

2023-02-14

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Springer Nature

<https://doi.org/10.1007/s11368-023-03440-y>

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Tracing the dominant sources of sediment flowing towards Lake Victoria using geochemical tracers and a Bayesian mixing model

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Received: 18 August 2022 / Accepted: 15 January 2023 / Published online: 14 February 2023
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Abstract

Purpose Lake Victoria has been increasingly silting over the past decades, impacting water quality and loss of biodiversity. Sediment control strategies require information on the relative and absolute contributions of sediment from different sources. However, to date, there is no continuous monitoring of sediment flux or water quality in any of the tributaries, prohibiting an assessment of the scale of the problem. The aim of this study was to trace the dominant sources of riverine sediment using geochemical fingerprinting, thereby generating a knowledge base for improving land management and reducing sediment yields in Simiyu River catchment, one of the main contributing rivers to Lake Victoria.

Materials and methods Geochemical tracer concentrations were analyzed in transported sediment from the main river and two tributaries (riverbed sediments) and from soils in five dominant land use types (agricultural land, bush land, forest land, channel banks, and main river banks). Dominant sources to the Simiyu main river sediment were attributed using the Bayesian MixSIAR model.

Results and discussion The mixing model outputs showed that the Simiyu tributary was the dominant source of sediment to the Simiyu main river with 63.2%, while the Duma tributary accounted for 36.8%. Cultivated land was shown to be the main land use source of riverine sediment, accounting for 80.0% and 86.4% in Simiyu and Duma sub-tributaries, respectively, followed by channel banks with 9.0% in both sub-tributaries. Direct unmixing of the Simiyu main river sediment to the land use sources yielded 64.7% contribution of cultivated land and 26.5% of channel banks.

Conclusion The demonstrated application of sediment source tracing provides an important pathway for quantifying the dominant sources of sediment in the rivers flowing towards Lake Victoria. Eroded soil from agricultural areas is the biggest contributor to transported sediment in the Simiyu River. This information is vital for the design of catchment wide management plans that should focus on reducing soil erosion and sediment delivery from farming areas to the river networks, ultimately supporting both food security and water quality in the Lake Victoria Basin.

Keywords Soil erosion · Water quality · Lake Victoria Basin · Sediment fingerprinting · MixSIAR · Simiyu catchment

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1 Introduction

Deterioration of water quality due to nutrient and sediment loading is impacting lakes around the world, leading to eutrophication and siltation (Søndergaard et al. 2003). These impacts are mostly driven by catchment-wide changes in land use through increased fertilization, soil erosion, and increased downstream transport of eroded sediments and nutrients (Quinton et al. 2010). The interaction of climatic variability, vulnerable soils, distinct topography, and rapid land use change makes the East African region one of the hotspots of land and water degradation in the world (Wynants et al. 2019). The succession of droughts and erratic and torrential rainfall explains the big interannual differences in sediment yields observed in the region (Vanmaercke et al. 2014). High-intensity rainfalls after a long dry period can generate extreme amounts of eroded soil and downstream sediment transport. Hudson (1993) emphasized this in Zimbabwe, where about 50% of the annual soil loss was found to occur in only two storms and that during year even 75% of the erosion took place in 10 min. Moreover, as shown in northern Tanzania, gully incision can be triggered by extreme rainfall years, especially if they follow years of progressive soil degradation and drought (Wynants et al. 2021b). Gully-ing can subsequently cause positive feedback responses by increasing hydrological and sediment connectivity in the catchment, leading to rapid removal of water, soil, and nutrients from hillslopes (Wynants et al. 2021a). This major driver of land degradation directly impacts socio-economic development and community resilience (Blake et al. 2018a). A reconstruction in sediment yield change over the past century in northern Tanzania has shown an exponential increase from 8 to 149 t km⁻² year⁻¹ in a small lower sloped catchment and from 57 to nearly 1600 t km⁻² year⁻¹ for a larger complex catchment (Wynants et al. 2021b). The importance of event-based sediment export is expected to increase even further in the context of future climatic changes (Borrelli et al. 2020). The combination of increasing land use pressures and extreme climatic events thus poses an acute threat to the soil and water resources East African rivers and lakes.

One particular area of interest is the Lake Victoria Basin, which spans over 250,000 km² in four countries and is of major importance for biodiversity, regional water, food, and livelihood security. The population increase in the basin is estimated on 3.5% annually, with currently roughly 50 million inhabitants (Food and Agriculture Organisation of the United Nations 2020). The inhabitants of this region are generally resource-poor and heavily dependent on subsistence agriculture, leading to a rapid expansion of agricultural land area (Wynants et al. 2019). A study by Wasige (2013) reported a reduction of forest land from 7.0 to 2.6%, savannas

35.0 to 19.6%, and woodland from 51.0 to 6.9% in the Lake Victoria Basin from 1901 to 2010, whereas farmland grew by 60.0%. This has a major impact on the dynamics of surface runoff, erosion, and downstream sediment transport, which has led to sediment loading, eutrophication, and recurrent blooms of water hyacinth and cyanobacteria in Lake Victoria (Tamatah 2003; Dutton et al. 2018; Jacobs et al. 2018; Olokotum et al. 2020). Increasing erosion following land use and rapid downstream transport of eroded sediment is thus one of the biggest threats for the sustainability of Lake Victoria (Zhang et al. 2020) necessitating soil and water management plans. However, sediment control strategies require confirmation on the relative and absolute contributions of sediment from different sources (Collins et al. 2017; Amasi et al. 2021b), and in the Lake Victoria Basin, a lack of water quality monitoring and empirical data on soil erosion prohibits an assessment of the scale of the problem. Sediment tracing techniques can partly fill in this knowledge gap by elucidating the dominant sources of sediment to the main river (Dutton et al. 2019; Wynants et al. 2021a). These techniques evaluate the similarities and dissimilarities between the physical or chemical traits of downstream sediments and the catchment potential sediment sources (Collins and Walling 2004; Nosrati et al. 2019). Broad-spectrum geochemical fingerprinting is the most commonly used sediment fingerprinting method (Owens et al. 2016). Since eroded sediment carries the conservative properties of the parent material downstream, the geochemical composition of downstream reservoir sediments depends on the relative contributions and geochemical properties of different tributaries (Haddadchi et al. 2013; Walling 2013). The proportional attribution of the tributary sources to downstream sediment can therefore be obtained through integration of the multivariate source and mixture geochemical fingerprints within mixing models (Blake et al. 2018b). The integration of geochemical tracers within mixing models has proved a robust technique for sediment source tracing because it integrates multivariate tracer signals that encompass various distinctive signatures affected by different environmental factors, thus improving the validity of discrimination of sediment sources (Smith et al. 2018).

In this study, we aim to quantify the relative contribution of sediment sources to the Simiyu River by using a scientifically robust sediment source tracing technique (Blake et al. 2018b). The Simiyu River is one of the main rivers feeding into the Speke Gulf of Lake Victoria. However, due to demographic changes and a population heavily reliant on subsistence agriculture, livestock keeping, fishing, and forest resources, the catchment is facing similar issues with land degradation (Kimwaga et al. 2012b; Mulungu and Kashaigili 2012). Although some empirical findings have been reported on the potential impacts of land use and climate change in Simiyu River catchment (Myanza et al. 2005; Mulungu and Kashaigili 2012), there

has been no monitoring of sediment flux or water quality in the river. Little is therefore known about the main sources of eroded sediment to the river, nor have the effects of land degradation in the catchment been evaluated. In this context, we will use the Simiyu catchment as a case study for filling gaps in our understanding of soil erosion and sediment transport dynamics, which are faced in all of Lake Victoria catchments. Soils and sediments in the catchment will be geochemically fingerprinted allowing the comparison of the physical or chemical (dis)similarities (Collins et al. 2017). Particle size effects will be minimized by focusing on fine sediments (Lacey et al. 2017), and tracers will be checked for conservative behavior. The results on the dominant sources of sediment will aid the Lake Victoria Basin Water Board in designing targeted management intervention for reducing soil erosion and sediment yield in the Simiyu catchment (Owens 2022). Moreover, the work can be used as an example for applying sediment source tracing studies in other catchment draining to Lake Victoria.

2 Materials and methods

2.1 Description of the study site

The Simiyu main river catchment is located in the south-east of Lake Victoria, and its altitude ranges between 1100 and 2000 m.a.s.l. The catchment covers ca. 11,000 km² and receives water from two main tributaries the Simiyu River and the Duma River (Fig. 1). The Simiyu sub-catchment covers ca. 5541 km² and the Duma ca. 5435 km² of the total catchment. The Simiyu and the Duma sub-tributaries drain from the Maswa Game Reserve and the Serengeti National Park plains, respectively, joining together into the Simiyu main river about 2 km before the inlet in Lake Victoria. The catchment has a semi-arid climate, experiencing seasonal fluctuations of rainfall, wherein most rainfall occurs in two wet seasons with the long rains from March through May and short rains in October through December. The dry season occurs between June and September

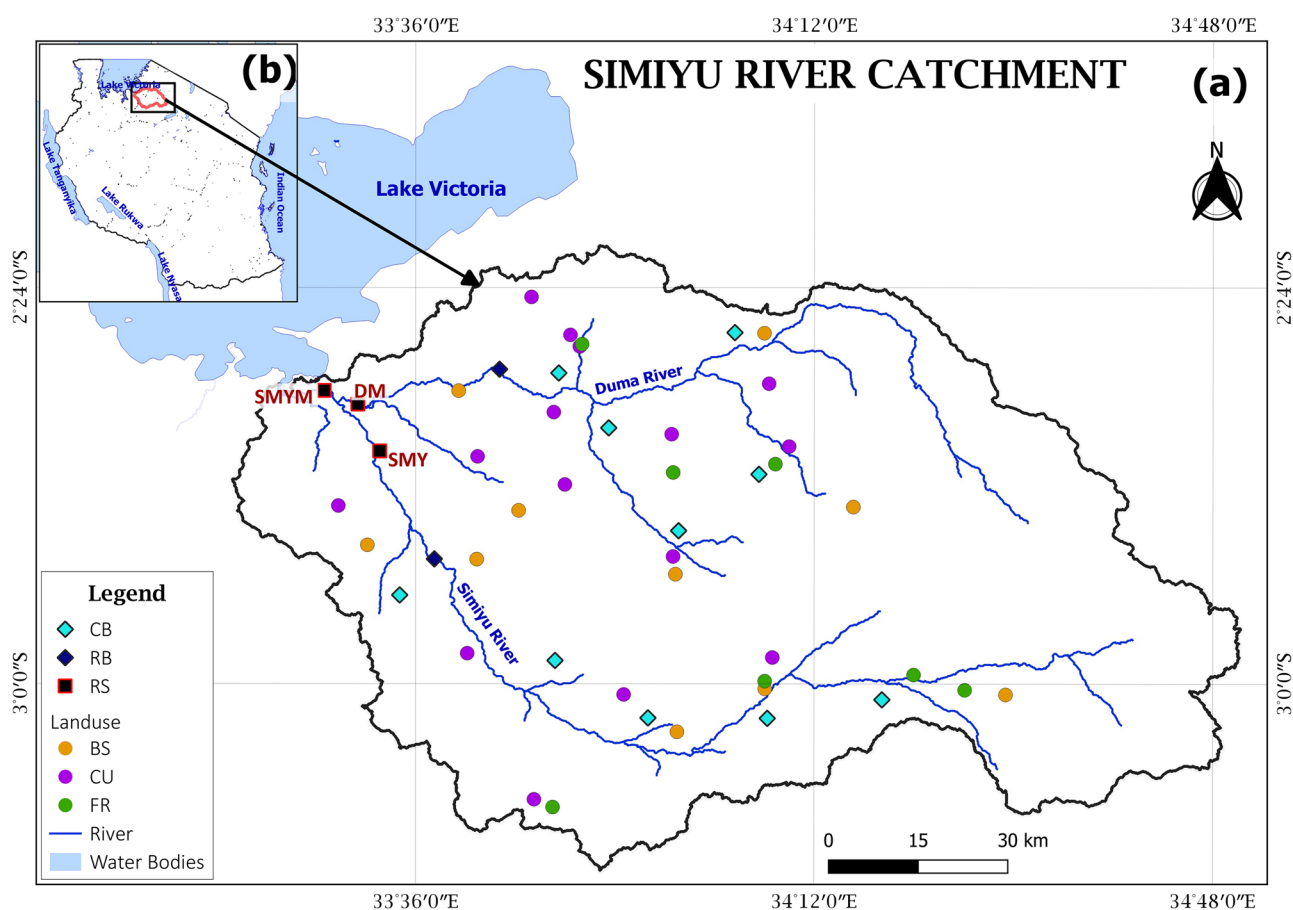


Fig. 1 a A detailed map of the Simiyu catchment with the Simiyu (SMY) and Duma (DM) sub-tributaries, the riverbed sediment sampling locations (RS, black rectangles), and the potential sediment

sources from land use (BS, CU, FR), and subsurface erosion (CB and RB). b Location of the Simiyu River catchment within Tanzania

and the transition period between the two seasons in the intermediate months of January and February (Lubini and Adamowski 2013). The rainfall also varies spatially in the catchment wherein the hydrological mean annual rainfall is around 750 mm in the lower parts and 1100 mm in the upper part of the catchment. The rainfall intensity follows a similar pattern and is shown in Fig. 2a. Furthermore, the area also experiences high interannual variability in rainfall, with drier and wetter years. For example, in 1988, an annual rainfall of 1312 mm was recorded in one of the climate stations in the catchment, while in 1989 only 774 mm. The most distinct slopes can be found in the northeastern part of the catchment, with other sloped areas spread out more evenly (Fig. 2b). The major land cover types include natural forests, bushland, grassland, wetlands, and woodlands that do not form a thickly interlaced canopy (Fig. 2d). Rainfed agriculture, fishing, wildlife tourism, and pastoralism are the main economic activities in the catchment. The Serengeti National Park/Game Reserve covers the upstream part of the catchment in the east and is dominated by natural grassland and bushland. The geology in the catchment is mainly dominated by granite with smaller intercalations of

magmatite, sedimentary, metamorphic, and volcanic rocks (Fig. 2c). The main soil types are sandy loam (63.8%), sandy clay loam (13.5%), clay loam (12.9%), clay (5%), loam (2.9%), and sandy clay (1.9%) (Rwetabula et al. 2007) (Appendix 1). Modeling studies of the Simiyu catchment estimated sediment yield between 0 and 38.8 t ha⁻¹ year⁻¹ for the period 1980–2009 and between 0.5 and 11.9 t ha⁻¹ year⁻¹ for the period 2010–2016 (Ndomba et al. 2005; Kimwaga et al. 2012b; Van Griensven et al. 2013). A study by Kimwaga et al. (2012b) revealed a dramatic expansion of agricultural land from 19.3% in 1975 to 73.4% in 2006 at the expense of bushland, forests, grassland, and woodlands. The Tanzania Participatory Poverty Assessment conducted in 2002–2003 also reported high deforestation rates in Meatu district to clear land for cultivation (Kimwaga et al. 2012a). The domestic animal and wildlife populations have been increasing since the eradication of rinderpest in the 1960s (Ogutu et al. 2016; Food and Agriculture Organisation of the United Nations 2020). Anecdotal evidence from the area indicates that the catchment has experienced dramatic changes over the past decades through increased agriculture, livestock-keeping, deforestation, and urban and

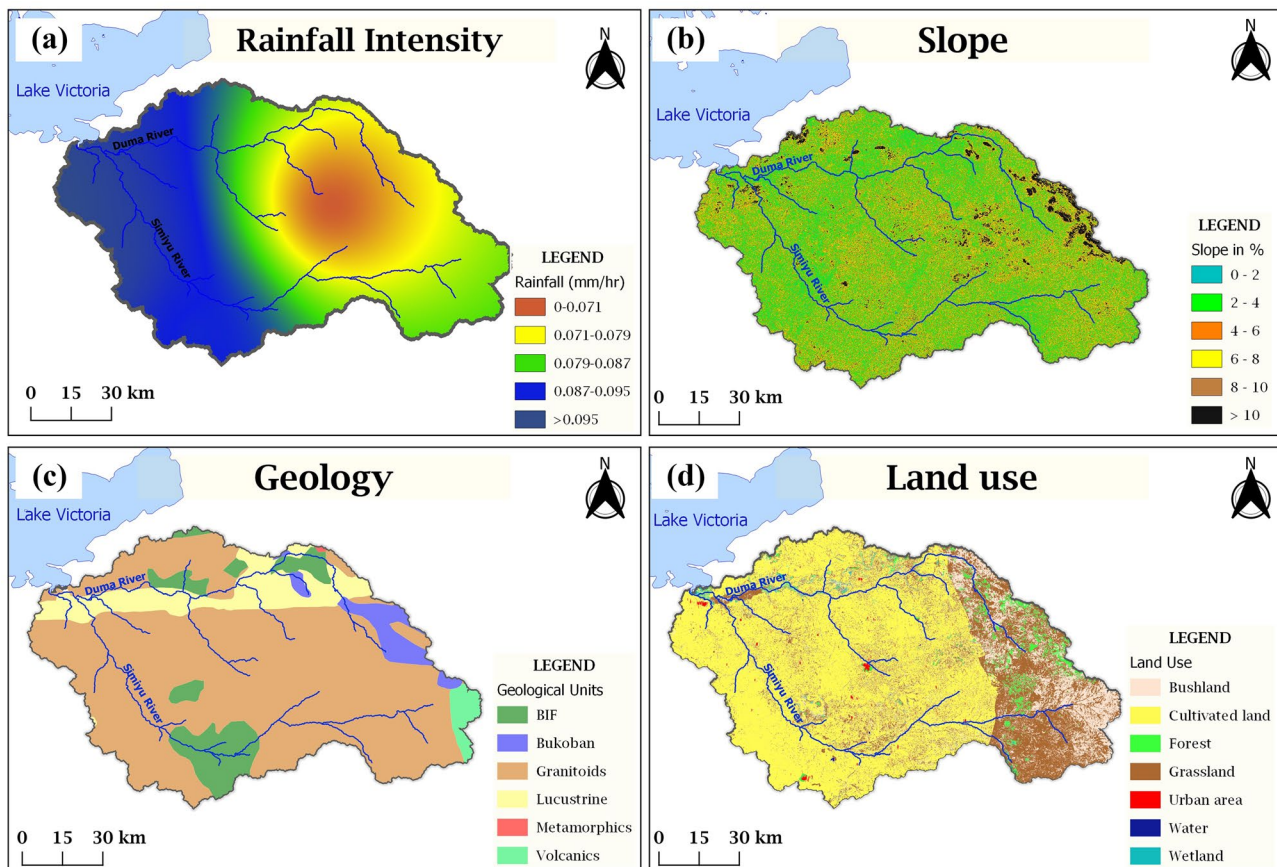


Fig. 2 a The rainfall intensity, b slope, c geology, and d land use distributions of the Simiyu catchment

rural settlement (Zhang et al. 2020). Several studies also report high densities of gullies in the area (Ndomba et al. 2005; Zhang et al. 2020), and this was also observed during the field work campaign (Appendix 2).

2.2 Sampling strategy

Due to the challenging environment and logistical constraints, samples could only be taken in the dry season from the exposed river beds, which is why we only included deposited river bed sediments (RS) in our analysis. RS samples were taken from the downstream reaches of the sub-tributaries and main river (Fig. 1). Because of these logistical constraints, this study works from the assumption that RS samples provide a time-integrated and representative mixture from their respective sources throughout the catchment area, and implications of this assumption will be discussed in Section 4. Thirty-two composite samples of RS each composed of 10 to 12 sub-samples were collected from the main Simiyu River over a range length of about 300 m to include potential spatial differences in riverine sediment deposition (Gellis and Noe 2013; Wilkinson et al. 2013). RS samples were collected at the mouth of the inflow, at the point of confluence of the two tributaries. Fifteen and 16 sub-tributary RS samples were also collected from lower reaches of the two major tributaries, Duma and Simiyu, respectively, at points where reciprocal influencing through flooding could be excluded. Surface soil samples as potential sediment sources were collected from the catchment's dominant land use types, which includes bushland (BS), agricultural land (CU), and forest land (FL). Sub-surface soil as potential sediment sources were sampled from channel banks (CB) and the mainstream river banks (RB). Surface soils were sampled from all major land use types by taking composite samples from 0 to 5 cm depth from areas assumed to be susceptible to soil erosion based on visual evidence of erosive features and location in the landscape. Channel bank materials were sampled in the upstream areas of the catchment characterized by exposed banks devoid of vegetation with actively eroding bank sections. The banks from the main river (RB) were also sampled further downstream. Sampling locations depended on the accessibility, necessary permits, and safety. At each site, samples comprised a composite of 10 to 15 random scoops pooled into a single composite sample to ensure the representativeness of the corresponding fingerprint property datasets. A total of 69 samples were collected to characterize five main potential sediment sources: (i) forest (FR, $n = 13$), (ii) bushland (BS, $n = 11$), (iii) channel banks (CB, $n = 14$), (iv) cultivated agricultural land (CU, $n = 15$), and (v) mainstream river banks (RB, $n = 16$), all collected in the same year.

2.3 Geochemical laboratory sample preparation

Prior to analysis, all dried soil and sediment samples were oven-dried at 55–60 °C, disintegrated using a mortar and pestle, and subsequently sieved at < 63 μm fraction to minimize particle size effects on tracer signals that can bias fingerprint property (Lacey et al. 2017). The elemental concentrations are generally enriched in the fine, < 63 μm , particle size fraction in comparison to < 2 mm bulk fraction of the soil (Rawlins et al. 2010). Subsequently, about 4 g of dried and sieved sample material was mixed with about 0.9 g of cellulose binder (FLUXANA®), homogenized in a pulverizer, and pressed into a pellet of approximately 32 mm diameter. The validation of the method was done by using the IAEA Soil 7 certified reference materials (CRM) as described in Amasi et al. (2021b). The dried soil and tributary potential sediment sources were analyzed as pressed pellets for minor and major elemental geochemistry by an energy dispersive X-ray fluorescence (EDXRF) spectrometer (Spectro Xepos, Spectro Analytical Instruments, Boschstrasse 10, D-47533 Kleve, Germany) coupled with Xlab ProTM software. Triplicates were made from arbitrarily selected samples about once every three samples for assessment of the analytical variability and sample homogeneity. Only those elements returning measurements above the limit of detection were employed in the analysis. The limit of detection varies with the element and depends upon several factors including the sample matrix. The geochemical analysis of sediment and soil samples was done at the Tanzania Atomic Energy Commission (TAEC).

2.4 Data analysis

2.4.1 Bayesian mixing model for source apportionment

The yielded tracer concentrations from the RS mixtures and the potential soil and riverbed sources were represented as multivariate elemental concentration matrices. The Bayesian mixing model (BMM) draws upon these matrices to quantitatively compare the multivariate fingerprints between different sources and determine the relative contribution to the sediment mixture. A Bayesian mixing model was built in the open-source MixSIAR framework (Stock et al. 2018), as first demonstrated by Blake et al. (2018b) for sediment source apportionment in river systems. The MixSIAR methodology was used to unmix the Duma and Simiyu tributary sediment sources and land use potential sediment sources from the Simiyu main river riverbed sediment mixture after confluence downstream. For accurate use of the BMM model, the following four assumptions must be met: (1) the model includes all dominant sources contributing to the sediment, (2) the value of the tracers are known in both sources and mixture, (3) tracers behave conservatively

throughout the mixing processes, and (4) fingerprint variability between sources is larger than within sources, and the different sources are geochemically distinct. In addition, the major advantage of BMM is based on its flexibility in model structure tailored on the following specifications as described by Stock et al. (2018). The following specifications were built into the model runs:

- (i) In large complex catchment systems, it is difficult to capture the entire variability of the sediment flux by time-specific sampling events, creating a sampling error. In view of this, the “residual error” formulation was incorporated in the model. A “process error” was not included as the transport of sediment from hillslopes to the river/lake in this river system is not based on targeted processes such as a reservoir release (Stock and Semmens 2016).
- (ii) Uninformative prior: Since there is no empirical information on the dominant sources of sediments contributing to the major tributary, an uninformative prior was used: (1, 1, 1, 1, 1) and (1, 1) for land use and tributary sources, respectively.
- (iii) A mixture of sediment samples was analyzed without fixed or random effects to infer the proportions of the tributaries and land uses to the bed river sediment. The BMM model outputs were evaluated under different scenarios of covariate structure. For all model runs, the following provisions were used: a residual error term only and an uninformative Dirichlet prior ($= 1$). Model convergence was assessed by the Gelman–Rubin diagnostic (variables < 1.05), rejecting model output if $> 5\%$ of total variables were above 1.05. Model convergence indicates that the model found a singular solution to the problem decreasing the chances of equifinality. Using the selected 10 tracers, the model passed the Gelman–Rubin convergence diagnostic with the parameters of the Markov chain Monte Carlo (MCMC) chain run length set as follows: chain length = 1,000,000, burn = 700,000, thin = 300, and chains = 3.

2.4.2 Tracer conservation test and principal component analysis

Comparing the geochemical fingerprinting of the sediment samples with those of the potential source materials using the Bayesian mixing model requires tracers to behave independently and conservatively (assumption 3) in the environment (Motha et al. 2002). The tracer conservatism concept implies that the chemical composition of the tracers does not change during detachment, transport, deposition, and/or after deposition (Belmont et al. 2014). The tracer screening process for source apportionment

only excluded tracers on the basis of non-conservative behavior based on their performance from the range test (Smith et al. 2018). Prior to tracer screening, the elemental concentrations of the samples that were below the detection limit were dropped. Subsequently, the basic tracer screening approach of Blake et al. (2018b) was adopted with additional evaluation of geochemical behavior. Boxplots were produced for each set of sources and associated mixtures for all tracers and the means of the mixture data assessed to see if they largely fell within or outside of the mean concentrations of the different sources (Appendix 3). The mean of the mixture of the tracers that fell outside the mean of the source ranges was removed. Furthermore, the tracers that were found to have higher intrasource variance than intersource variance were also removed. Finally, the normality assessment using the Shapiro–Wilk test for the individual tracer mixtures was done because the model assumes normal distribution of the mixture tracer data (Stock et al. 2018).

One of the assumptions of the BMM model is that the intersource differences of fingerprints have to be larger than the intrasource differences in fingerprints. In this context, a principal component analysis (PCA) was applied to reduce the dimensionality of the entire multivariate tracer dataset, allowing a visual scrutinization of the variance between and within the different sources and the mixture (Blake et al. 2018b). This allows to evaluate if the different land use classes and sub-tributaries group into distinct geochemical groups. A mixture of the sediment at the point of the river confluence was used to attribute the sub-tributary sediment sources and soil samples from different land use class upstream of the catchment.

3 Results

3.1 Tracer conservation test and source discrimination from the PCA

Ten tracers qualified the range test (Al, P, K, Ti, Mn, Co, Ni, Cu, Zn, Nb), while 21 tracers (Na, Mg, Si, S, Cl, Ca, Cr, Fe, Ga, Br, Rb, Sr, Zr, Ba, Ce, Pb, Th, La, Y, Hf, Sn) were excluded from the analysis based on their indication of non-conservative behavior or high intrasource variability (Appendix 3). The first PCA was performed to check the differences between sediment gathered from the main river and tributaries and showed distinct fingerprint clusters between the two tributaries (Fig. 3). The sediment mixture of the main river occupies a larger cluster compared to the sub-tributaries. The second PCA comprised the sediment from the main river and the soils from the different land use types (Fig. 4). The land use PCA highlighted a complex soil system wherein some overlap was observed between the topsoil

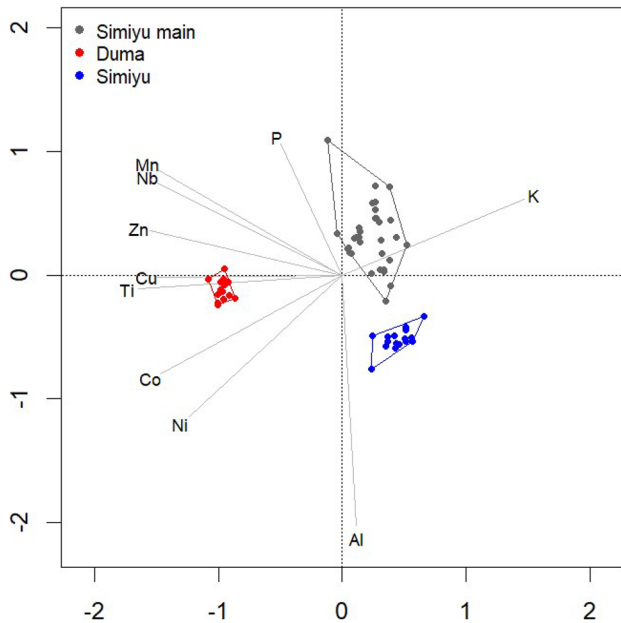


Fig. 3 PCA plot with X-axis explaining 63.8% and the Y-axis explaining 16.0% of variance, highlighting the intersource and intrasource variance in geochemical fingerprints of the Duma and Simiyu tributaries and the Simiyu main river sediment. Hull areas are drawn around the sources and mixtures

land use sources, mainly between forest and bushland. The forest cluster was very small and distinct. The agricultural cluster occupied the largest space on the PCA, and seemed to exist out of two sub-clusters, wherein the lower cluster was clearly driven by higher values in phosphorus (P). There was some overlap between the upper agriculture cluster with the bushland and forest clusters. The sub-surface soil samples (riverbank and channel bank) occupied a significantly different space on the X-axis, indicating a distinct difference in surface and sub-surface geochemical fingerprint. The surface soil samples generally have higher concentrations in the metal tracers, except for K.

3.2 Proportional sediment contribution from land use and riverine sources

The MixSIAR outputs for the Simiyu Main RS revealed that the Simiyu sub-tributary accounted for $63.2\% \pm 10.4\%$ and the Duma sub-tributary for $36.8\% \pm 10.4\%$ of the total sediment (Fig. 5a). Unmixing of the land use types against the Simiyu Main RS revealed that cultivated land had the greatest contribution of sediments, accounting for $64.7\% \pm 4.1\%$, channel banks with $26.5\% \pm 5.0\%$, riverbanks with $5.8\% \pm 3.1\%$, bushland with $1.6\% \pm 1.7\%$, and forest $1.4\% \pm 1.5\%$ (Fig. 5b). The MixSIAR outputs for the land use types against the individual RS also revealed that cultivated land had the greatest contribution of

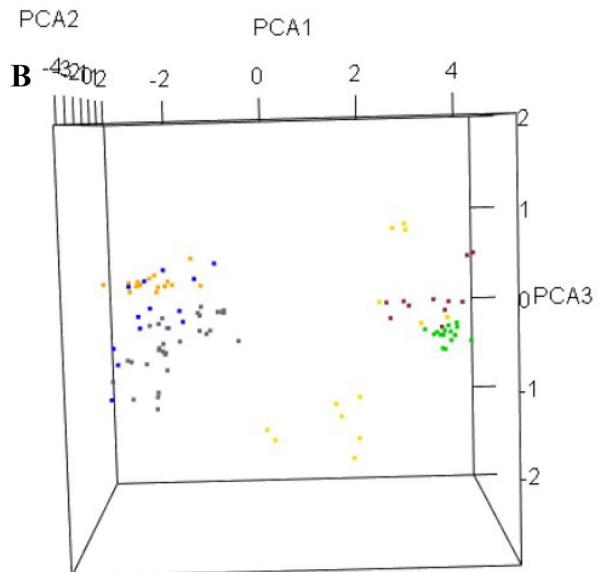
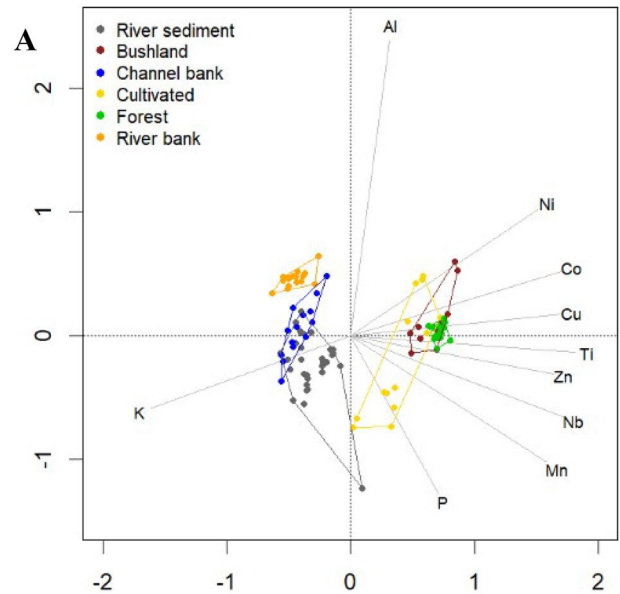


Fig. 4 **A** PCA plot with X-axis explaining 63.2% and the Y-axis explaining 13.8% of variance, highlighting the inter- and intrasource variance in geochemical fingerprints of the land use sources and mixture pool of Simiyu main river sediment. **B** 3D PCA plot highlighting the more nuanced difference between forest and bushland. Hull areas are drawn around the sources and mixtures

sediments in both sub-tributaries with $86.4\% \pm 7.6\%$ and $80\% \pm 8.2\%$ to the Duma and Simiyu, respectively. In the Duma sub-tributary, channel banks contributed $9.0\% \pm 7.2\%$, riverbanks contributed $2.7\% \pm 2.1\%$, bushland contributed $1.1\% \pm 0.9\%$, and forest contributed $0.7\% \pm 0.6\%$ (Fig. 6a). In the Simiyu sub-tributary, channel banks contributed $9.0\% \pm 6.8\%$, riverbank contributed $6.3\% \pm 5.2\%$, bushland contributed $2.9\% \pm 2.1\%$, and forest contributed

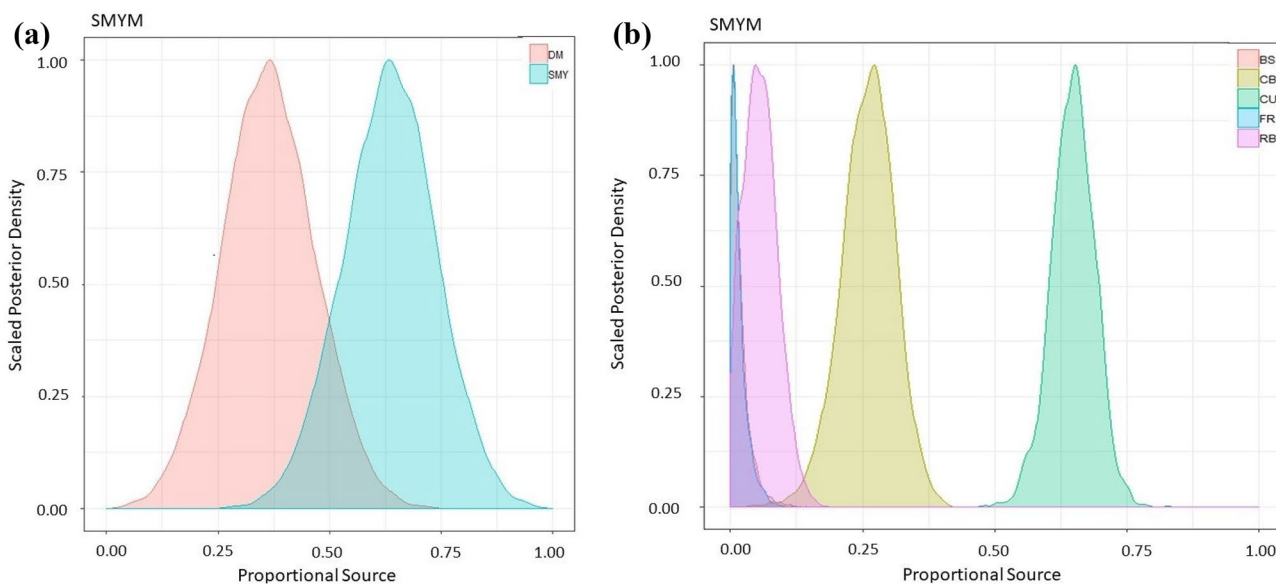


Fig. 5 Sediment source apportionment of the main Simiyu River against the riverine sources **(a)** and land use sources **(b)**. The Simiyu sub-tributary (SMY) accounted for 63.2% and Duma (DM) for

36.8%. Agricultural land (CU) accounted for 64.7%, channel banks (CB) for 26.5%, river banks (RB) for 5.8%, bushland (BS) for 1.6%, and forest (FR) for 1.4%

1.7% ± 1.4% (Fig. 6b). Interestingly, direct unmixing of the Simiyu Main RS against the land use sources revealed a higher proportional contribution of channel banks (26.5% ± 5.0%) compared to the separate unmixing of the two sub-tributaries (9.0% ± 6.8% and 9.0% ± 7.2% in Simiyu and Duma, respectively).

4 Discussion

4.1 Tracer conservation and discrimination

The elimination of tracers requires some geochemical clarification. Non-conservative behavior of soluble salt elements,

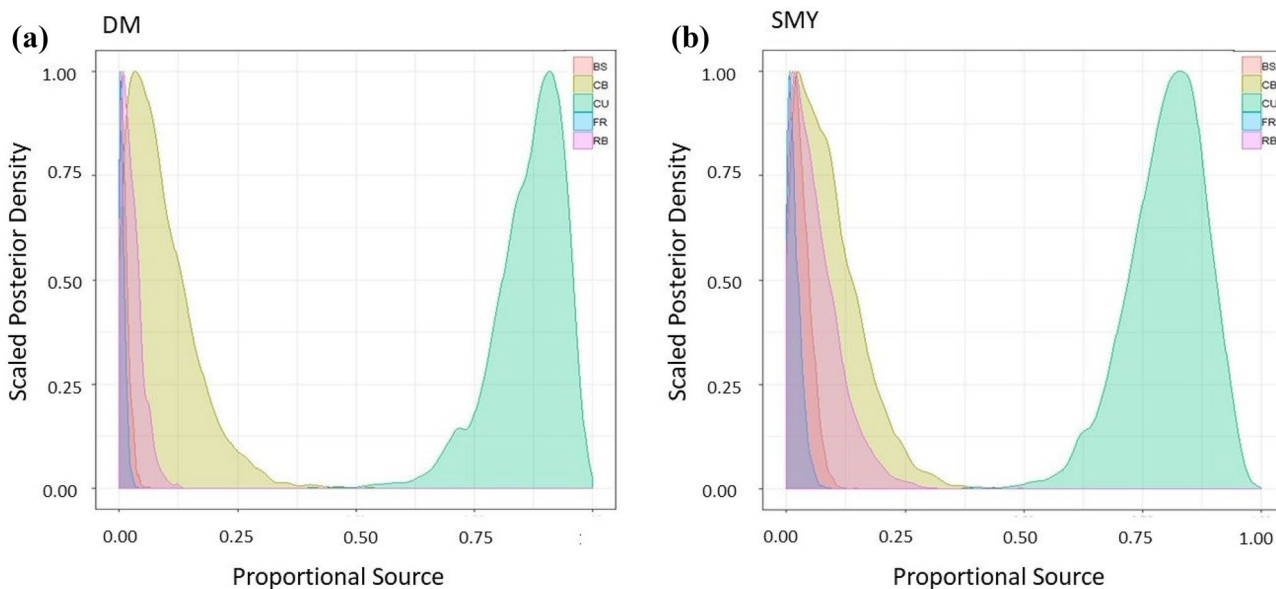


Fig. 6 a MixSIAR of the land use from the Duma (DM) tributary where cultivated land (CU) accounted for 86.4%, channel banks (CB) with 9.0%, river banks (RB) with 2.7%, bushland (BS) with 1.1%, and

forest (FR) 0.7%, and **b** the Simiyu (SMY) tributary where cultivated land accounted for 86.4%, gully banks with 9.0%, river banks with 6.3%, bushland with 2.9%, and forest 1.7%

such as, alkali metals, e.g., Na, Mg, and Ca, and halogens, such as Cl, F, and Br, is probably due to their tendency to enrich their concentration driven by evaporation (Wynants et al. 2021a). Several elements, such as Si, Cr, Y, Pb, and Zr, are identified to undergo alterations in medium- to long-term storage elements such as floodplains, lakes, and wetlands due to changes in redox, pH, salinity, and other environmental conditions (Owens et al. 1999; Pulley et al. 2015). Changes in concentrations of Sr and Rb may have been a result of their irregularity in the soil depth as a function of weathering processes and mixing of soil horizons by cultivation (Tyler 2004). Ce, La, and Th were removed because of the observed high intrasource variability, which are potential artifacts of analytical challenges due to low abundance or high variability in the terrestrial source concentrations (Wynants et al. 2020). Concentrations of Si and Zr may be due to wider fluvial sorting, e.g., textural controls on mineral composition, i.e., changing proportions of silt versus clay minerals in mixtures, which has been shown to exert a strong influence on sediment concentrations (Cuven et al. 2010).

The PCA of the tributaries highlight distinct differences between both tributaries, indicating a strong geochemical basis on which the model can draw. On the PCA of the land use sources, the soil samples also form distinct clusters that seem to be mainly driven by geochemical differences between catchment zones and soil depth (Fig. 4). It is important to highlight the differences in both principal components, wherein the X-axis represents 63% of variance and the Y-axis 14%. Differences along the Y-axis therefore get conflated, while the main differences in fingerprint are along the X-axis. The forest cluster is relatively small, which is not surprising and can be explained by the more constrained locations of forests in the uplands and their relatively undisturbed soils. The forest cluster was partly overlapped by a larger bushland cluster between forest and bushland, which is probably because there is no distinct border between those land cover types and bushland tends to gradually transition into forests. However, when a third principal component is plotted, a difference between bushland and forest is still evident, showcasing the more nuanced geochemical difference between those two groups (Fig. 4B). The forest fingerprint seems to have slightly higher concentrations of Cu and Ti, while the bushland is more characterized by higher concentrations of Cu, Ti, Zn, and Co tracers (Fig. 4, and Appendix 3). The overlap between forest and bush land is therefore due to surface tracers Ti and Cu, which are probably indicative of highly weathered soils, typical for East African hillslopes (Wynants et al. 2021a). The agricultural cluster was larger and seemed to consist out of two sub-clusters, which can be explained because agricultural is spread over the catchment, both on hillslopes, and on wetter areas closer to the river. The bigger size of the cluster can be further explained by differences in underlying geology, soil type, soil management, redox conditions, and climate.

The hillslope agricultural soils seem to be more driven by Al concentrations, while the wetter areas seem to be more driven by P concentrations. The strong driving effect of P on agricultural soils can be explained by the application of mineral fertilizers. The overlap between agricultural soils and bushland/forest soils may be due to similarities in location, but also due to legacy effects of previous land cover wherein bushland/forest is converted to cultivated land and some cultivated land was abandoned and developed back to bushland/forest. The clear difference shown between the surface (FR, CU, and BS) and sub-surface materials (RB and CB) on the PCA plot can be attributed to weathering and pedogenic processes. As shown by the range tests, CB soils were higher in K (Appendix 3), which might be due to evaporation enrichment or lack of weathering (Wynants et al. 2021a). Generally, the distinct clustering between the source groups on the PCA plot shows that the mixing model is a robust tool for sediment attribution from selected land use types (Smith and Blake 2014).

4.2 Proportional sediment contribution to sub-tributaries and to the Simiyu main river

The higher proportion of sediment from Simiyu tributary to the main river was expected since its sub-catchment is slightly bigger (5541 km² compared to 5435 km² in the Duma) and has higher average slopes and rainfall compared to the flatter and drier areas in the west of the Duma sub-catchment. Moreover, some of the headwaters of Duma sub-catchment are protected as Serengeti National Park (Fig. 2d), where there is a more permanent vegetation cover and only moderate sediment yield was modeled in previous studies (Kimwaga et al. 2012b; Van Griensven et al. 2013). Although the Simiyu sub-tributary has higher sediment contribution to the main river than Duma, the difference is relatively small, indicating that high sediment yield is not limited to the Simiyu alone. Both sub-catchments have been modeled to have high soil erosion risk, which is mostly attributed by the expansion of agricultural land and overgrazing on sloped areas with high-intensity rainfall (Mati et al. 2008; Zhang et al. 2020). Besides surface erosion risk, unsustainable farming practices in both sub-catchments may also promote sediment connectivity from hillslope to the channel networks (Guzha et al. 2018). Overall, only 57.0% of the total catchment experiences low to very low soil erosion risk, while the high and very high patches of soil loss risk of 16.1% and 2.2%, respectively, are distributed mainly in the cultivated part of the catchment, characterized by gentle slopes (Zhang et al. 2020). The high contribution of eroded soils from agricultural land to riverine sediment is also found in the neighboring Mara catchment (Dutton et al. 2019; Stenfort Kroese et al. 2020). The dominant contribution from cultivated land to the sediment in both sub-tributaries confirms the high impact that agriculture has on soil erosion and sediment transport in the catchment and is probably due to its

large proportion of the catchment, combined with bad soil and water management. Previous research in Northern Tanzania has shown that poor agricultural practices lead to decreasing soil organic matter content and soil structure, increasing the susceptibility to water erosion (Amasi et al. 2021a). This assertion is further supported from the study by Kimwaga et al. (2012b) that revealed the agricultural land expanded significantly from 19.3% in 1975 to 73.4% in 2006. A parallel study found similar temporal trends in land cover between 1986 and 2016, wherein agricultural land increased from 8.7 to 68.4%, bush land decreased from 30.1 to 23.7%, and the grassland decreased from 59.3 to 7.6% (Zhang et al. 2020). The land use and land cover changes have likely altered the hydrology in the Simiyu River, leading to increased peak flows (Guzha et al. 2018), erosion rates, and suspended sediments and nutrients in the river (Mango et al. 2011; Dutton et al. 2018).

Interestingly, the proportional contribution of channel banks was higher to the Simiyu main river (26.5%) compared to the two sub-tributaries (9.0% in both). A potential explanation for the higher importance of channel banks further downstream could be the complex hydrology of the catchment, which is characterized by distinct topographic changes and high seasonality in rainfall and river flow. During extreme rainfall events, it is possible that there is a higher contribution of gully erosion, but also that the high river flow transports the sediment further downstream (Wynants et al. 2021a). Another explanation could be that there is significant channel bank erosion closer to the outlet that enters the main stream through small sub-tributaries below the sampling points. However, field observations and a study by Zhang et al. (2020) locate most gullies upstream of the sub-tributary sampling points. Finally, the complex soil geochemistry in the catchment could also influence the model performance, leading to better representations on smaller scales (Blake et al. 2018a, b). Nonetheless, the dominance of CU with significant contribution of CB indicates that the model finds similar outcomes on both spatial levels and is thus a robust tool for catchment soil and water management in the Lake Victoria Basin. It is also important to note that the low proportional contribution of other land use types does not necessarily reflect low absolute rates of soil erosion on these land use types, but can be masked by high absolute values of sediment originating from cultivated land, and/or the lower proportions of these land cover types in the catchment. In this study, CB contributed between 9 and 26% of the total sediment, which is significant considering the more spatially constrained location of gully erosion in the catchment. The impacts of gully erosion also go beyond direct contribution of sediment, since they increase the connectivity between hillslopes and the river channel as demonstrated by Wynants et al. (2021b) in northern Tanzania. Gully erosion and hillslope surface erosion are likely connected, leading to a rapid downstream movement of eroded soils from agricultural

hillslopes through highly connected ephemeral gully networks. Further research is needed on integrating geochemical fingerprinting with sediment dating techniques on deposited sediments in floodplains or reservoirs (Pulley et al. 2015) to evaluate how sedimentation rates and sources have changed historically through a period marked by major changes in human and livestock population densities and land use.

Despite the distinct results obtained from this study, a critical reflection on the assumptions of the Bayesian mixing model is warranted. The first major challenge of this study was the difficulty to capture the entire variability of the sediment flux by time-specific sampling events, creating a sampling error. Our results represent a snapshot of time, which might be potentially impacted by seasonal or interannual variations in source contribution (Lizaga et al. 2019, 2020). This uncertainty is, however, partly accounted for in the model structure as a residual error. Secondly, some areas in the catchment are potentially not captured during sampling due to its large size and logistical constraints (lack of roads, necessary permits, and safety). As shown by Wynants et al. (2021a), gullies that develop in deeply weathered hillslope soils have similar geochemical fingerprints as surface erosion from those hillslopes. If there are gullies like this in the Simiyu catchment that were not captured by sampling, this could have led to an underestimation of the contribution of hillslope gully erosion in the mixing model. In addition, the observed overlap between forest and bushland, and the large variance in cultivated land, might have influenced the model performance. However, since the contribution of both forest and bushland is marginal, the impact of this overlap is unlikely to be significant. Moreover, while the PCA highlights overlap from individual sampling points, the model accounts for the mean and the variance of the entire group, which is distinctively different between forest and bushland. The representation of this study could be improved by integrating other types of tracers, such as compound specific stable isotopes of fatty acids (Upadhayay et al. 2017), or fallout radionuclides (Evrard et al. 2020), which are driven by vegetation and erosion processes, respectively. However, given the strong difference in signature between the Simiyu and Duma River sediment, the application of geochemical fingerprints has proved robust tool for source attribution of tributary sources. Moreover, the distinct differences in source contribution of land use types and the similar outcomes for both model runs are promising results and demonstrate the potential of geochemical tracers for attributing the contribution of major soil source groups in the data-poor Lake Victoria Basin.

5 Conclusion

The relative contributions of tributary and land use potential sediment sources were assessed using geochemical fingerprinting integrated within the Bayesian MixSIAR mixing model.

The model output ascribed the Simiyu sub-tributary (63.2%) as the dominant contributing sub-tributary to the main Simiyu riverbed sediment over the Duma sub-tributary (36.8%). In addition, the fingerprinting analysis pointed the cultivated land (CU) and channel banks (CB) with 64.7% and 26.5%, respectively, as the main sources of the main Simiyu riverine sediment. A similar observation was observed in individual Simiyu and Duma tributary sediments where the main sources are agricultural land and channel banks. Although the CU from Duma sub-catchment accounted for 86.4% while the Simiyu sub-catchment accounted for 80.0%, overall, the contribution seems to be well balanced between both sub-catchments. Combined with observations of high sediment yield from other research, this study revealed that agricultural practices in the area are causing high rates of soil erosion, which cascades down the river leading to high sediment supply in the main Simiyu River and eventually to Lake Victoria. Generally, the results provide the requisite for catchment wide management plans on mitigation strategies with an emphasis on decreasing soil erosion rates on agricultural areas and disconnecting sediment delivery to the Simiyu River networks and to the Lake Victoria to maintain food, livelihood, and water security in the Lake Victoria Basin.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11368-023-03440-y>.

Acknowledgements The first author would like to acknowledge the Lake Victoria Basin Water Board (LVBWB) for funding this research as part of his PhD study.

Funding Open access funding provided by Swedish University of Agricultural Sciences.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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