, and Martapura rivers have been determined to be of concern at the level 4 level. The average levels of the heavy contents Zn and Hg found in sediment samples taken from the rivers Riam Kanan, Riam Kiwa, and Martapura all fall into the level 1 concern category. The average levels of heavy metals, especially Cu, found in sediment samples from the rivers Riam Kanan, Riam Kiwa, and Martapura are at the level 2 level of concern. The average heavy Mn content found in sediment samples from the Riam Kanan river is at a level of concern called Level 2, the same as that from the Riam Kiwa and Martapura rivers. The presence of heavy metals at concentrations greater than the threshold effect concentration values in the sediments of the Riam Kanan, Riam Kiwa, and Martapura rivers is evidence of anthropogenic effects on those sediments [24,25].

4.4. Correlation between magnetic susceptibility and heavy metals

At room temperature, elemental mercury does not exhibit magnetic properties. Because of its extremely low negative magnetic susceptibility, it has been shown to have a negative correlation with χ_{LF}. These findings lend credence to the hypothesis that an increase in the magnetic particle concentration in the Riam Kiwa and Martapura rivers is correlated with heavy metal pollution caused by anthropogenic factors. Referring to Turekian and Wedepohl [63], the presence of mercury in nature naturally ranges from 0.09 mg/kg for igneous rocks to 0.04 mg/kg for sedimentary rocks, while the Hg content in all MP samples and some RW samples exceeds these Hg levels. The increase in Hg levels in these sediment samples is certainly strongly influenced by (anthropogenic) human activities [64,65]. The anthropogenic materials at this research location are closely related to gold mining that is not managed properly. This mining waste is disposed of carelessly, so that it accumulates in rivers [66]. The same thing was also found in the sediments of the Kahayan River in Central Kalimantan [67].

Table 2 also shows the strong correlation between Fe and Zn. According to these findings, magnetic susceptibility has the potential to serve as a proxy for the presence of heavy metals associated with Fe, such as Zn. Because heavy metal emissions are linked to ferromagnetic minerals, magnetic susceptibility has been put to use as a proxy for the detection of pollutants. The use of magnetic susceptibility as a reliable indicator of the presence of contaminants led to the development of this method [68].

The correlation coefficient between χ_{LF} and Zn in the RN sample is 0.17, while in the MP sample it is −0.81. This difference is due to the fact that the two rivers are in different geological conditions. RN is located in an area with a high weathering influence of ultramafic and igneous rocks. This will affect the river sediments in addition to anthropogenic influences around the river. While MP is located in an alluvial area with peat content. According to Yoon et al. [69], peat has the potential to retain the presence of heavy metals, including Zn. The Martapura River, which is located in a densely populated location with busy traffic, will certainly affect the

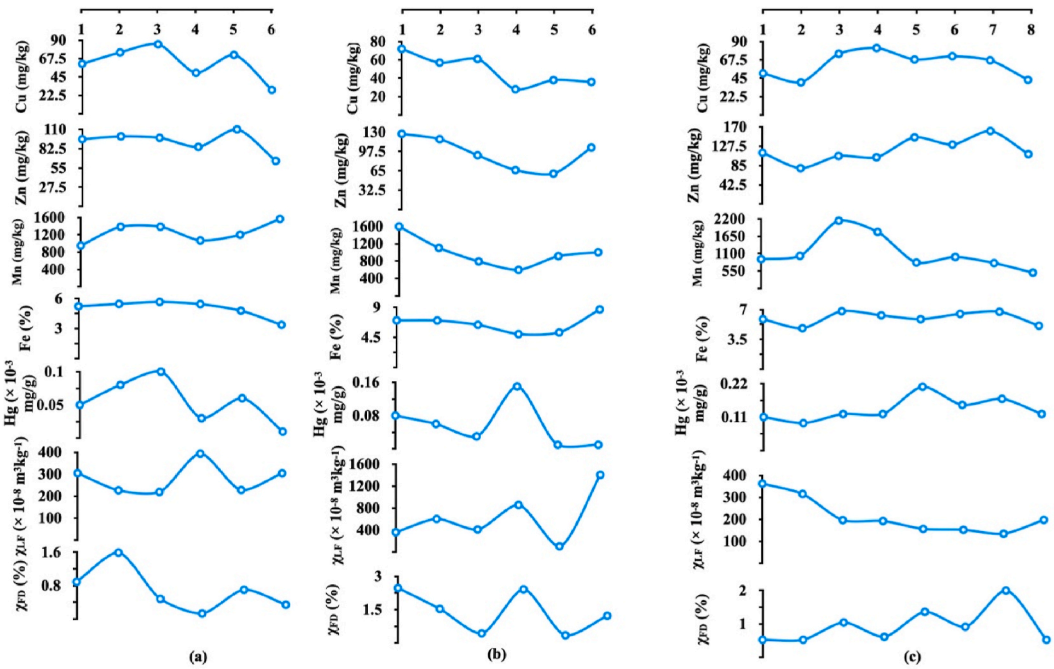

Fig. 7. Trend of heavy metal content and magnetic parameter of sediment sampling points in Riam Kiwa river (a); Riam Kanan River (b); Martapura River (c).

increase in the Zn content of anthropogenic origin [70,71]. This situation will affect the correlation between χ_{LF} and Zn as well as with other metals. This study shows that the bedrock conditions and the environment in which the river is located will affect the correlation between χ_{LF} and heavy metals. Desenfant et al. [7] and Chaparro et al. [18] also reported on this.

Based on the studies of these three rivers, the interpretation of the magnetic properties of river sediments in a peatland environment should be treated with caution. The abundance of magnetic minerals in river sediments in this environment must be carefully considered, considering that peatland can affect the decrease in the value of the magnetic parameter [72].

It is possible for the circumstances of sampling sites, particularly the land use along the Riam Kanan, Riam Kiwa, and Martapura Rivers, to have an effect on the sources of magnetic susceptibility and heavy metals in surface sediments (Fig. 7). As shown in Fig. 7, the amount of Fe that is enriched in river sediments varies from one location to the next. Alterations in Fe's abundance may be the result of a number of factors that depend on each river in this location.

4.5. Riam Kanan River

At point RK6, a number of heavy metals have the highest content. This is due to the fairly heavy flow of water from RN1 to RN5 [73], so the heavy metals accumulate at the RN6 point. Therefore, the content of all heavy metals at the RN6 point increased from the previous point, except for Cu. Points RK1 (Cu, Zn, and Mn), RK4 (Hg), and RK6 (Fe) have the highest concentration of heavy metal contents in the Riam Kanan River. There are many fish cages with floating net activities in the Riam Kanan River, especially from points RN3 to RN4. This activity leaves waste in the form of heavy metals such as Zn, Cu, Pb, Ni, and Hg [74], in addition to other waste in the form of organic matter (N and P) [75]. As well as the fish cage with floating net activity, mining could be to blame for the enrichment of Hg at point RK4 [47, [76]. Hg may also be obtained from gold mines in this area. Gold mining activities can cause mercury pollution in river sediments [77].

4.6. Riam Kiwa River

Changes in heavy metal accumulation have been suggested based on several factors. Point RW3 (Cu and Hg), RW5 (Zn), and RW6 (Mn) have the highest concentration of heavy metal contents in the Riam Kiwa river. Agricultural activities carried out along the Riam Kiwa River are oil palm plantations and paddy fields (Fig. 2). The water flow of the Riam Kiwa river is not too heavy from one point to another because the slope of the slopes in this area is not too large [78]. Based on this, as can be seen in Fig. 7, all heavy metals along the Riam Kiwa River tended to increase from point RW1 to RW3, decreased at point RW4, increased again at point RW5, and decreased again at point RW6 (Cu, Zn, Hg, and Fe), while Mn continued to increase from point RN4 to RN6. The increase in Mn value is thought to have come from the enrichment process due to agricultural activities. The application of phosphate fertilizers can lead to an increase in the concentration of some heavy metals, such as Cr, Mn, and Fe, in both soil and aquatic environments [79]. Meanwhile, enrichment of Hg at point RW3 is suspected to be from mining [4,76,80].

4.7. Martapura River

Points MP3 (Mn and Fe), MP4 (Cu), MP5 (Hg), and MP7 (Zn) have the highest concentration of heavy metal contents in the Martapura river (Fig. 7). Cu, Mn, Zn, and Hg are suspected from phosphate-containing pesticides and fertilizers containing these metals entering irrigation systems and rivers [81–83]. These metals are used in farmland around rivers, as shown in Fig. 2. The usage of phosphate fertilizers can lead to an increase in the amount of certain heavy metals found in soil and aquatic systems, including Fe, Cr, and Mn [66]. On the other hand, pesticides that protect crops from insects have heavy metal compositions, for example, Cr, Mn, Cu, As, Pb, Hg, and Zn [84,85]. These findings highlight the importance of implementing measures to reduce pollution caused by the use of fertilizers and pesticides in order to ensure the continued viability of ecosystems in the future.

A busy residence and highway, as well as a place for watercraft and industrial traffic, are close to the container port (MP8), as shown in Fig. 2. This also has an impact on the abundance of heavy metals such as Fe, Cu, Pb, Cr, Hg, and Zn [86–89]. Mn, Cu, and Fe have the same trend from points MP1 to MP8. In point 8, they tend to decrease. The most likely cause of the decline is mechanical, which depends on characteristics of river flow and river transpiration, such as bottom friction velocity and roughness coefficient. These factors are responsible for the decrease [90–92]. The Fe–Mn correlation provides support for the findings that indicate that Fe–Mn is capable of forming a chemical association brought about as a direct result of the cycle of sediment deposition. Fe–Mn oxyhydroxides are the result of this association [93]. Similarly, the oxyhydroxides of Fe are generally thought of as being a useful sink for Cu [94], and it has also been demonstrated that the adsorption of Cu prevents the complexation of other divalent contaminants, such as Zn, by competing with these contaminants for sorption sites on the surface of Fe oxyhydroxide [95].

Pramono et al. [96] reported that the PH of the Martapura River water ranged from 6.4 to 6.6, while in 2019, Mulyani et al. [97] reported that the PH of the Martapura River water ranged from 6 to 7. The pH of the Riam Kanan River water ranges from 6.4 to 6.6, as reported by Wahyuni et al. [20] Riam Kiwa River water has a PH ranging from 7.77 to 7.78 [35]. Referring to Pan et al. [98], the pH increases with a decrease in the redox potential and vice versa. The solubility of Mn and Fe increases during flooding due to reductive solubilization of the (hydro)oxides and decreases during drainage due to re-oxidation. The predicted levels of dissolved Mn and Fe in an acid environment are much higher than their measured values, due to the kinetically limited reductive dissolution of Mn and Fe (hydr)oxides in the medium. The solubility of dissolved organic matter increased during submergence, possibly due to the reductive dissolution of Fe(hydr)oxide and the observed increase in pH. However, the three rivers in this study have water with a relatively normal PH, so the redox potential in these three river environments does not show a significant role in enriching heavy metals.

Fig. 7 also depicts the inverse trend between magnetic susceptibility and magnetic susceptibility based on the frequency of the three rivers. The pattern of magnetic susceptibility in the three rivers is opposite the pattern of frequency-dependent magnetic susceptibility, which is when the value of magnetic susceptibility increases at a point and the value of frequency-dependent magnetic susceptibility tends to decrease, especially on the Riam Kiwa and Martapura rivers. Both of these rivers pass through peatland areas, whereas the Riam Kanan river does not. It is suspected that the cause of the change in magnetic susceptibility and magnetic susceptibility values depending on frequency is caused by the enrichment of magnetic minerals with high magnetic susceptibility values, such as Fe_3O_4, and/or the enrichment of magnetic minerals with smaller grain sizes, which originates from the sediment transport mechanism [99]. Magnetic mineral particles that are found in sediments may have originated from lithogenic and biogenic particles, the atmosphere, liquid waste from urban and industrial areas, or the process of sedimentation itself [100].

5. Conclusion

This research is to investigate the flow of river sediments in the South Kalimantan region in terms of magnetic mineralogy and to determine the relationship between increased concentrations of anthropogenic magnetic particles, concentrations of Fe, Zn, Cu, Mn, and Hg, sources of pollution, and pollution assessment. The trend of the susceptibility values of the three rivers tends to be the same and shows an increase in the susceptibility values at the point that is downstream of the river. The magnetic mineral magnetite, which is found in sediments, is associated with heavy metals such as Fe, Mn, Cu, Zn, and Hg, which are thought to originate from lithogenic, paedogenic, and anthropogenic processes. Correlation analysis showed that heavy metals such as Hg showed a strong positive correlation with χ_{FD} for the Riam Kanan River, whereas Zn, Cu, and Hg showed a strong negative correlation with χ_{LF} for the Riam Kiwa and Martapura Rivers. The analysis of the geoaccumulation index shows that there are several points in the three rivers that show unpolluted to moderately polluted conditions, and the lightly polluted category at several points in the Martapura River. Since the conventional analytical measurement of heavy metal contamination is expensive and laborious, the magnetic susceptibility measurement method has the potential to become an efficient alternative technique for assessing heavy metal pollution in river sediments in this area.

Author contribution statement

Sudarningsih Sudarningsih: Analyzed and interpreted the data, wrote the paper. **Aditiya Pratama**: Analyzed and interpreted the data, wrote the paper. **Satria Bijaksana**: Analyzed and interpreted the data, wrote the paper. **Fahruddin Fahruddin**: Analyzed and interpreted the data. **Andi Zanuddin**: Analyzed and interpreted the data. **Abdus Salim**: Analyzed and interpreted the data, wrote the paper. **Muhammad Rusnadi**: Analyzed and interpreted the data**. Mariyanto Mariyanto**: Analyzed and interpreted the data, wrote the paper.

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Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

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.

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