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Determining sources of sediments at Nkula Dam in the Middle Shire River, Malawi, using mineral magnetic approach

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ABSTRACT

Shire River is the largest and longest in Malawi supporting many livelihoods. Degradation in the river's catchment is now a major problem causing excessive siltation in the Nkula Dam which is a terminal sink for sediments eroded and transported by the river and its tributaries. In this study, source of sediments that are deposited into the Nkula Dam were determined by analysing sediment samples from western and eastern tributaries of the Shire River using mineral magnetic approach. Representative samples were collected from tributaries on both sides of the Shire River and Nkula Dam, and subjected to magnetic measurements on bulk samples and sized fractions (<250 μm and >250 μm). Results show significantly higher ferrimagnetic mineral contents and ferrimagnetic to anti-ferromagnetic ratios in the eastern tributaries than the western side of the Shire River. Lithology and weathering conditions are suggested to be the main cause for magnetic contrast between the two sides of the river. It is concluded that most sediments in the Nkula Dam originate from the western side of the Shire River, presumably due to excessive erosion. This study demonstrates that magnetic method is a promising approach in assessing fluvial sediment source.

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1. Introduction

Information about sediment source is critical to studies of sediment erosion and deposition in fluvial, coastal and marine systems (Walling, 2005; Zhang et al., 2008; Wang et al., 2010; Yamazaki and Ikehara, 2012; Wilkinson et al., 2013). Methods including geochemistry, mineral analysis and environmental magnetic approach have been used in tracing source of sediment (Walden et al., 1997; Owens et al., 1999; Walling, 2005; Fialová et al., 2006; Zhang et al., 2008; Wilkinson et al., 2013). Most of these studies suggest that particle size is an important factor affecting magnetic properties of sediments, even if they are from the same source (Oldfield et al., 1985; Thompson and Oldfield, 1986; Walden et al., 1997; Wang et al., 2011). This is due to the fact that different particle size fractions contain magnetic minerals of distinct mineralogy, size and amounts (Oldfield et al., 1985; Zhang et al., 2008; Dong et al., 2014; Pulley and Rowntree, 2016). Hydrodynamic variation can result in particle size and density sorting in the process of sediment transport and deposition (Oldfield and Yu, 1994; Venkatachalapathy et al., 2011; Gallaway et al., 2012; Wilkinson et al., 2013). Typically, larger particles and denser components will be transported less downstream compared to smaller and lighter ones. Only a particular fraction of the material eroded on a hill slope therefore, reaches the catchment outlet or downstream due to sediment sorting (Booth et al., 2005; Wang et al., 2010; D'Haen et al., 2013; Skolasińska, 2014; Pulley and Rowntree, 2016). This in turn, will influence magnetic properties of sediments on the pathway from source to sink. Particle-size specific measurement of magnetic properties was therefore introduced to minimize the effect of sorting for sediment source tracing purpose (Oldfield et al., 1985; Hatfield and Maher, 2008; Zhang et al., 2008).

In Malawi, Nkula Dam, which is located in the middle section of the Shire River, is under massive siltation due to unabated anthropogenic activities in the river's catchment, causing reduction

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of the capacity of the Dam reservoir from 14 m to about 1.5 m (Osborne, 2000; Palamuleni, 2010; Birch, 2011; Kaunda and Mtalo, 2013; Mzuza et al., 2015). Although some studies suggest sediments from Lake Malawi might be transported to the Shire River (Owen and Crossley, 1992), it seems that such a contribution is not significant considering the ox-bow lake known as Lake Malombe downstream of Malawi Lake, which may act as a sink of sediments from Lake Malawi. Lake Malombe is an ox-bow lake formed as a result of the meandering and swelling of the Shire River about 19 km away from the mouth of the southeast arm of Lake Malawi. Current studies in the Shire River Basin indicate that tributaries flowing into the Shire River are major sources of sediments downstream (FAO, 1993; Osborne, 2000; Kaunda and Mtalo, 2013). However, there is limited knowledge regarding source of sediment deposited into the Nkula Dam reservoir, particularly considering the contribution of tributaries on both sides of the middle Shire River. This study builds upon magnetic 'fingerprinting' of contemporary river bed sediments in tributaries of the Shire River in Malawi, and attempt particle size-specific magnetic discrimination of sediment source with the aim of contributing to the understanding of the accelerating siltation problem at the Nkula Dam reservoir.

2. Study area and methods

2.1. Study area

Shire River, originating from the south east arm of Lake Malawi (Malawi, southern Africa), is divided into three sections, namely, Upper, Middle and Lower Shire (Fig. 1). The study area (where Nkula Dam is located), lies within the middle part of river, which primarily comprises the Shire Plain - a flat-lying featureless landform on both sides of the Shire River, with elevations ranging from 500 m to 1300 m above sea level (Osborne, 2000). The plain is more extensive to the west of the Shire River consisting of highlands (FAO, 2006). The area experiences a continental tropical climate with two seasons, dry season (May to October) and rainy season (November to April). There are local variations in climate in the Middle Shire area, which are probably due to differences in physiography (Maher, 2007). The eastern part of the Middle Shire receives more rainfall due to its mountainous topography, which is 1150 mm/yr in comparison to 900 mm/yr in the western part year (Kaunda, 2013). Annual temperature ranges from 17 °C to 29 °C, with highlands experiencing lower temperatures than plains. According to data from water gauging stations in the eastern side (Lirangwe River) and western side (Riviridzi River), there is much higher specific flow (two times) in the former particularly in dry season due to a large ground water outflow component (Ministry of Water Development and Irrigation, 2013).

The study area is underlain by Pre-Cambrian Basement Complex gneisses. The dominant rock formations include garnetiferous hypersthene-biotite gneiss, garnetiferous biotite gneiss, and hornblende-biotite gneiss with pyroxene in parts. Quartzo-feldspathic gneisses occurs near Liwonde while perthitic norites and meta-pyroxenites are common south east of the area on the eastern side of the Shire River. Calc-silicate granulites occur as

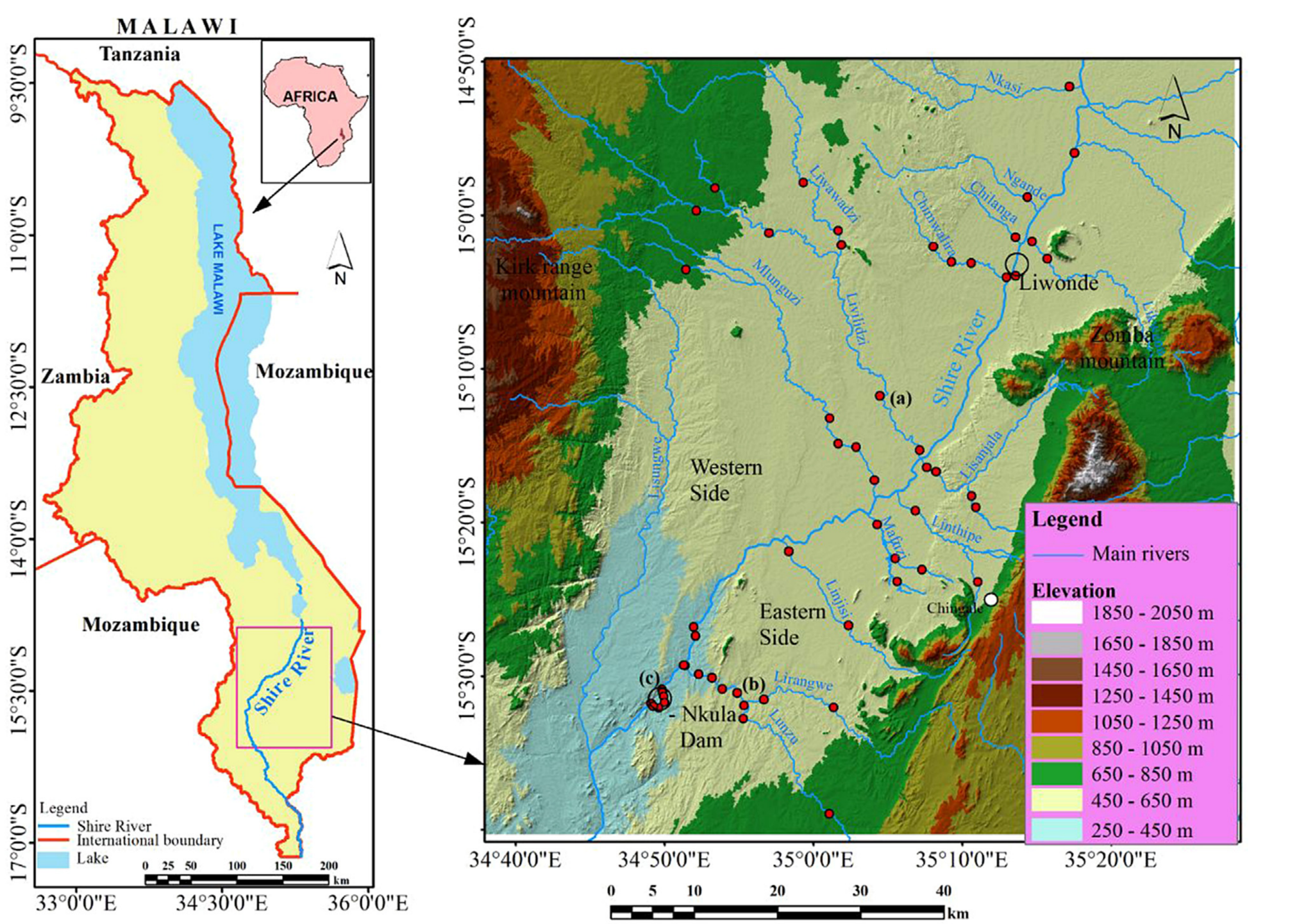

Fig. 1. Map of the middle Shire River, Malawi, showing the sampling sites. The symbols (a), (b) and (c) mark the samples selected for thermomagnetic analysis as shown in Fig. 5.

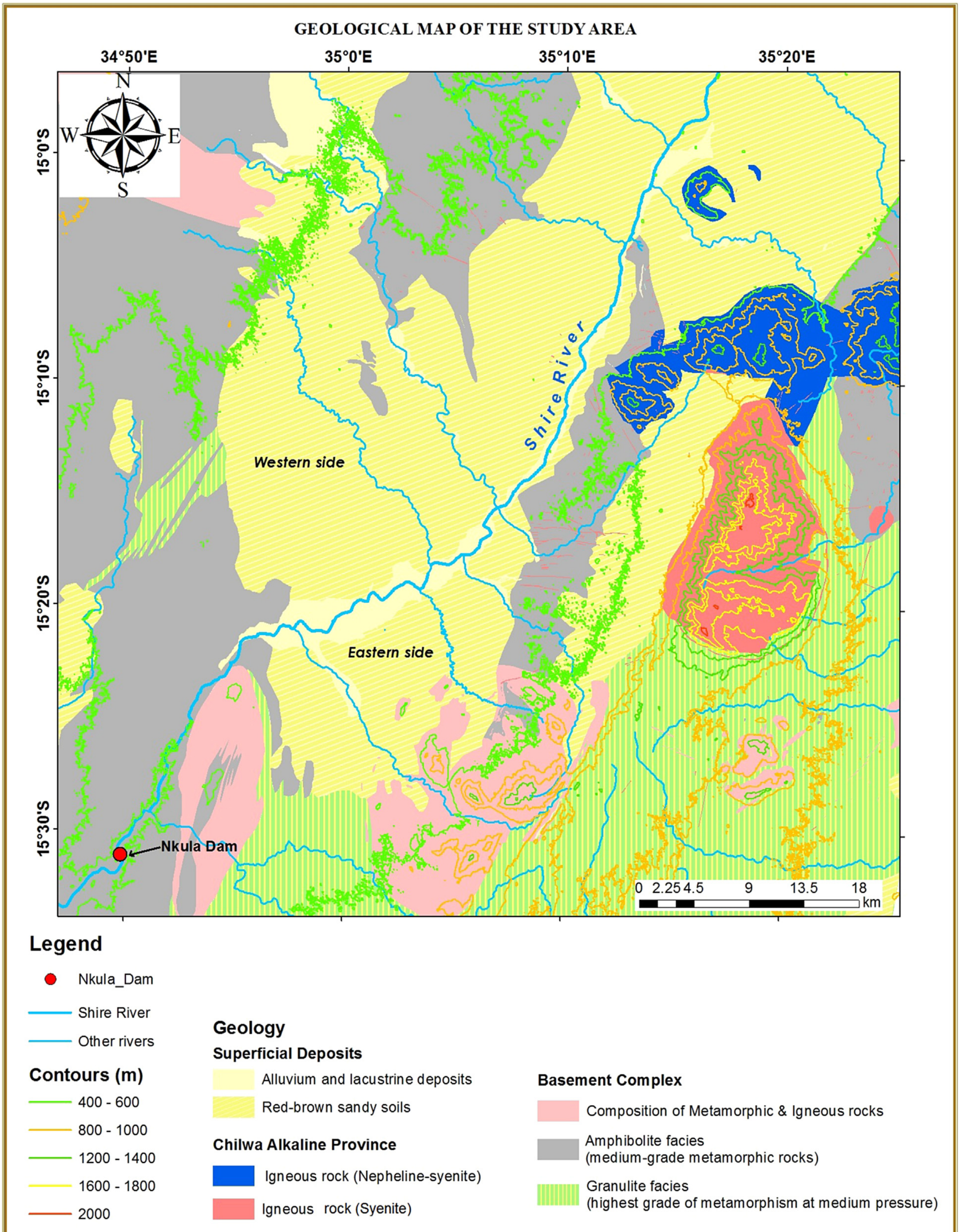

Fig. 2. Geological map of the study area, showing the difference in rock types on both sides of the Shire River (modified from Geological Map of Malawi).

narrow bands following foliation trends. Amphibolitic bands are common in the gneisses and are thought to represent metadolerites (Morel, 1958; Bloomfield, 1965; Bloomfield and Garson, 1965).

Soils are classified as red-brown sandy soils with loamy red clay soils in some parts of the Shire highlands. In the Shire Plain, the gnisseses are covered by pale brown and black clay; and sandy clay colluvial soils commonly known as mopanosols. People around the middle Shire River catchment area rely on firewood and charcoal for their livelihoods hence deforestation which appears to be more pronounced in the western side of the river's catchment (Kaunda and Mtalo, 2013).

2.2. Methods

Soil samples were collected from river banks of 16 main tributaries in the Middle Shire River represented by red dots on the catchment map (Fig. 1). Western side consists of 6 tributaries and 10 rivers from the eastern side. Sample collection sites on the tributary rivers were selected based on the accessibility of the area. . Two to three surface samples were obtained at each site mixed, making a total of 49 samples during dry season between May and July 2014 and 2015 respectively. Samples from Nkula Dam reservoir (7) were obtained within a water depth of 14 m when the reservoir was drained in May 2014.

2.3. Laboratory analysis

Samples were dried at a room temperature of <40 °C and then, disaggregated with a mortar and pestle. Particle size analysis showed that the dam samples were dominated by sand (>63 μm) fraction, with the <250 μm fraction accounting for size 81% on average. For the sediments from the tributaries, the <250 μm fractions were 58% for the west and 76% for the east on average. Samples were therefore, separated into two size fractions, i.e., <250 μm and>250 μm size.

Bulk and particle-sized samples were packed into plastic boxes for subsequent analysis. Magnetic susceptibility was measured using Bartington MS2B Magnetic susceptibility meter at low (0.47 kHz) and high (4.7 kHz) frequencies (χ_{lf} and χ_{hf}), respectively. Anhysteretic Remnant Magnetization (ARM) was acquired in a 0.04 mT direct current (DC) field superimposed on a peak AF demagnetization field of 100 mT, and expressed as susceptibility (χ_{ARM}) by normalizing ARM with DC field. Isothermal Remnant Magnetization (IRM) measurements were made using a forward field of 1 T followed by backfields of −100 mT and −300 mT. The corresponding IRM is referred to as $IRM_{\chi mT,}$ where χmT indicates the field value. Frequency-dependent susceptibility was calculated as $\chi_{fd}\% = (\chi_{lf}\text{-}\chi_{hf})/\chi_{lf} \times 100$ in percentage form. In this study, IRM obtained at 1T was referred to as saturated IRM (SIRM). Hard IRM (HIRM) was defined as HIRM = 0.5 × (SIRM+IRM_{-300mT}). S_{-100} and S_{-300} were calculated as $S_{-100} = 0.5 \times (SIRM\text{-}IRM_{-100mT})/SIRM \times 100$ and $S_{-300} = 0.5 \times (SIRM\text{-}IRM_{-300mT})/SIRM \times 100$, respectively. On the basis of room-temperature measurements, 18 samples from different tributaries and the dam were selected for thermomagnetic measurements using AGICO MFK1-FA Kappa bridge equipped with a CS-3 high-temperature furnace. Each sample was heated from room temperature to 700 °C and then cooled to room temperature in an argon atmosphere.

Approximation of total magnetic mineral concentration was provided by χ and SIRM (Oldfield and Thompson, 1986; Walden et al., 1997). χ_{fd}% was considered to reflect contribution of fine viscous grains close to the super-paramagnetic (SP)/single domain (SD) boundary to total ferrimagnetic assemblage (Oldfield and Thompson, 1986). χ_{ARM} is sensitive to single domain ferromagnetic grains (Maher, 1988). An estimation of the concentration of anti-ferromagnetic minerals was provided by the changes in HIRM (Bloemendal and Liu, 2005). χ_{ARM}/SIRM is commonly used as a grain-size indicator of ferrimagnetic minerals which peaks in a single domain (SD) range and decreases with increasing grain size (Maher, 1988). S_{-300} was used to measure the relative importance of higher coercively of minerals and lower coercivity components in the total assemblage (Bloemendal and Liu, 2005; Zhang et al., 2007). S_{-100} indicates the mineral assemblage variations but also, can be influenced by grain size variation in ferrimagnetic minerals, with higher coercivities of SD grains than that of multi-domain (MD) grains (Yamazaki, 2009; Yamazaki and Ikehara, 2012). Thermomagnetic analysis provides mineralogy of magnetic minerals contained in the sediments (Oldfield and Thompson, 1986).

Particle size of sediment was analyzed by initially adding 5 ml of 10% hydrochloric acid (HCl) into the samples to remove carbonate. After 30 min, 5 ml of 10% hydrogen peroxide (H_2O_2) was added to remove organic matter. The samples were then heated at 100 °C after another 30 min, until no bubble could be seen. Ten ml of 0.5% of sodium hexametaphosphate [Na $(PO_3)_6$] was added to the sample and ultra-sonicated to ensure complete disaggregation before analysis. Finally, the sediment particles were analyzed with laser size analyzer Coulter LS-1000.

3. Results

3.1. Particle size

Particle size analysis shows that <250 μm fraction accounts for an average of 70% in river bed sediments and 81% in the Nkula Dam sediments. On average, river bank sediment from the western tributaries of the Shire River consisted of 9% clay (<4 μm), 26% silt (4–63 μm) and 65% sand (>63 μm), while sediment from the eastern tributaries consisted of 10% clay, 34% silt and 56% sand. Nkula Dam sediments are finer, consisting of 40% sand and the other 60% for silt and clay (Table 1, Fig. 3).

3.2. Sedimentary magnetic properties comparison between western and eastern tributaries

3.2.1. Bulk sediments

All the samples had S_{-300} values greater than 90%, implying a

Table 1
Sediment particle size composition and magnetic characteristics (mean ± SD, minimum and maximum value).

Parameter	Western tributaries (n = 20)			Eastern tributaries (n = 29)			Nkula Dam (n = 7)		
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum
Clay (%)	7 ± 3	1	13	10 ± 5	3	21	18 ± 9	7	31
Silt (%)	22 ± 11	2	48	29 ± 15	6	66	46 ± 14	31	64
Sand (%)	71 ± 14	41	97	61 ± 19	16	91	36 ± 20	4	61
χ ($10^{-8}m^3kg^{-1}$)	104 ± 46	36	205	352 ± 312	34	1225	193 ± 58	106	284
$\chi_{fd\%}$ (%)	5 ± 2	1	10	4 ± 2	0	9	6 ± 1	4	8
χ_{ARM} ($10^{-8}m^3kg^{-1}$)	381 ± 176	139	713	680 ± 437	149	2136	792 ± 175	550	987
SIRM ($10^{-6}Am^2kg^{-1}$)	8111 ± 3005	2639	13,530	26,914 ± 21,691	2751	92,899	15,894 ± 5524	7197	24,520
HIRM ($10^{-6}Am^2kg^{-1}$)	371 ± 176	52	772	954 ± 787	191	3551	579 ± 260	269	1058
S_{-100} (%)	78.1 ± 8.4	64.2	99.6	81.0 ± 5.9	69.3	97.0	84.0 ± 3.2	79.3	88.2
S_{-300} (%)	95.2 ± 2.2	91.0	98.3	95.9 ± 1.8	92.4	99.5	96.4 ± 0.4	96.0	97.0
χ_{ARM}/SIRM ($10^{-5}mA^{-1}$)	48 ± 17	18	86	35 ± 25	11	129	58 ± 31	33	117

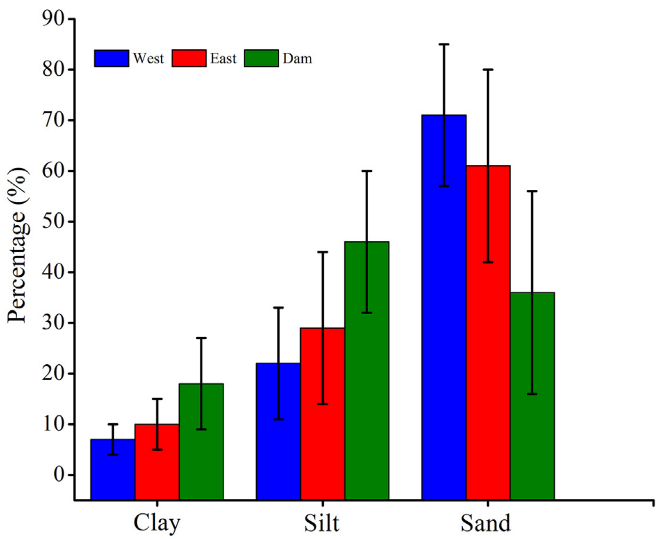

Fig. 3. Comparison of sediment particle size compositions in western and eastern tributaries, and Nkula Dam.

dominance of magnetic properties by ferrimagnetic minerals (Thompson and Oldfield, 1986) (Table 1). The positive correlation between χ and SIRM (Fig. 4), further may suggest that χ is dominated by ferrimagnetic minerals (Thompson and Oldfield, 1986). Thermomagnetic analysis revealed Curie temperature around 600 °C, confirming that magnetite is the dominant ferrimagnetic mineral (Fig. 5). Samples from the western tributaries and Nkula dam showed obvious Hopkinson peaks (Fig. 5a, c). There were significant differences in concentration related parameters (e.g., χ, χ_{ARM}, SIRM and HIRM) between western and eastern tributaries ($p < 0.05$). On average, concentration related parameters were two to three times higher in eastern tributaries sediments than those in western tributaries (Table 1), as exemplified by χ shown in Fig. 6a. Mean particle size (μm) was generally higher in the western than eastern tributaries (Fig. 6b).

Lower χ_{ARM}/SIRM ratios (averaged at 47 × 10^{-5}mA^{-1} and 36 × 10^{-5}mA^{-1} for western and eastern tributaries), respectively, suggest the dominance of coarse SD grains in sediments of eastern and western sides (Oldfield, 1994). Mean value for χ_{ARM}/SIRM was higher in western tributaries than eastern tributaries, suggesting finer ferrimagnetic magnetic grain size in the former (Table 1). However, there were no significant differences in $\chi_{fd\%}$ between western and eastern tributaries ($p > 0.05$). Mean values for parameters indicating magnetic mineralogy (S_{-100}, S_{-300}) were slightly higher in eastern than western tributaries (Table 1), suggesting higher proportions of ferrimagnetic minerals in the eastern side.

3.2.2. Particle-sized fractions

There was a positive SIRM versus χ relationship in both the <250 μm and >250 μm fraction (Fig. 4b and c). Magnetic characteristics of the two size fractions (<250 μm and >250 μm) are shown in Table 2. In both size fractions, concentration related parameters (χ, χ_{ARM}, SIRM and HIRM) were higher in east tributaries, as exemplified by χ and HIRM shown in Fig. 7a and b. Slightly higher values for grain-size indicators (χ_{fd}% and χ_{ARM}/SIRM) were observed in the western tributaries (Fig. 7c). On average, mineralogy related parameters (S_{-100}, S_{-300}) were slightly higher in the >250 μm fraction than in the <250 μm fraction in tributaries from both sides of the Shire River (Table 2).

3.3. Magnetic properties comparison between tributaries and Nkula-Dam sediments

3.3.1. Bulk sediments

Concentration related parameters (χ, SIRM and HIRM) in eastern tributaries were higher than the values of Nkula Dam, while values for Nkula Dam were higher than those of the western tributaries. Although grain-size indicator (χ_{ARM}/SIRM) was slightly lower in eastern tributaries than in western tributaries, there were no significant differences between the tributaries on both sides of the river and Nkula Dam ($p > 0.05$). Furthermore, though mineralogy related parameters (S_{-100}, S_{-300}) were slightly higher in eastern than western tributaries, there were no significant differences between tributaries and Nkula Dam ($p > 0.05$) (Table 1).

3.3.2. Particle-sized fractions

Concentration related parameters (χ, SIRM and HIRM) of Nkula-Dam samples were higher in the <250 μm fraction as they were in samples from the western and eastern tributaries. Significant

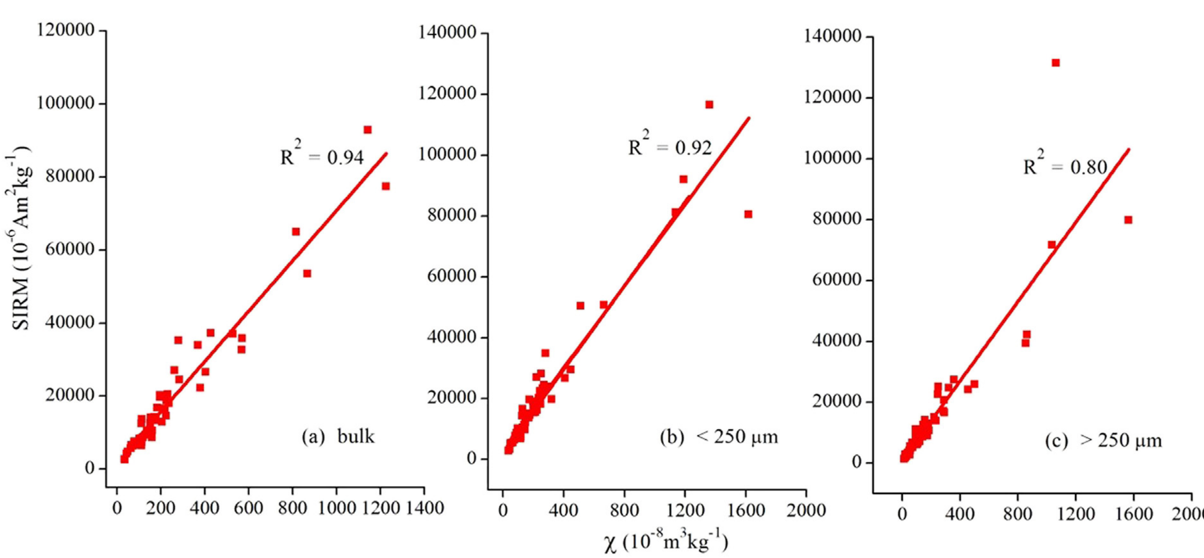

Fig. 4. Positive relationship between SIRM and χ in (a) bulk samples, (b) the <250 μm fraction and (c) the >250 μm fraction.

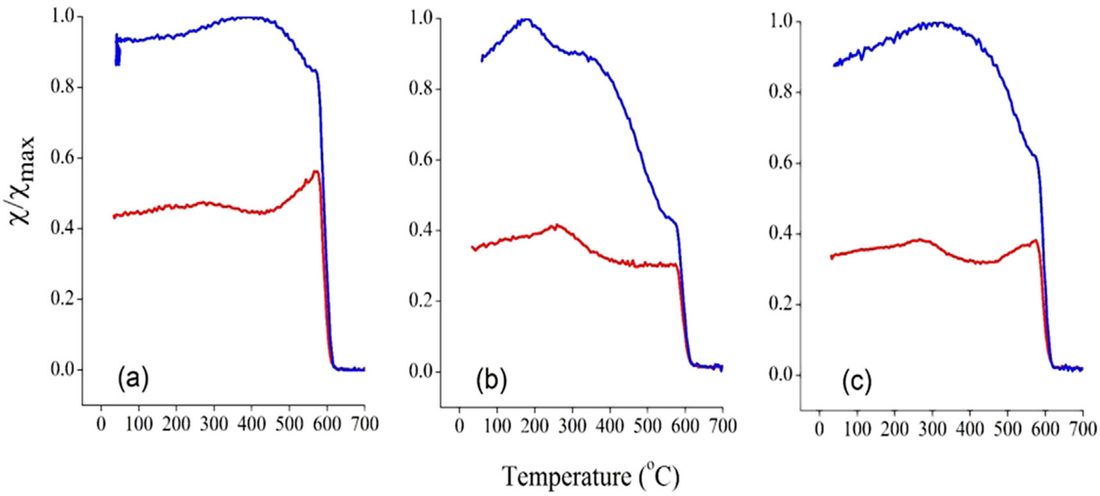

Fig. 5. Magnetic susceptibility versus temperature curves for selected bulk samples. Red and blue lines represent heating and cooling curves, respectively. (a) western tributaries, (b) eastern tributaries, and (c) Nkula Dam, and site of these samples are shown in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differences in χ, SIRM and HIRM were observed between western and eastern tributaries in both size fractions, but no significant differences were reported between tributaries and the Nkula-Dam ($p > 0.05$). There were also no significant differences in mineralogy related parameters between tributaries and Nkula Dam ($p > 0.05$) (Table 2).

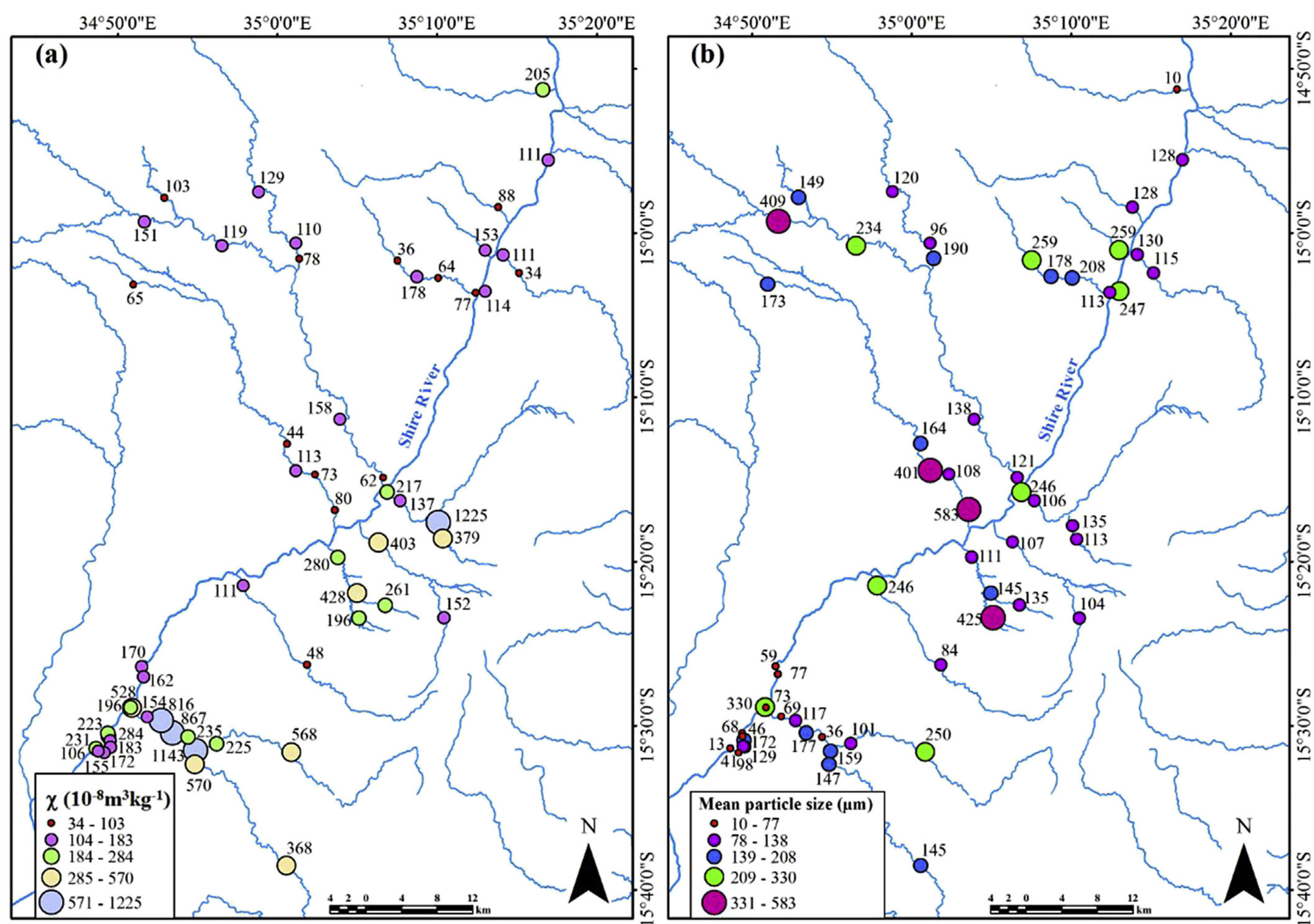

Fig. 6. Spatial variations of (a) bulk χ and (b) mean particle size in the study area. The number indicates the values of χ and mean particle size at each site.

Table 2
Magnetic properties (mean ± SD, minimum and maximum) of sized fractions for tributaries of the Shire River and Nkula Dam (<250 μm and >250 μm).

Parameter	Size (μm)	Western tributaries (n = 20)			Eastern tributaries (n = 29)			Nkula Dam (n = 7)		
		Mean ± SD	Min	Max	mean ± SD	Min	Max	Mean ± SD	Min	Max
χ ($10^{-8}m^3kg^{-1}$)	>250	71 ± 39	22	176	346 ± 375	14	1565	145 ± 78	56	286
	<250	122 ± 57	45	263	385 ± 413	36	1620	195 ± 60	106	296
$\chi_{fd\%}$ (%)	>250	5 ± 2	2	9	3 ± 2	0	9	6 ± 2	4	8
	<250	6 ± 3	3	14	4 ± 3	0	13	7 ± 2	5	9
χ_{ARM} ($10^{-8}m^3kg^{-1}$)	>250	310 ± 141	110	617	663 ± 625	146	2964	850 ± 303	494	1229
	<250	406 ± 182	162	813	796 ± 547	158	2385	775 ± 173	539	993
SIRM ($10^{-6}Am^2kg^{-1}$)	>250	4990 ± 2239	1630	10,059	24,012 ± 27,668	1354	131,524	10,070 ± 4536	5138	17,083
	<250	9821 ± 4624	3313	23,342	30,220 ± 28,312	2855	116,526	16,674 ± 5343	7237	23,959
HIRM ($10^{-6}Am^2kg^{-1}$)	>250	193 ± 124	38	465	1069 ± 1068	102	4858	331 ± 161	173	672
	<250	557 ± 336	64	1610	1289 ± 1220	218	5407	563 ± 185	256	773
S_{-100} (%)	>250	85.0 ± 9.3	67.4	99.4	81.0 ± 5.1	72.0	93.0	86.3 ± 3.8	79.0	90.0
	<250	76.3 ± 8.2	57.0	87.0	79.7 ± 5.3	69.0	93.1	83.4 ± 2.0	80.3	88.3
S_{-300} (%)	>250	96.0 ± 2.4	89.0	99.5	95.0 ± 2.8	84.5	99.0	97.0 ± 1.1	95.0	98.0
	<250	94.3 ± 2.3	89.0	98.1	95.4 ± 1.7	92.0	99.0	97.0 ± 0.4	96.2	97.3
χ_{ARM}/SIRM ($10^{-5}mA^{-1}$)	>250	65 ± 17	38	101	47 ± 55	5	282	95 ± 34	29	119
	<250	44 ± 17	19	84	38 ± 27	10	131	54 ± 32	28	118

4. Discussion

4.1. Magnetic differences between western and eastern tributaries

Higher values of concentration related magnetic parameters (χ, SIRM, χ_{ARM} and HIRM) in sediment from the eastern tributaries can be caused by several factors, including differences in lithology, climate and weathering conditions, and particle size (Dunlop and Prévot, 1982; Oldfield and Thompson, 1986; Robson and Sahota, 2000; Walling, 2005; Fialová et al., 2006; Orme, 2013; Kulkarni et al., 2014; Pulley and Rowntree, 2016). Correlation analysis indicates that χ and SIRM of the sediments are independent of particle size. HIRM in the tributaries samples is positively correlated with clay or silt, while χ_{ARM} and χ_{ARM}/SIRM of the dam sediments are negatively and positively correlated with clay fraction, respectively (Table 3). The whole middle Shire River is underlain by crystalline metamorphic rocks (Morel, 1989). The western part of Shire River lies along the eastern slopes of the Kirk Mountains while the eastern part extends into the Shire highlands. The eastern part consists of two-pyroxene granulites with subordinate skarns and biotide-garnet granulites (perthitic norite gneiss, syenite gneiss, pyroxenite gneiss, gneiss and granulite, basalt, marble). The

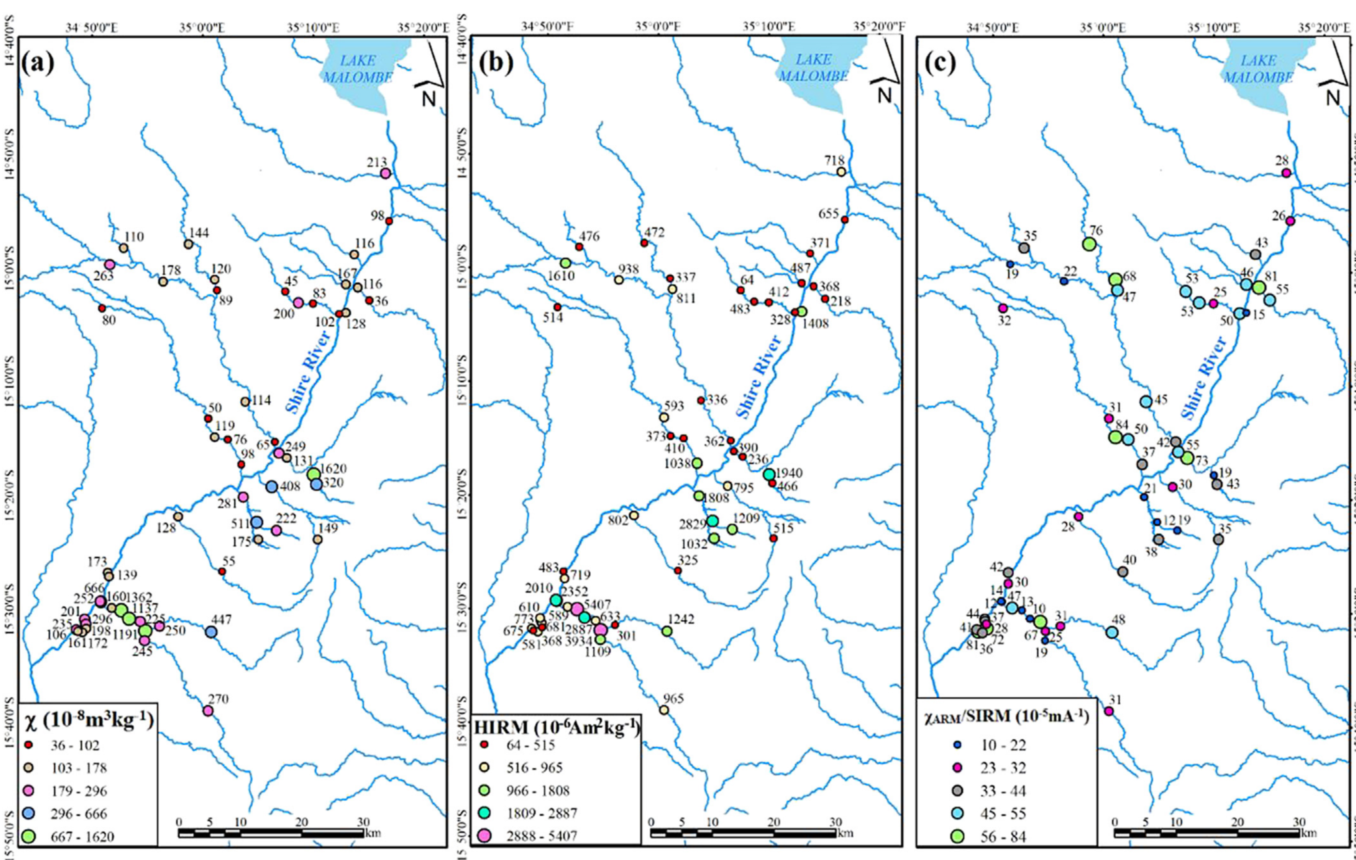

Fig. 7. Spatial variations of χ (a), HIRM (b) and χ_{ARM}/SIRM (c) in the <250 μm fraction. The number indicates the value of magnetic parameters at each sampling site.

Table 3
Correlation coefficients between particle size and magnetic properties.

	Particle size	χ	SIRM	HIRM	$\chi_{fd\%}$	χ_{ARM}	χ_{ARM}/SIRM	χ_{ARM}/χ	S_{-100}	S_{-300}
Western tributaries	<4 μm	0.01	−0.14	0.42	0.05	0.24	−0.24	−0.41	0.58*	0.43
	4-63 μm	0.06	0.08	0.53*	0.04	−0.05	0.11	−0.04	0.57*	0.58*
	>63 μm	−0.05	−0.03	−0.53*	−0.04	−0.02	−0.03	0.14	−0.60*	−0.57*
	Mean size	0.03	−0.35	−0.04	0.11	0.11	0.14	0.08	−0.15	−0.15
Eastern tributaries	<4 μm	−0.08	0.19	0.54*	−0.11	−0.05	0.27	0.00	0.45*	0.47*
	4-63 μm	−0.18	0.28	0.40*	−0.20	−0.05	0.20	−0.07	0.44*	0.46*
	>63 μm	0.16	−0.27	−0.45*	0.19	0.05	−0.23	0.05	−0.46*	−0.48*
	Mean size	−0.21	0.02	−0.27	−0.16	−0.01	−0.25	0.03	−0.17	−0.19
Dam	<4 μm	−0.18	0.44	0.60	−0.49	−0.71*	0.78*	0.52	0.84*	0.88*
	4-63 μm	0.15	0.23	0.45	−0.01	−0.37	0.57	0.56	0.53	0.52
	>63 μm	−0.04	−0.33	−0.55	0.18	0.53	−0.70*	−0.59	−0.69*	−0.70*
	Mean size	−0.27	−0.01	−0.46	0.06	0.43	−0.59	−0.55	−0.42	−0.50

Note: * is significant at $p < 0.05$.

western part consists of biotite-gneisses and hornblende-biotite gneisses together with subordinate pelitic and calcareous metasediments (Morel, 1989; Sehatzadeh, 2011). Accordingly, a well-defined transition zone separates the western side which has prograde amphibolite facies gneisses from the eastern which consists of granulite facies (Morel, 1989). It has been demonstrated that magnetic mineral concentration increases with grade of metamorphism (Nakamura and Borradaile, 2004). In addition, dolerite dyke swarms control the topography of the eastern side of the Middle Shire River (Morel, 1989; Munthali, 2007; Sehatzadeh, 2011). The eastern part of the Middle Shire River is thus, composed of metamorphic rocks that are richer in ferrimagnetic minerals (Fig. 2). The dominance of rocks richer in ferrimagnetic minerals in the eastern contributes to higher concentration related parameters (e.g., χ and SIRM). Differences in concentration related parameters were also observed within each side of the middle Shire River (Fig. 6). This might be due to differences in lithology within each side of the river as shown in Fig. 2. Although the eastern side receives more rainfall, magnetic minerals in the sediments are coarser than those from the western side, an indication that ferrimagnetic minerals are coarse-grained in the eastern side, and therefore inherited from primary minerals in the rock. It seems that rainfall and chemical weathering plays a minor role in generation of fine-grained ferrimagnetic minerals. Additionally, human activities may cause the difference in magnetic properties. Burning of soils may alter the magnetic mineralogy, and it is reported that fine-grained magnetic minerals may be produced in burned soils (Blake et al., 2006; Oldfield and Crowther, 2007; Pulley and Rowntree, 2016). This could be one reason for finer magnetic grain size in samples from the western side, since this part of the river has been subjected to more intense deforestation and burning (Davies et al., 2010). The highest χ and SIRM values occur at the tributaries which flow through the densely populated towns of Lirangwe and Lunzu on the eastern side of the river Shire (Fig. 6). Anthropogenic input in these towns may contribute to the high ferrimagnetic mineral concentrations.

4.2. Source of sediments in Nkula Dam

Since the dam sediments are dominated by the <250 μm fraction, we compared the tributaries with dam using this size fraction. Mean values of SIRM versus χ in the <250 μm of the western tributaries and eastern tributaries and Nkula Dam are shown in Fig. 8. The Nkula Dam sediments plot more closely to the river samples from the western side in the plot than the eastern side (Fig. 8). This may suggest that sediment at Nkula Dam originate from both sides of the Shire River, but with more sediment from the western rivers. Considering that most of the tributaries flowing into the Shire River are located in the middle reach (Fig. 1), we consider the possible sediment contribution to the dam from the upper Shire River to be minor. Similar thermomagnetic curves in Fig. 4a and c also suggest that the Nkula Dam sediments have similar magnetic mineralogy to those of the western tributaries. This is consistent with high anthropogenic activities mainly agriculture which result into high deforestation and soil erosion causing increased runoff in the western side of the Shire River (Birch, 2011; Kaunda and Mtalo, 2013). On the western side of middle Shire River, the growing population since 1990s has expanded land area under cultivation and exploited forests and woodlands for firewood and charcoal production (Davies et al., 2010; Birch et al., 2012). Hudak and Wessman (2000) reported that refugees from Mozambique fleeing the civil war contributed to the population increase since 1994 in Mwanza district (located in the western side of the Shire River), causing a greater demand for resources. High population density and poverty have led to significant human pressure on the environment and degradation of the Shire River Basin's natural resources, especially on land and forests (Osborne, 2000; Koroluk and de Boer, 2007; Orme, 2013; Mayes et al., 2015). The western catchment of the Shire River has also experienced increased proliferation of small-scale mining industries which has resulted into cutting of forests for small-scale industrial purposes leading to opening up of large areas which are void of vegetation (Nanthambwe, 2013). One major example of the small-scale mining

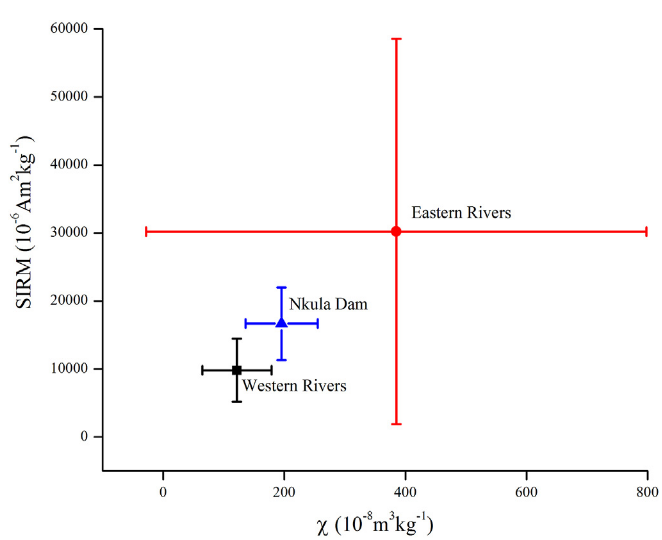

Fig. 8. Plot of SIRM versus χ in the <250 μm fraction of sediments from the western and eastern tributaries, and Nkula-dam of the Shire River.

industries on the western side of the Shire River Basin is the mining of lime in Balaka District which demands that trees have to be cut for baking the rocks before they are prepared into the end product (Nanthambwe, 2013). Deforestation leads to increased incidence of soil erosion, run-off and flash floods in the western side of the Shire River (FAO, 2006). On the contrary, the eastern catchment of the Shire River has more land cover (forest), chiefly the Liwonde National Park, Zomba and Machinga mountain forest reserves which are protected areas. Forests absorb, retain and release water slowly, resulting into reduced erosion rates (Davies et al., 2010). According to the water gauging stations in eastern and western sides of the Shire River, there is higher specific flow of water, almost two times higher in the eastern side especially from Lirangwe River than the western side (Ministry of Water Development and Irrigation, 2013). Despite the higher water discharge, the eastern side of the middle Shire River has been affected less by anthropogenic activities (Kaunda and Mtalo, 2013) and therefore, less soil erosion and fluvial sediment discharge.

5. Conclusions

Tributaries from both sides of the Shire River show differences in magnetic properties with the eastern tributaries showing higher concentration-related magnetic parameters, indicative of higher concentration of ferrimagnetic minerals. Grain-size indicators are slightly higher in western tributaries, suggesting finer ferrimagnetic grains. Lithology of the catchment can largely explain the higher concentrations of magnetic minerals in the eastern side of the Shire River. A comparison of sedimentary magnetic properties of the <250 μm fraction between tributaries and Nkula Dam suggests that the dam sediments have a mixture of sediment sources from both sides of the Shire River, with higher contribution from the western side. This is consistent with the fact that soil erosion is much obvious due to increased human activities in the western side of the Shire River. Our findings demonstrate that magnetic approach is a promising means of understanding sources of sediments in dams.

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