Sediment Source Determination by Fingerprinting:
Ruvu River Basin, Tanzania

Tanzania Integrated Water, Sanitation and Hygiene (iWASH) Program

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Summary

This study was designed to determine the primary sources of suspended sediments into the Ruvu River so that detailed follow-up studies can be planned and remediation measures undertaken.

A sediment fingerprinting technique was utilized to identify the major sources of sediment within the basin. Suspended sediment laden filters and soil samples were collected throughout the basin and used to develop composite fingerprint signatures for each source. Suspended sediment laden filters were also collected at the furthermost downstream point and analyzed to determine the relative proportions of each of the sources in that sample.

In addition to a statistical technique utilizing Bayesian Inference and a Markov Chain Monte Carlo, this study used a very robust method of calculating error. As with any sediment study, error rates must be carefully considered to give credibility to any result.

We found that two specific areas within the upper catchment of the Ruvu Basin were contributing disproportionately high amounts of sediment compared to the other potential sources. These two areas make up only 3% of the study area yet potentially contribute over 30% of the suspended sediment load in the Ruvu River. One area in particular, “m”, is an ideal candidate for follow-up soil conservation activities due to its relatively small size and disproportionately large contribution of sediments.

Introduction

This study utilized methods recently developed in the Mara River Basin of Kenya and Tanzania, to identify source proportions of sediments in downstream water samples (Dutton 2012; Dutton et al. 2013). These methods allow a very small portion of suspended sediments to be collected and analyzed on a filter. Bayesian statistics are then employed to determine the relative source proportions in a downstream sample from the different potential sources within the catchment.

Initial discussions about utilizing a sediment fingerprinting approach in the basin began in 2012. In March, 2013, a sediment fingerprinting team was convened to explore the possibilities for fingerprinting the Ruvu Basin. The team agreed on the methodology to be utilized and a two week intensive field campaign began with the following personnel:

- Ms. Mercy Mohammed – iWASH employee
- Mr. James Renatus – UDSM student
- Ms. Rosemary Masikini – Wami-Ruvu Basin Water Office employee
- Mr. Lema – Consultant and retired Wami-Ruvu Basin Water Office employee

After the two week intensive campaign, additional suspended sediment samples were collected over a two month period in order to capture as much of the natural variability in suspended sediments as possible in a relatively short amount of time.

Sample processing occurred in the field, at Yale University in New Haven, CT, and at Florida International University (FIU) in Miami, Florida. All samples were analyzed for their element composition at FIU through laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS).

Background

The Ruvu River is the domestic water supply source for the over 3 million inhabitants in the largest city of Tanzania, Dar es Salaam (Yanda and Munishi 2007). Suspended sediments have been increasing in the Ruvu Basin over the last 20 years (Yanda and Munishi 2007). Increasing sediment loads in the river lead to increased costs of water treatment (Ngana et al. 2010). There is an increasing desire to implement suspended sediment controls but the primary locations of erosion have not yet been conclusively determined.

There has been little research conducted into the sediment dynamics of the Ruvu River. One early study determined the annual sediment yield to be approximately 50 tons/km^2 (Gondwe 2000) yet an older study has estimated it to be in excess of 200 tons/km^2 (Rapp 1972). Gondwe also speculated that the primary sources of suspended sediments were probably coming from a relatively small area of the catchment. A recent consultant report speculated that over 70% of the suspended sediments were coming from the upper catchment (Yanda and Munishi 2007).

During the March, 2013, meeting of the sediment fingerprinting team, participants discussed the sediment fingerprinting approach and our experiences in the Mara River Basin, Kenya. After initial discussions, it was decided to focus on the following:

- Fingerprinting each specific geologic group by collecting five samples within each group. There are thirteen groups in the Ruvu Basin.
- Collecting 5 suspended sediment samples over two months at four primary locations;
    - Ruvu Bridge, to serve as the most downstream target sample
    - The outlet of the Ngerere, in order to use that sample to develop a source signature for the entire catchment and to specifically fingerprint that entire catchment by utilizing the geologic samples
    - The outlet of the Upper Ruvu, in order to use that sample to develop a source signature for the entire catchment and to specifically fingerprinting that entire catchment by utilizing the geologic samples

- The outlet of the Mgeta, in order to use that sample to develop a source signature for the entire catchment and to specifically fingerprinting that entire catchment by utilizing the geologic samples

It was agreed that suspended sediment samples would be taken over a 2 month period (April and May) during a variety of different flow events. The goal was to capture as much of the natural variability in suspended sediments present in the river as possible during that short time.

The target watersheds are illustrated in Figure 2.

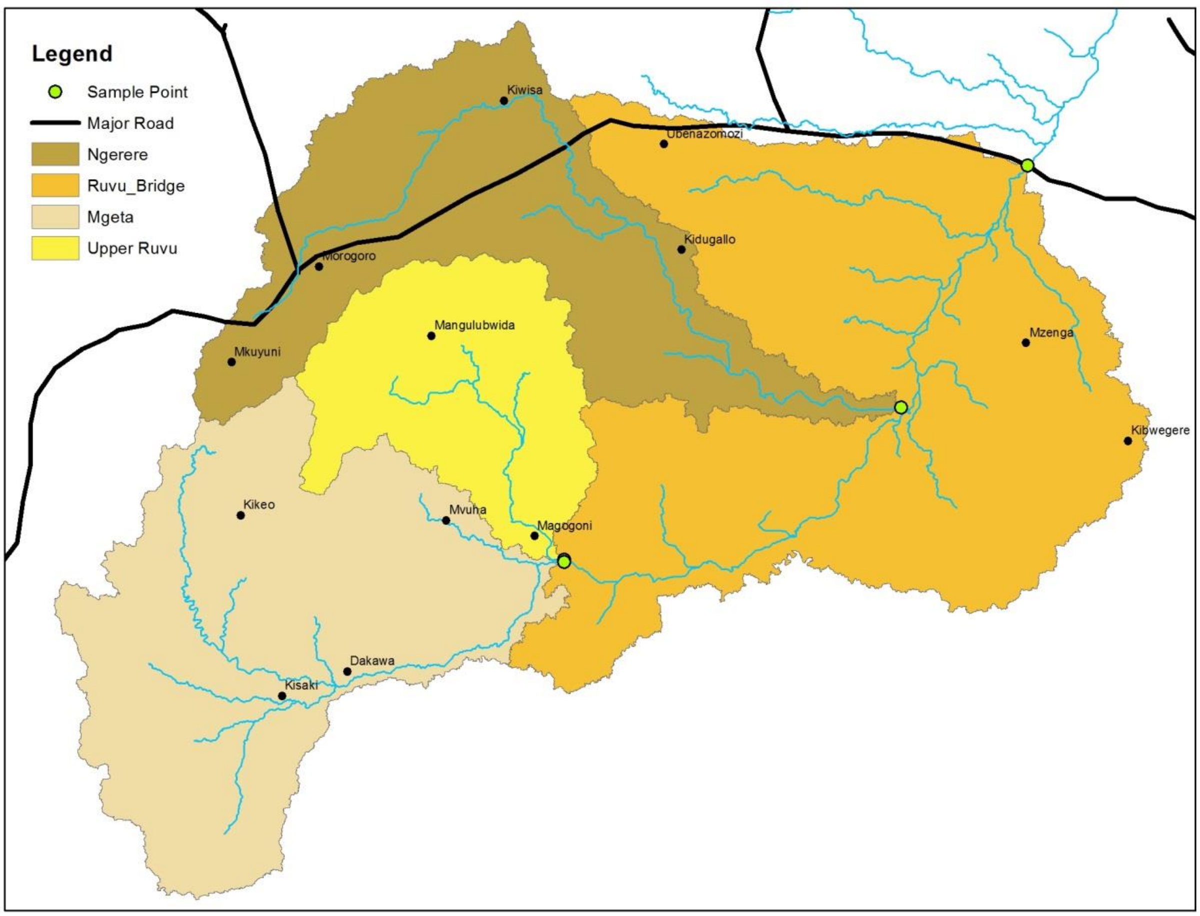

Figure 2: Target Watersheds

The target geologic groups are illustrated in Figure 3 and Table 1.

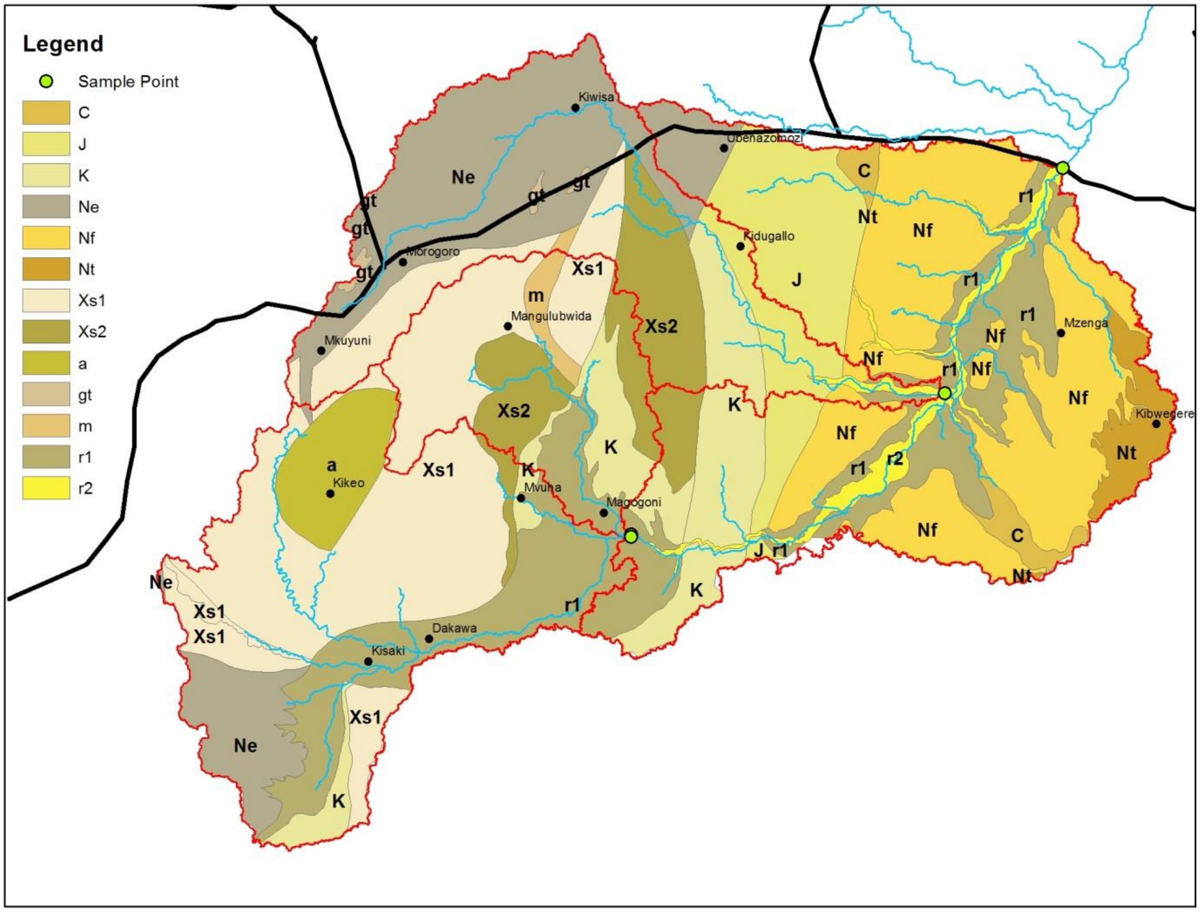

Figure 3: Target Watersheds and Geologic Groups

Table 1: Ruvu Basin Lithology

Name	Lithology
r1	Alluvium deposits
Ne	Composite metamorphic crust domain
K	Conglomerate and tillite
C	Continental and marine sand stone
Nf	Fluvial marine sand
Xs1	Granulite,gneiss and migmatite
Xs2	Marble
a	Meta-anorthosite complex
m	Meta-anorthosite complex (interlayed)
gt	Migmatite,granite and mafic dykes
J	Mudstone and Shale
r2	Stream deposits
Nt	Terrace deposits

It was agreed that once sample analysis is completed, several different models will be created in order to explore the data.

> Model I: Each unique lithology will be fingerprinted. The Ruvu Bridge suspended sediment samples will then be utilized as the downstream target samples to determine the source proportions of the four potential sources.
>
> Model II: The three watersheds will also be fingerprinted as three different sources using the suspended sediment samples and the Lower Ruvu area will be fingerprinted as a source using the soil samples. The Ruvu Bridge suspended sediment samples will then be utilized as the downstream target samples to determine the source proportions of the four potential sources.
>
> Model III: The Mgeta watershed suspended sediment samples will be fingerprinted as the downstream target sample and the geologic samples collected within that watershed will be fingerprinted as the source samples.
>
> Model IV: The Upper Ruvu watershed suspended sediment samples will be fingerprinted as the downstream target sample and the geologic samples collected within that watershed will be fingerprinted as the source samples.
>
> Model V: The Ngerengere watershed suspended sediment samples will be fingerprinted as the downstream target sample and the geologic samples collected within that watershed will be fingerprinted as the source samples.

The preliminary analysis plan was for all digestions to occur at Yale University. Later, a laser ablation laboratory at Florida international university agreed to process all samples in Miami and develop a new method for analyzing sediments from filters.

Methods

Sediment fingerprinting involves 5 basic steps:

1. collection of samples representing a range of possible sediment sources ("source samples")
2. collection of one or more receiving-water samples, for which the source of sediment is to be determined ("downstream samples")
3. analysis of both types of samples for a variety of potential tracer properties
4. statistical analysis of the potential tracer properties in the source samples to determine which ones are able to reliably discriminate between the potential sources
5. statistical apportioning of downstream sediment to the various potential sources using a mixing model.

Sources of uncertainty at each of these stages need to be recognized and quantified.

Source Samples

Source samples were collected throughout the Ruvu Basin. Two different types of source samples were collected; soil samples and suspended sediment samples.

Soil Samples

Each soil sample collected was a composite sample composed of five surface samples collected from the top 2cm within a several meter radius within erosion prone areas. At least five composite samples were collected from each lithographic group except area "C". Area "C" is in the lower Ruvu area and it was not possible to gain access further into that area to collect more samples during the field work. Soil samples were collected utilizing the following guidelines:

- Each soil sample collected was a composite sample composed of five surface samples collected from the top 2cm of soil within a 50 meter radius within erosion prone areas. A minimum of five composite samples were collected from each lithographic group. Specific sample locations were chosen by utilizing a lithographic map uploaded to a handheld GPS unit. The lithographic map provided guidance as to the type of area that we were traveling through. We would then choose to sample a location when there were visible signs of erosion.

- Soil samples were air dried in the field then sealed within a plastic bag. The bag was then taped at the seams to ensure an air-tight seal.

All soil samples were then placed into a hard plastic container. This container was then sealed with duct-tape in order to achieve a second, air-tight seal.

Figure 5 illustrates the different lithologies and the locations that soil samples were taken.

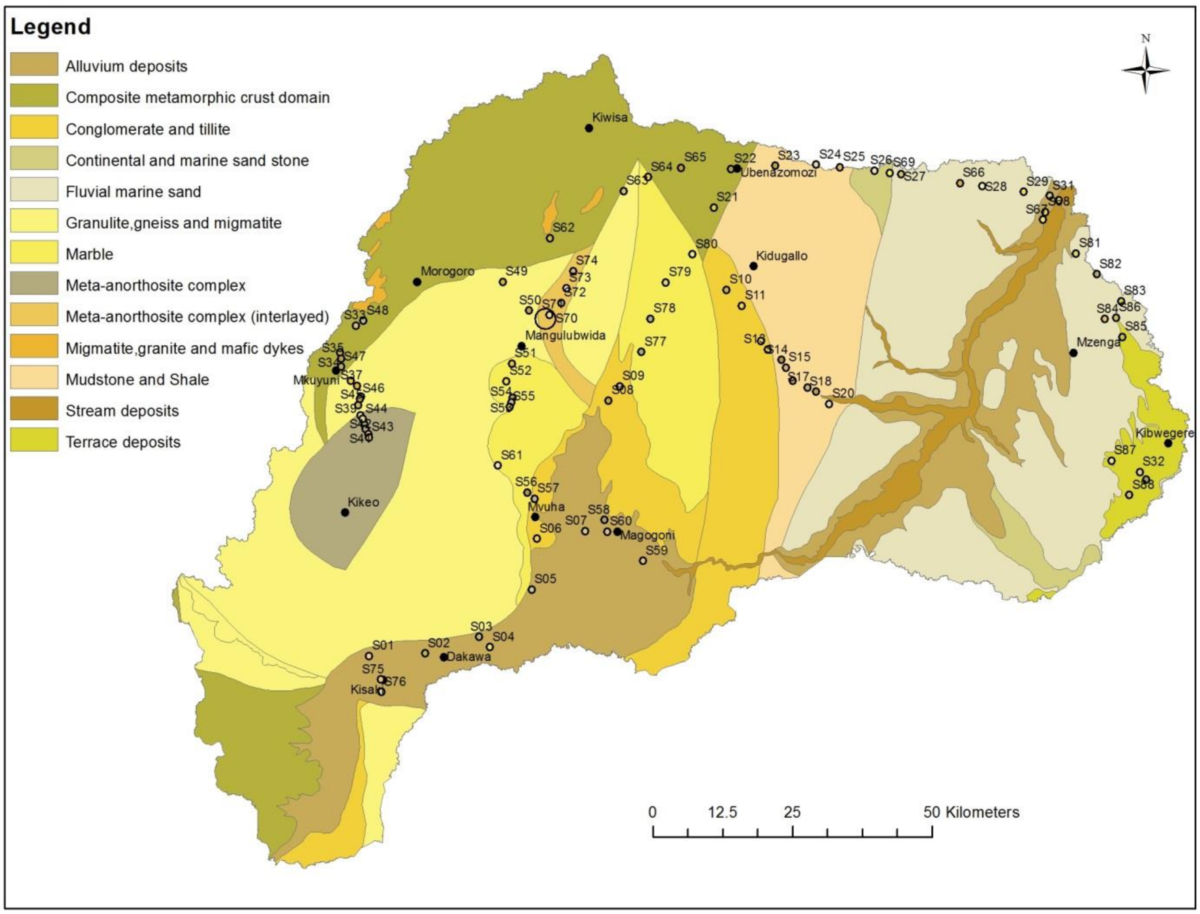

Figure 4: Soil Samples and Lithology. This map excludes the Coastal Ruvu area.

Appendix 1 provides a full list of the soil samples collected in the field.

Suspended Sediment Samples

Suspended sediment samples were collected utilizing the following guidelines:

- Suspended sediment samples were collected by taking a one liter sample of water from a representative reach of the river that appeared to be well mixed. This was typically in the middle of the river.
- Samples were taken in a Nalgene 1-Liter sample bottle after it had been rinsed three times in the sample water. Samples were also collected utilizing a clean and rinsed plastic water bottle housed within a metal canister suspended by a rope. This setup was utilized when taking a sample from a bridge.
- A pre-cleaned, pre-dried, and pre-weighted 0.45 um Whatman Cellulose Nitrate filter paper was then removed from a petri dish. The filter was carefully placed within the filter apparatus using cleaned filter forceps. The apparatus was then carefully assembled, ensuring not to rip the filter paper while screwing the top of the unit onto the bottom of the unit. The bottle containing the water samples was then shaken well, and a subsample of the water was then measured in a clean graduated cylinder and poured into the filter apparatus. 100mL to 500mL was typically filtered depending on the turbidity of the water. The specific amount measured was written on the tape affixed to the petri dish. The goal was to have the filter process take at least 15 minutes to ensure that enough mass was collected on the filter. All sample filtration was done in the field.
- The filter apparatus was pumped up to approximately 15 psi.
- After all the water had filtered through the filter, the top of the apparatus was checked for residual sediments. If there were residual sediments present, deionized water (we used battery water in the field) was sprayed into the top of the unit utilizing the handheld sprayer. The goal of this was to dislodge any sediments remaining on the top of the unit and transfer them to the filter paper. The filter apparatus was then pumped up again to allow the deionized water to filter through the filter.
- The filter was then removed from the apparatus and placed back into its original petri dish to air-dry.

- The filter pump apparatus was rinsed three times with deionized water and wiped clean with tissue paper. A black laboratory grade scrub brush was utilized occasionally to clean the interior of the apparatus. The apparatus was then rinsed one final time with deionized water to remove any of the tissue paper residues.

The prioritized catchments were sampled from the following locations:

- Upper Ruvu at Bwira Chini
- Mgeta @ Dutumi gauging station
- Ngerengere @ Utari

Figure 5 provides an overview of the prioritized catchments and the suspended sediment sample locations.

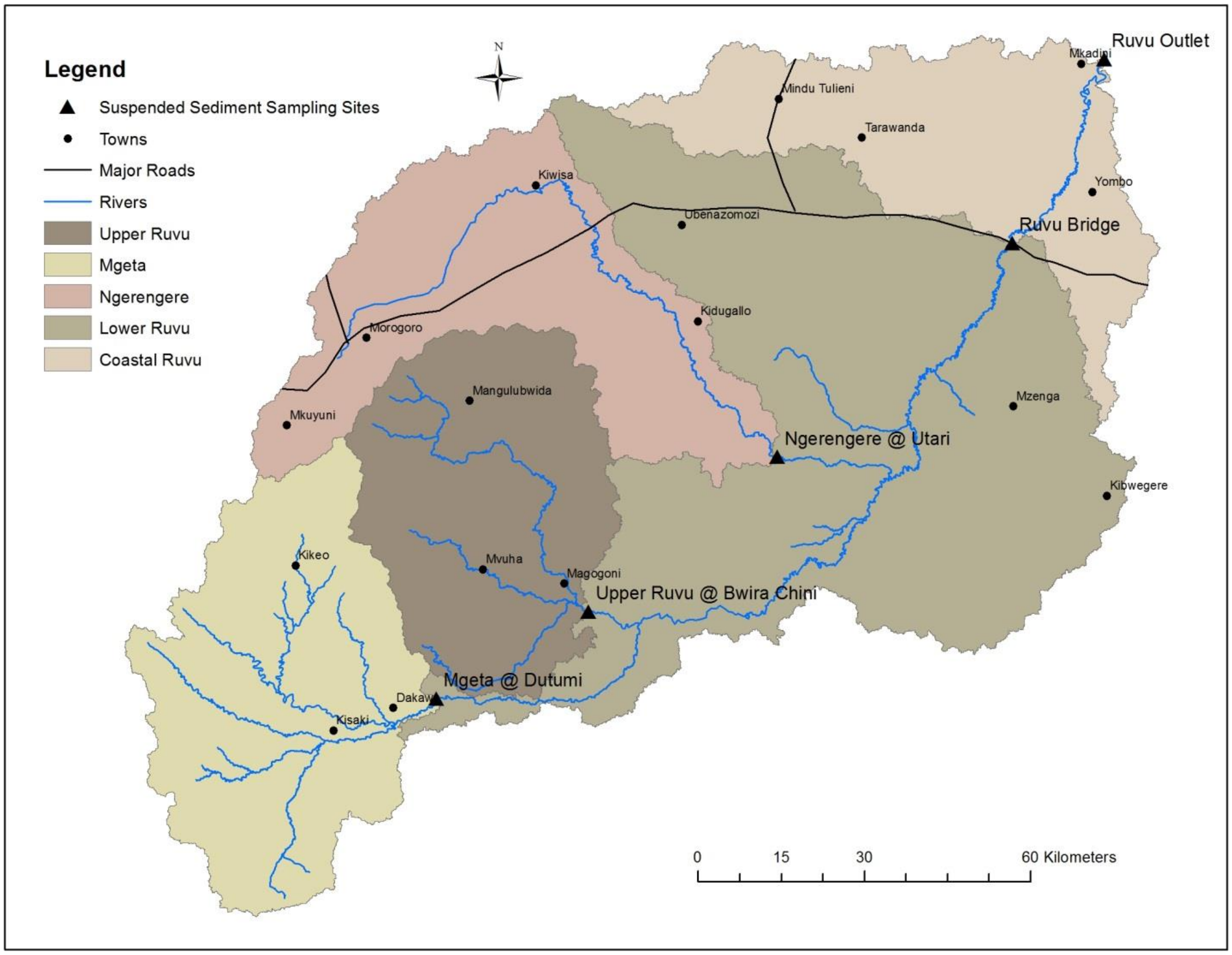

Figure 5: Map of the priority catchments. Note: the Coastal Ruvu area is not being considered as part of this study.

Appendix 2 provides a full list of the suspended sediment samples collected in the field.

Downstream Samples

Downstream samples were taken as suspended sediment samples on filter papers in accordance with the procedures detailed above. Downstream samples were collected for the Ruvu Morogoro Bridge, Mgeta at Dutumi, Ngerengere at Utari and for the Upper Ruvu at Bwira Chini (Figure 5).

Analysis

Preliminary sample preparation occurred at Yale University. Soil samples and suspended sediment laden filter samples were dried at 60 degrees C for 24 hours in a drying oven. Soils were then sieved through a <63 micron stainless steel mesh. Suspended sediment laden filters were then placed in a desiccator to allow them to reach ambient room temperature. Once at temperature, they were weighed on a microbalance. Samples were then packaged securely and transported to FIU.

Tracers for use in the sediment fingerprinting approach were considered from a suite of major, minor and trace elements. Concentrations of were determined at FIU by laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS).

For detailed sample preparation and analysis information, please refer to Florida International University Trace Evidence Analysis Facility Laboratory Reports TEAF-AS-IC082113 (suspended sediments) and TEAF-AS-IC081913 (soils).

Statistical Analysis

All elements were log transformed for normality before analysis. All statistical analysis were done in R (2.15.1). The Kruskal-Wallis H test was first used to identify tracers that showed significant differences between source types (kruskal.test function); any tracer with a p value greater than 0.05 was discarded. A step-wise discriminant function analysis based on the minimization of Wilks' lambda was then used to determine which parameters were capable of discriminating between source types (greedy.wilks function in the klaR package and the lda function in the MASS package). A jackknifed discriminant function analysis was then used to assess the discriminatory power of the tracers through a cross-validation procedure (lda function in the MASS package). With the jackknifed procedure, the discriminant function analysis is run multiple times, leaving a different sample out each time. The procedure then provides a value of the success in the reclassification of the source samples that is often more conservative than a discriminant function analysis utilizing all source samples (Borcard et al. 2011).

Parameters identified as useful by the Kruskal-Wallis H test and verified with the discriminant function analysis were then examined to ensure that the tracer values exhibited by the downstream samples were within the range of values presented by the upstream samples.

These statistical analyses were undertaken independently for the five different areas in which source determination was desired.

Mixing Model

A mixing model with Bayesian Inference was utilized to determine the likely sources of sediments. The SIAR mixing model (Stable Isotope Analysis in R) was originally developed for inferring diet composition from stable isotope analysis of consumers and sources (Parnell et al. 2010). SIAR allows for all sources of uncertainty to be propagated through the model. The model is fit via a Markov Chain Monte Carlo (MCMC) routine. MCMC produces a simulation of the plausible values of the posterior distribution given the data provided.

The general model of SIAR allows for a trophic enrichment factor and for isotope ratios as well as concentrations; we have omitted both from our model:

$$X_{ij} = \frac{\sum_{k=1}^{k} p_k s_{jk}}{\sum_{k=1}^{k} p_k} + e_{ij}$$

X_{ij} = observed value of tracer j in sample i

s_{jk} = concentration of tracer j in source k, assumed to be normally distributed (after transformation), with mean and standard deviation derived from the measurements

p_k = proportion of source k in sample i, estimated by the model

e_{ij} = residual error

The MCMC routine will run through a user specified number of iterations and attempt to determine plausible values of *pk*, or the proportion of each source in a sample, given the data input into the model. This information is then used to create the confidence intervals of the model sources. It is advisable to discard the first set of values determined in the MCMC as these may not represent a true convergence of the posterior distribution (McCarthy 2007). This is referred to as “burn-in.”

Tracer concentrations for each source sample were input into the model as the mean and standard deviation of each tracer concentration (s_{jk}). Downstream or target samples were input into the model as tracer concentration values (x_{ij}).

The model was run for 500,000 iterations with the first 50,000 iterations discarded (burn-in). An uninformative prior distribution was specified in the models. The mixing model assumes the contribution of the sources add up to 100%. We will report the modes of the distribution of possible source contributions, since the mode represents the maximum likelihood value when utilizing a vague prior distribution (McCarthy 2007). The modes of all potential sources within the model will not necessarily add up to exactly 100% due to the different distributions for each source.

Results

Soil sample analysis data was received from FIU on August 23rd. 20 elements passed all quality control procedures; ^{7}Li, ^{25}Mg, ^{31}P, ^{39}K, ^{51}V, $^{52,53}Cr$, ^{57}Fe, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{71}Ga, ^{75}As, ^{85}Rb, ^{98}Mo, ^{118}Sn, $^{123}Sb^{b}$, ^{137}Ba, ^{205}Tl, $^{207,208}Pb$, ^{238}U.

Suspended sediment analysis data was received from FIU on September 19th. 20 elements passed all quality control procedures; ^{7}Li, ^{23}Na, ^{25}Mg, $^{31}P^{d}$, ^{39}K, ^{51}V, $^{52,53}Cr$, $^{57}Fe^{d}$, ^{63}Cu, ^{66}Zn, ^{71}Ga, $^{75}As^{d}$, ^{85}Rb, ^{98}Mo, $^{118,120}Sn$, ^{137}Ba, ^{176}Lu, ^{205}Tl, $^{206,207,208}Pb$, and ^{232}Th.

Out of the two analyses, 17 elements (19 isotopes) passed quality control procedures for both sets of samples; ^{7}Li, ^{25}Mg, ^{31}P, ^{39}K, ^{51}V, $^{52,53}Cr$, ^{57}Fe, ^{63}Cu, ^{66}Zn, ^{71}Ga, ^{75}As, ^{85}Rb, ^{98}Mo, ^{118}Sn, ^{137}Ba, ^{205}Tl, $^{207,208}Pb$.

The study area was divided into five separate fingerprinting units. Each unit was treated individually as a discrete study to illustrate the different levels of discrimination capable with the data collected. The five separate fingerprinting units are as follows:

1. Ruvu Basin upstream of the Ruvu-Morogoro Bridge - soils
    a. Sources – soil samples collected throughout the different lithology types in the entire basin upstream of the Ruvu-Morogoro Bridge

   b. Downstream Samples – 13 suspended sediment samples collected from the Ruvu-Morogoro Bridge.
2. Ruvu Basin upstream of the Ruvu-Morogoro Bridge – soils + catchments
   a. Sources – suspended sediment samples were used to characterize the three major catchments; the Ngerengere catchment, the Mgeta catchment, and the Upper Ruvu catchment. Soil samples were then utilized to characterize the other geologic areas not contained within those catchments.
   b. Downstream Samples – 13 suspended sediment samples collected from the Ruvu-Morogoro Bridge.
3. Mgeta Catchment
   a. Sources – soil samples collected through the different geologic areas within the Mgeta catchment.
   b. Downstream Samples – 5 suspended sediment samples collected from the outlet of the Mgeta catchment near Dutumi.
4. Upper Ruvu Catchment
   a. Sources – soil samples collected throughout the different geologic areas within the Mgeta catchment.
   b. Downstream Samples – 5 suspended sediment samples collected from the outlet of the Upper Ruvu catchment near Bwira Chini.
5. Ngerengere Catchment
   a. Sources – soil samples collected through the different geologic areas within the Ngerengere Catchment
   b. Downstream Samples – 5 suspended sediment samples collected from the outlet of the Ngerengere catchment near Utari.

Model I - Ruvu Basin Upstream of the Ruvu-Morogoro Bridge - soils

11 geologic areas represent the range of potential sources in the Ruvu Basin; a, C, J, K, m, Ne, Nf, Nt, r1, Xs1, Xs2. All elements which passed the quality control procedures were natural log transformed and examined to ensure that the downstream sample values were within the range of the values offered by the potential sources. All elements passed the range test.

The elements were then tested for their ability to discriminate between the potential sources with the Kruskal-Wallis H-test. Out of 19 elements, only one element failed the test (arsenic).

Table 2: Model I - Kruskal-Wallis H Test Results

Analyte	H	p
Li7	18.62	0.05
Mg25	29.31	0.00
P31	27.44	0.00
K39	33.16	0.00
V51	34.49	0.00
Cr52	22.65	0.01
Cr53	22.68	0.01
Fe57	43.92	0.00
Cu63	32.18	0.00
Zn66	24.10	0.01
Ga71	46.41	0.00
As75	12.70	0.24
Rb85	40.08	0.00
Mo98	21.94	0.02
Sn118	18.72	0.04
Ba137	32.60	0.00
Tl205	40.06	0.00
Pb207	41.43	0.00
Pb208	40.59	0.00

Redundant isotopes were removed from consideration (^{53}Cr and ^{207}Pb). With arsenic and the redundant isotopes excluded, a Discriminant Function Analysis (DFA) was run on the remaining elements to identify the optimum combination of elements to utilize as tracers. The DFA found that ^{7}Li, ^{52}Cr and ^{66}Zn increase the error associated with the discrimination of sources. Those three elements were then excluded from the rest of this process.

Table 3: Model I - Discriminant Function Analysis Results

Formula					Error
Ga71					80%
Ga71	Pb208				66%
Ga71	Pb208	Ba137			52%
Ga71	Pb208	Ba137	Mg25		51%
Ga71	Pb208	Ba137	Mg25	Tl205	45%

Ga71	Pb208	Ba137	Mg25	Tl205	Rb85											40%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57										37%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98									37%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51								31%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39							32%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39	Cu63						30%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39	Cu63	P31					28%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39	Cu63	P31	Sn118				24%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39	Cu63	P31	Sn118	Li7			24%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39	Cu63	P31	Sn118	Li7	Cr52		25%
Ga71	Pb208	Ba137	Mg25	Tl205	Rb85	Fe57	Mo98	V51	K39	Cu63	P31	Sn118	Li7	Cr52	Zn66	26%

A jack-knifed Discriminant Function Analysis (jDFA) was then utilized to provide a conservative estimate of the ability of the tracers to discriminant between the different sources. The following confusion matrix illustrates the difficulty that the discriminant function has in identifying several of the sources. Source “C” was never identified, although it was composed of only two samples and represents a very small portion of the basin (<0.5%). Source “a” and “Nf” were very well identified with 83% and 75% accuracy. Overall accuracy is approximately 46%.

Table 4: Model I - Jackknifed DFA Results

	a	C	J	K	m	Ne	Nf	Nt	r1	Xs1	Xs2	Accuracy
a	5	0	0	0	0	0	0	0	0	1	0	83%
C	0	0	1	0	0	0	0	0	1	0	0	0%
J	0	1	4	2	0	0	0	1	1	0	0	44%
K	0	0	2	3	0	0	0	0	2	0	1	38%
m	0	0	0	0	3	1	0	0	0	1	0	60%
Ne	0	0	1	0	0	5	0	0	0	1	2	56%
Nf	0	0	0	0	0	0	6	0	2	0	0	75%
Nt	0	0	0	1	0	1	1	3	0	0	0	50%
r1	0	0	1	0	0	0	4	0	6	2	1	43%
Xs1	1	0	1	0	0	0	0	0	2	3	1	38%
Xs2	1	1	0	2	1	2	2	0	0	1	2	17%

The SIAR model was run with the remaining 13 elements. Source proportions with the 13 downstream samples run as a composite are presented in Figure 6.

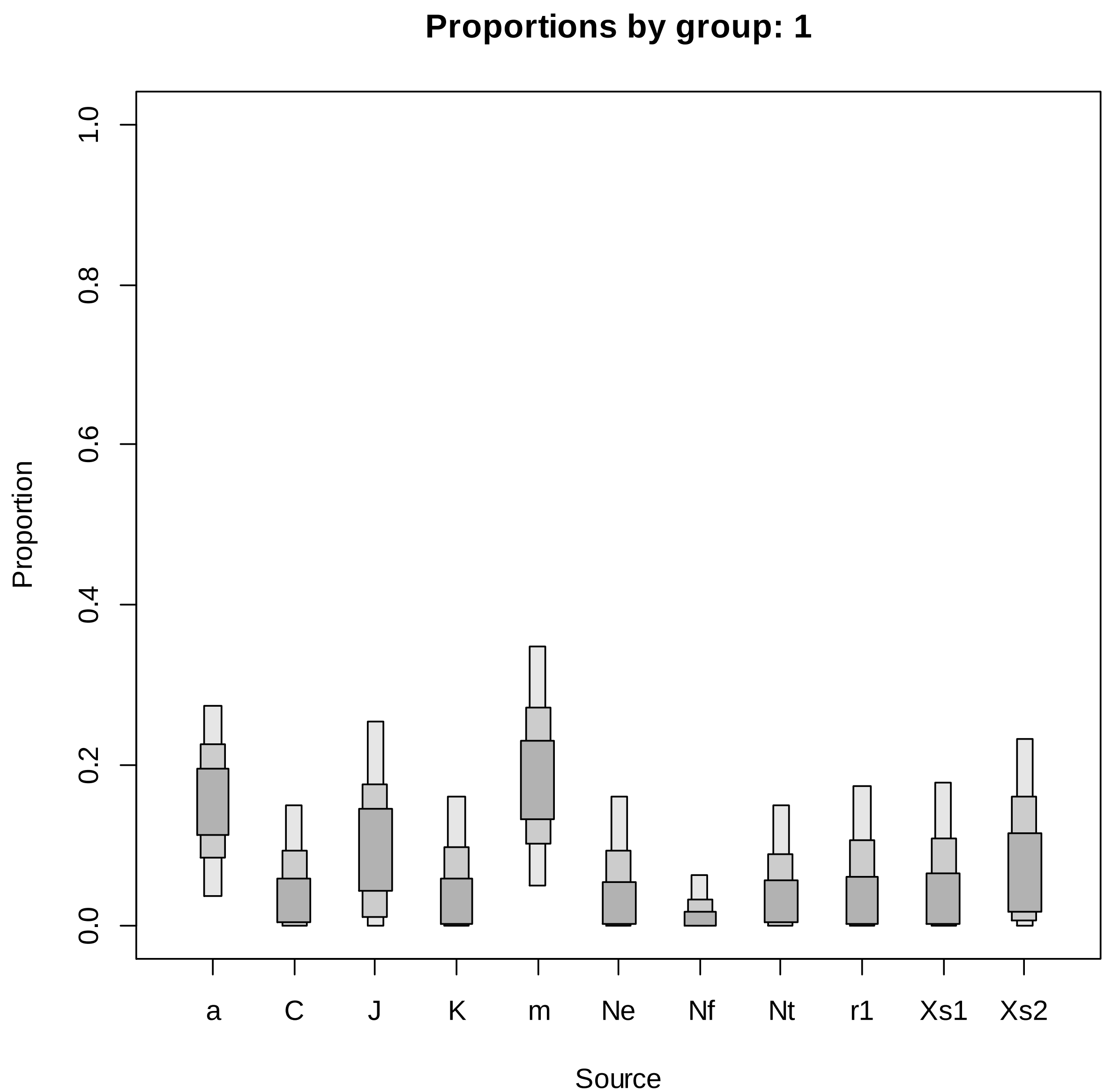

Figure 6: Model I - SIAR Source Proportions Results

Each downstream sample was then run in the model independently to provide estimates for specific suspended sediment samples. Source proportion data for each sample are presented in Appendix 3 – Ruvu Basin Soils Individual Sample Source Proportions.

Model II - Ruvu Basin Upstream of the Ruvu-Morogoro Bridge – soils + catchments

8 geologic areas and 3 catchments represent the range of potential sources within this fingerprinting unit; Mgeta, Ngerengere, Upper Ruvu, C, J, K, Ne, Nf, Nt, r1, and Xs2. All elements which passed the quality control procedures were natural log transformed and examined to ensure that the downstream sample values were within the range of the values offered by the potential sources. All elements passed the range test.

The elements were then tested for their ability to discriminate between the potential sources with the Kruskal-Wallis H-test. Out of 19 elements, only one element failed the test (molybdenum).

Table 5: Model II – Kruskal-Wallis Test Results

Analyte	H	p
Li7	30.69	0.00
Mg25	27.84	0.00
P31	24.37	0.01
K39	35.42	0.00
V51	27.15	0.00
Cr52	23.43	0.01
Cr53	23.83	0.01
Fe57	38.50	0.00
Cu63	36.65	0.00
Zn66	29.76	0.00
Ga71	39.66	0.00
As75	19.18	0.04
Rb85	37.74	0.00
Mo98	19.17	0.04
Sn118	22.34	0.01
Ba137	37.38	0.00
Tl205	41.19	0.00
Pb207	31.07	0.00
Pb208	30.30	0.00

Redundant isotopes were removed from consideration (^{53}Cr and ^{207}Pb). With molybdenum and the redundant isotopes excluded, a Discriminant Function Analysis (DFA) was run on the remaining elements to identify the optimum combination of elements to utilize as tracers. The

DFA found by including all elements, there is only approximately 18% error associated with the discrimination of the sources when excluding phosphorus.

Table 6: Model II – Discriminant Function Analysis Results

Formula																	Cumulative Error
Tl205																	76%
Tl205	Pb208																58%
Tl205	Pb208	K39															43%
Tl205	Pb208	K39	Ga71														39%
Tl205	Pb208	K39	Ga71	Mg25													37%
Tl205	Pb208	K39	Ga71	Mg25	Rb85												36%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75											31%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137										29%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51									30%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63								27%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98							23%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98	Fe57						19%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98	Fe57	Cr52					19%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98	Fe57	Cr52	Li7				22%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98	Fe57	Cr52	Li7	Sn118			20%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98	Fe57	Cr52	Li7	Sn118	Zn66		18%
Tl205	Pb208	K39	Ga71	Mg25	Rb85	As75	Ba137	V51	Cu63	Mo98	Fe57	Cr52	Li7	Sn118	Zn66	P31	19%

A jDFA was then run on the remaining elements. Source C was never identified. All three catchments were very well identified. Overall accuracy is approximately 49%.

Table 7: Model II – Jackknifed Discriminant Function Analysis Results

	C	J	K	Mgeta	Ne	Nf	Ngerengere	Nt	r1	Upper Ruvu	Xs2	Accuracy
C	0	1	0	0	0	1	0	0	0	0	0	0%
J	1	4	2	0	0	0	0	1	1	0	0	44%
K	0	2	3	0	1	0	0	0	1	0	1	38%
Mgeta	0	0	0	5	0	0	0	0	0	0	0	100%
Ne	0	1	0	0	4	0	0	0	0	0	4	44%
Nf	0	0	1	0	0	4	0	0	3	0	0	50%
Ngerengere	0	0	0	0	0	0	5	0	0	0	0	100%
Nt	0	0	2	0	0	0	0	2	0	1	1	33%
r1	0	1	0	0	0	5	0	0	7	1	0	50%

	C	J	K	Mgeta	Ne	Nf	Ngerengere	Nt	r1	Upper Ruvu	Xs2	Accuracy
Upper Ruvu	0	0	0	0	0	0	1	0	0	3	1	60%
Xs2	1	0	0	0	5	0	1	1	0	0	4	33%

The SIAR model was run with the 15 elements that passed all statistical tests. Source proportions with the 13 downstream samples run as a composite are presented in Figure 7.

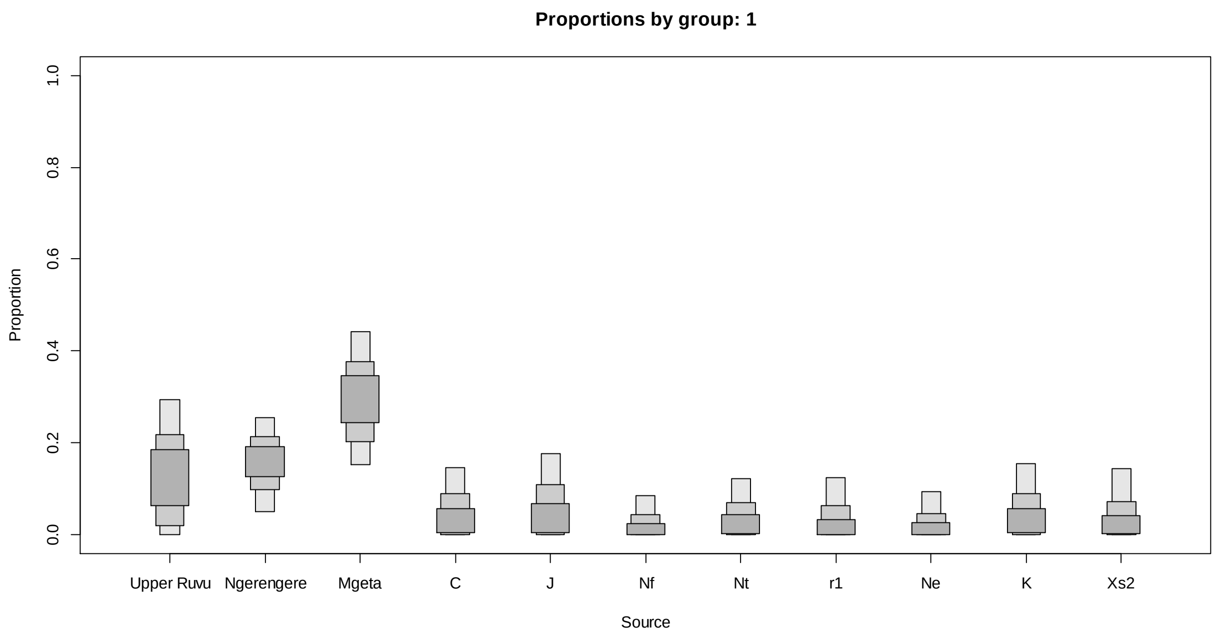

Figure 7: Model II – SIAR Source Proportions Results

Each downstream sample was then run in the model independently to provide estimates for specific suspended sediment samples. Source proportion data for each sample are presented in Appendix 4 - Ruvu Basin Soils + Catchments Individual Sample Source Proportions.

Model III – Mgeta Catchment

5 geologic areas represent the range of potential sources within this fingerprinting unit; a, k, Ne, r1, Xs1. All elements which passed the quality control procedures were natural log transformed and examined to ensure that the downstream sample values were within the range of the values offered by the potential sources. Potassium and gallium did not pass the range test.

The remaining elements were then tested for their ability to discriminate between the potential sources with the Kruskal-Wallis H-test. Out of 17 elements, 9 failed the test. After eliminating redundant isotopes, 7 elements remain.

Table 8: Model III – Kruskal-Wallis Test Results

Analyte	H	p
Li7	3.78	0.44
Mg25	7.08	0.13
P31	6.59	0.16
V51	12.99	0.01
Cr52	5.00	0.29
Cr53	5.01	0.29
Fe57	15.76	0.00
Cu63	7.42	0.12
Zn66	7.27	0.12
As75	4.71	0.32
Rb85	27.28	0.00
Mo98	15.81	0.00
Sn118	10.18	0.04
Ba137	8.65	0.07
Tl205	23.29	0.00
Pb207	24.89	0.00
Pb208	24.05	0.00

A DFA was run on the remaining 7 elements. The discriminant function found a cumulative error of approximately 27% utilizing all elements.

Table 9: Model III – Discriminant Function Analysis Results

Formula							Cumulative Error
Rb85							51%
Rb85	Tl205						49%
Rb85	Tl205	Fe57					49%
Rb85	Tl205	Fe57	Mo98				33%
Rb85	Tl205	Fe57	Mo98	V51			24%
Rb85	Tl205	Fe57	Mo98	V51	Pb208		29%
Rb85	Tl205	Fe57	Mo98	V51	Pb208	Sn118	27%

A jDFA was then run on the remaining elements. All sources were relatively well identified except for Xs1 (25%). Overall accuracy is approximately 60%.

Table 10: Model III – Jackknifed Discriminant Function Analysis Results

	a	K	Ne	r1	Xs1	Accuracy
a	4	0	0	0	2	67%
K	0	6	2	0	0	75%
Ne	1	0	8	0	0	89%
r1	0	1	2	7	4	50%
Xs1	0	0	1	5	2	25%

The SIAR model was run with the 7 elements that passed all statistical tests. Source proportions with the 5 downstream samples run as a composite are presented in Figure 8.

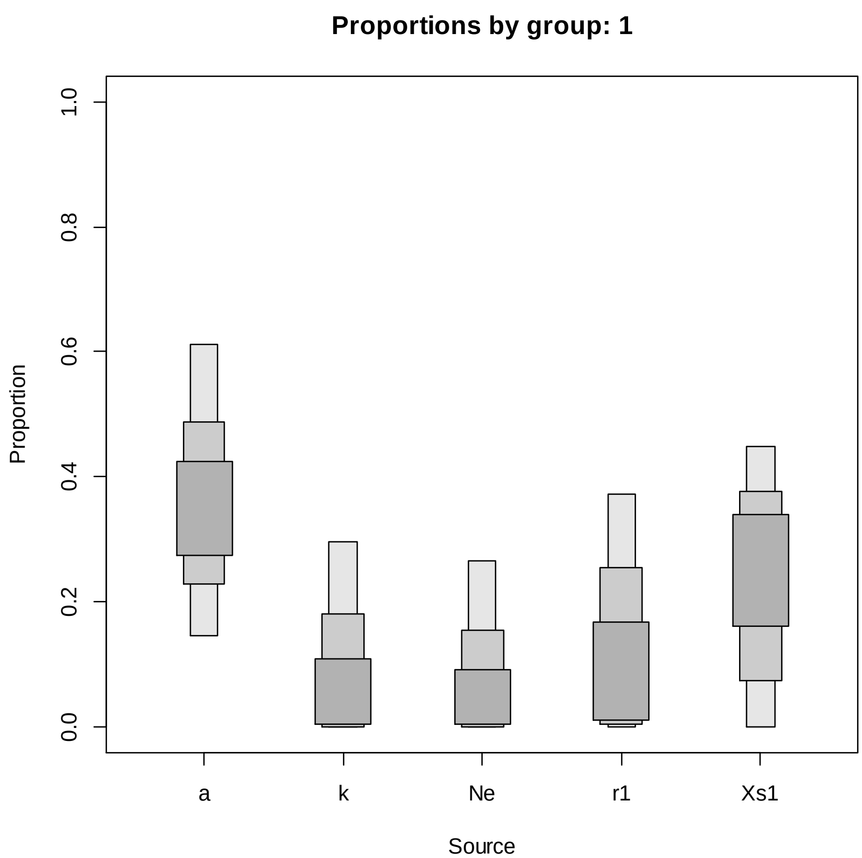

Figure 8: Model III – SIAR Source Proportions Results

Each downstream sample was then run in the model independently to provide estimates for specific suspended sediment samples. Source proportion data for each sample are presented in Appendix 5 – Mgeta Catchment Individual Sample Source Proportions.

Model IV – Upper Ruvu Catchment

5 geologic areas represent the range of potential sources within this fingerprinting unit; m, k, r1, Xs1, Xs2. All elements which passed the quality control procedures were natural log transformed and examined to ensure that the downstream sample values were within the range of the values offered by the potential sources. Lead did not pass the test.

The remaining elements were then tested for their ability to discriminate between the potential sources with the Kruskal-Wallis H-test. Out of 17 elements, 8 failed the test. After eliminating redundant isotopes, 8 elements remain.

Table 11: Model IV – Kruskal-Wallis Test Results

Analyte	H	p
Li7	5.40	0.25
Mg25	2.73	0.60
P31	2.37	0.67
K39	9.53	0.05
V51	11.94	0.02
Cr52	11.63	0.02
Cr53	11.71	0.02
Fe57	19.79	0.00
Cu63	11.37	0.02
Zn66	8.63	0.07
Ga71	17.60	0.00
As75	5.58	0.23
Rb85	11.10	0.03
Mo98	8.10	0.09
Sn118	1.40	0.84
Ba137	7.31	0.12
Tl205	12.68	0.01

A DFA was run on the remaining 8 elements. The discriminant function found a cumulative error of approximately 26% utilizing all elements.

Table 12: Model IV – Discriminant Function Analysis Results

Formula								Cumulative Error
Ga71								70%
Ga71	Tl205							49%
Ga71	Tl205	Cr52						45%
Ga71	Tl205	Cr52	Rb85					43%
Ga71	Tl205	Cr52	Rb85	K39				36%
Ga71	Tl205	Cr52	Rb85	K39	Cu63			32%
Ga71	Tl205	Cr52	Rb85	K39	Cu63	Fe57		30%
Ga71	Tl205	Cr52	Rb85	K39	Cu63	Fe57	V51	26%

A jDFA was then run on the remaining elements. All sources except r1 had an accuracy rate less than 50%. Overall accuracy is approximately 43%.

Table 13: Model IV – Jackknifed Discriminant Function Analysis Results

	K	m	r1	Xs1	Xs2	Accuracy
K	2	0	3	0	3	25%
m	0	2	1	1	1	40%
r1	2	0	10	1	1	71%
Xs1	0	0	3	3	2	38%
Xs2	3	3	3	0	3	25%

The SIAR model was run with the 8 elements that passed all statistical tests. Source proportions with the 5 downstream samples run as a composite are presented in Figure 9.

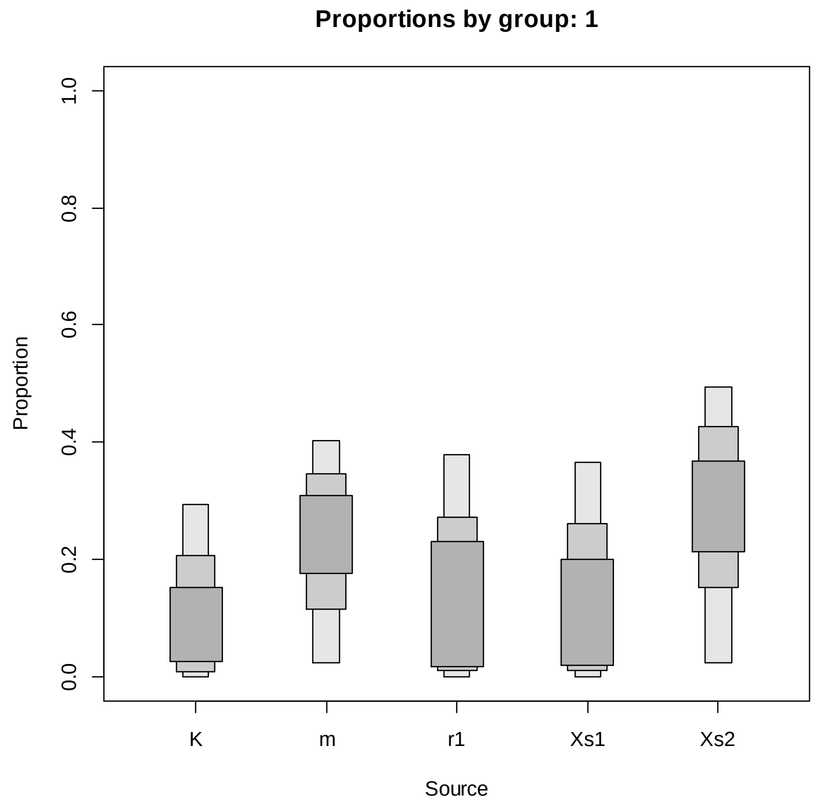

Figure 9: Model IV - SIAR Source Proportions Results

Each downstream sample was then run in the model independently to provide estimates for specific suspended sediment samples. Source proportion data for each sample is presented in Appendix 6 – Upper Ruvu Catchment Individual Sample Source Proportions.

Model V – Ngerengere Catchment

6 geologic areas represent the range of potential sources within this fingerprinting unit; j, k, m, Ne, Xs1, Xs2. All elements which passed the quality control procedures were natural log transformed and examined to ensure that the downstream sample values were within the range of the values offered by the potential sources. Gallium, rubidium and thallium did not pass the test.

The remaining elements were then tested for their ability to discriminate between the potential sources with the Kruskal-Wallis H-test. Out of 16 isotopes, 7 failed the test. After eliminating redundant isotopes, 7 elements remain.

Table 14: Model V – Kruskal-Wallis Test Results

Analyte	H	p
Li7	6.15	0.29
Mg25	10.26	0.07
P31	5.39	0.37
K39	12.70	0.03
V51	19.18	0.00
Cr52	12.66	0.03
Cr53	12.66	0.03
Fe57	27.86	0.00
Cu63	14.79	0.01
Zn66	9.71	0.08
As75	9.31	0.10
Mo98	9.28	0.10
Sn118	5.43	0.37
Ba137	19.40	0.00
Pb207	19.13	0.00
Pb208	17.79	0.00

A DFA was run on the remaining 7 elements. The discriminant function found a cumulative error of approximately 33% utilizing all elements.

Table 15: Model V – Discriminant Function Analysis Results

Formula							Cumulative Error
Fe57							67%
Fe57	Pb208						55%
Fe57	Pb208	Cu63					45%
Fe57	Pb208	Cu63	Ba137				37%
Fe57	Pb208	Cu63	Ba137	K39			31%
Fe57	Pb208	Cu63	Ba137	K39	Cr52		35%
Fe57	Pb208	Cu63	Ba137	K39	Cr52	V51	33%

^{52}Cr and ^{51}V were eliminated because they increased the error. A jDFA was then run on the remaining elements. All sources were reasonably well identified except for K and Xs2. Total accuracy was approximately 57%.

Table 16: Model V – Jackknifed Discriminant Function Analysis Results

	J	K	m	Ne	Xs1	Xs2	Accuracy

J	6	2	0	0	0	1	67%
K	2	4	0	0	0	2	50%
m	0	0	3	1	1	0	60%
Ne	0	0	0	6	1	2	67%
Xs1	0	0	1	0	7	0	88%
Xs2	1	2	2	2	2	3	25%

The SIAR model was run with the 5 elements that passed all statistical tests. Source proportions with the 5 downstream samples run as a composite are presented in Figure 9.

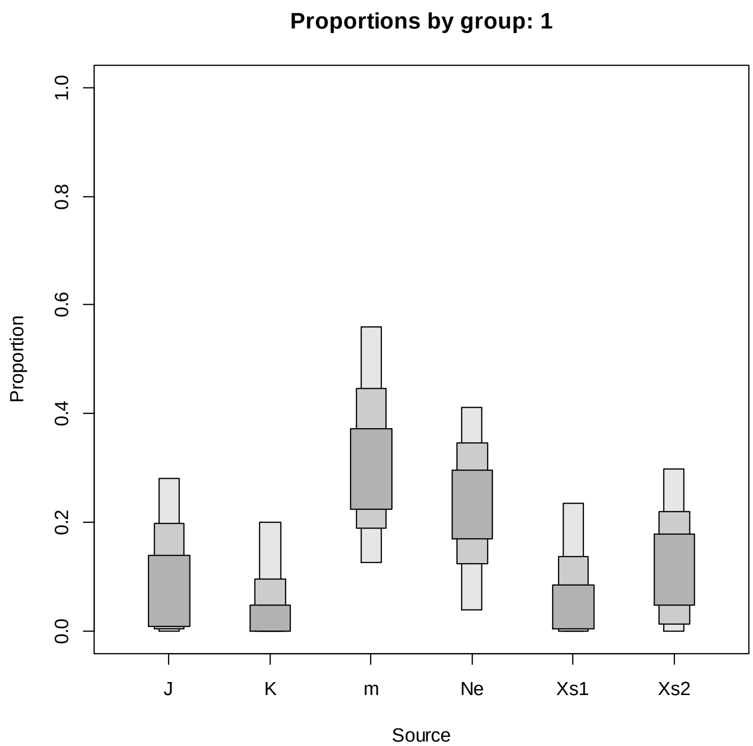

Figure 10: Model V – SIAR Source Proportions Results

Each downstream sample was then run in the model independently to provide estimates for specific suspended sediment samples. Source proportion data for each sample are presented in Appendix 7 – Ngerengere Catchment Individual Sample Source Proportions.

Discussion

Suspended sediment samples were taken over a three month period from March through May, 2013. Those suspended sediment samples were used to create the model estimates presented in this study. Long-term or yearly suspended sediment trends may not be accurately reflected in these results due to the relatively short period of time when these samples were collected. However, these results are representative of the time period in which they were collected.

This study has included a very robust consideration of potential error. The discriminant function analysis results have provided estimates of the error involved in using the chosen tracers to discriminant between the potential sources within each model. The jackknifed discriminant function analysis has provided an even more conservative consideration of potential error in source discrimination. These were two different statistical techniques to help elucidate potential error within the discrimination of sources.

The SIAR model has its own consideration of potential error. The error bars identified within the SIAR source proportion charts also account for the potential source errors. It is critical to understand the potential for error when attempting to apply a sediment fingerprinting technique to a large area and a large number of sources. By using multiple nested models, trends become apparent.

Sediment source determination is difficult due to the routing of sediments through the catchments. Sediment mobilized from their origin in one event may be deposited throughout different “sinks” within the catchment, only to be re-mobilized during a later flood event. However, with sediment fingerprinting, re-mobilized sediments will still “look” like the sediments they originated from due to the use of conservative tracers in our models.

Model I

Model I, which utilized all lithology types, is perhaps the most difficult model for SIAR to create since it uses the largest number of potential sources. When more potential sources are utilized, average source proportions will be less since the model will want to consider every potential source as likely having a contribution.

Model I, which utilized all the lithology types as source samples, found that the two highest proportions of sediments at the Ruvu Morogoro Bridge were coming from two specific areas in the upper catchment of the basin; "a" and "m" (Figure 11). This finding is unsurprising given that it has been well documented that the upper catchments of watersheds are instrumental in controlling the water supply within their drainages.

However, it is surprising that area "m" is contributing a large proportion of the sediments due to the relatively small size it occupies in the basin.

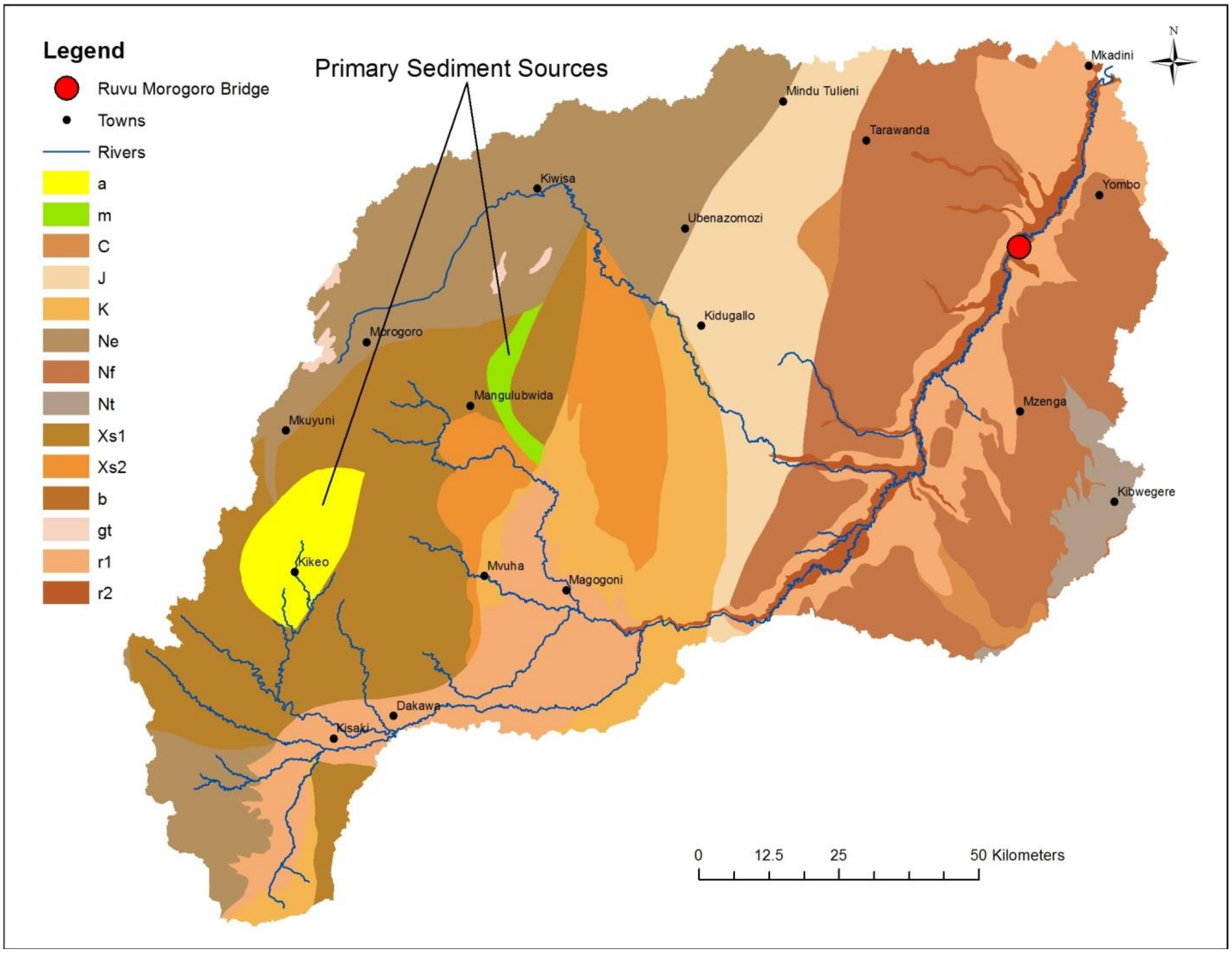

Figure 11: Model I - Source Locations

Model II

Model II is a similar to Model I except all soil types upstream of the three main catchment sampling points (Mgeta, Ngeregere and Upper Ruvu) are no longer considered in the model.

Instead of considering the individual soil types upstream, we used the suspended sediment samples collected from those three points to create a fingerprint for each of those catchments (Figure 12). This approach allowed us to look at the relative sediment contributions from those three catchments in the downstream sample collected at the Ruvu Morogoro Bridge.

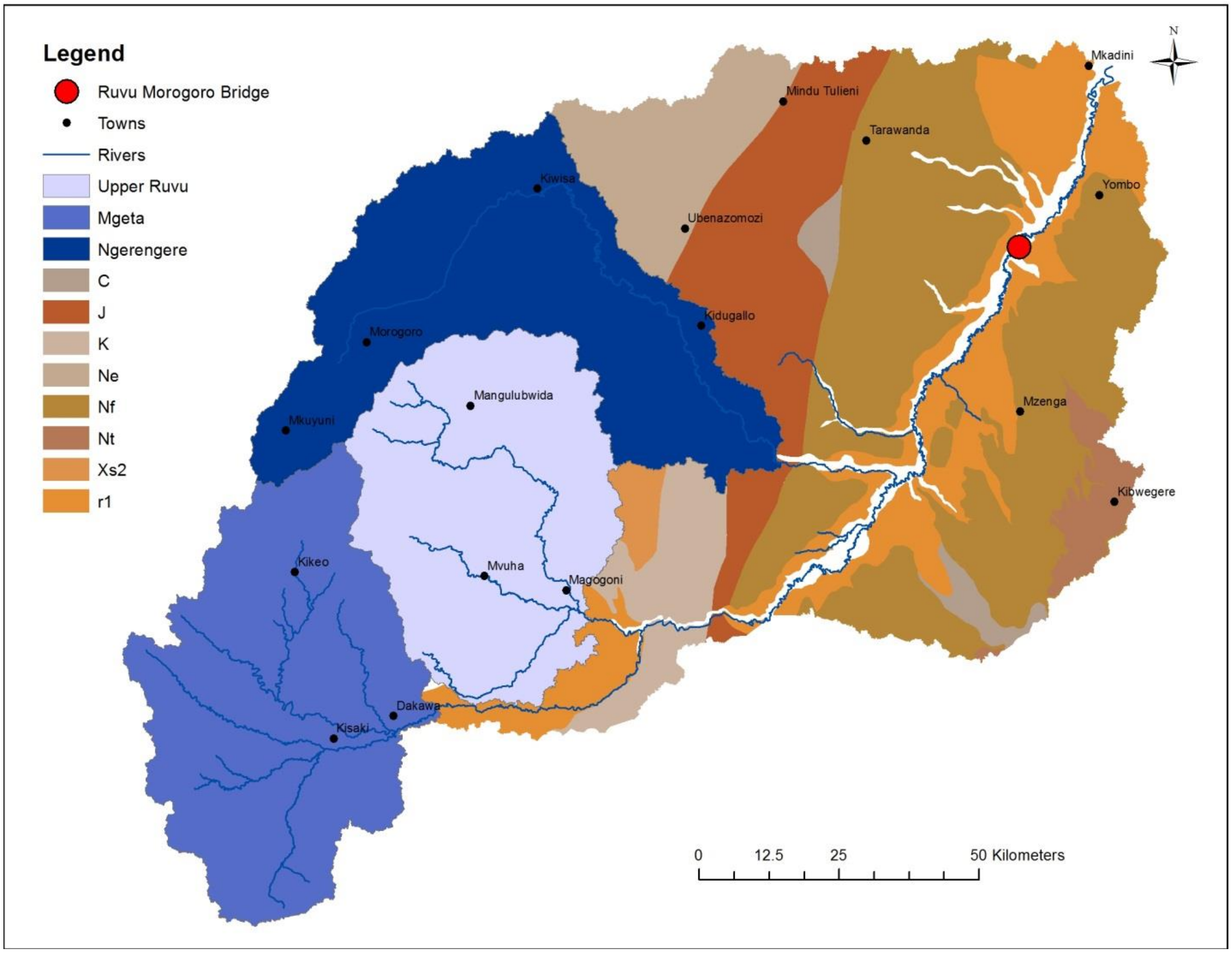

Figure 12: Model II - Source Locations

This model found that the Mgeta catchment was the largest contributor of sediments during the sampling period followed by the Ngerengere (30% and 14%). The Upper Ruvu contributes approximately 13% of the suspended sediments.

SIAR did have a more difficult time determining the contribution of the Upper Ruvu catchment, as evident by the larger error bars.

Model III

Model III found that area “a” was the largest contributor of sediments from the Mgeta catchment. This is also confirmed with the results of Model I. “Xs1” is the second largest contributor.

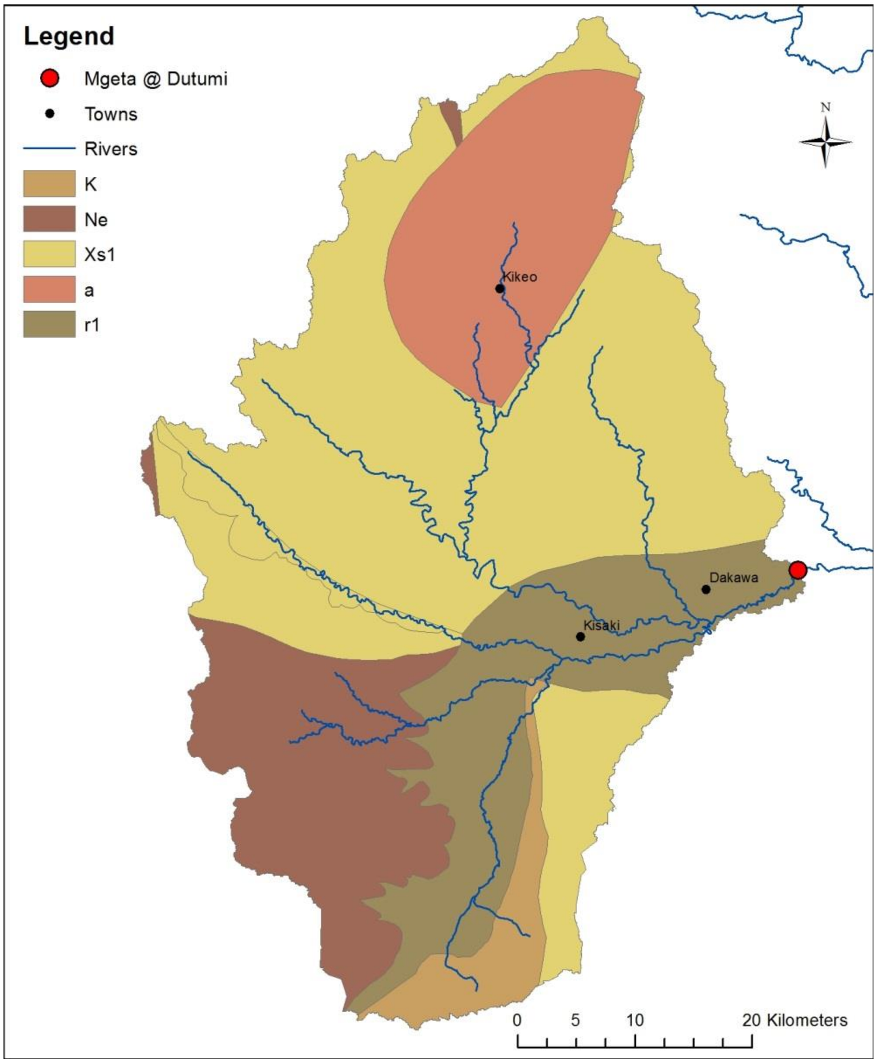

Figure 13: Model III - Source Locations

The “a” area makes up only 15% of the surface area of the catchment yet it contributes approximately 40% of the suspended sediments. “a” is in the upper catchment in an area that receives most of the rainfall in the entire basin.

Model IV

Model IV, which measured soil sources in the Upper Ruvu catchment, identified “Xs2” as the largest contributor in the samples collected at Bwiria Chini (Figure 14). Area “m” was the second largest contributor. Similar to other models that include the area “m”, it remains a relatively small area contributing a higher than average amount of suspended sediments. Only 4% of the Upper Ruvu catchment is in the “m” area yet it contributes up to 24% of the sediments. “Xs2” accounts for 18% of the catchment and it contributes approximately 26% of the suspended sediments.

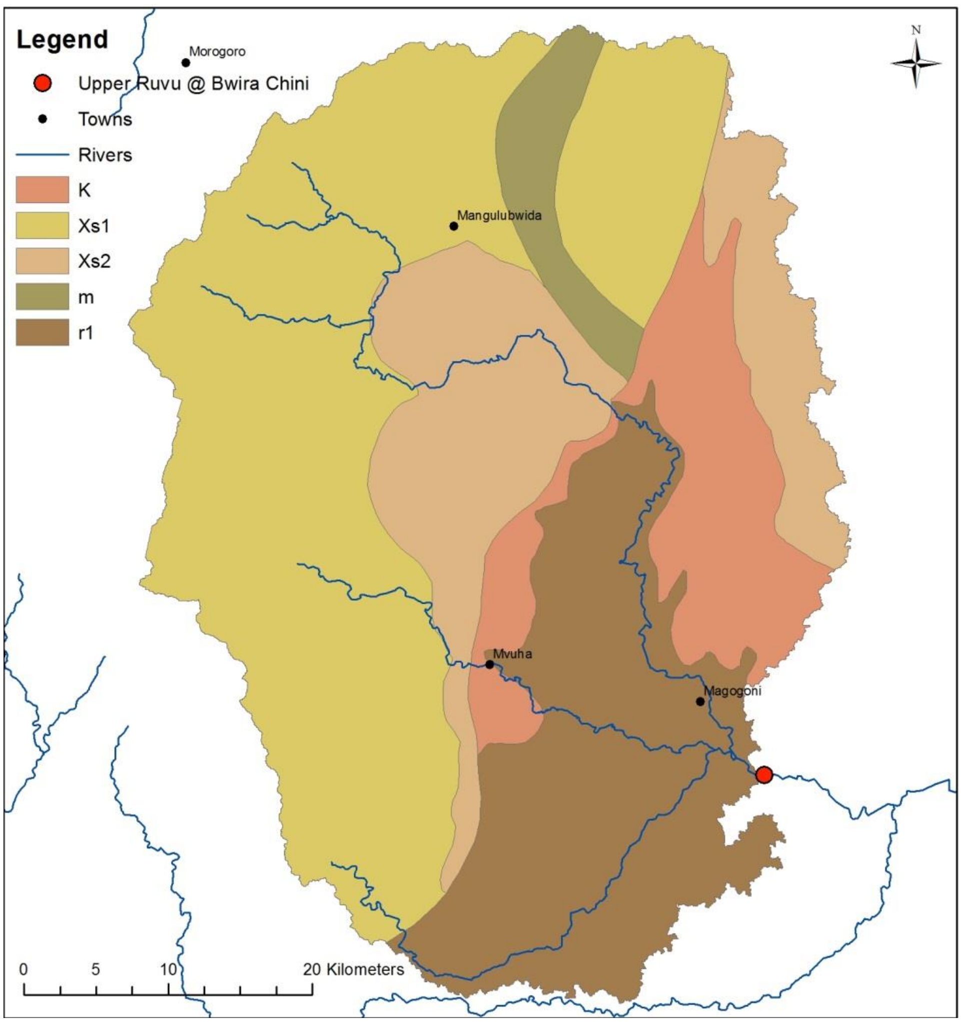

Figure 14: Model IV - Source Locations

Model V

Model V, which measured soil sources in the Ngerengere catchment, found that “m” contributes the largest amount of sediments. The second largest contributor in this catchment is “Ne”.

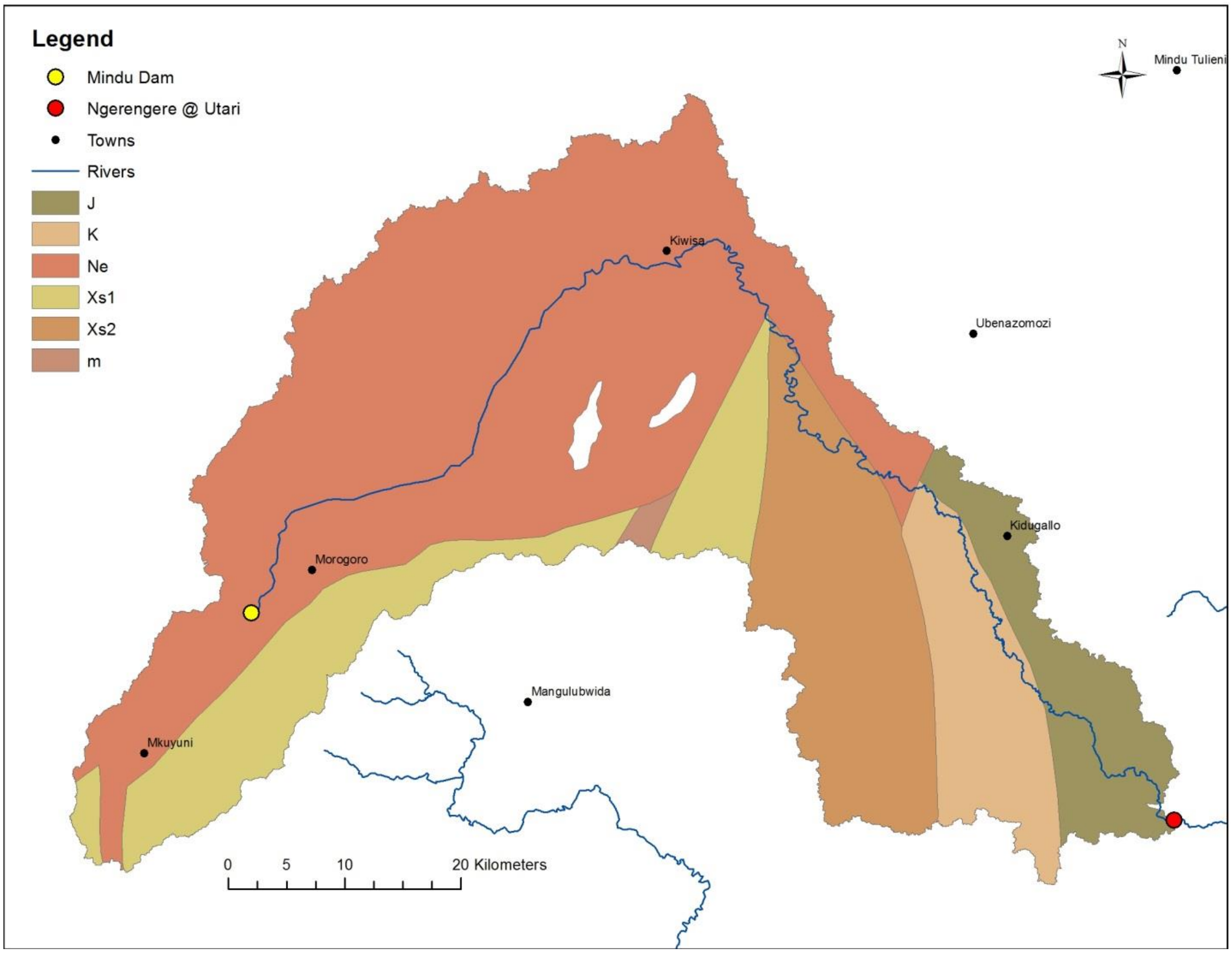

Figure 15: Model V - Source Locations

“m” accounts for just 1% of the Ngerengere catchment yet it is contributing approximately 29% of the sediments. This relatively small area may be able to generate a disproportionately large portion of the suspended sediment load in part due to the large sediment storage capacity of the Mindu Dam. The Mindu Dam is likely trapping sediments coming in from the furthest upstream sources of this catchment. However, during field work, we did observe the mass wasting of soils in that area (area “m”, Figure 16), leading us to support the results of this model.

Figure 16: Mass movement of soils across a roadway in the "m" area

Conclusions

All models were created with a different combination of elements, as driven by the statistical treatments of the data. Model error could be reduced by utilizing more samples from potential source areas or focusing the approach on a smaller area.

Out of the three priority catchments, the Mgeta catchment is responsible for the largest amount of suspended sediments. This is unsurprising given that the largest amount of rainfall also occurs in this area. Within that catchment, area “a” was identified as the largest contributor.

Out of the entire study area, “m” and “a” were identified as the two top contributors of suspended sediments. Those two areas account for just 3% of the surface area in the basin yet the models found they contributed approximately 35% of the suspended sediment during the study period.

All models that included the area “m” identified that area as a large contributor of suspended sediments. “m” occupies a relatively small area of the entire basin. That area should be prioritized for soil management interventions. The most value for the intervention could be achieved in that area.

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Appendix 1

Soil Sample	Name	Lithology
S01	r1	Alluvium deposits
S02	r1	Alluvium deposits
S03	r1	Alluvium deposits
S04	r1	Alluvium deposits
S05	r1	Alluvium deposits
S06	K	Conglomerate and tillite
S07	r1	Alluvium deposits
S08	K	Conglomerate and tillite
S09	K	Conglomerate and tillite
S10	K	Conglomerate and tillite
S11	K	Conglomerate and tillite
S12	K	Conglomerate and tillite
S13	K	Conglomerate and tillite
S14	J	Mudstone and Shale
S15	J	Mudstone and Shale
S16	J	Mudstone and Shale
S17	J	Mudstone and Shale
S18	J	Mudstone and Shale
S19	Nt	Terrace deposits
S20	J	Mudstone and Shale
S21	Ne	Composite metamorphic crust domain
S22	Ne	Composite metamorphic crust domain
S23	J	Mudstone and Shale
S24	J	Mudstone and Shale
S25	J	Mudstone and Shale
S26	C	Continental and marine sand stone
S27	Nf	Fluvial marine sand
S28	Nf	Fluvial marine sand
S29	Nf	Fluvial marine sand
S30	r2	Stream deposits
S31	r1	Alluvium deposits
S32	Nt	Terrace deposits
S33	Ne	Composite metamorphic crust domain
S34	Ne	Composite metamorphic crust domain
S35	Ne	Composite metamorphic crust domain
S36	Xs1	Granulite,gneiss and migmatite
S37	Xs1	Granulite,gneiss and migmatite
S38	Xs1	Granulite,gneiss and migmatite
S39	a	Meta-anorthosite complex

Soil Sample	Name	Lithology
S40	a	Meta-anorthosite complex
S41	a	Meta-anorthosite complex
S42	a	Meta-anorthosite complex
S43	a	Meta-anorthosite complex
S44	a	Meta-anorthosite complex
S45	Xs1	Granulite,gneiss and migmatite
S46	Xs1	Granulite,gneiss and migmatite
S47	Ne	Composite metamorphic crust domain
S48	Ne	Composite metamorphic crust domain
S49	Xs1	Granulite,gneiss and migmatite
S50	Xs1	Granulite,gneiss and migmatite
S51	Xs2	Marble
S52	Xs2	Marble
S53	Xs2	Marble
S54	Xs2	Marble
S55	Xs2	Marble
S56	Xs2	Marble
S57	K	Conglomerate and tillite
S58	r1	Alluvium deposits
S59	r1	Alluvium deposits
S60	r1	Alluvium deposits
S61	Xs2	Marble
S62	Ne	Composite metamorphic crust domain
S63	Xs1	Granulite,gneiss and migmatite
S64	Xs2	Marble
S65	Ne	Composite metamorphic crust domain
S66	Nf	Fluvial marine sand
S67	r1	Alluvium deposits
S68	r1	Alluvium deposits
S69	C	Continental and marine sand stone
S70	m	Meta-anorthosite complex (interlayed)
S71	m	Meta-anorthosite complex (interlayed)
S72	m	Meta-anorthosite complex (interlayed)
S73	m	Meta-anorthosite complex (interlayed)
S74	m	Meta-anorthosite complex (interlayed)
S75	r1	Alluvium deposits
S76	r1	Alluvium deposits
S77	Xs2	Marble
S78	Xs2	Marble
S79	Xs2	Marble

Soil Sample	Name	Lithology
S80	Xs2	Marble
S81	Nf	Fluvial marine sand
S82	Nf	Fluvial marine sand
S83	Nf	Fluvial marine sand
S84	Nf	Fluvial marine sand
S85	Nt	Terrace deposits
S86	Nt	Terrace deposits
S87	Nt	Terrace deposits
S88	Nt	Terrace deposits

Appendix 2

Date	Time	Sample	Filter Weight (mg)	Sediment (mg)	Volume (mL)
3/18/2013	13:56	Mgeta @ Duthumi	88.815	72.955	200
3/25/2013	16:20	Mgeta @ Duthumi	86.097	135.831	200
4/13/2013	16:52	Mgeta @ Duthumi	87.509	190.601	200
5/4/2013	11:20	Mgeta @ Duthumi	85.231	52.371	250
5/12/2013	13:51	Mgeta @ Duthumi	83.548	41.012	250
3/18/2013	12:00	Mgeta @ Kisaki Bridge	83.508	104.422	250
5/4/2013	13:29	Mgeta @ Kisaki Bridge	85.096	75.984	250
3/23/2013	13:00	Ngerengere - Mindu Dam Outlet	91.894	19.954	250
4/14/2013	16:48	Ngerengere @ Mgude	88.852	197.243	150
3/19/2013	11:50	Ngerengere @ Utari	89.986	304.244	200
3/26/2013	15:00	Ngerengere @ Utari	89.495	234.085	150
4/15/2013	15:45	Ngerengere @ Utari	86.431	147.818	200
5/3/2013	13:00	Ngerengere @ Utari	83.102	211.448	200
5/13/2013	12:54	Ngerengere @ Utari	80.035	115.713	250
4/15/2013	15:45	Ngerengere @ Utari Duplicate	90.457	150.362	200
3/21/2013	14:04	Ruvu @ Bwira Chini	85.309	162.189	200
3/26/2013	8:00	Ruvu @ Bwira Chini	84.810	42.836	200
4/14/2013	10:52	Ruvu @ Bwira Chini	82.334	50.718	250
5/4/2013	16:20	Ruvu @ Bwira Chini	90.013	25.857	250
5/12/2013	10:06	Ruvu @ Bwira Chini	85.907	22.692	250
5/4/2013	8:05	Ruvu @ Kibungo	84.338	15.003	500
3/19/2013	16:54	Ruvu @ Morogoro Bridge	85.045	82.845	250
3/22/2013	15:00	Ruvu @ Morogoro Bridge	86.246	89.789	200
3/22/2013	15:00	Ruvu @ Morogoro Bridge	82.201	83.876	200
3/27/2013	7:54	Ruvu @ Morogoro Bridge	83.934	92.726	200
3/27/2013	18:00	Ruvu @ Morogoro Bridge	87.704	105.606	200
3/28/2013	9:58	Ruvu @ Morogoro Bridge	79.928	107.339	200
4/13/2013	7:15	Ruvu @ Morogoro Bridge	84.290	46.040	250
4/14/2013	18:22	Ruvu @ Morogoro Bridge	82.496	49.268	250
4/15/2013	7:30	Ruvu @ Morogoro Bridge	85.797	56.246	250
5/2/2013	19:15	Ruvu @ Morogoro Bridge	90.387	67.693	250
5/3/2013	6:45	Ruvu @ Morogoro Bridge	95.191	90.399	250
5/13/2013	7:58	Ruvu @ Morogoro Bridge	85.499	32.168	250
5/13/2013	7:58	Ruvu @ Morogoro Bridge	90.581	32.738	250
3/25/2013	10:00	Ruvu @ Kibungo	85.289	15.867	500
5/13/2013	9:25	Ngerengere @ Mgude	79.931	83.019	250
5/12/2013	15:00	Mgeta @ Kisaki Bridge	84.760	47.676	250
3/21/2013	11:56	Ruvu @ Magogoni Bridge	89.905	192.150	150
5/12/2013	7:38	Ruvu @ Kibungo	89.990	7.661	400
5/3/2013	8:35	Ngerengere @ Mgude	84.638	93.885	200
4/13/2013	18:06	Mgeta @ Kisaki Bridge	81.540	99.298	250
4/13/2013	12:36	Ruvu @ Kibungo	83.029	43.871	400
4/15/2013	9:53	Ngerengere @ Mgude	92.407	194.616	150
3/25/2013	10:00	Mgeta @ Kisaki Bridge	80.775	148.980	150
3/20/2013	17:10	Ruvu @ Kibungo	83.460	28.233	500
3/25/2013	14:00	Mgeta @ Kisaki Bridge	86.244		200

Appendix 3 – Ruvu Basin Soils Individual Sample Source Proportions

Sample	Source	Low 95%	High 95%	Mode	Mean
1	a	0%	13%	1%	5%
	C	0%	7%	1%	2%
	J	0%	11%	1%	4%
	K	0%	8%	1%	3%
	m	0%	57%	9%	25%
	Ne	0%	23%	2%	9%
	Nf	0%	5%	0%	2%
	Nt	0%	14%	1%	4%
	r1	0%	25%	1%	7%
	Xs1	0%	14%	1%	5%
	Xs2	0%	14%	43%	34%
2	a	0%	14%	1%	5%
	C	0%	8%	1%	3%
	J	0%	13%	1%	5%
	K	0%	9%	1%	3%
	m	4%	58%	43%	36%
	Ne	0%	27%	4%	12%
	Nf	0%	5%	1%	2%
	Nt	0%	11%	1%	4%
	r1	0%	19%	1%	6%
	Xs1	0%	18%	1%	7%
	Xs2	0%	42%	3%	17%
3	a	0%	12%	1%	4%
	C	0%	8%	1%	3%
	J	0%	12%	1%	4%
	K	0%	8%	1%	3%
	m	0%	59%	6%	25%
	Ne	0%	28%	3%	11%
	Nf	0%	5%	0%	2%
	Nt	0%	13%	1%	4%
	r1	0%	16%	1%	5%
	Xs1	0%	14%	1%	5%
	Xs2	0%	17%	43%	33%
4	a	0%	9%	1%	3%
	C	0%	8%	1%	3%
	J	0%	12%	1%	4%

Sample	Source	Low 95%	High 95%	Mode	Mean
	K	0%	8%	1%	3%
	m	0%	39%	3%	17%
	Ne	0%	29%	2%	11%
	Nf	0%	6%	0%	2%
	Nt	0%	16%	1%	5%
	r1	0%	12%	1%	4%
	Xs1	0%	12%	1%	4%
	Xs2	0%	11%	52%	45%
5	a	0%	14%	1%	6%
	C	0%	7%	1%	3%
	J	0%	12%	1%	4%
	K	0%	8%	1%	3%
	m	11%	63%	45%	41%
	Ne	0%	25%	2%	10%
	Nf	0%	5%	0%	2%
	Nt	0%	15%	1%	5%
	r1	0%	18%	1%	6%
	Xs1	0%	17%	1%	6%
	Xs2	0%	37%	2%	14%
6	a	0%	9%	1%	3%
	C	0%	7%	1%	3%
	J	0%	11%	1%	4%
	K	0%	7%	1%	3%
	m	0%	37%	2%	11%
	Ne	0%	23%	2%	9%
	Nf	0%	6%	0%	2%
	Nt	0%	14%	1%	4%
	r1	0%	11%	1%	4%
	Xs1	0%	11%	1%	4%
	Xs2	0%	3%	57%	54%
7	a	6%	43%	27%	25%
	C	0%	11%	1%	4%
	J	0%	26%	1%	8%
	K	0%	20%	1%	7%
	m	0%	20%	2%	7%
	Ne	0%	7%	1%	3%
	Nf	0%	9%	1%	3%
	Nt	0%	7%	30%	28%
	r1	0%	12%	1%	4%
	Xs1	0%	15%	1%	5%

Sample	Source	Low 95%	High 95%	Mode	Mean
	Xs2	0%	12%	1%	4%
8	a	2%	40%	23%	22%
	C	0%	11%	1%	4%
	J	0%	12%	1%	4%
	K	0%	24%	1%	8%
	m	0%	14%	1%	5%
	Ne	0%	6%	1%	2%
	Nf	0%	10%	1%	4%
	Nt	25%	55%	39%	40%
	r1	0%	11%	1%	4%
	Xs1	0%	13%	1%	4%
	Xs2	0%	9%	1%	3%
9	a	0%	25%	3%	11%
	C	0%	10%	1%	4%
	J	0%	10%	1%	3%
	K	0%	22%	1%	7%
	m	0%	9%	1%	3%
	Ne	0%	6%	1%	2%
	Nf	0%	11%	1%	4%
	Nt	41%	71%	56%	56%
	r1	0%	10%	1%	3%
	Xs1	0%	10%	1%	4%
	Xs2	0%	7%	1%	3%
10	a	4%	44%	26%	25%
	C	0%	11%	1%	4%
	J	0%	24%	1%	8%
	K	0%	31%	2%	10%
	m	0%	17%	1%	6%
	Ne	0%	7%	1%	2%
	Nf	0%	9%	1%	3%
	Nt	0%	8%	30%	28%
	r1	0%	11%	1%	4%
	Xs1	0%	14%	1%	5%
	Xs2	0%	10%	1%	3%
11	a	0%	19%	7%	9%
	C	0%	16%	1%	7%
	J	1%	36%	20%	20%
	K	0%	18%	1%	7%
	m	1%	31%	16%	17%
	Ne	0%	15%	1%	6%

Sample	Source	Low 95%	High 95%	Mode	Mean
	Nf	0%	8%	1%	3%
	Nt	0%	23%	2%	10%
	r1	0%	14%	1%	5%
	Xs1	0%	17%	1%	6%
	Xs2	0%	24%	2%	10%
12	a	0%	25%	12%	13%
	C	0%	15%	1%	6%
	J	0%	38%	3%	19%
	K	0%	19%	1%	7%
	m	0%	28%	13%	14%
	Ne	0%	10%	1%	4%
	Nf	0%	10%	1%	4%
	Nt	0%	30%	20%	15%
	r1	0%	13%	1%	5%
	Xs1	0%	16%	1%	6%
	Xs2	0%	21%	1%	7%
13	a	0%	19%	2%	7%
	C	0%	9%	1%	3%
	J	0%	9%	1%	3%
	K	0%	19%	1%	6%
	m	0%	8%	1%	3%
	Ne	0%	6%	1%	2%
	Nf	0%	11%	1%	4%
	Nt	50%	76%	63%	63%
	r1	0%	9%	1%	3%
	Xs1	0%	9%	1%	3%
	Xs2	0%	7%	1%	2%

Appendix 4 - Ruvu Basin Soils + Catchments Individual Sample Source Proportions

Sample	Source	Low 95%	High 95%	Mode	Mean
1	Upper Ruvu	0%	23%	2%	8%
	Ngerengere	35%	63%	52%	50%
	Mgeta	1%	27%	18%	16%
	C	0%	4%	0%	2%
	J	0%	6%	0%	2%
	Nf	0%	3%	0%	1%
	Nt	0%	5%	0%	2%
	r1	0%	14%	1%	4%
	Ne	0%	10%	1%	4%
	K	0%	4%	0%	2%
	Xs2	0%	24%	1%	10%
2	Upper Ruvu	0%	22%	6%	10%
	Ngerengere	36%	58%	48%	47%
	Mgeta	2%	22%	14%	13%
	C	0%	8%	1%	3%
	J	0%	10%	1%	4%
	Nf	0%	4%	0%	2%
	Nt	0%	6%	1%	2%
	r1	0%	15%	1%	6%
	Ne	0%	12%	1%	4%
	K	0%	8%	1%	3%
	Xs2	0%	16%	1%	6%
3	Upper Ruvu	0%	16%	2%	6%
	Ngerengere	43%	67%	57%	55%
	Mgeta	0%	16%	8%	8%
	C	0%	5%	1%	2%
	J	0%	7%	1%	2%
	Nf	0%	4%	0%	1%
	Nt	0%	5%	0%	2%
	r1	0%	16%	1%	6%
	Ne	0%	13%	1%	5%
	K	0%	6%	0%	2%
	Xs2	0%	21%	11%	10%
4	Upper Ruvu	0%	14%	1%	6%
	Ngerengere	59%	79%	70%	69%
	Mgeta	0%	8%	1%	3%
	C	0%	4%	0%	1%

Sample	Source	Low 95%	High 95%	Mode	Mean
	J	0%	6%	1%	2%
	Nf	0%	3%	0%	1%
	Nt	0%	6%	1%	2%
	r1	0%	8%	1%	3%
	Ne	0%	13%	1%	5%
	K	0%	4%	0%	1%
	Xs2	0%	14%	1%	6%
5	Upper Ruvu	0%	27%	13%	14%
	Ngerengere	33%	55%	46%	44%
	Mgeta	4%	27%	17%	16%
	C	0%	6%	1%	2%
	J	0%	9%	1%	3%
	Nf	0%	5%	0%	2%
	Nt	0%	8%	1%	3%
	r1	0%	12%	1%	4%
	Ne	0%	10%	1%	4%
	K	0%	6%	1%	2%
	Xs2	0%	14%	1%	5%
6	Upper Ruvu	0%	11%	1%	4%
	Ngerengere	57%	82%	72%	70%
	Mgeta	0%	6%	1%	2%
	C	0%	3%	0%	1%
	J	0%	4%	0%	1%
	Nf	0%	3%	0%	1%
	Nt	0%	5%	0%	2%
	r1	0%	6%	0%	2%
	Ne	0%	12%	1%	4%
	K	0%	3%	0%	1%
	Xs2	0%	22%	12%	12%
7	Upper Ruvu	0%	26%	2%	11%
	Ngerengere	0%	7%	1%	3%
	Mgeta	21%	53%	37%	37%
	C	0%	13%	1%	5%
	J	0%	19%	1%	7%
	Nf	0%	17%	1%	7%
	Nt	0%	25%	12%	13%
	r1	0%	13%	1%	5%
	Ne	0%	7%	1%	3%
	K	0%	20%	2%	8%
	Xs2	0%	10%	1%	4%

Sample	Source	Low 95%	High 95%	Mode	Mean
8	Upper Ruvu	0%	15%	1%	5%
	Ngerengere	0%	5%	0%	2%
	Mgeta	28%	63%	47%	45%
	C	0%	11%	1%	4%
	J	0%	16%	1%	5%
	Nf	0%	19%	2%	7%
	Nt	0%	31%	2%	14%
	r1	0%	10%	1%	4%
	Ne	0%	6%	1%	2%
	K	0%	21%	2%	8%
	Xs2	0%	8%	1%	3%
9	Upper Ruvu	0%	9%	1%	3%
	Ngerengere	0%	4%	0%	1%
	Mgeta	0%	55%	4%	20%
	C	0%	10%	1%	3%
	J	0%	8%	1%	3%
	Nf	0%	13%	1%	5%
	Nt	0%	6%	58%	48%
	r1	0%	9%	1%	3%
	Ne	0%	5%	0%	2%
	K	0%	31%	1%	9%
	Xs2	0%	6%	0%	2%
10	Upper Ruvu	0%	22%	1%	8%
	Ngerengere	0%	6%	1%	2%
	Mgeta	26%	56%	41%	41%
	C	0%	14%	1%	5%
	J	0%	20%	1%	7%
	Nf	0%	17%	1%	7%
	Nt	0%	23%	2%	10%
	r1	0%	12%	1%	4%
	Ne	0%	7%	1%	2%
	K	0%	24%	2%	10%
	Xs2	0%	10%	1%	3%
11	Upper Ruvu	0%	23%	11%	12%
	Ngerengere	2%	22%	13%	13%
	Mgeta	5%	29%	17%	17%
	C	0%	17%	3%	8%
	J	1%	29%	17%	17%
	Nf	0%	10%	1%	4%
	Nt	0%	16%	1%	7%

Sample	Source	Low 95%	High 95%	Mode	Mean
	r1	0%	13%	1%	5%
	Ne	0%	13%	1%	5%
	K	0%	18%	2%	8%
	Xs2	0%	17%	1%	7%
12	Upper Ruvu	0%	27%	10%	13%
	Ngerengere	0%	13%	1%	5%
	Mgeta	11%	40%	25%	25%
	C	0%	18%	2%	7%
	J	0%	27%	2%	13%
	Nf	0%	12%	1%	5%
	Nt	0%	21%	2%	9%
	r1	0%	13%	1%	5%
	Ne	0%	10%	1%	4%
	K	0%	20%	2%	8%
	Xs2	0%	14%	1%	5%
13	Upper Ruvu	0%	8%	1%	3%
	Ngerengere	0%	4%	0%	1%
	Mgeta	0%	30%	4%	24%
	C	0%	9%	1%	3%
	J	0%	8%	1%	3%
	Nf	0%	12%	1%	4%
	Nt	0%	16%	66%	50%
	r1	0%	8%	1%	3%
	Ne	0%	5%	0%	2%
	K	0%	17%	1%	6%
	Xs2	0%	6%	1%	2%

Appendix 5 – Mgeta Catchment Individual Sample Source Proportions

Sample	Source	Low 95%	High 95%	mode	mean
1	a	8%	45%	28%	27%
	k	0%	31%	2%	12%
	Ne	0%	34%	15%	16%
	r1	0%	40%	24%	21%
	Xs1	0%	43%	25%	23%
2	a	0%	15%	1%	5%

Sample	Source	Low 95%	High 95%	mode	mean
	k	0%	16%	1%	5%
	Ne	14%	79%	44%	46%
	r1	0%	62%	3%	30%
	Xs1	0%	35%	3%	13%
3	a	53%	89%	72%	71%
	k	0%	30%	8%	13%
	Ne	0%	9%	1%	3%
	r1	0%	19%	1%	7%
	Xs1	0%	16%	1%	6%
4	a	0%	34%	17%	18%
	k	0%	17%	1%	6%
	Ne	0%	27%	2%	11%
	r1	14%	63%	35%	38%
	Xs1	1%	51%	29%	28%
5	a	68%	94%	83%	81%
	k	0%	19%	1%	7%
	Ne	0%	7%	1%	2%
	r1	0%	14%	1%	5%
	Xs1	0%	12%	1%	4%

Appendix 6 – Upper Ruvu Catchment Individual Sample Source Proportions

Sample	Source	Low 95%	High 95%	mode	mean
1	K	0%	12%	1%	4%
	m	9%	88%	72%	55%
	r1	0%	22%	1%	8%
	Xs1	0%	23%	2%	9%
	Xs2	0%	65%	4%	24%
2	K	3%	48%	29%	28%
	m	0%	28%	3%	12%
	r1	0%	35%	5%	16%
	Xs1	0%	28%	2%	11%
	Xs2	13%	57%	34%	34%
3	K	0%	18%	2%	7%
	m	13%	68%	36%	39%
	r1	0%	31%	3%	13%
	Xs1	0%	38%	14%	18%

Sample	Source	Low 95%	High 95%	mode	mean
	Xs2	0%	43%	27%	23%
4	K	0%	44%	26%	22%
	m	0%	19%	1%	7%
	r1	0%	29%	2%	10%
	Xs1	0%	22%	2%	8%
	Xs2	30%	80%	52%	53%
5	K	0%	15%	1%	6%
	m	18%	77%	54%	48%
	r1	0%	27%	2%	10%
	Xs1	0%	36%	7%	16%
	Xs2	0%	44%	4%	21%

Appendix 7 – Ngerengere Catchment Individual Sample Source Proportions

Sample	Source	Low 95%	High 95%	Mode	Mean
1	J	0%	24%	2%	8%
	K	0%	19%	1%	6%
	m	1%	49%	29%	26%
	Ne	0%	37%	3%	17%
	Xs1	0%	28%	2%	11%
	Xs2	1%	6%	30%	32%
2	J	0%	23%	2%	8%
	K	0%	19%	1%	6%
	m	1%	48%	26%	26%
	Ne	0%	38%	5%	18%
	Xs1	0%	29%	2%	12%
	Xs2	1%	8%	29%	30%
3	J	0%	27%	2%	11%
	K	0%	22%	1%	8%
	m	6%	54%	28%	30%
	Ne	0%	35%	15%	17%
	Xs1	0%	31%	3%	13%
	Xs2	0%	39%	25%	21%
4	J	0%	26%	2%	10%
	K	0%	22%	1%	7%
	m	5%	54%	28%	30%

Sample	Source	Low 95%	High 95%	Mode	Mean
	Ne	0%	35%	14%	17%
	Xs1	0%	31%	3%	13%
	Xs2	0%	41%	26%	23%
5	J	0%	31%	11%	14%
	K	0%	25%	2%	9%
	m	6%	49%	26%	28%
	Ne	0%	34%	20%	17%
	Xs1	0%	30%	7%	14%
	Xs2	0%	34%	21%	17%

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