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Modelling spatial distributions of sediments fingerprinting in the Ruvu Basin of Tanzania without continuous sediment monitoring.

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Abstract

This study investigates various hinterlands' contribution of sediments into the sub-basin known as Ruvu that comprises Mindu, Kibungo, Mvuha and Mindu catchments of Morogoro, Eastern Tanzania. An integrated geochemical and isotopic data were used to constrain this. Strategic sampling of basement and silty-sized sediments was conducted and the data were modelled using mass-balance computations. This approach revealed that, more than 70% of suspended sediments in the Mgeta River originate from Kigalamila, Sezima, Kingule, Mafumbo and Kibuko areas. Thus, hills north of Kisaki are major contributors of sediments with less contribution from the southern terrain. After modelling of the data from Mvuha sub-catchment, results suggest that the sediments (~50%) originate from Msuluzi area and significant erosion comes from Vihengele region. Evidence for Vihengele is also due to elevated $CaCO_3$ abundances in the Mvuha samples from the calcareous rocks. Sediments in the Mindu sub-catchment largely originate from Msaga and Monde areas that are dominated by granulites and gneisses based on simulated mixing calculations. Thus, the extreme southern part of the sub-catchment is more prone to erosion. Sediments of more than 47% for the Kibungo sub-catchment originate from the Mfizigo area. However, no significant erosive activities in the catchment were noted.

Keywords: Ruvu Basin, fingerprinting, erosion, geochemical data, Sm-Nd ratios

Introduction

Enhanced regolith erosion and subsequent sediments loading in water basins is a serious environmental problem that has the potential to affect physical and biogeochemical cycles and water flow dynamics (Malhotra et al. 2018, Wang et al. 2020). A number of studies have recently reported the efficacy of sediment fingerprinting approaches in tracing sources of detritus in terrestrial and aquatic systems using geochemical (e.g. major and trace elements) and isotopic (e.g. Sm-Nd) information from suspended sediments in basin catchment areas (Gellis and Walling 2011). Key to such approaches is that they can put important constraints on soils and sediment dynamics in river basins and thus aide in the understanding of landscape evolution and help in water catchment management and drainage systems restoration (Smith and Blake 2014). For instance, pervasive water flow degradation has been mostly associated with excessive sediments input and accumulation in river systems (Sanisaca et al. 2017).

In this study, a composite fingerprinting approach using proxy elemental ratios and Sm-Nd isotopic data in-tandem mass balance computations are used to determine source terrain contributions of sediments to the Ruvu sub-basin of south-eastern Tanzania and to downstream river systems that pour their waters to the Indian Ocean (Figures 1A and B).

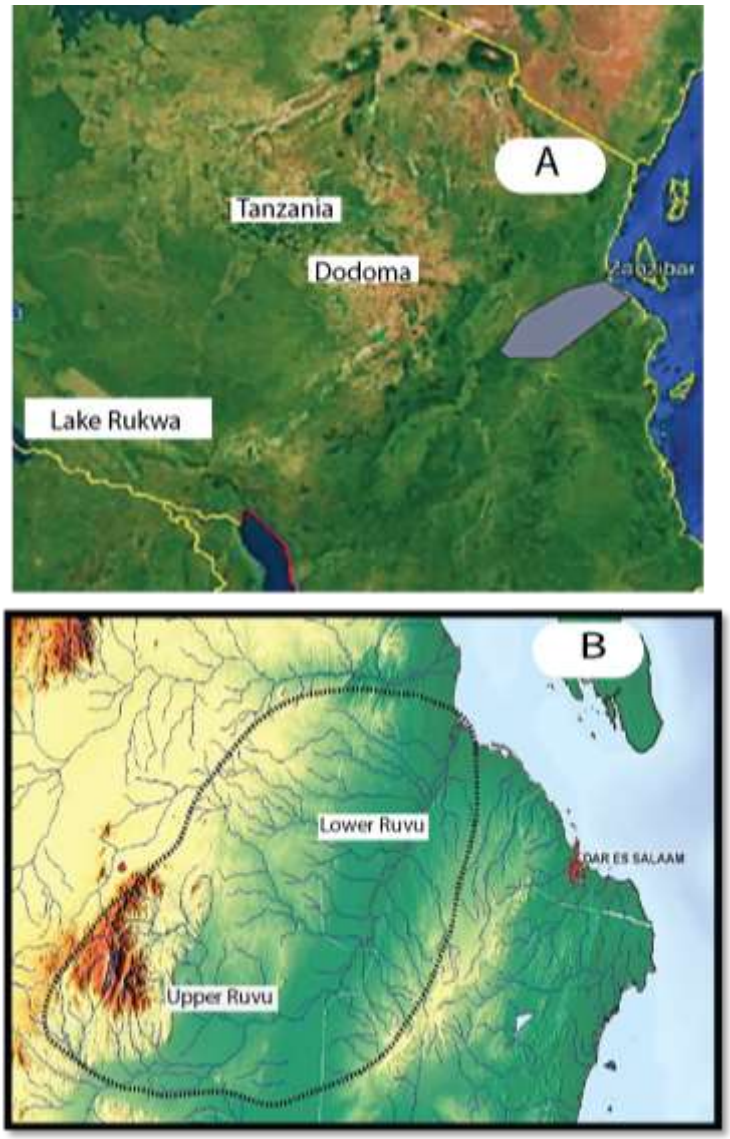

Figure 1: A: Google Earth map showing geographical location of the studied Ruvu Basin in Morogoro Rural B: A digital elevation model showing the aerial extent of the Ruvu-Basin. The studied area is located in Figure A as a grey polygon.

The sub-basin constitutes an excellent example of a rural river system without strong anthropogenic influences on its sediments' geochemistry. This sub-basin is vital for sustainable livelihood of the surrounding community both distal and proximal to the catchment. Sediments in waterbodies are a result of weathering, erosion and transportation of detritus from surrounding upland areas above the floodplain either naturally or due to anthropogenic activities. In general, uplands from which sediments are generated are called 'sources' whereas areas where the sediments are deposited are called 'sinks' (Smith and Blake 2014, Figure 2). Accumulation of sediments in waterbodies

can trigger flooding and has the potential to a decrease in water quality, increase in water turbidity and has the potential to impair sunlight penetration and thus hindering primary production (Walling et al. 1993).

Several techniques to identify source of sediments in water basin exist; these include visual estimates (Reid and Dunne 1996), long-term field monitoring (e.g. Gellis et al. 2015) and geochemical studies (see Kasanzu et al. 2008, Kasanzu et al. 2016). The process of identifying sources of suspended sediments and bed load in basins is called fingerprinting. This process involves collection and analysis of different types of suspended river sediments, dam reservoir and flood surface samples (Figure 2, Devereux et al. 2010).

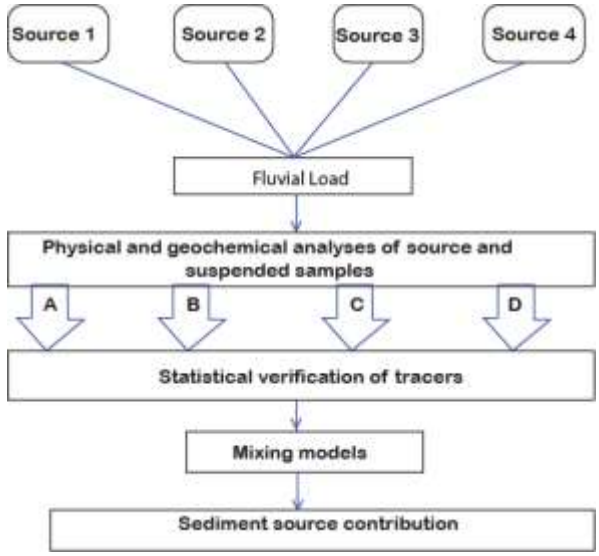

Figure 2: A schematic representation of fingerprinting conceptual framework. A = Mineralogical analyses; B = Major and trace elements analysis; C = Radionuclides D =Physical traces.

Geochemistry of suspended sediments has widely been applied as a fingerprinting proxy in many water basin studies (see Haddadchi et al. 2014). Tracers in such investigations involve the analysis/measurements of sediments chemistry, which reflects the chemical compositions of sources. Important elemental abundances that are used in fingerprinting include the rare earth elements (Ce, Eu, La, Lu, Sm, Tb, Yb), trace elements (As, V, Tl, Sb, Ni, Co, Th, Hf, Cr, Zn, U, Sc and Ta), major elements (CaO, Al_2O_3, Fe_2O_3, K_2O, CaO, MgO, Ti_2O, P_2O_5, SiO_2 and MnO_2; Kasanzu et al. 2008). Such abundances can be used for mixing calculations to understand ediment contributions of different sources using multivariate mixing appropriate algorithms (Walling et al. 1993).

Central to this research is to use selected geochemical fingerprinting elements and isotopic data to elucidate the temporal sediment distribution in various catchments in the Ruvu basin (Figure 3). The results will be modelled to discriminate specific sediment sources to the basin.

Study area topography

The study is located in River Ruvu, a region dominated by agricultural. Soil and sediments sampling was conducted from tributaries, main streams and convergence points. The sub-basin comprises four micro-catchments that are shown in Figure 3, an example of the geology and topography of the area, which is similar to all other sub-catchments, can be summarized using the Mgeta catchment (Figures 4 and 5). The Ruvu-sub basin is

located south of the Morogoro region and runs through Ngerengere and ends in the main Ruvu River before draining its waters in the Indian Ocean. The influence of anthropogenic activities in and around the upstream has been recently reported in GLOWS-FIU (2014) where the authors point to possible risks of pollution due to contaminated waters and sedimentation caused by accelerated erosion. Average annual rainfall distribution has been reported to be circa. 2500 mm. Thus, the upstream parts of the catchment are characterised by high erodability factors. Major land use and cover include agriculture, cattle grazing, charcoal burning and, in some parts, small scale mining. It has been documented that, during rainfall seasons sediments are remobilized and transported along the drainage pattern causing sedimentation (Dutton et al. 2013).

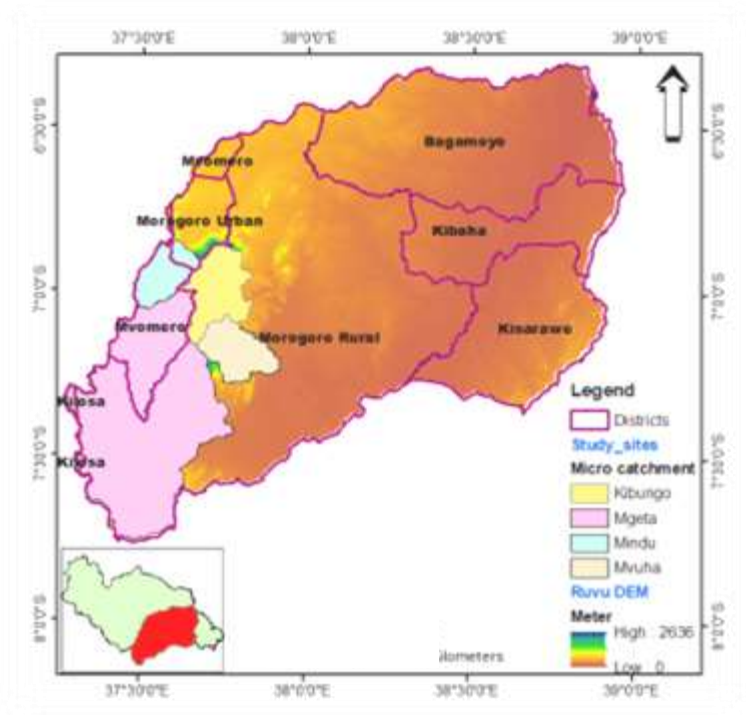

Figure 3: A local elevation map showing the locations of micro-catchments that constitute the Ruvu-basin.

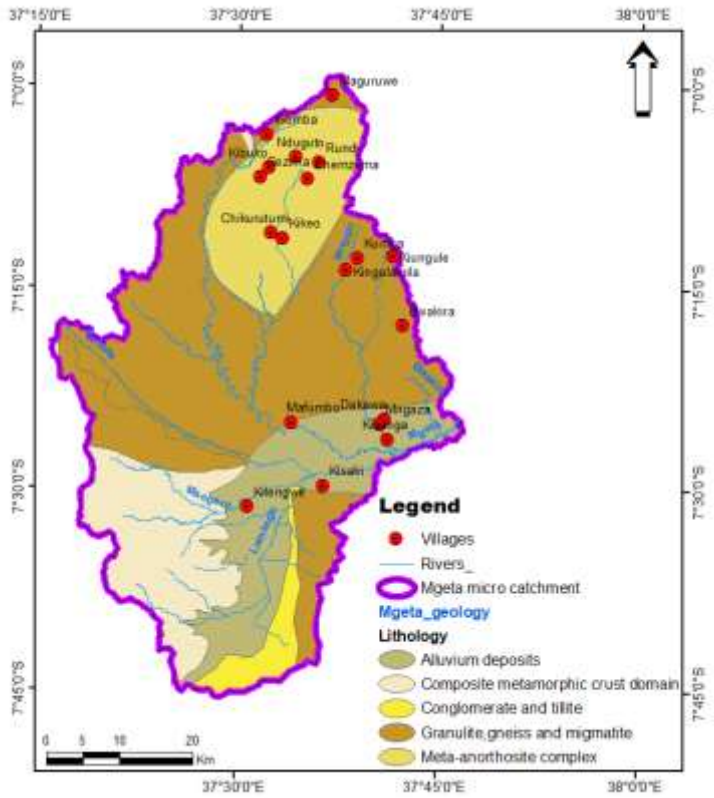

Figure 4: Geological map of Mgeta showing lithological units and their extent, whereby in the north, north west and the west the area is dominated by metamorphic complexes whereas in the south and south eastern part the area is dominated by sedimentary terrains which are a product of ancient deposition by the rivers given the elevation differences.

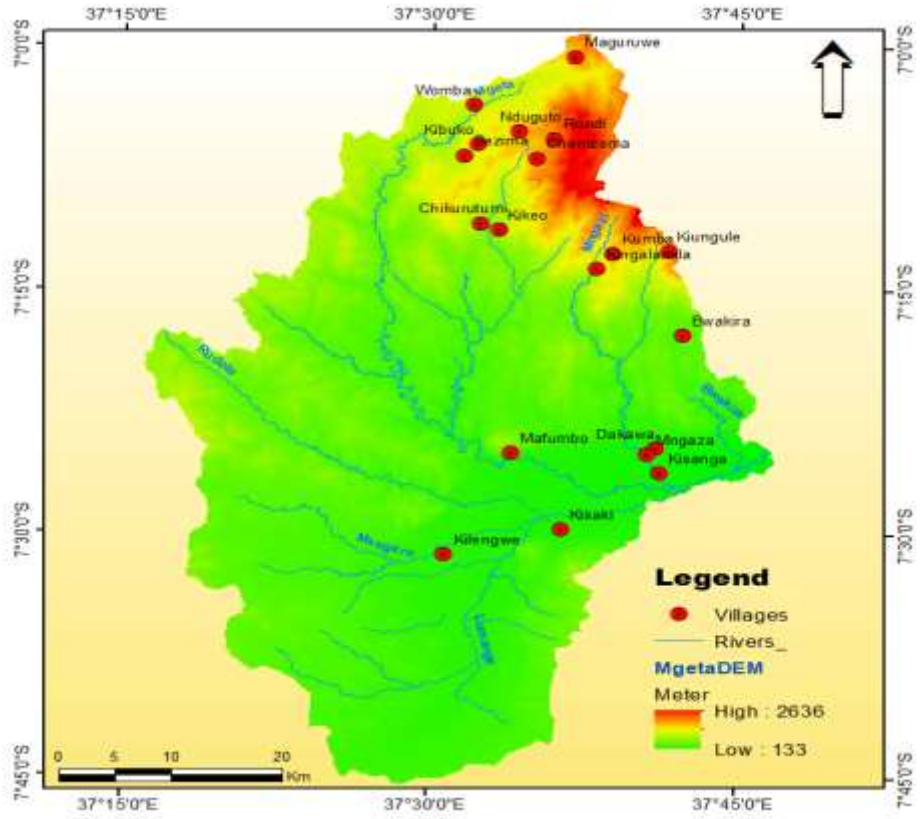

Figure 5: A map showing drainage pattern and Digital Elevation Model (DEM) of Mgeta area. Also visited sites are indicated as red dots.

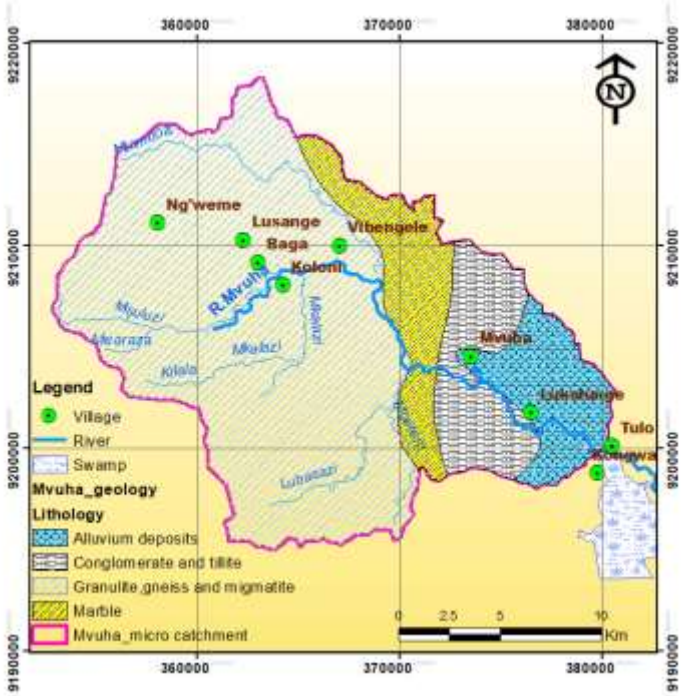

Figure 6: A geological map showing various lithologies in the Mvuha. It is largely made up of granulite, gneiss and migmatite, progressing eastward are marble, conglomerate and tillite, with alluvium deposits in the far east.

Stratigraphically, the region comprises Precambrian basement rocks and more recent alluvial covers that originate from the weathering and erosion of hinterlands. Geology of the sub-basin is dominated by high grade metamorphic rocks that are partly intercalated with fluvial sedimentary deposits. The Mgeta and Mvuha catchments are mainly made of Paleoprotezoic granulites, biotite migmatites, and micaceous gneisses and to a lesser extent, clastic sedimentary high energy facie (Muhongo et al. 2001, Maboko and Nakamura 1995). Along the flanks facing the rivers are thick deposits of loose sediments. Geology of Kibungo is similar to that of Mgeta and Mvuha with the exception of the presence of marbles. Ngerengere is mainly composed of post-orogenic granite as reported in Muhongo et al. 1998. Considerations of topographic contrasts in the sub-basins Mgeta and Mvuha hinterlands are susceptible to high risk of erosion due to their being highly elevated, the local geology is dominated basement rocks, marbles and extensive soil covers (Figure 6). After identifying hotspot areas that are prone to erosion, a fingerprinting study was conducted in order to assess the proportions of sediment input from various tributaries in the sub-basin.

Topography of the upstream catchment of the basin comprises mainly undulating hills of vegetated metamorphic rocks, separated by valleys of the Ruvu dendritic drainage system rivers. Major land use and cover include agriculture, cattle grazing, charcoal burning and, in some parts, small scale mining. It has been documented that, during rainfall seasons sediments are remobilized and transported along the drainage pattern causing sedimentation (Figure 7; Dutton et al. 2013).

Figure 7: Pictorial examples (Mgeta and Mvuha sub-catchments) of the sampled streams.

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Methods and Materials

During sampling of the sediments, leaves and other organic materials were removed. Only fine-grained sediments were collected in order to avoid the influence of mineral sorting (Kasanzu et al. 2008). At each sampling site, sediments were taken and packed in plastic containers. Figure 7 and 8 show examples of points from which the samples were taken. A total of 17 samples were collected from the catchment areas.

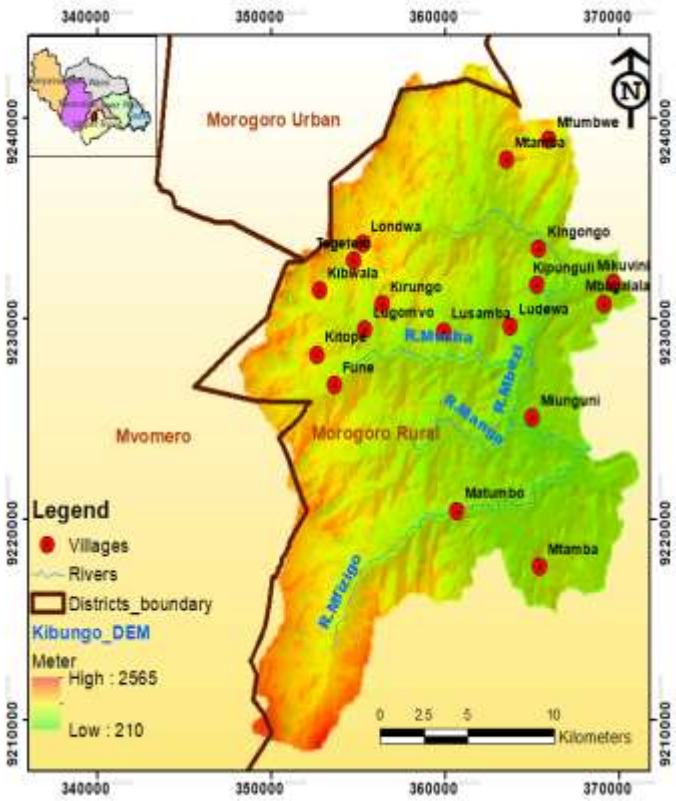

Figure 8: A map showing sites (red dots) in the river drainage system where samples were obtained.

Samples analysis and results

The samples were washed and oven-dried at 70 ^{o}C overnight at the University of Dar es Salaam, Geology Department in Tanzania. The dried samples were left to cool for 24 hours. The samples were then pulverized in an agate mill to <0.063 mm grain size, homogenized and packed into plastic bags. 5 g aliquots of each powdered sample were packed and sent to the Activation Laboratories Ltd. of Ontario, Canada, for major, trace elements, Sm-Nd data determination. Major and trace elements analyses were performed using a Thermo Jarrell- Ash ENVIRO II Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) and a Perkin Elmer SCIEX ELAN 6000 Inductively Coupled Plasma Mass Spectrometer (ICP-MS), respectively.

For ICP analyses, 0.25 g aliquots of each sample were mixed with a flux of lithium metaborate and lithium tetraborate and fused in an induction furnace. The molten melt was immediately poured into a solution of 5% HNO_3 containing an internal in standard, and was thoroughly mixed for ~30 minutes to achieve complete dissolution.

An aliquot of the sample solution was analysed for major oxides and the trace element Sc, on a combination sequential Thermo Jarrell-Ash ENVIRO II ICP-OES. Detection limits were 0.01 wt% for all major elements and 2 ppm for Sc. Calibration was performed using seven USGS and Canmet certified reference materials. Loss on Ignition (LOI) was determined from the weight loss after roasting the samples at 1050 ^{o}C for 2 hours. Totals ranged between 98.13 wt% and 101 wt% for major elements. The other aliquot of the sample solution was spiked with internal in and Rh standards to cover the entire mass range, and further diluted. Compared to the USGS W-2a standard, analytical errors for major elements were better than 3% (except for P_2O_5 which was 7%) and better than 8% for most trace elements. Loss on Ignition (LOI) was determined from the weight loss after roasting the samples at 1050 °C for 2 hours.

Rock powders for Sm-Nd were dissolved in a mixture of HF, HNO_3 and $HClO_4$. Each sample was totally spiked with a ^{149}Sm-^{146}Nd mixed solution prior to decomposition. Sm and Nd were separated by extraction chromatography on HDEHP covered Teflon powder. Accuracy of the measurements of Sm, Nd contents is
± 0.5%, ^{147}Sm/^{144}Nd ± 0.5% (2s). Analyses were performed on a Triton-MC mass-spectrometer.

Table 1: Geochemical results for sediments collected from catchment areas.
Key: MIND = Mindu; MGT = Mgeta; RUV = Ruvu; KIB = Kibangu

Analyte	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	LOI	Sc	Co	Ni	Cu	As	La	Pb	Th	U
Unit Symbol	wt%	wt%	wt%	wt%	wt%	wt%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit	0.01	0.01	0.01	0.01	0.01		1	1	20	10	5	0.1	5	0.1	0.1
Analysis Method	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	GRAV	FUS-ICP	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS
MIND 01	60	17	8	5	4	1	17	18	40	10	< 5	21.4	11	1.4	0.5
MIND 03	58	16	9	3	2	5	20	22	50	20	< 5	34.2	14	5.2	1.3
MIND 04	59	17	7	4	3	4	16	20	40	20	< 5	22.7	11	1.8	0.5
MGT 01	69	17	3	3	5	1	5	6	< 20	< 10	< 5	16	13	0.7	0.1
MGT 02	58	16	11	6	3	1	20	21	40	10	< 5	20.2	7	1.5	0.4
MGT 03	68	15	5	4	3	1	13	11	20	10	< 5	14.6	9	0.5	0.2
MGT 06	58	20	5	7	4	1	9	13	40	10	< 5	12	8	0.6	0.2
MVU 01	68	12	8	2	1	6	19	12	30	30	< 5	19.4	11	4.5	1.9
MVU 04	77	10	5	2	2	2	11	6	40	10	< 5	12.5	9	1.8	1
MVU 07	40	21	11	2	1	19	26	29	60	40	< 5	49	9	4.8	2.3
RUV06	68	15	9	5	3	2	15	17	< 20	20	< 6	29.78	9	1.1	0.6
RUV05	55	10	8	4	4..02	3	18	15	< 20	20	< 7	40.15	8	0.7	1.1
RUV04	61	17	10	3	2	4	17	22	< 20	10	< 8	35.57	11	1.5	0.46
KIB 05	60	13	10	4	2	3	19	18	40	20	< 5	32.3	10	4.5	1.3
KIB 07	53	14	13	2	2	10	24	23	40	20	< 5	46.7	8	9.1	2.1
KIB 08	67	14	7	3	4	0	17	15	30	30	< 5	32.6	7	1.2	0.5
KIB 08R	68	14	5	3	4	0	14	12	< 20	20	< 5	33.7	6	1	0.6
RUV 01	59	16	7	2	1	11	17	23	50	40	< 5	35.6	11	5.6	1.4
RUV 03	60	16	6	2	2	8	14	18	40	30	< 5	34.4	13	6.1	1.5
KIB 07R	54	11	11	11	3	0	35	26	30	< 10	< 5	41.8	19	< 0.1	0.3
MVU 05R	65	15	5	1	3	5	8	13	30	40	6	40.1	35	11.3	4.5
MGT 01R	69	16	3	3	4	1	5	5	< 20	< 10	< 5	15.9	10	1.1	0.2

Table 2: Sm-Nd data for selected catchment areas.

Sample	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Ɛ(Nd) today	T_{DM} (Ma)
MVU	1.06	1.2	0.511738	0.1268	0.511738	-17.56	2193
MGT	8.7	8.7	0.511872	0.1291	0.511872	-14.94	1908
KIB	8.40	8.8	0.511871	0.1203	0.511742	-15.93	1863
MGT	10.13	6.6	0.511894	0.1271	0.511894	-15.51	1918

Table 3: Average Sm-Nd isotopic results of elected sediment samples. Also previous isotopic data for the surrounding basement rocks are included.

Sample	T_{DM} ages (Ga)
MG02	1.9
MVU	2
KIB	1.8
MIND	2
MG Basement	2
KIB_Basement	1.9
MIND_Basement	1.8
MVU_Basement	2

Basement rock ages are inferred from Maboko and Nakamura (2002) and Muhongo (1999).

Discussions

The sediment samples' overall geochemical data are presented in Table 1. The overall patterns for all major oxide samples are comparable (Figure 9). However, inter-sample abundances display enrichments in Al_2O_3. Kasanzu et al. (2008) and Kasanzu et al. (2016) contend that, mobile elements such as Ca, Na and K are normally leached away from weathering profiles at the expense of relatively immobile major elements such as Al. Discrepancies are, however, notable for CaO and Na_2O contents that are elevated throughout the sampled itinerary. Enrichments of these elements is not unusual since their origin could be explained by dissolution of the surrounding marble basement rocks in the field (e.g. Kasanzu et al 2008). SO_2 remains in the weathered profile due to its' immobility and demonstrated resilience under surface conditions, thus, depicting and overall enrichment for all samples (Figure 9).

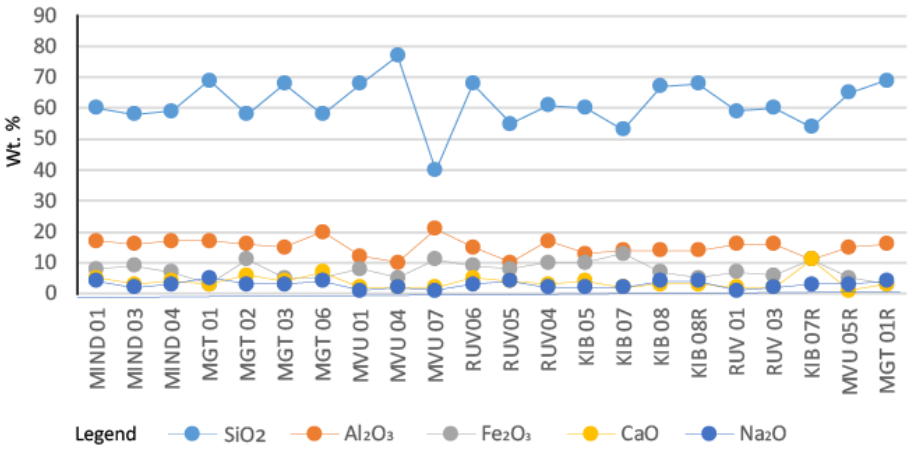

Figure 9: Inter-sample comparisons of analysed oxides abundances. Note that, TiO_2, K_2O and P_2O_5 were not analysed for the purpose of this study.

Sc, Co, Ni, Cu, As, La, Pb, Th and U contents are variable (see Table 1 and Figure 10). Samples from Mindu, Mvuha and Ruvu show overall enrichments in Ni contents. Large Ion Lithophile elements (Th and U) are lowest in all sampled locations. Relative enrichments in Sc is indicated for samples from Mvuha and Kibungo (Figure 10). Another remarkable observation in Figure 10 is the depletions of La for Mgeta samples relative to other sites. Insights from Sm-Nd data point to Precambrian sources terrains for sediment fed in the catchment.

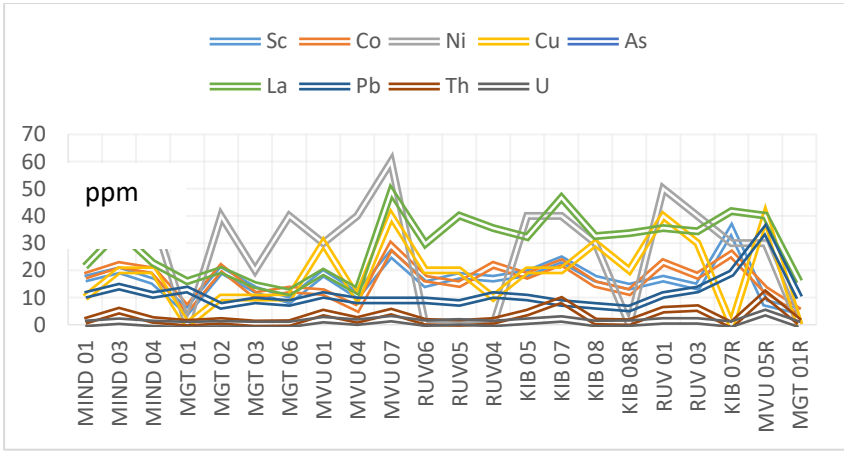

Figure 10: Comparisons of trace elemental contents for samples collected from Ruvu-Sub basin. All concentrations are in ppm.

Relative enrichments in La for samples from Mvuha, Ruvu, Kibungo could suggest a rather felsic source. Elements such as Th and La have been used to be proxy for felsic hinterlands (Kasanzu et al. 2008, indicating a felsic source) and Sc (indicative of a mafic source) has been used to distinguish between felsic and mafic provenances by various authors (e.g. McLennan 1989).

Statistical analysis on fingerprinting

Statistical analyses were done in order to aide modelling strategies. Modelling procedures are described in Albarede (2002) and as applied in Kasanzu et al. (2008) and Kasanzu (2017). Models were conducted independently with the assumption of a closed system for every possible combination of geologic sources in the catchments. A mixing model with a Bayesian Inference was used to determine the likely sources of sediments. The mixing models for each sub-catchment was initially developed for constraining source materials from feeder streams/terrains. Principally, the model is set with a Markov Chain Monte Carlo (MCMC) protocol that produces reliable simulations with the posterior display of the results following the mathematical expression below.

For a system 'o', containing several elements (i = 1…, m) hosted in phases (j = 1…., n), if M_j is the mass of phase j and m^i_j the mass of element (or species) i hosted in the phase j, the composition of species (or element) 'i' in phase 'j' can be presented as:

$$C^i_j = \frac{m^i_j}{M_j} \qquad \text{(i)}$$

Thus, for the bulk material, mass conservation requires that

$$M_0 = \sum_{j=1}^{n} Mj \qquad \text{(ii)}$$

$$f_j = \frac{M_j}{M_0} C^i_0 = \frac{m^i_0}{M_0} = \frac{\sum_{j-1}^{n} m^i_j}{M_0} \qquad \text{(iii)}$$

Therefore, for a given element, *'i',* the proportion of f_j of the phase *j* is given by equation (iii) (adopted from Albarede 2002).

After uncooperating equations (*i, ii and iii*), models were conducted for each sub-catchment present in the basin; that is Mgeta, Mvuha, Mindu and Kibungo. Input parameters used are typical provenance proxies that have been widely used in various studies (e.g. Kasanzu et al. 2008, Kasanzu et al. 2016).

Modelling Results

Mvuha River/Sub catchment

Geological inputs of sediments to Mvuha:

Sc/Th

Co/Th

$(Sm/Nd)_{age}$

$$\begin{bmatrix} Sc/Th \\ Co/Th \\ Sm/Nd \end{bmatrix} = \begin{bmatrix} \mathbf{a} & \mathbf{b} & \mathbf{c} \\ 12 & 0.7 & 0.03 \\ 7.5 & 4.5 & 0.69 \\ 2 & 2 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} x = 0.45 \\ y = 0.06 \\ z = 0.49 \end{bmatrix}$$

Key: X Msulunzi = Y = Other basement rocks, Z = Mhelenge

After modelling the data, results suggest that the sediments significantly originate from Msuluzi area and significant erosion comes from Mhelenge region. Evidence for Mhelenge is also due to elevated carbonates in the Mvuha samples.

Mindu sub-catchment

Input parameters for Mindu

Sc/Th

Co/Th

$(Sm/Nd)_{age}$

$$\begin{bmatrix} Sc/Th \\ Co/Th \\ Sm/Nd \end{bmatrix} = \begin{bmatrix} a & b & c \\ 2.4 & 10 & 0.028 \\ 7.5 & 10 & 0.0204 \\ 2 & 2 & 2 \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} x = 0.215695 \\ y = 0.7782160 \\ z = -0.006084 \end{bmatrix}$$

Key: x = Kisaka; y = Monde and Msaga; z = other basement rocks including mafic dykes

Geochemical data modelling of suspended sediments from Mindu largely suggest sources to be Msaga and Monde areas that are dominated by granulites and gneisses based on simulated mixing calculations. Thus, the extreme southern part of the sub-catchment is more prone to erosion. I also attempted to model the northern section which is dominated by granites and minor mafic dykes but their contribution does not suite into mass balance mixing.

Geological inputs of sediments to Mgeta catchment.

Input parameters:

Sc/Th

Co/Th

$(Sm/Nd)_{age}$

$$\begin{bmatrix} Sc/Th \\ Co/Th \\ Sm/Nd \end{bmatrix} = \begin{bmatrix} a & b & c \\ 4.5 & 43 & 13 \\ 4.5 & 5.5 & 0.037 \\ 2 & 2 & 2 \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} x = 0.759999 \\ y = 0.2675862 \\ z = -0.927586 \end{bmatrix}$$

X = Kibuko, Y = other basement rocks; Z = Kisaki.

Sediments of more than 70% of suspended in the Mgeta River originate from Kigalamila, Kumba, Sezima, Kingule, Mafumbo and Kibuko areas. Therefore, hills north of Kisaki are major contributors of sediments with less contribution from the southern terrain.

Kibungo sub-catchment

Input parameters for Kibungo

Sc/Th

Co/Th

$(Sm/Nd)_{age}$

$$\begin{bmatrix} Sc/Th \\ Co/Th \\ Sm/Nd \end{bmatrix} = \begin{bmatrix} a & b & c \\ 14 & 0.78 & 0.02 \\ 12 & 5.5 & 0.037 \\ 2 & 2 & 2 \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} x = 0.479064 \\ y = 0.371948 \\ z = 0.148973 \end{bmatrix}$$

Key: X = Mfigizo, y and z are surrounding basement rocks.

It follows, therefore that, significant erosion is notable for the Mfizigo area into the catchment.

On the overall, erosion of basement metamorphic rocks also contributes the total budget of sediments in the Kibungo catchment.

Conclusions

Modelling results from the Ruvu Sub-basin indicate the followings:

Most erosion in the Mgeta River originates from Kigalamila, Kumba, Sezima, Kingule, Mafumbo and Kibuko areas. Hills north of

Kisaki need more interventions to protect the catchment from sedimentation and environmental pollution. Mindu erosional signals largely suggest significant in Msaga and Monde areas. Thus, the extreme southern part of the sub-catchment is more prone to erosion.

For the case of Kibungo sub-catchment, most sediments are sourced from the Mfizigo area relative to basement rocks. After modelling the data, more erosion for the Mvuha sub-catchment is from Msuluzi area and significant erosion comes from Mhelenge region. Evidence for Mhelenge is also due to elevated carbonates in Mvuha sub-catchment.

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