Rwanda Integrated Water Security Program (RIWSP)

Sediment Fingerprinting for the Nyabarongo Upper Catchment in Rwanda
(under USAID/Rwanda Cooperative Agreement No. AID-696-LA-11-00001)

PHASE II

FINAL TECHNICAL REPORT

November 2016

Contents

Contents 2
List of Figures 4
List of Tables 6
Acronyms and abbreviations 7
Acknowledgments 7
Executive Summary 8
1. Introduction 9
1.1 Soil erosion – a critical issue facing Rwanda 9
1.2 Identifying sources of soil erosion 10
1.3 Sediment fingerprinting – a tool to identify sources of soil erosion 11
1.3.1 Soil and Suspended Sediment Sampling Approach 11
1.3.2 Brief Review: Evolution from single to multi-component techniques 13
1.3.3 Selection of tracers 13
1.3.4 Statistical analyses: DFA and mixing models 15
2.Sediment fingerprinting in the Nile Nyabarongo Upper Catchment (NNYU) 16
2.1 The Nile Nyabarongo Upper Catchment 16
2.2 Sampling sites and methodology 19
2.2.1 Soils: 19
2.2.2 Suspended Sediments: 20
2.2.3 Subcatchment delineation from suspended sediment sampling points 20
2.3 Laboratory Analysis and results 22
Trace Element Analysis Facility, FIU 22
Rwanda Bureau of Standards Laboratory 22
2.4 Statistical Analysis 23
3. Sediment Fingerprinting Results 24
3.1 Approach to interpret results 24
3.2 Subcatchment analysis results 25
3.2.1 Mwogo Upper subcatchment – one of the headwaters of the NNYU 26
Upper Mwogo Catchment 28
3.2.2 Rukarara subcatchment - one of the headwaters of the NNYU 30
Rukarara Catchment 32
3.2.3 Mbirurume sub catchment - one of the headwaters of the NNYU 34
Mbirurume Catchment 36
3.2.4 Nyabarongo Headwaters sub catchment – combination of Mwogo, Rukarara and

Mbirurume subcatchments **38**
Nyabarongo Headwaters 40
3.2.5 Nyabarongo Upper sub catchment **42**
3.2.6 Kiryango sub catchment **44**
Kiryango Catchment 46
3.2.7 Nyagako subcatchment **48**
Nyagako Catchment 50
3.2.8 Secoko subcatchment **52**
Secoko Catchment 54
3.2.9 Nyabarongo Hydropower subcatchment **56**
Nyabarongo Hydropower Subcatchment 58
3.2.10 Satinsyi sub catchment **60**
3.2.11 NNYU outlet **64**
3.3 Sediment concentration differences across NNYU 69
4. Priority rehabilitation focal areas in NNYU **71**
4.1 From Results to Priority Locations – the approach 71
4.2 Prioritization process 71
4.3 The next step - Validation of Potential Hotspots 72
References **74**
Annex 1: DESCRIPTION OF THE LABORATORY ELEMENTAL ANALYSIS **77**
ANNEX B: List of maps **84**
ANNEX 3: Prioritization Level for Rehabilitation – list of Cells **94**
ANNEX 4: The Sediment Fingerprinting Team **102**

List of Figures

Figure 1: Extensive conversion of natural forest to agriculture with insufficient soil conservation measures leads to active erosion of topsoil into rivers, where siltation is evident. Photo credit: Rwanda Environmental Management Authority (REMA). 9
Figure 2: A highly turbid Nyabarongo River leaves the NNYU catchment and joins the much-less turbid Karonga River. Source Google Earth, 2014. 10
Figure 3: Watershed showing possible erosion sources, locations of sediment sampling sites along with the catchments for Sediment samples 1 and 3 drawn in. 12
Figure 4: Location of NNYU in southwestern Rwanda shown in brown. To the west is Lake Kivu. Source: Water for Growth, Rwanda. 16
Figure 5: Subcatchments delineated from the 14 sampling points for suspnded sediment in the Upper Nyabarongo river network 17
Figure 6: Primary forest in the Nyungwe National Park, headwaters of the Nyabarongo. 18
Figure 7: Some views of NNYU. Top left - papyrus wetlands on Mwogo river; top right - Secoko floodplain laden with mining deposits; bottom left - silty Secoko river; bottom right: Satinsyi laden with sediment 19
Figure 8: (L): sampling river water for suspended sediments mid-channel (R): suspended sediments on filter paper after filtration 21
Figure 9: Geological formations in the Upper Mwogo Catchment 26
Figure 10: Land use in the Upper Mwogo Catchment 26
Figure 11: Bar chart indicating the relative proportions of geological types in sediment in the Upper Mwogo River at each of the sampling campaigns as well as the composite sample 27
Figure 12: Box Plot showing proportions of sediment composition represented by each geological type in Upper Mwogo catchment. 28
Figure 13: Source proportions of sediment sampled in the Mwogo river (bottom right). 29
Figure 14: Geological formations in the Rukarara Subcatchment 30
Figure 15: Land use in the Rukarara subcatchment 30
Figure 16: Sediment proportions by source geological types over 5 samplings and composite (last bar in each series) for Rukarara subcatchment. 31
Figure 17: Proportions of sediment represented by each geological type. 32
Figure 18: Source proportions of sediment sampled in the Rukarara river. Bottom right shows the Rukarara emerge from tea plantations, where the water is still relatively clear. 33
Figure 19: Geological formations in Mbirurume Catchment 34
Figure 20 : Land Use in Mbirurume catchment 34
Figure 21: Bars showing source proportions of sediment at 5 sampling events. Last bar in each series represents the composite from pooling all samples. 35
Figure 22: Source proportions of sediment pooled over five sampling events 36
Figure 23: Source proportions in sediment sampled in the Mbirurume River. 37
Figure 24: Geological formations in Nyabarongo headwaters region 38
Figure 25: Land use in Nyabarongo headwaters region38
Figure 26: Bar chart showing source proportions in the 5 individual sampling events as well as the composite (last bar in each group) 39

Figure 27: Source proportions in sediment samples pooled into a composite 40
Figure 28: Source proportions for sediment in the Nyabarongo river headwaters, that is the confluence of the Mwogo and the Mbirurume (bottom right). 41
Figure 29: Geological formations in the Nyabarongo Upper Catchment 42
Figure 30: Land use in the Nyabarongo Upper Catchment 42
Figure 31: Source proportions of sediment sampled on 5 individual events as well as the composite of all 5 events. 43
Figure 32: Geological Formations in the Kiryango catchment 44
Figure 33: Land use in the Kiryango atchmemt 44
Figure 34: Source contributions to sediment composition sampled five times; the last bar represents the composite over the 5 samplings. 45
Figure 35: Source proportions of sediment composition of the composite of 5 individual sampling events. 46
Figure 36: Source proportions in sediment sampled in the Kiryango catchment. 47
Figure 37: Geological formations in Nyagako catchment 48
Figure 38: Land use in Nyagako catchment 48
Figure 39: Source proportions in individual sediment sampling events as well as in the composite obtained by pooling all 5 events. 49
Figure 40: Source proportions in ssdiment composite 50
Figure 41: Source proportions in sediment present in the Nyagako river. 51
Figure 42: Geological formations in Secoko catchment 52
Figure 43: Land use in Secoko catchment 52
Figure 44: Source proportions in sediment sampled in 5 indivudual events; last bar shows composite acorss pooled samples. 53
Figure 45: Source proportions in the composite of all 5 sediment samples , Jan- April 54
Figure 46: Source proportions in sediment sampled in five individual events. Bottom right – view of sediment laden Secoko river 55
Figure 47: Geologival types in the Hydropower catchment 56
Figure 48: Land use in the HYdropower catchment 56
Figure 49: Source proportions in sediment sampled in 5 individual events,; also shown is the composite 57
Figure 50: Source proportions in the composite sediment pooling analysis from all 5 sampling events. 58
Figure 51: source proportions of sediment in each of the five sampling events (Table 1). Bottom right – turbid reservoir 59
Figure 52: Geological formations in Satinsyi Catchment 60
Figure 53: Land use in Satinsyi catchment 60
Figure 54: Source proportions in sediment sampled five times as well as the composite 61
Figure 55: Source proportions in sediment - composite 62
Figure 56: Source proportions in sediment sampled in the five individual events (Table 1) 63
Figure 57: Geological formations in NNYU 64
Figure 58: Land cover in NNYU 65

Figure 59: Source proportions in sediment sampled in the 5 events; also showing the composite 66
Figure 60: Source proportions in sediment - composite 67
Figure 61: Source proportions in sediment from the five individual samplings. Confluence of Karonga with Nyabarongo as the latter leaves the NNYU. 68
Figure 62: Average sediment concentration at the sediment sampling stations averaged over January-April 2016. 69
Figure 63: Average sediment concentrations in all sampling points on the Nyabarongo drainage except Secoko and Satinsyi, as these latter are of a higher order of magnitude. 69
Figure 64: Muddy banks of the SecokoFigure 65: Satinsyi laden with sediment just before confluence with Nyabarongo 70
Figure 66: Potential hotspots in the Nyabarongo Headwaters region with a 3-level scale of intervention. 73
Figure 67: Participants at the Statistical Training Workshop in the Sediment Fingerprinting Workshop Series at Kigali, April 2016. 102

List of Tables

Table 1: Suspended sediment sampling dates in the NNYU sediment fingerprinting study, 20
Table 2: Geological formations in NNYU catchment 23
Table 3: Geological types that are dominant sources of suspended sediments in various subcatchments of NNYU over January-April 2016. 25
Table 4: Mean, standard deviation and confidence intervals of sediment proportions by constituent geological types or sources 28
Table 5: Mean, standard deviation and confidence intervals of sediment proportion held by each geological type in Rukarara catchment. 32
Table 6: Mean, standard deviation and confidence intervals of source proportions - composite 36
Table 7 : Mean, standard deviation and confidence intervals of the sediment composition proportion of each geological type 40
Table 8: Mean, standard deviation and confidence intrervals of diferent constituent geologivcal types in the Iryango catchment 46
Table 9: Means, standard deviation and confidence intervals of source proportions in the sediment composite sample. 50
Table 10: Mean, standard deviation and confidence intervals of source proportions in composite sediment samples. 54
Table 11: Mean, standard deviation and confidence intervals of source proportions of composite sediment. 58
Table 12: Mean, standard deviation and confidence intervals for source proportions in sediment - composite 62
Table 13. Instrumental parameters used for the LA-ICP-MS analysis. 77
Table 14. Quality Data for Soils. Calibrator: NIST SRM 2704 (except Y, Mo, Ag, Nd, Au)a. 80
Table 15. Quality Data for Soils. Calibrator: NIST SRM 2704 (except Y, Mo, Ag, Nd, Au)a 81

Acronyms and abbreviations

FIU	Florida International University
GLOWS	Global Water for Sustainability Program
GoR	Government of Rwanda
ICIWaRM	International Center for Integrated Water Resources
ICP-MS	Inductively Coupled Plasma Mass Spectrometer
IWRM	Integrated Water Resources Management
MINIRENA	Ministry of Environment and Natural Resources
NNYU	Nile Nyabarongo Upper [Catchment]
RIWSP	Rwanda Integrated Water Security Program
RNRA/IWRA	Rwanda Natural Resources Authority
SFT	Sediment Fingerprinting Team
TEAF	Trace Evidence Analysis Facility
USAID	United States Agency for International Development

Acknowledgments

The Sediment Fingerprinting Project team is very grateful for the enthusiasm and leadership of Dr Vincent Biruta, the Honorable Minister of Natural Resources, Government of Rwanda.

Equally important has been the technical inputs, cooperation and dedication shown by officials from the Rwanda Natural Resources Authority for a successful execution of the multifaceted activities of the Project in a very short and tight timeline, given their numerous other duties. Their knowledge and understanding of land use and soil erosion processes in the large and topographically complex NNYU catchment has greatly facilitated field sampling activities. The genuine desire shown by the entire Department in finding solutions to soil erosion for the effective management of natural resources and the environment, together with their technical expertise and dedication makes it possible to overcome the serious challenges of soil erosion, river sedimentation and catchment ecosystem degradation.

This study would not be possible without funding from the American people through USAID. The team wishes to acknowledge the participation and financial support provided by USAID Rwanda for this project.

Executive Summary

Sediment fingerprinting involves a statistical comparison of the elemental composition of suspended sediments in rivers with the elemental composition of soils belonging to the various geological types throughout the catchment. Elements are chosen that reliably distinguish between the different geological types in the catchment. The final results indicate the most likely levels of sediment contribution from the different geological types.

The process of sediment fingerprinting as carried out in NNYU involved five basic steps as follows:

i. *Collection of soil samples from all geological types present in the catchment*. There are 14 geological types in the NNYU. For each geological type, five composite samples were collected (with the exception of the Ho alluvial soil type that was not included).

ii. *Collection of suspended sediment samples from the river system.* This was done at 14 locations at the confluences of major tributaries as well as at the Nyabarongo Hydropower Reservoir. Five collection campaigns were carried out at each site at intervals of 2 weeks, from January 21 to April 25, 2016, to also observe seasonal variations in sediment load distribution in the river in relation to their sources.

iii. *Laboratory analysis of soil and sediment samples*. This was done at FIU using an inductively coupled plasma mass spectrometer which determines the elemental composition of soils and sediments with a very high level of accuracy and sensitivity. Results were also obtained using an X-ray fluorescence spectroscopy technique at the RSB lab, which had lower levels of sensitivity but still showed relatively similar results.

iv. *Statistical analysis of laboratory results*. The first part of the analysis identified a set of elements that can reliably distinguish between geological types (sediment sources). The second part used a mixing model that compared the elemental composition of a sediment sample to those of the geological types in the watershed. The product of this step is to have a probabilistic distribution of each geological unit contribution within a particular sample. The analysis was performed on each sample per collection campaign.

v. *Identification of potential hotspots for prioritization of rehabilitation*. The potential sources identified (in terms of geological types) were located on a map and the land use and land cover were analyzed to determine the probable causes leading to soil erosion and sediment load in the river. A three level system was devised with level 1 indicating the areas with the most serious erosion, and Level 3 contributing relatively less sediment. Such a map allows focusing of site visits to locate the precise spots and causes of erosion, followed by deciding and embarking on site-appropriate catchment rehabilitation efforts.

While the loss of primary forest cover will always result in some degree of soil erosion, the study helps focus on specific areas in the very large hilly catchment that are identified as major sources of sediment.

1. Introduction

1.1 Soil erosion – a critical issue facing Rwanda

Soil erosion is the biggest source of nonpoint pollution in watersheds worldwide, with fine sediment being the most common pollutant (eg. Gurgen 2003, Yanda & Munishi 2007, Davis & Fox 2009). In Rwanda and other areas within the Nile Basin, suspended sediments have been sharply increasing in water bodies since the 1990s (Probst & Suchet 1992, Odado & Olaga 2007, REMA 2009). The State of the Environment Report (REMA 2009) mentions that the Nyabarongo river system carries 51 kg/second of soil at Nyabarongo-Kigali, 44 kg/s at Nyabarongo-Kanzenze and 26 kg/s at Akagera-Rusumo. Increasing sediment loads in rivers leads to the deterioration of water quality, a condition that affects freshwater ecosystems and their capacity to deliver the critical freshwater ecosystem services upon which human populations depend in a timely and cost-effective way. For instance, sediment settles on streambeds and fill up the gaps underneath stones, thus removing habitat for aquatic macroinvertebrates (insect larvae) which feed on detritus, thus maintain water quality and constitute food for stream fishes. Sediment deposition in river channels and reservoirs also reduces volume capacity that worsens flooding during periods of high rainfall. Furthermore, the irreversible loss of valuable topsoil from catchments leads to the generation of barren land within just a few decades, severely limiting agricultural productivity (Figure 1).

Figure 1: Extensive conversion of natural forest to agriculture with insufficient soil conservation measures leads to active erosion of topsoil into rivers, where siltation is evident. Photo credit: Rwanda Environmental Management Authority (REMA).

A 2006 environmental profile of Rwanda financed by the European Union (Twagiramungu 2006) suggested that Rwandan soils were naturally fragile and that approximately 15,000,000 tons of soil is lost annually; both of these conditions were linked to degradation of natural environments. About 40 per cent of Rwanda's land is classified by the FAO as having a very high erosion risk with about 37 per cent requiring soil retention measures before cultivation (REMA 2009) with only 23 per cent of the country's lands are not prone to erosion. The increase in soil erosion is a direct consequence of increasing human activities in catchments, the major ones being clearing of native forest for agriculture, inadequate soil conservation measures such as terraces and mulching, road-building, fires and mining (REMA 2009). Furthermore, the hilly terrain makes Rwanda particularly susceptible to soil erosion (eg.

Clay & Lawrence 1990). Despite a general rule of thumb of the necessity of erosion control measures on slopes of more than 5 per cent, the reality in Rwanda is that most cultivation is carried out on steep slopes without any recommended soil control measures (REMA 2009). This is despite awareness that soil erosion control on farms leads has been clearly linked with higher productivity in Rwanda (Byringiro & Reardon 1995).

Figure 2: A highly turbid Nyabarongo River leaves the NNYU catchment and joins the much-less turbid Karonga River. Source Google Earth, 2014.

However, despite their valuable contributions of general information on sediment loads in Rwandan rivers, there are no studies that provide detailed information on the particular geographic areas potentially contributing to sediment loads in water bodies. Consequently, water resources management in Rwanda faces a major challenge in relation to the sedimentation of rivers and lakes due to soil erosion from both agricultural and industrial (mining) practices (SHER Ingenieurs-Conseils s.a. 2014). Addressing the issue of river sedimentation requires controlling erosion, starting from the most affected areas, which requires prior accurate identification of those areas contributing disproportionately to sediment loads in catchments' rivers. FIU has been working on the identification of sediment sources using a technique known as sediment fingerprinting in rivers in East Africa for several years now, and is in the process of working with the Ministry of Natural Resources (MINIRENA), Rwanda Environment Management Authority (REMA) and Rwanda Agricultural Board (RAB) to identify the areas contributing the highest amounts of sediment. The hilly terrain makes this endeavor a time-consuming and logistically challenging exercise.

1.2 Identifying sources of soil erosion

Knowing which parts of a catchment suffer the largest soil erosion allows for the effective use of limited resources to target soil conservation efforts. Insufficient knowledge of river sediment sources greatly limits the effectiveness of the environmental management of watersheds. Addressing the issue of river sedimentation requires controlling erosion, starting from the most affected areas, which requires prior accurate identification of those areas contributing disproportionately to sediment loads in catchments' rivers. The aim of sediment transport studies at the watershed scale is to understand the source, fate, and transport of sediments mobilized within a catchment. However, identifying areas with high soil erosion rates is challenging in a large catchment, as soil erosion is not always a visible process, and is also impacted by differences in climate, vegetation, topography, soil type and human disturbances.

Traditional direct monitoring techniques using soil erosion pins (monitoring the change in the depth of soil along a pin stuck into the soil) or soil erosion troughs (quantifying amount of sediment in a trough brought in by uphill runoff over a year) have not been very successful in identifying sources, because of the intensive amount of sampling all over the catchment at various times that is needed with such approaches (Collins et al 1997). The use of Google Earth imagery, while enabling a landscape-level perspective, lacks temporal resolution – the time gap between individual images is long (9-12 months or more), and thus cannot yield a comprehensive look at soil erosion events that arise from localized rainfall and human activities. Hence, an alternative technique, sediment fingerprinting, has been increasingly used worldwide since the mid-1970s. The next section introduces the approach, details the continued evolution of this method, followed by a description of the approach.

1.3 Sediment fingerprinting – a tool to identify sources of soil erosion

Sediment fingerprinting is a method to identify potential sediment sources in a catchment and allocate the amount of sediment contributed from each source through the use of natural tracer technology with a combination of fieldwork, laboratory analyses of soils and sediments, and statistical modeling techniques (Davis & Fox 2009). Sediment fingerprinting essentially is a two-step process: first, the selection of diagnostic physical and chemical properties ('fingerprints') that unambiguously differentiate between different soil groups (potential sources of sediment) in a catchment, and secondly, comparison of these fingerprint properties with those of suspended sediment samples taken from rivers (particle size < 62 µm) within the catchment. The approach is based on the assumption that some of the properties of sediment reflect those of the sources (Collins at el 1997). As long as soils consistently differ in some aspects within a catchment, the sediment fingerprinting approach can discriminate between the different soil types and infer the relative contribution of each soil type to sediment loads in rivers. Thereby, the areas contributing the largest amounts of sediment can be prioritized for soil conservation and erosion control measures, which is an enormous undertaking, especially in a large hilly catchment. Sediment fingerprinting thus offers a potentially valuable tool for watershed management and total maximum daily load of sediment (TMDL) development in rivers that focusses on the assessment of sediment source to aid in developing efficient remediation strategies for soil erosion-related problems.

1.3.1 Soil and Suspended Sediment Sampling Approach

Sediment in water bodies can result from one or more of the following processes: surface soil erosion and mass wasting (from landslides for instance) from upland areas of a catchment; soil erosion from human activities (agriculture, deforestation, intensive grazing, mining, roads); floodplain and streambank erosion during high flows and the remobilization of sediment previously deposited on streambeds. Foremost, it is essential to be familiar with the watershed by describing the land use, soil type, topography, geomorphology, hydrology and climate characteristics. The basic principle of choosing where to sample is illustrated in Figure 3 that shows a catchment with three potential sources of erosion (brown circles labelled Source 1, 2 and 3). These potential sources could be based on geological differences, or differences in land use, such as a ploughed farm vs a natural forest. If these sources are seen to differ in one of more soil properties (either physical or geochemical), then one can proceed with sampling sediment at different sites in the rivers. The blue circles (labelled Sediment Sample 1, 2 and 3) represent potential sites for sampling suspended sediment in the rivers. Sediment Sample 1 would be expected to have soil from upstream within its own catchment (drawn in), possibly including Source 1 if soil from Source 1 can travel all the way downstream to Sediment Sample 1. Similarly, Sediment sample 3 would be expected to have soils from its own sub-catchment including Source 3. Sediment Sample 2 being downstream of the entire catchment can be expected to have soils from all over the catchment, including Source sites 1, 2 and 3.

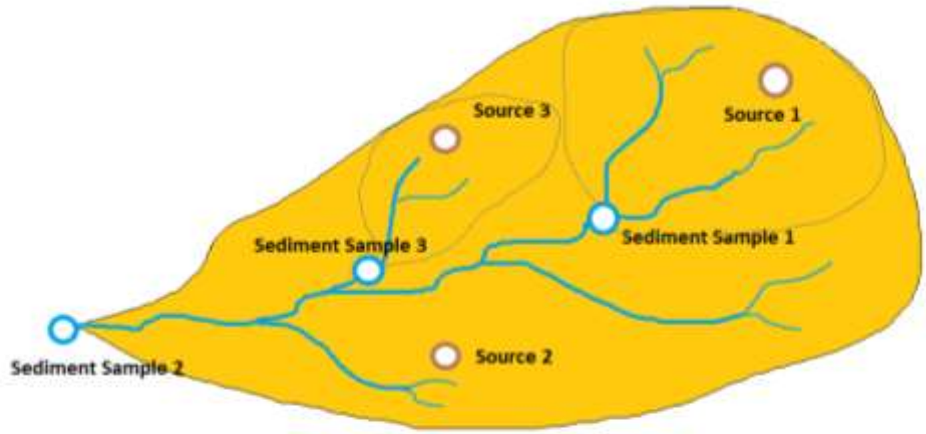


Figure 3: Watershed showing possible erosion sources, locations of sediment sampling sites along with the catchments for Sediment samples 1 and 3 drawn in.

The intention of sediment fingerprinting being to detect all the major sources of erosion in a catchment, choosing sample sites is done on the basis of prior knowledge of erosion-prone areas (such as information from local communities), aerial photos and satellite maps, and in some cases, the use of GIS-based analysis combining topography (steep slopes) and land cover, to be able to predict areas very susceptible to erosion. The above information is combined with a lithology map that indicates different soil types in the catchment.

By combining all of the information using GIS, field reconnaissance and photographs, one can begin to understand the behaviour of the watershed and thereby understand the erosional processes and the various possible sources of sediment such as top soil (farms, pasture, deforestation), gullies, unpaved roads, streambanks and re-mobilized river bed sediment. This then determines the number and locations of sampling sites. Enough quantity of soil should be taken at each sampling site for replicate testing. Koiter et al (2014) summarize sampling /storage considerations and techniques for soils, suspended and settled sediments, as also prior studies by GLOWS in the Ruvu river basin in Tanzania (GLOWS 2014).

The process of sediment fingerprinting, as performed by FIU-GLOWS in East Africa (Dutton 2013, GLOWS 2014), involves five 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. laboratory analysis of both types of samples depicted above.
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.

The following sections detail the evolution of the technique, sampling, the different approaches of soil analyses possible followed by the statistical approach.

1.3.2 Brief Review: *Evolution from single to multi-component techniques*

The intention in sediment fingerprinting is to identify one or more natural tracers that are unique to each potential sediment source; these tracers are termed 'sediment fingerprints' of those sources. Fingerprinting techniques began in the 1970s with a qualitative comparison of individual soil properties within a watershed, such as physical particle size, color, density, isotopic ratios, radiometric/mineralogic/chemical composition and organic properties (eg. Klages & Hsieh 1975, Oldfield et al 1985, Fenn & Gomez 1989, Walling & Woodward 1992). These single-component signatures have been successfully used to infer sediment origin from both spatial origin (based on lithological differences within the catchment), as well as source type (land cover/land use – agriculture, pasture, forest, etc). However, such qualitative approaches were seen to have several possible limitations, as described in an early review by Collins et al (1997). For instance suspended sediment in the river may resemble a particular source in the catchment, but could also result from a combination of several other sources in the catchment. Individual tracers can also be subject to physical and chemical changes from further weathering, color change and geochemical transformation during transport in streams and interaction with the environment. Koiter *et al* (2014) discuss this further. Walling et al (1993) showed that no single diagnostic sediment property can reliably distinguish between different sources. Hence, to overcome these problems of single component signatures, the use of composite multiple signatures began, so as to decrease ambiguity and improve accuracy of determination (Oldfield & Clark 1990, Walling et al 1993, Collins 1995). This was accompanied by the development of rigorous quantitative procedures that included both the statistical verification of the ability of parameters to distinguish between potential sources, followed by the use of multivariate mixing models to determine the percentages of the various sources (Yu and Oldfield 1989, Walling et al 1993, Collins 1995).

1.3.3 Selection of tracers

Since the late 1990s, researchers from various disciplines have applied the sediment fingerprinting method to a wide range of watersheds globally (review – Davis & Fox 2009) utilizing many different physical and biogeochemical tracers at a variety of landscape scales, from single field plot studies to large river basins, such as the 650,000 km2 Murray-Darling basin in Australia (Olley & Caitcheon 2000). Most studies go in for a wide group of tracers to be able to accurately and unambiguously distinguish between sediment sources. It is to be borne in mind that no single type of natural tracer can be used globally to infer sediment sources in all watersheds (Collins and Walling 2002); hence the choice of tracers makes sediment fingerprinting very site-specific. This is because tracer properties depend on watershed geology, soil type and land cover/land use (Fox & Papanicolaou 2008). Davis et al (2009) gives a comprehensive review of the types of tracers that have been employed over the past 2 decades.

Tracers can be grouped into physical and biogeochemical.

Physical - density, particle size and colour. The advantage is that these are readily identifiable and easily measurable in the field. However, physical tracers can be nonconservative, ie their properties can change during transport from source to the river and further instream. For instance, colour can change depending upon moisture content, particle size breakdown and subsequent chemical reactions with other natural elements in the catchment. Similarly, particle size can change due to aggregation and disaggregation during transport.

Biogeochemical – includes organic, inorganic and radionuclides. The availability of analytical laboratory techniques such as atomic and mass spectrometry has enabled studies to obtain the elemental or spectroscopic composition of soils and sediments, and thereby use a whole group of tracers if these have unique values for different soils in the catchment.

Organic tracers include total organic carbon (TOC), total organic nitrogen (TON), total organic phosphorus (TOP), C : N ratio and stable isotopes of carbon (δC^{13}) and nitrogen (δN^{15}). Organic tracers are useful to distinguish between different categories of land use, as they are affected by both vegetation type and soil exposure (tilling vs no tilling) activity. However, organic tracers are not conservative; ie they can undergo biological transformations to other forms, as well as be taken up by plants (for N, P). Hence they are not suitable as catchment-scale tracers.

Radionuclides (lead-210 and cesium-137) are present in soil from atmospheric fallout (either natural processes or nuclear weapons testing), and their concentration can vary with soil depth; thus they are used to infer the depth from which soil erosion might be happening.

Inorganic tracers form a large group (eg. Ag, Al, As, Ca, Ce, Co, Cr, Cu, Fe, K, La, Mg, Mn, Na, Ni, Pb, S, Si, Sr, Ti, Y, Zn, total inorganic carbon, total inorganic nitrogen, total inorganic phosphorus). Unlike organic and radionuclide tracers that discriminate sources based on soil organic matter cycling and soil depth respectively, inorganic tracers are less associated with specific environmental processes because of the large number of processes that affect elemental composition of sediments. Furthermore, studies have focused on multivariate methods to handle these large numbers of inorganic tracers, more as a way to distinguish between sources and less on the emphasis of the mechanisms or explanations between the differences in an element, say Cr, between different soil types or sources.

Prior to analyzing soil samples for elemental composition, they are typically dried and sieved. Tracer analysis relies on biochemical and geochemical or image analysis instrumentation, depending on the specific tracer. Organic tracer concentration in a soil sample is measured using stable isotope mass spectrometry or elemental analyzers. Inorganic tracers are subjected to acid digestion or plasmafication followed by one of the following analytical methods - atomic absorption spectrophotometry, energy dispersive spectrometry, x-ray influorescence and inductively coupled plasma emission spectrometry, in increasing order of detection precision and sensitivity. Specific methods for the study in NNYU are provided in Chapter 2.

1.3.4 Statistical analyses: DFA and mixing models

Statistical tests, such as the Kruskal–Wallis H-test are used to identity tracer properties that are statistically different between source areas. Thereafter, cluster analysis coupled with analysis of variance and Discriminant Function Analysis (DFA) coupled with a multivariate stepwise algorithm, based on the minimization of Wilks' Lambda, have been successfully employed to identify the smallest number of tracer properties that provide maximum discrimination of source properties. However, a purely statistical approach may not be the most appropriate method as the conservative behavior of sediment properties and the underlying processes that lead to their ability to discriminate between sources are not considered. Understanding the physical basis for discrimination for a given tracer as well as the behaviour of the fingerprinting properties will have to be taken into account to choose the potential fingerprinting properties. More information can be obtained from the sediment fingerprinting work in the Ruvu basin, Tanzania (GLOWS 2014).

A multivariate approach is chosen in the majority of sediment fingerprinting studies (as reviewed by Davis & Fox 2009) to handle the wide suite of inorganic tracers in soil samples. This is because the dependence of inorganic tracer composition upon a variety of watershed characteristics (geology and geomorphology processes, vegetation cover and history, land use) is difficult to characterize. The multivariate approach tests a large group of potential tracers (elements obtained in the soil analysis process) to determine a subset of tracers that can effectively discriminate between different soil sources. A review of various statistical approaches has been provided by Davis & Fox (2009); a common approach being Discriminant Function Analysis (DFA), whereby the tracer values for each source are compared to the same tracer values for all other sources to examine whether the particular tracer differs significantly between the sources. DFA then yields an optimal grouping of tracers to classify the sources, often using the technique of minimizing the value of Wilks' lambda (an independent statistical test for classification) with the fewest number of tracers to form the final group used for classification of sources. Once this group of tracers has been identified, a mixing model is used to estimate the contribution of sediment from each source. The mixing model essentially employs a mass balance approach, whereby the amount of a tracer in a sediment sample is held to be the equal to the sum across sources of the product of concentration of that tracer in each source and the fraction of sediment contributed by each of the sources. The unknown in the equation is the last term, ie the fraction of each source in the sediment.

When there are a number of tracers, as is typically the case, a set of matrices is used to store and process the system of linear mass-balance equations corresponding to the multiple tracers and sources. This set of matrices is then solved either by an error minimization approach or a Bayesian approach based on integration via Markov Chain Monte Carlo. A description of these approaches together with their respective advantages and limitations is available in Davis & Fox (2009). The next chapter describes the application of the sediment fingerprinting technique to the Nile Nyabarongo Upper Catchment.

2.Sediment fingerprinting in the Nile Nyabarongo Upper Catchment (NNYU)

2.1 The Nile Nyabarongo Upper Catchment

The overall objective of this assessment is to help the Government of Rwanda prioritize catchment rehabilitation work in the Nile Nyabarongo Upper Catchment (NNYU) that has been selected on account of the severity of siltation in the Upper Nyabarongo River (Figure 2). With most of the primary forest cover being replaced with agriculture, together with unregulated highly destructive mining practices has led to extremely turbid rivers. The high sediment loads in rivers pose grave challenges to water supply, the operation of hydroelectric reservoirs and degrade aquatic ecosystems. Furthermore, the silt travels downstream to the Lower Nyabarongo Catchment that is the main water supply for the capital city of Kigali and the industrial centres.

Figure 4: Location of NNYU in southwestern Rwanda shown in brown. To the west is Lake Kivu. Source: Water for Growth, Rwanda.

The Nile Nyabarongo Upper Catchment (Figure 4, Map in Annex) is part of the Nile basin within the hydrological system of Rwanda. The NNYU has a surface area (entirely within Rwanda) of 3,348 km², with an average estimated annual surface water runoff of 385 mm/yr (1,289 MCM/yr) and a total average rainfall of 1,365 mm. The NNYU catchment has an estimated population of 1.425 million people (per the 2012 population census) and is spread over eight districts (Ngororero, Rutsiro, Muhanga, Karongi, Nyamagabe, Ruhango, Nyanza, and Huye), with a very small part located in the districts of Nyamasheke and Nyaruguru. The land cover of the NNYU is primarily rain-fed agriculture and agroforestry along with mining activities and urban zones. Natural forests including the Nyungwe National Park cover about 7% (SHER Ingenieurs-Conseils s.a. 2014) of the catchment area.

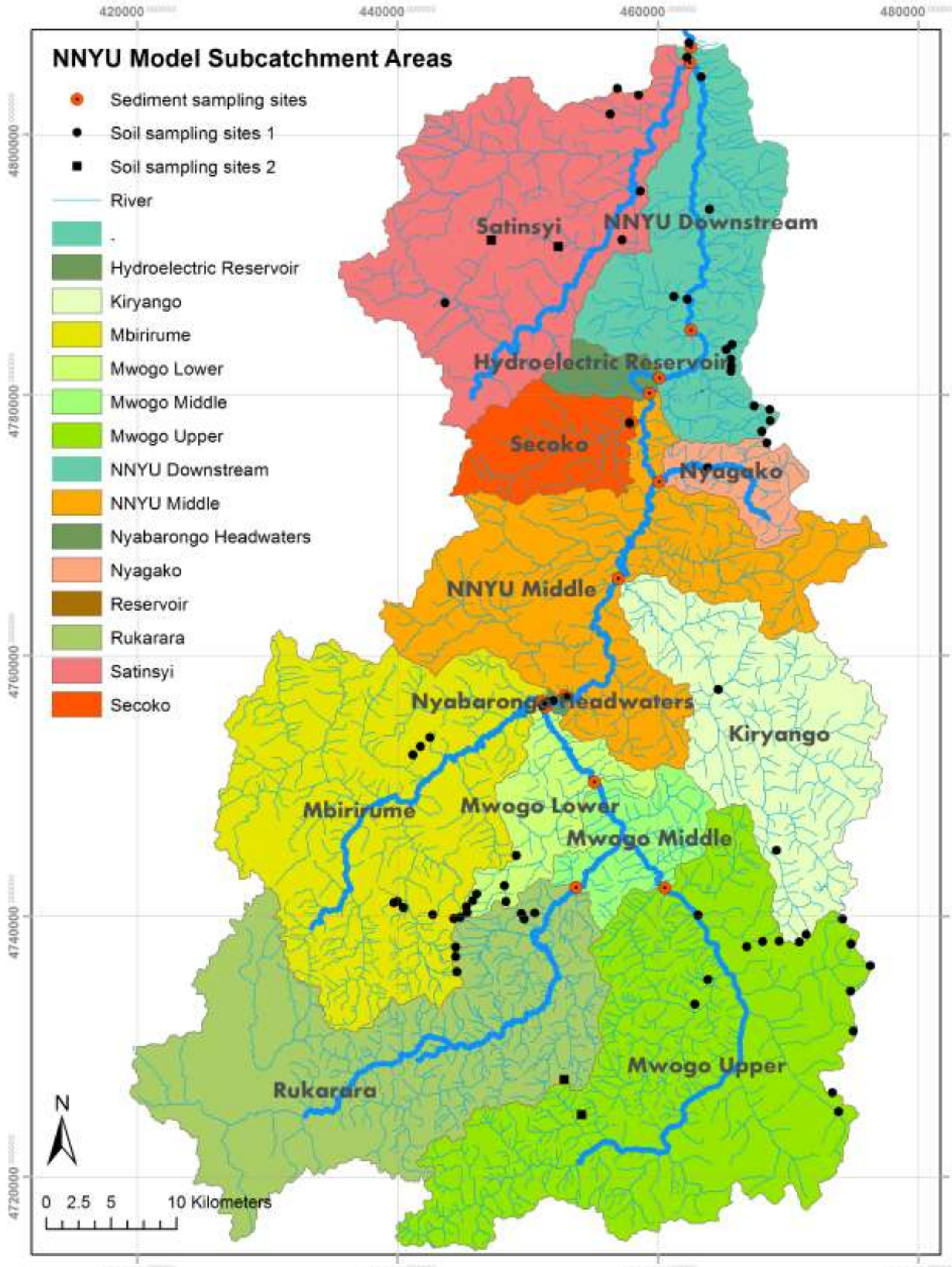


Figure 5: Subcatchments delineated from the 14 sampling points for suspnded sediment in the Upper Nyabarongo river network

The headwaters of the Nyabarongo arise in primary-forest covered mountains (Fig 6) along the western edge of the catchment. Streams flowing east from these mountains flow into the Nile Basin while streams flowing west of the catchment divide flow into the Congo Basin. East flowing streams arising in Nyungwe National Park are clear and flow into the Rukarara that flows into the Mwogo (Map 1, 5, Annex). The Mwogo passing through some extensive papyrus wetlands (Fig 7) then meets the Mbirurume to form the Nyabarongo, which then flows northwards and is joined by Kiryango, Nyagako and Secoko rivers (and numerous smaller streams) before entering the Nyabarongo Project Hydropower Reservoir. The river flows north, is met by Satinsyi (Fig 7) and finally turns sharply southeast into the NNYL catchment.

Figure 6: Primary forest in the Nyungwe National Park, headwaters of the Nyabarongo.

Figure 7: Some views of NNYU. Top left - papyrus wetlands on Mwogo river; top right - Secoko floodplain laden with mining deposits; bottom left - silty Secoko river; bottom right: Satinsyi laden with sediment

2.2 Sampling sites and methodology

Before the sampling of soils and sediments, the sediment fingerprinting study team examined the watershed terrain and land cover/land use in order to identify the erosional processes and possible sources of sediment such as topsoil (farms, pasture, and deforestation), gullies, unpaved roads, stream banks and re-mobilized riverbed sediment. Land use, soil type, topography, geomorphology, hydrology, and climate characteristics (maps 1-8 in Annex) data was obtained from the Ministry of Natural Resources and other sources. Erosion-prone areas (and/or potential deforested areas) in the NNYU were identified through map reconnaissance, field visits and interaction with government officials familiar with the region.

After obtaining a familiarity with the layout and land use of NNYU, sampling sites for suspended sediments were decided with the active participation of the technical staff from REMA familiar with the catchment at the initial training workshop on sediment fingerprinting held in January 18-19, 2016 and at the Inception Report presentation. Fourteen sites were chosen throughout the Nyabarongo drainage in the NNYU catchment on the main river and on major tributaries just before confluence with the Nyabarongo river (Table 4, Figure 7).

Both soils and suspended sediments were sampled for the study (map in Annex). Fieldwork commenced immediately after the Training Workshop, on January 21, 2016, and consisted of 5 campaigns until the end of April, 2016 (Table 1).

2.2.1 Soils:

Five soil samples per geological type were collected as wide apart as possible over the entire NNYU catchment. The NNYU has 14 geological types or formations (Table 2 and Map 7, Annex). The approach was to take 5 samples per geological type, analyze the elemental composition to a very precise level, and to see using statistical tools whether there were some elements that could distinguish the origin of soil samples to a geological type. Note that the geological type Ho was not collected, as Ho represents alluvial deposits along river floodplains, which could have come from various parts upstream in the catchment and thus are not useful for pinpointing sediment sources. Each of these 5 samples was a composite of soils from five spots within a 50 m radius, deposited in a clear polythene ZipLoc bag

(Figure 8). The purpose of having composite samples is to decrease chances of a single soil sampling site being unnaturally different owing to chance deposition of dung/urine or other pollutants. A plastic trowel was used to scoop soil from within the top 2-3 cm into a Ziploc bag, as it usually is the topmost soil that erodes naturally, except in cases of excavation for road building or mining or ploughed fields. Plastic scoops were used to avoid possible contamination of elements from metal shovels. The trowel was then cleaned with plain and battery water to avoid contamination of the next sample. GPS location, photographs and field notes were taken at each site for each sampling campaign. The map in the Annex shows these sites. Adequate soil sample amounts were taken at each site in a Ziploc bag so as to enable at least 4-5 analyses of the sample. Each sample bag was labeled with the date, number Geotype and GPS location. Samples were subsequently air-dried in the laboratory at RIWSP headquarters in Kigali, and a part of it separately packed and shipped to labs at FIU as well as RSB for elemental analysis.

2.2.2 Suspended Sediments:

In order to select the most appropriate sediment sampling sites for the application of the sediment fingerprinting methodology, a model of the Nyabarongo Upper catchment was conceptualized tracking sedimentation from upstream to downstream, keeping in mind the major tributaries that flow into the Nyabarongo, as described in the earlier section.

Table 1: Suspended sediment sampling dates in the NNYU sediment fingerprinting study,

Sampling round	Dates
1	January 21-25, 2016
2	February 9-13, 2016
3	March 7-11, 2016
4	March 28-April 1, 2016
5	April 21-24, 2016

Five sediment sampling campaigns were done at various points along the Nyabarongo River as explained above from January 2016 to April 2016, in order to cover both the short dry and the main rainy season that is the dominant influence on soil runoff. A 1 liter Nalgene bottle was filled with river water from a well-mixed section of the river (Figure 8 L), to avoid having a disproportionate amount of runoff from adjacent banks. 250 ml of this water was then filtered through a pre-weighed 63 nanometer Cellulose Nitrate filter paper. A filter apparatus driven by a manual pump (an automobile brake bleeding kit) was used to create suction to draw water through the filter paper, as else clogging of the filter paper would greatly delay the filtration process. Forceps were used to handle the filter paper by the edges. The filtering equipment and measuring cylinder were rinsed thrice with battery water in between successive samples, to avoid contamination from one sample to another. The filter paper with sediment was then stored inside a petridish (Figure 8 R) until further analysis.

2.2.3 Subcatchment delineation from suspended sediment sampling points

In order to know the possible region from where the suspended sediment sampled at a point in a river could be washed off from, a catchment delineation is carried out using GIS with the sampling point as the outlet of that catchment, known in GIS parlance as a pour point. Such an exercise was carried out using ArcMap for all 14 suspended sediment sampling points. Fig 7 shows the map of these catchments that are referred to from now on as subcatchments, indicating that these are part of the overall NNYU catchment. Note that these subcatchments are delineated from the sampling point and are not strictly hydrological catchments of the tributaries. For example, the Rukarara subcatchment as seen on this map demarcates the catchment for the sampling point on the Rukarara and not the entire catchment for the Rukarara, because the sampling point was not taken where the Rukarara ends and flows into the Mwogo.

Figure 8: (L) sampling soil from a farm open to erosion (R): sampling soil from exposed quarry soil piles

Figure 8: (L): sampling river water for suspended sediments mid-channel (R): suspended sediments on filter paper after filtration

2.3 Laboratory Analysis and results

Trace Element Analysis Facility, FIU

Soil and sediment samples were shipped to the Trace Evidence Analytical Facility Laboratory at FIU (http: teaf.fiu.edu) for elemental analysis via mass spectrometry. Samples were dried in an oven for 48 hours at 60 degrees F and then sieved to 63 microns using nylon filter screens. The fraction smaller than 63 microns was milled using a titanium-carbide ball mill. Part of that was made into pellets using a Carver die pelletizing machine. Each pellet was then subjected to laser ablation, and the resulting plasma sent element ions into a mass spectrometer for detection of elemental concentrations.

Mass spectrometer data was then assessed for quality control, processed with software and elemental composition results presented in an excel file. The process is described in detail in the report from the laboratory (Annex 1). Raw Data is included in Annex 2.

Figure 10: Left - LA-ICP-MS at FIU. Right - Niton XRF at RSB.

Rwanda Bureau of Standards Laboratory

In order to investigate the possibility of also carrying out elemental analyses with the required degree of sensitivity and precision locally in Rwanda, Rwandan analytical laboratories were assessed. Rwanda and the wider East African region was found to lack an operational mass spectrometer, whose precision is necessary for measuring trace elemental concentrations. The lab at RSB has an operational X-ray Diffraction (XRD) analytical system, which has a lower degree of precision than a mass spectrometer, but can still measure elemental concentrations. Hence a set of samples were analyzed in this lab, for comparison with the lab results from FIU.

2.4 Statistical Analysis

All statistical analysis was done in the statistical computing language R. The Kruskal-Wallis H test was used to identify tracers that showed significant differences between source types. 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. In addition, a jackknifed discriminant function analysis was used to assess the discriminatory power of the tracers through a cross-validation procedure. With the jackknifed procedure, the discriminant function analysis was run multiple times, leaving a different sample out each time. 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 sediment samples were within the range of values presented by upstream soil samples.

In order to ascertain the proportion of sediment contributed by each source, a mixing model with Bayesian inference was utilized. Specifically, the MIXSIAR Mixing Model, that allows for all sources of uncertainty to be propagated through the model. The model is fit by a Markov Chain Monte Carlo routine.

The entire procedure of running statistical models was taught to technical staff of several Rwandan institutions in the Workshop on Statistical Analysis in April 2016 at Kigali. A report of that workshop is available.

Table 2: Geological formations in NNYU catchment

Geological Formation	**Explanation**
Bb/Ng	Bumbugo/Nyabugogo formations. Quartzite and Sandstone alterations
Bu	Butare complex. Alteration of granites, gneiss and quartzitic metasediments
Gd	Granitoides divers.
Gi	Granitoides indifferencies
Gdm	Granites to Mica
Gt	Gatwaro superformation. Quartzite
Ho	Alluvial sediments
Ka	Kaduha formation. Quartzophylite.
Nz	Ndiza formation. Quartzite, sandstone and schist
Nw	Nyungwe formation.Quartzite, quartzophylite and phylite
Sk	Sakinyaga formation. Sandstone and quartzophylite
St	Satinsyi complex. Quartzite and volcanic intrusions
Uw/Cr	Uwinka/Cyurugeyo formations. Quartzophylite.

3. Sediment Fingerprinting Results

For each subcatchment, the mixing model suggests the proportions of sediment arising from each geological type present in that subcatchment. Locating the geological types that are the major sediment contributors enables one to identify the areas in the catchment that are the potential sediment sources. This chapter presents the results for each subcatchment, while the next chapter presents an analysis of these results whereby the major contributing geological types are examined on the map and the corresponding cells (administrative units) that fall in these geological types are identified.

3.1 Approach to interpret results

As described in Chapter 2, the conceptual model of the Nyabarongo Upper catchment tracked sedimentation from upstream to downstream with full control of the source location. The following model sub-catchments were analyzed: Rukarara River Catchment, Mwogo Upper River Catchment, Mwogo catchment (consists of the catchment of the entire Mwogo – Upper, Middle and Lower - river before its confluence with the Mbirurume), Mbirurume catchment, Nyabarongo headwaters (includes the Mbirurume and the Mwogo catchments), Kiryango catchment, Nyagako Catchment, Secoko Catchment, Hydropower catchment (includes the Kiryango, Nyagako, Secoko catchments and the catchment Nyabarongo upstream of the Hydropower reservoir), Nyabarongo downstream of reservoir catchment (which constitutes the entire Nyabarongo catchment just before the confluence with Satinsyi), Satinsyi catchment and finally the NNYU reaches the outlet site which represents the limit of the entire Nile Nyabarongo Upper Catchment. Figure 5 shows the various areas that comprise the modelled subcatchments.

Soil erosion and contribution to sediment loads being caused by rainfall and human activities, the localized and random nature of rainfall, together with certain activities that may happen at specific times only (road building, burning of fields, deforestation and excavation for mining) means that sources in a catchment usually varies with time. Hence statistical analysis is performed at the modeled subcatchment level on each individual set of samples as well as over the pool of all the samples (composite) across sampling campaigns. This modeling was carried out for each subcatchment. Results yielded the proportion of sediment arising from each geological type within that subcatchment and are presented in graphical format as explained in the next page. The dominant sources are summarized in Table 2. The geological types are explained in Map 7 in the Annex.

Table 3: Geological types that are dominant sources of suspended sediments in various subcatchments of NNYU over January-April 2016.

Subcatchment	Potential Sources over entire sampling period
Kiryango	Gdm (70%)
NNYU downstream	Bu, BbNg and Q1Q3
Mbirurume	Ka (40%), Q1Q3, Bu
Mwogo Middle	Bu, Nw and Q1Q3 (approx equal)
Mwogo	Nw (60%)
NNYU outlet	BbNg (50%), Nz (30%)
Nyabarongo Headwaters	Nw (40%), Bu, Ka
Reservoir	Q1Q3, Bu and BbNg
Rukarara	Gi (40%), Ka (25%)
Satinsyi	Bu, UwCr
Secoko	UwCr (80%)
Mwogo Upper	Q1Q3

Interpretation of statistical modeling results as presented in this report

Bar charts and box plots are utilized to show the results (examples Figures 10 and 11).

The ***bar chart*** shows the modelling results for each individual suspended sediment sample over January-April. The results for the individual suspended sediment samples illustrate the suspended sediment sources in the river at the time that the sample was taken, thus indicating any changes in sediment sources over time in a subcatchment owing to differences in rainfall and/or human activities. In addition, the last bar in each geological type cluster signifies the composite. Note that the composite is not the average of the 5 sampling campaigns; it is obtained by pooling together the analytical results of all the samples across the sampling events.

The ***box plot*** indicates the likely geological sources of sediments over the sampling period (January - April), and is a composite of the statistical results from all 5 sampling rounds. The box plot shows the composite result that was created by utilizing all of the individual suspended sediment samples taken from that catchment to create a best guess of the suspended sediment trends over time. The range of each sample in the box plot represents the 95% confidence intervals and the dot for each source represents the most likely value for that source (mean). Note that the composite is not the average of the 5 sampling campaigns; it is obtained by pooling together the analytical results of all the samples across the sampling events.

3.2 Subcatchment analysis results

The mixing model was run for each modeled subcatchment, for each of the 5 sediment sampling events (Table1) as well as on the composite pool of all samples. In some subcatchments, a large proportion of sediment arises from one of two geological types. In other catchments, the sediment sources have contributions from almost all geological types. This is especially true in downstream reaches of the river that have some amount of suspended sediments from far upstream.

3.2.1 Mwogo Upper subcatchment – one of the headwaters of the NNYU

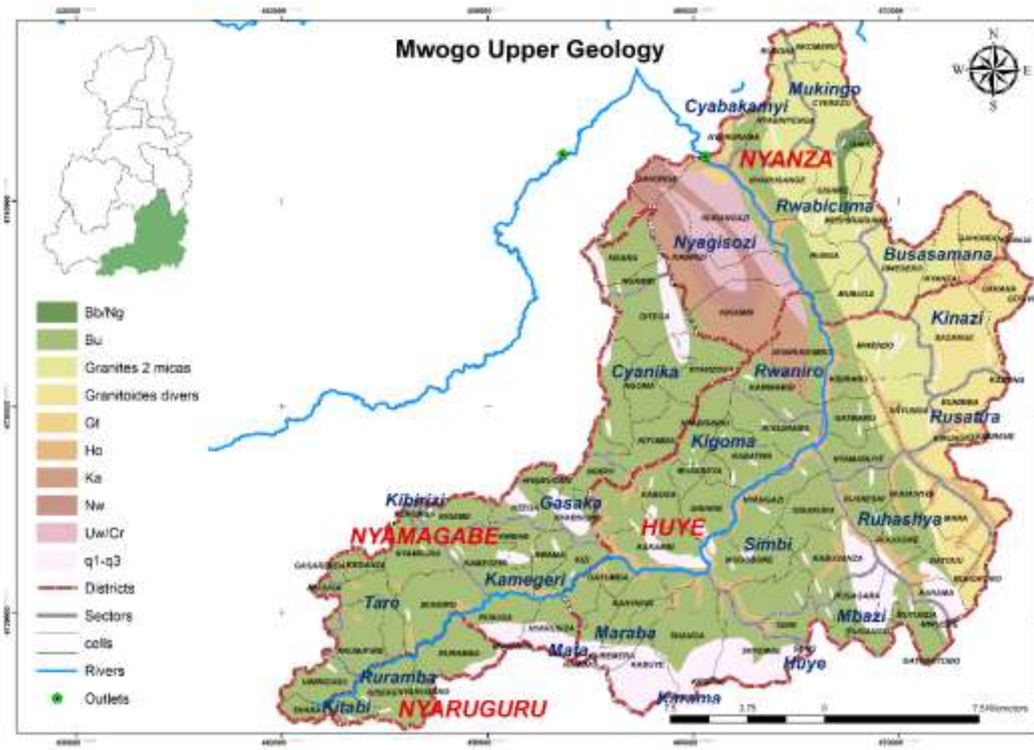


Figure 9: Geological formations in the Upper Mwogo Catchment

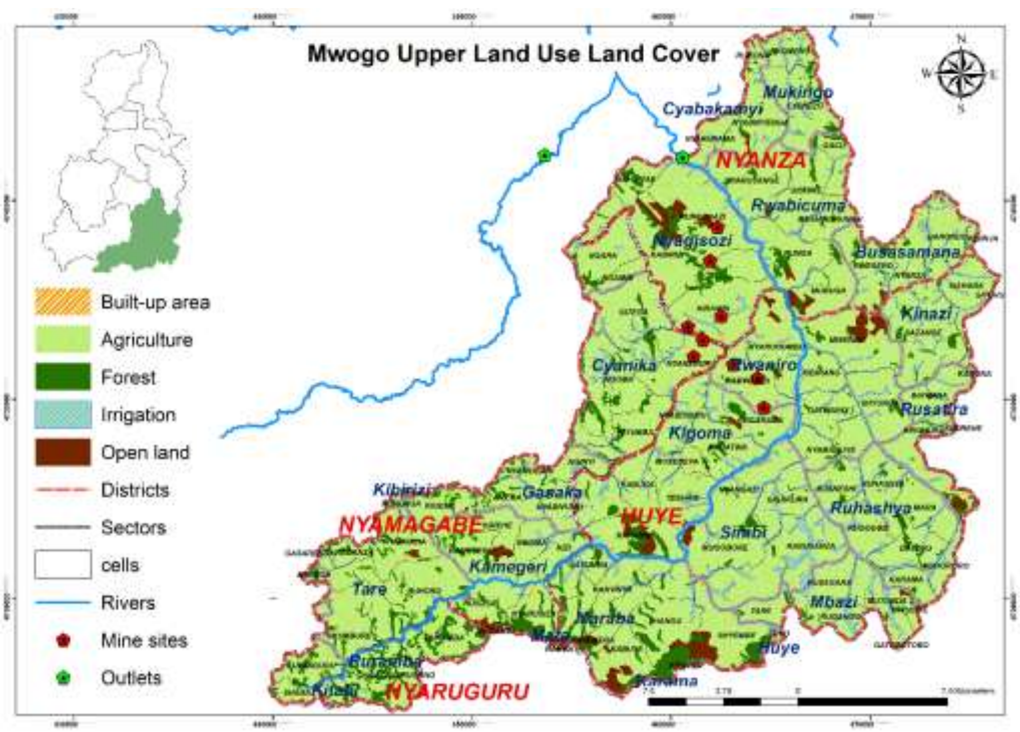


Figure 10: Land use in the Upper Mwogo Catchment

Sediment fingerprinting (Table 2) indicates that Q1-Q3 is the dominant source of sediments in this subcatchment in both the composite (Figure 3) as well as in each sample through Jan-April (Figure 4). This is an interesting result because Q1Q3 is not widely present throughout the catchment, only in specific areas of the headwaters, and hence this result suggests severe localized disturbances in these areas.

The composite values (Figure 10) indicates that the geological unit Q1-Q3 was the major contributor in Mwogo Upper subcatchment over January-April, 2016. This geological unit contributed 18 to 60% and is dominant in Nyamagabe district (Cyanika and Gasaka sectors); Huye district (Rwaniro, Kigoma, Simbi , Ruhashya, Mbazi sectors). The land use is mainly open agriculture and mining. The dominance of Q1-Q3 in sediment composition is also seen in each of the individual sampling rounds (Figure 6), followed by Nw that has a uniform value of 10-15% and Gt.

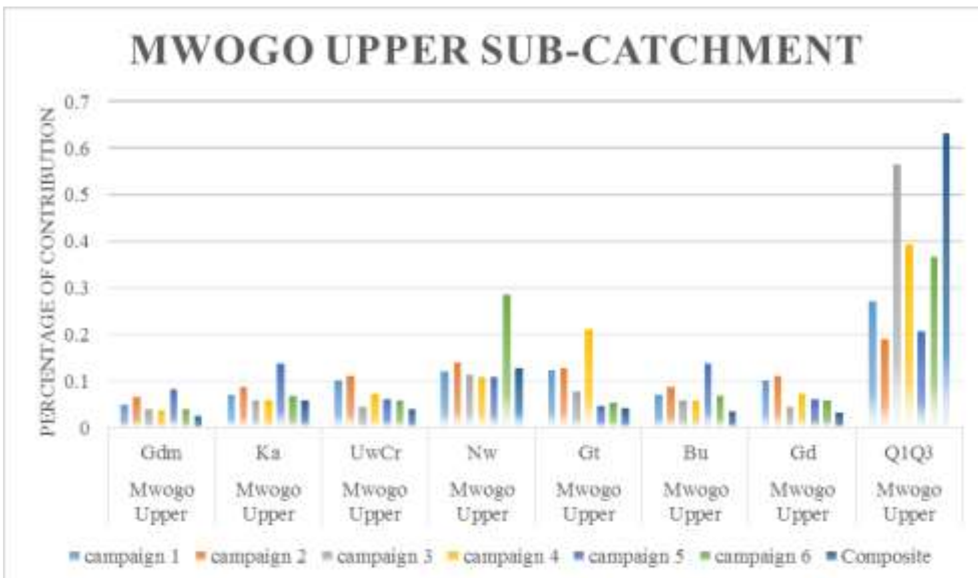


Figure 11: Bar chart indicating the relative proportions of geological types in sediment in the Upper Mwogo River at each of the sampling campaigns as well as the composite sample

Upper Mwogo Catchment

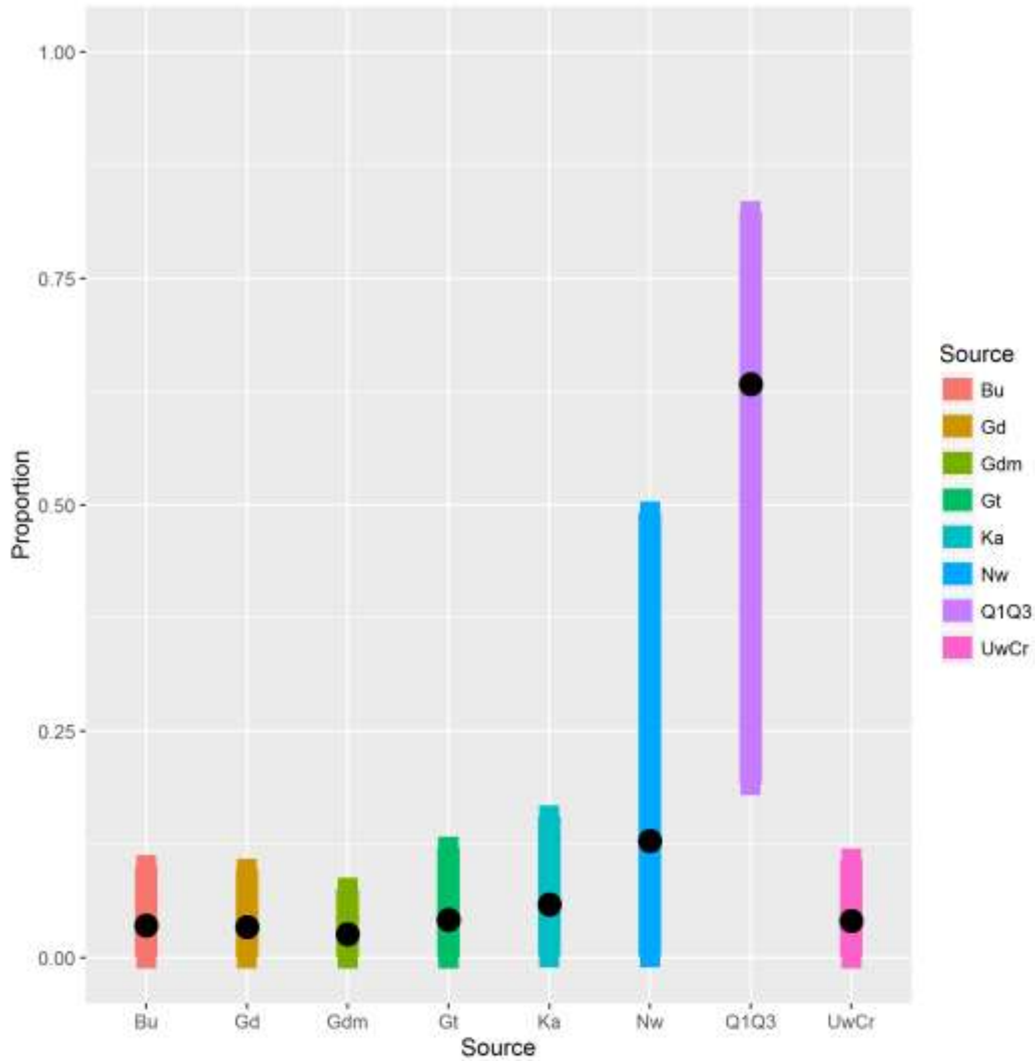
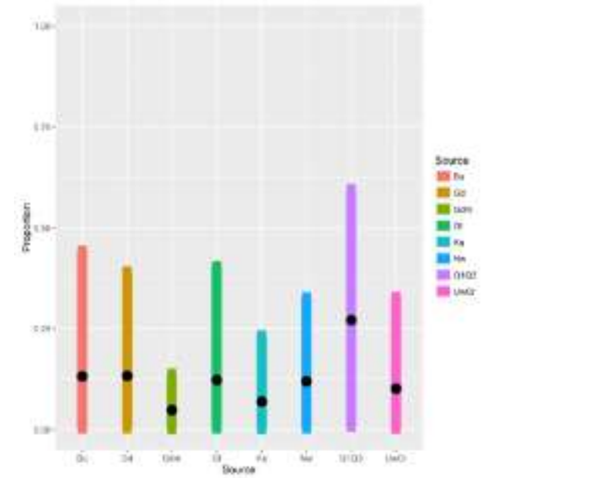


Figure 12: Box Plot showing proportions of sediment composition represented by each geological type in Upper Mwogo catchment.

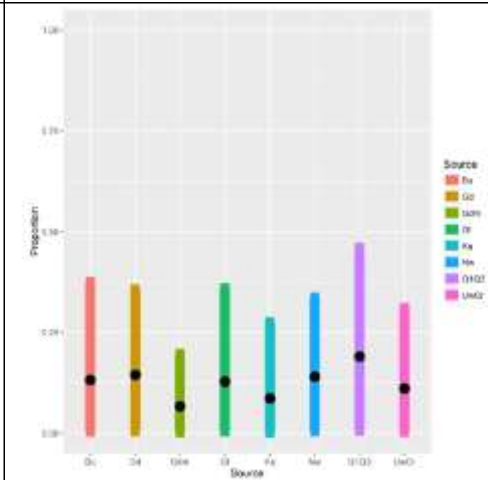
Table 4: Mean, standard deviation and confidence intervals of sediment proportions by constituent geological types or sources

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Q1Q3	0.633	0.159	0.192	0.284	0.571	0.67	0.739	0.823	0.845
Nw	0.129	0.156	0.002	0.004	0.021	0.063	0.184	0.491	0.573
Ka	0.059	0.049	0.002	0.003	0.019	0.047	0.086	0.156	0.18
Gt	0.042	0.039	0.001	0.002	0.013	0.031	0.06	0.121	0.143
UwCr	0.041	0.035	0.001	0.002	0.014	0.032	0.059	0.108	0.129
Bu	0.036	0.034	0.001	0.002	0.01	0.026	0.05	0.101	0.127
Gd	0.034	0.032	0.001	0.002	0.011	0.025	0.048	0.097	0.119
Gdm	0.026	0.025	0.001	0.002	0.008	0.019	0.036	0.076	0.094

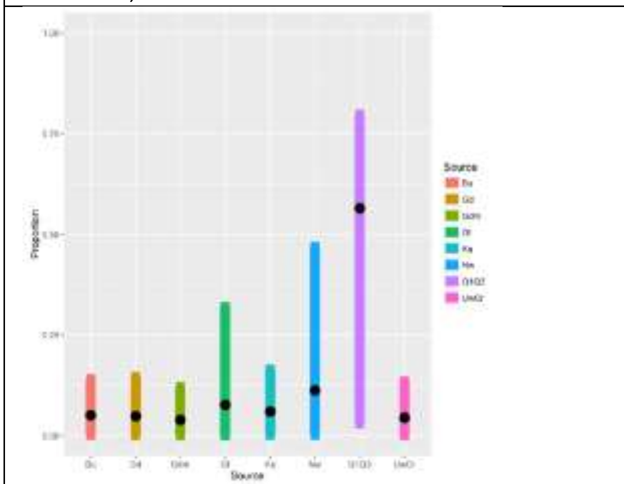
January 21-25, 2016



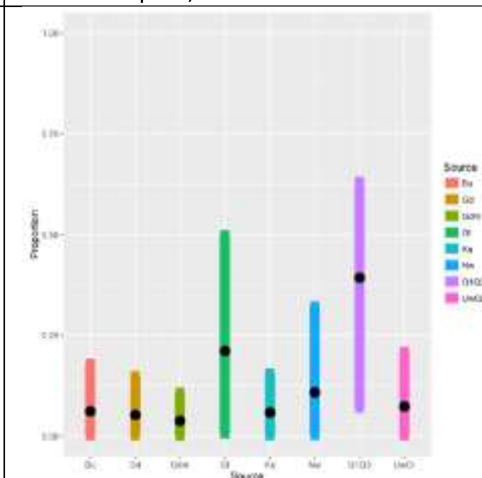
February 7-12, 2016



March 3-7, 2016



March28-April1, 2016



April 21-25, 2016

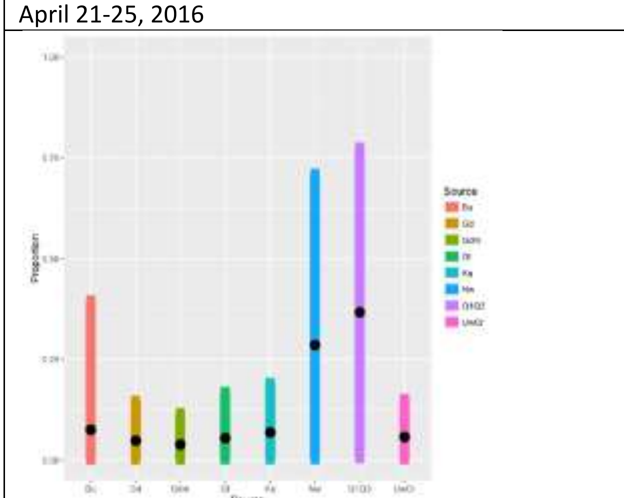


Figure 13: Source proportions of sediment sampled in the Mwogo river (bottom right).

3.2.2 Rukarara subcatchment - one of the headwaters of the NNYU

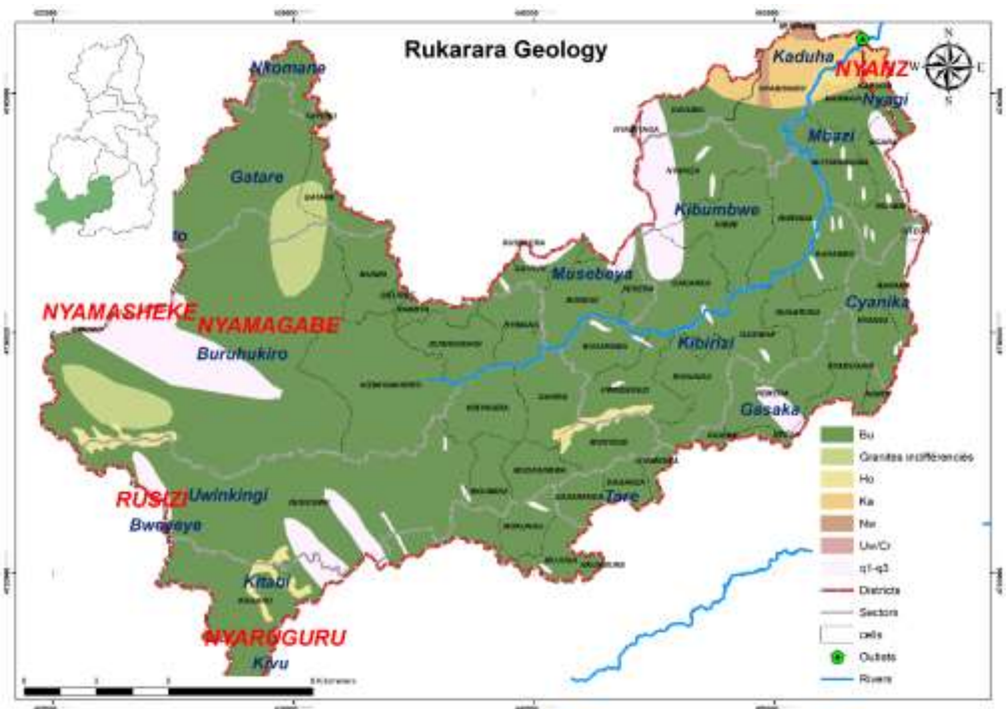


Figure 14: Geological formations in the Rukarara Subcatchment

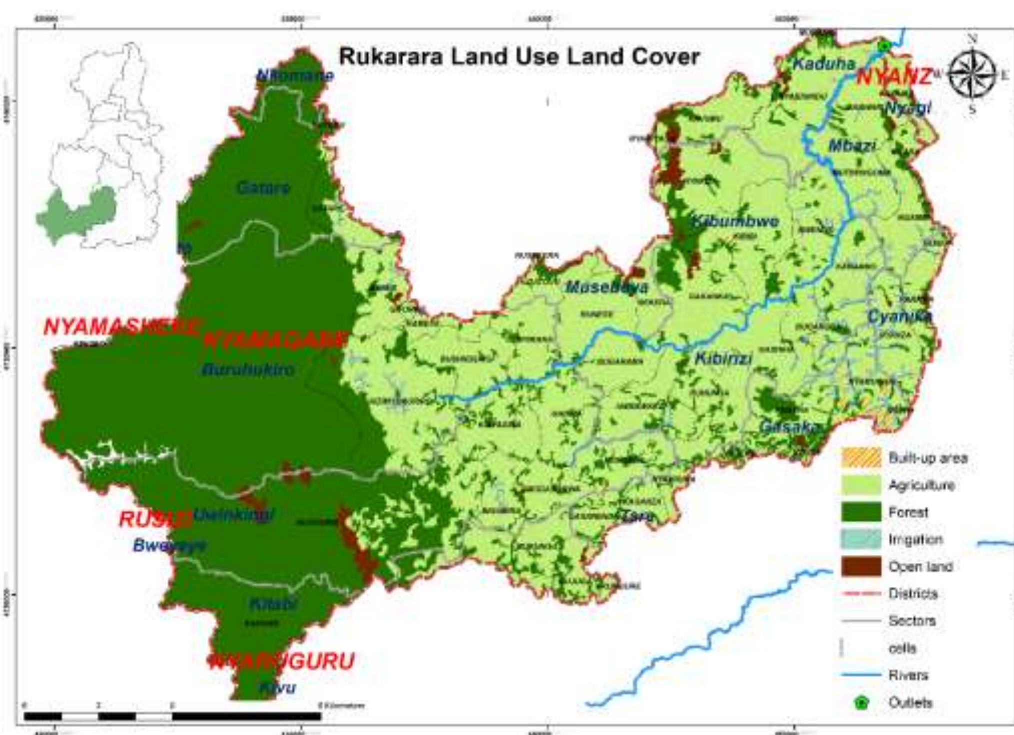


Figure 15: Land use in the Rukarara subcatchment

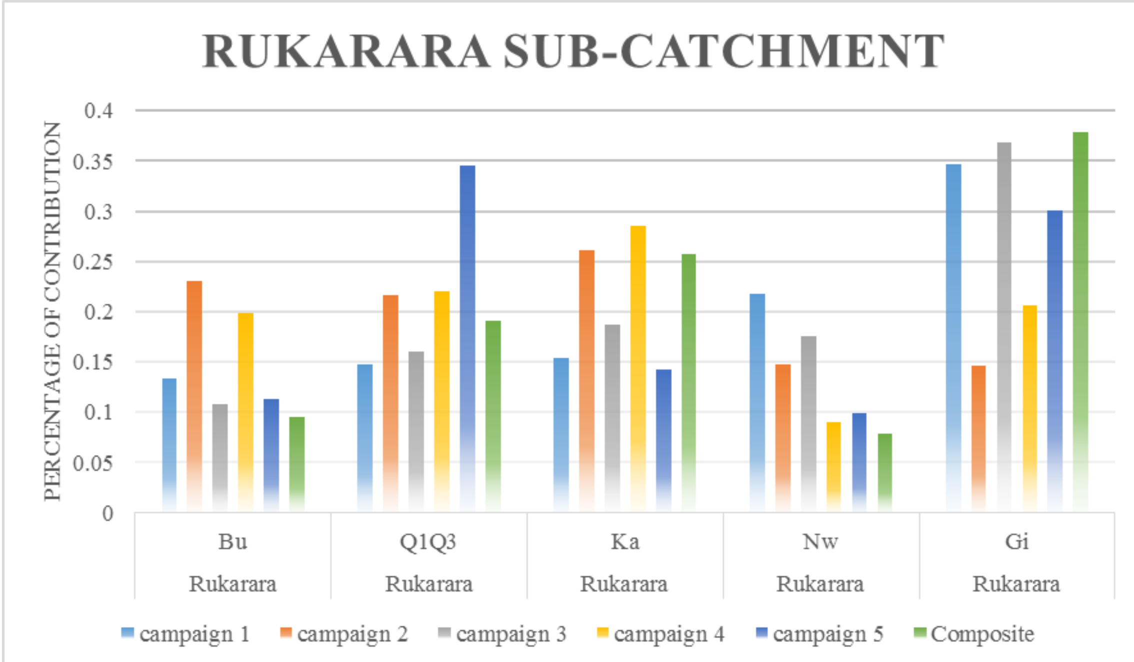


Figure 16: Sediment proportions by source geological types over 5 samplings and composite (last bar in each series) for Rukarara subcatchment.

In Rukarara sub catchment (Table 2), the sediment major contributors geological units are GI (Granite indifferecie) with 14% to 37 % followed by Q1-Q3 with 14% to 34% and Ka with Q1 - Q3 is dominant in Gasaka, Kibirizi and Mbazi sectors with open agriculture land use while Ka is dominant in Kaduha with open agriculture land use. The western part of the catchment has primary forest (Nyungwe National Park) foillowed by tea plantations and agroforestry. Hence the streams are clear running more than halfway down the catchment. However, as will be seen later in section 3.3, the average sediment concentration between January and April measured on the Rukarara catchment outlet (close to the confluence with Mwogo) is on the same order as other tributaries in the Upper Nyabarongo system, indicating significant sediment entering the Rukarara river in the lower part of the Rukarara catchment.

Rukarara Catchment

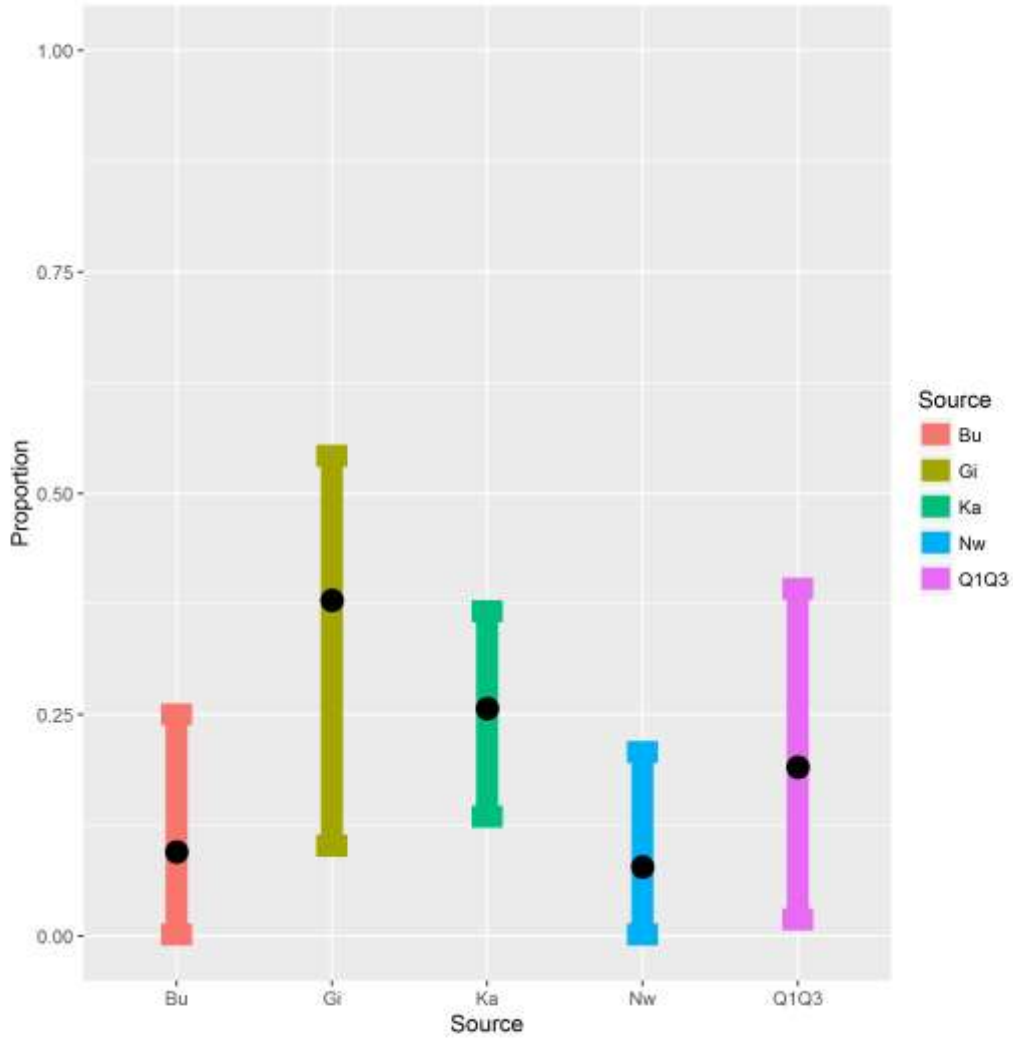


Figure 17: Proportions of sediment represented by each geological type.

Table 5: Mean, standard deviation and confidence intervals of sediment proportion held by each geological type in Rukarara catchment.

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Gi	0.379	0.111	0.102	0.165	0.318	0.389	0.453	0.542	0.563
Ka	0.257	0.065	0.135	0.153	0.215	0.254	0.299	0.367	0.387
Q1Q3	0.191	0.11	0.019	0.033	0.112	0.178	0.254	0.392	0.441
Bu	0.095	0.084	0.002	0.005	0.032	0.075	0.132	0.25	0.309
Nw	0.078	0.071	0.002	0.005	0.026	0.059	0.111	0.208	0.253

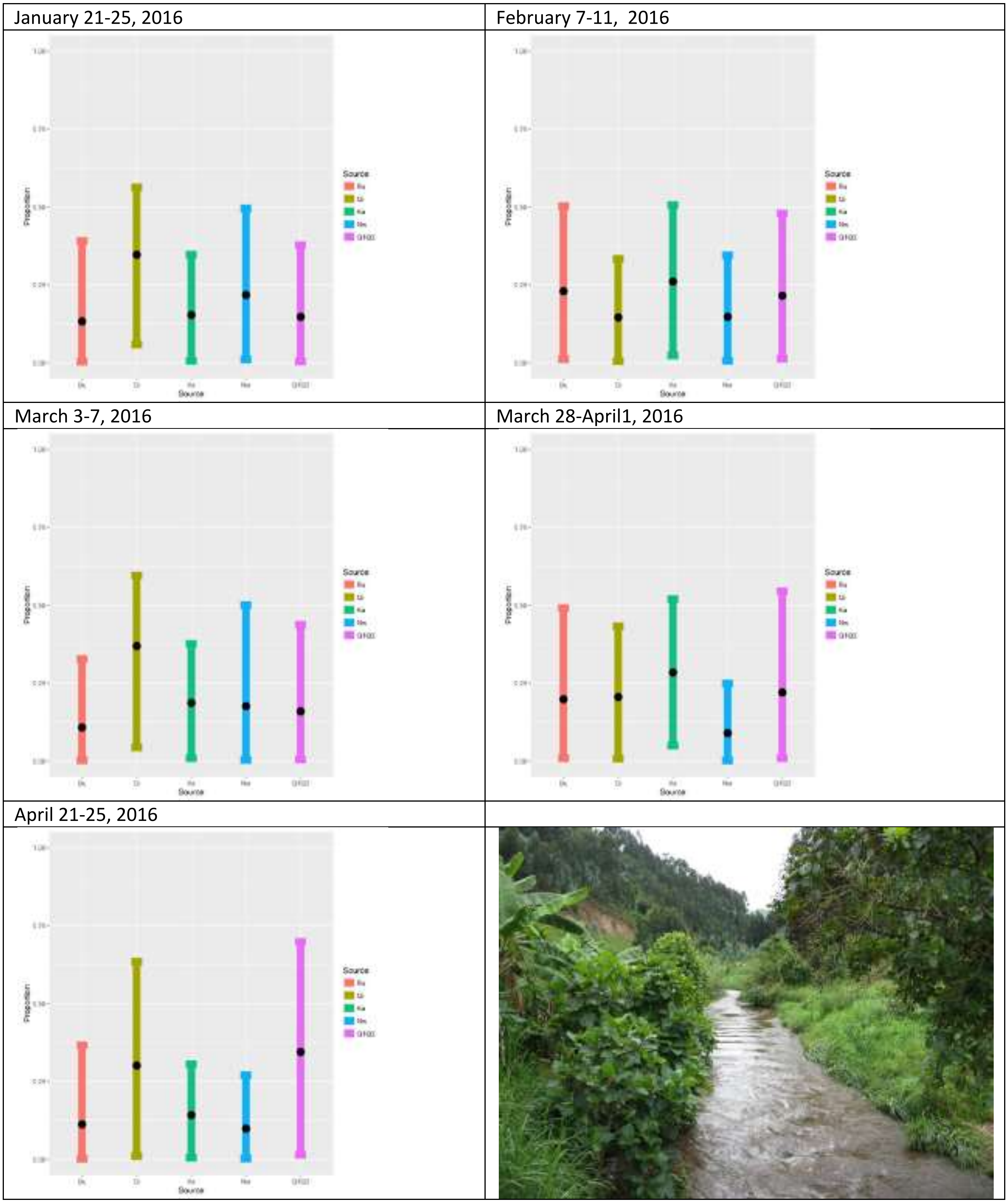


Figure 18: Source proportions of sediment sampled in the Rukarara river. Bottom right shows the Rukarara emerge from tea plantations, where the water is still relatively clear.

3.2.3 Mbirurume sub catchment - one of the headwaters of the NNYU

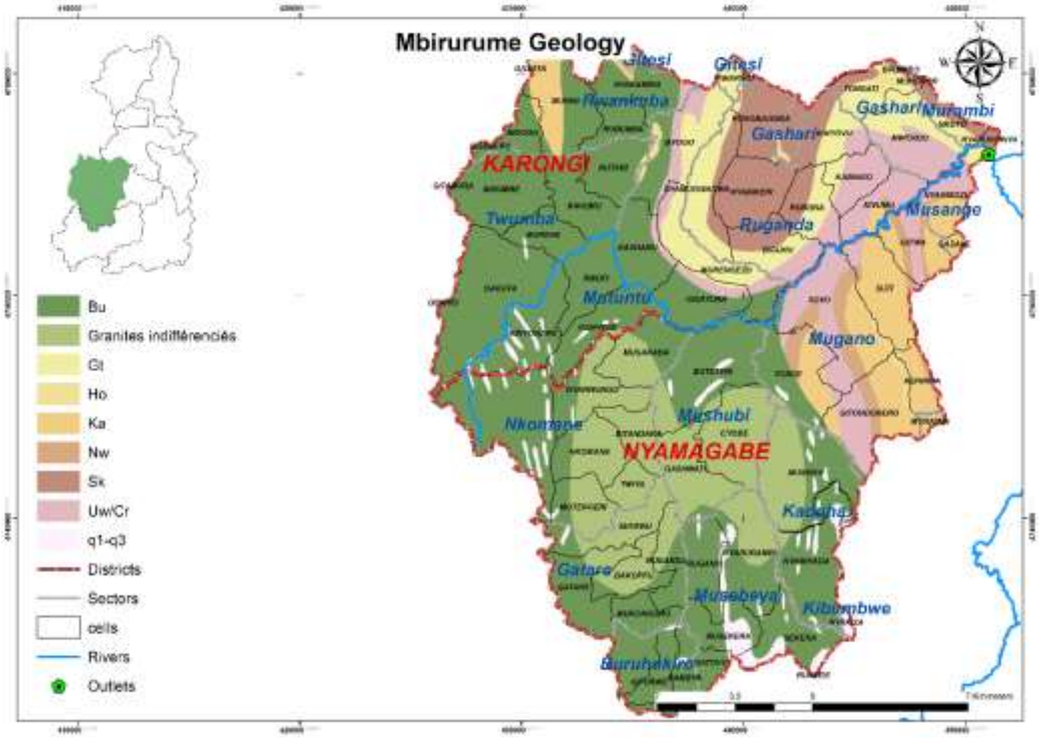


Figure 19: Geological formations in Mbirurume Catchment

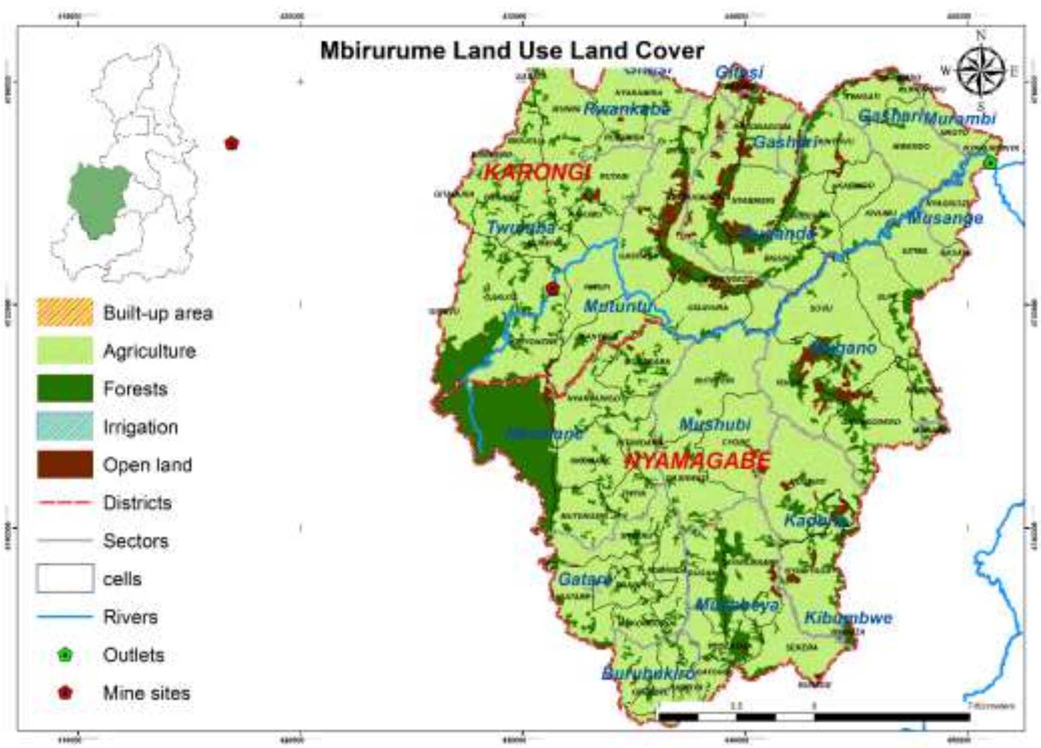


Figure 20 : Land Use in Mbirurume catchment

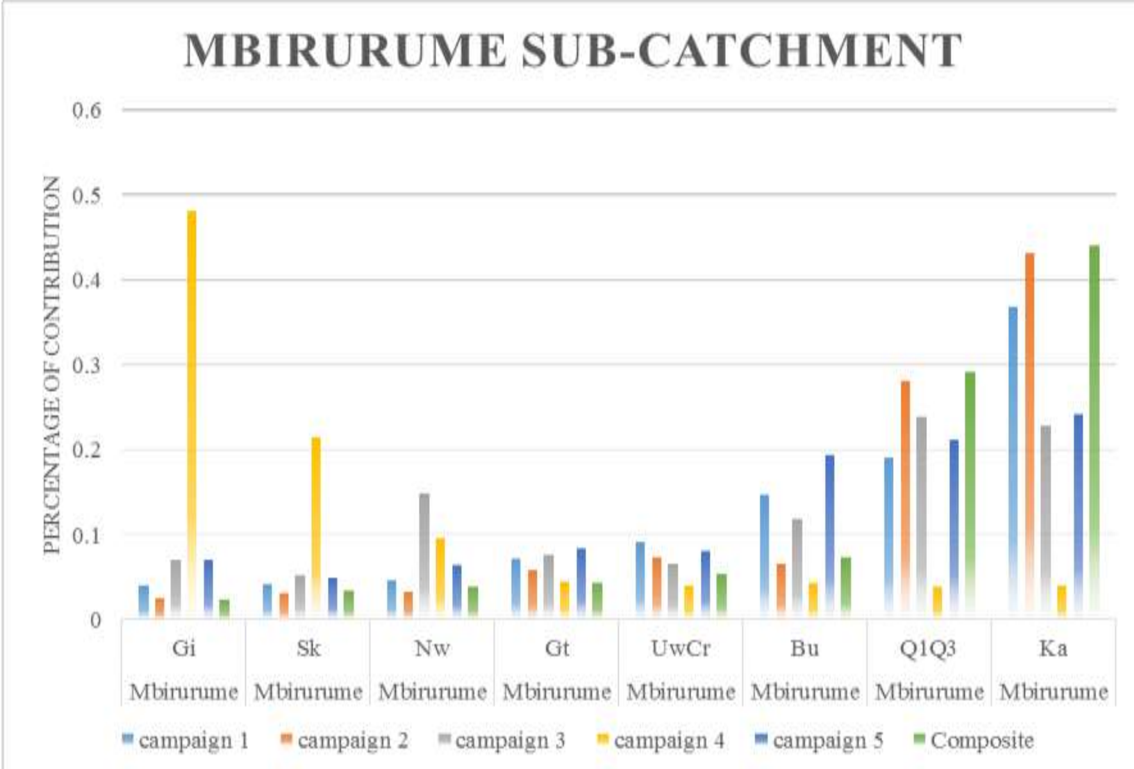


Figure 21: Bars showing source proportions of sediment at 5 sampling events. Last bar in each series represents the composite from pooling all samples.

In Mbirurume subcatchment, the geological units that are major sediment contributors are Ka with 22 % to 44% for most of the sampling campaign, dominant in Nyamagabe District in Musange sector with open agriculture land use. The second geological unit is qi-q3 with 18% -28% and it dominant in Nyamagabe district Kaduha sector with open agriculture land use while Bu geological units come third with around 5% to 18 % as major sediment contributor and it in Rwankuba sector in Nyamagabe distric with open agriculture as land use activity.

Mbirurume Catchment

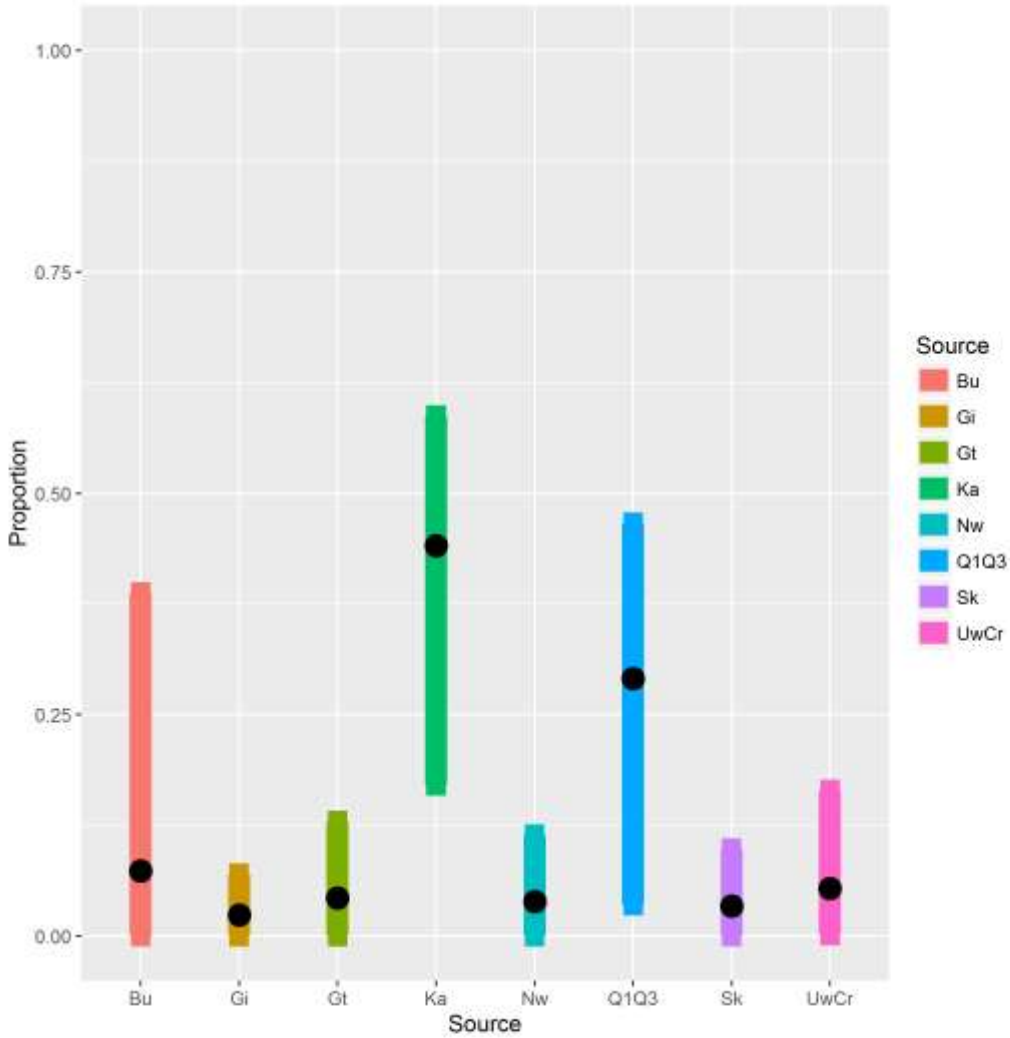


Figure 22: Source proportions of sediment pooled over five sampling events

Table 6: Mean, standard deviation and confidence intervals of source proportions - composite

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Ka	0.441	0.107	0.171	0.251	0.388	0.452	0.509	0.587	0.612
Q1Q3	0.291	0.109	0.036	0.109	0.221	0.292	0.364	0.466	0.504
Bu	0.074	0.131	0.001	0.002	0.013	0.032	0.072	0.387	0.594
UwCr	0.054	0.054	0.002	0.003	0.016	0.037	0.077	0.164	0.2
Gt	0.043	0.044	0.001	0.002	0.012	0.029	0.058	0.129	0.156
Nw	0.039	0.037	0.001	0.002	0.013	0.029	0.055	0.114	0.134
Sk	0.034	0.033	0.001	0.002	0.01	0.024	0.048	0.098	0.121
Gi	0.024	0.023	0.001	0.002	0.007	0.017	0.033	0.07	0.087

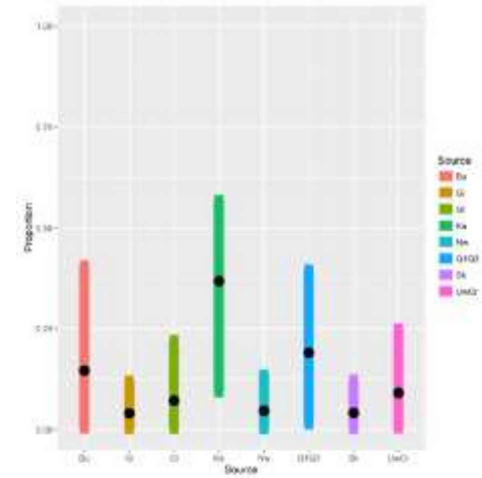
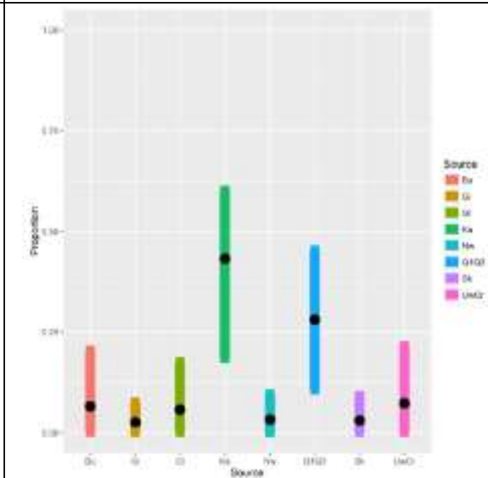
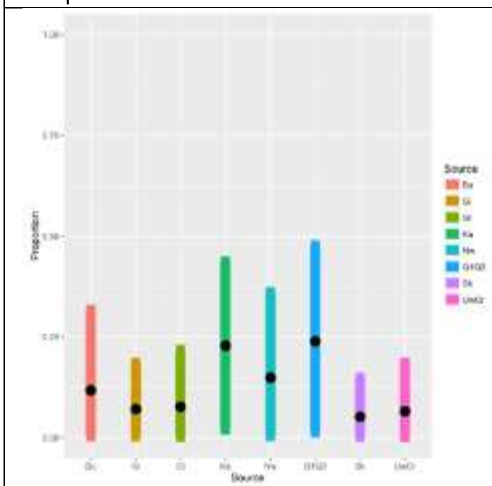
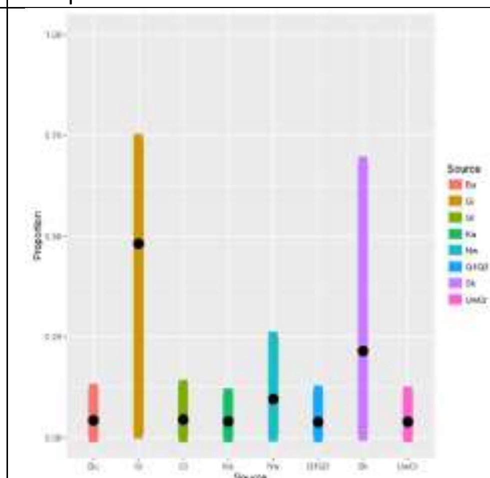
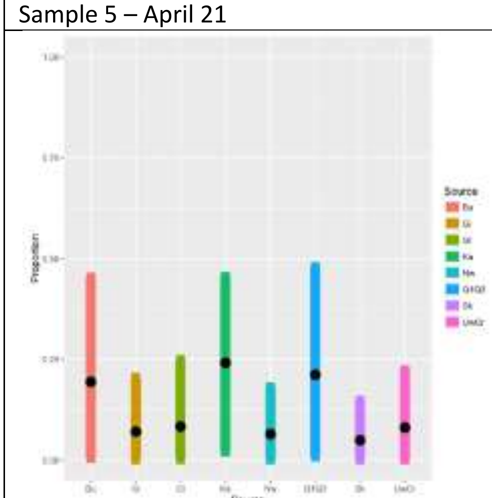
Sample 1 – January 21	Sample 2 – February 10
	
Sample 3 – March 7	Sample 4 – March 28
	
Sample 5 – April 21	
	

Figure 23: Source proportions in sediment sampled in the Mbirurume River.

3.2.4 Nyabarongo Headwaters sub catchment – combination of Mwogo, Rukarara and Mbirurume subcatchments

Figure 24: Geological formations in Nyabarongo headwaters region

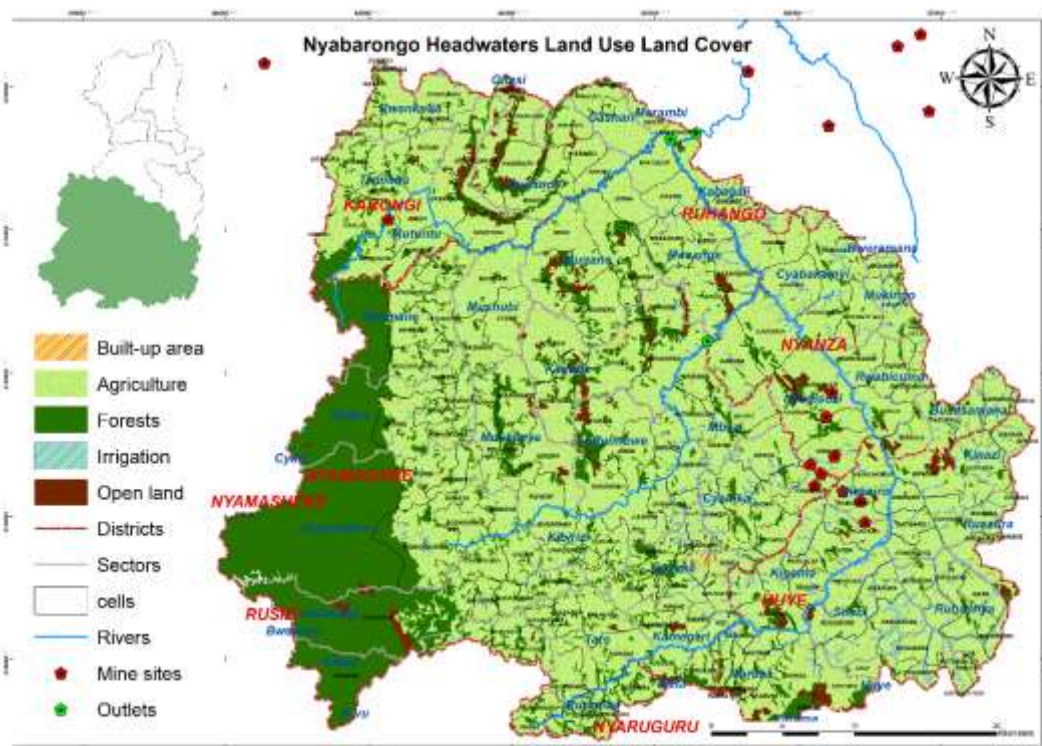


Figure 25: Land use in Nyabarongo headwaters region

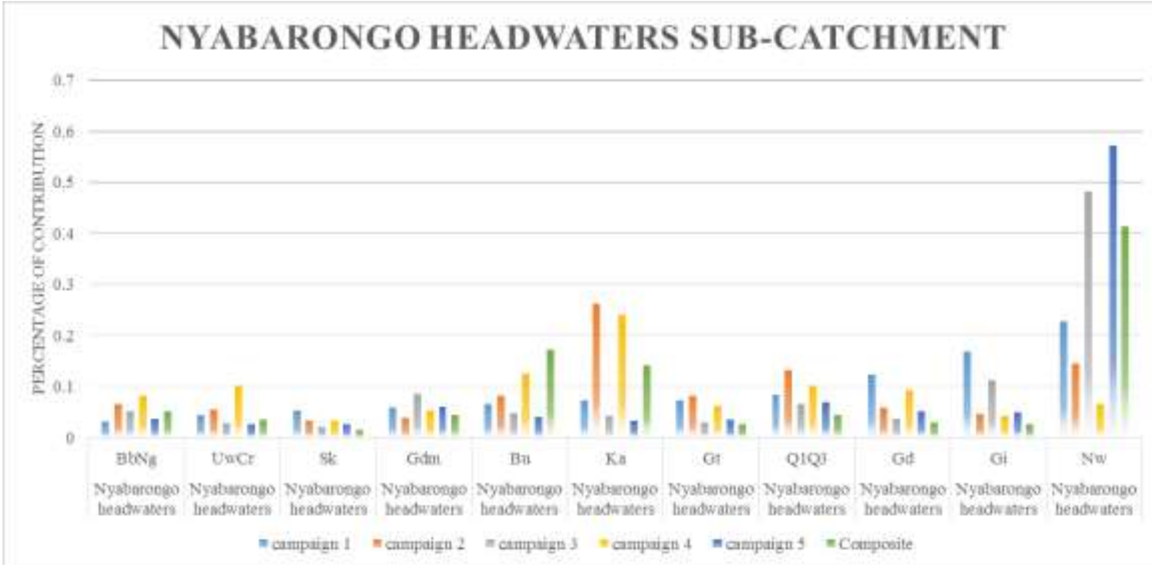


Figure 26: Bar chart showing source proportions in the 5 individual sampling events as well as the composite (last bar in each group)

In the Nyabarongo headwaters region, the major sediment contributing geological unit is Nw with around 15% to 58 %. Nw is dominant in Nyagisozi sector in Nyanza District. The major activities are mining and open agriculture land use. Note that the geological types that were dominant contributors in the upstream headwater tributaries are no longer dominant after the Mwogo meets the Mbirurume to form the Nyabarongo. This indicates that the sediment composition changes along different reaches of the river system.

Nyabarongo Headwaters

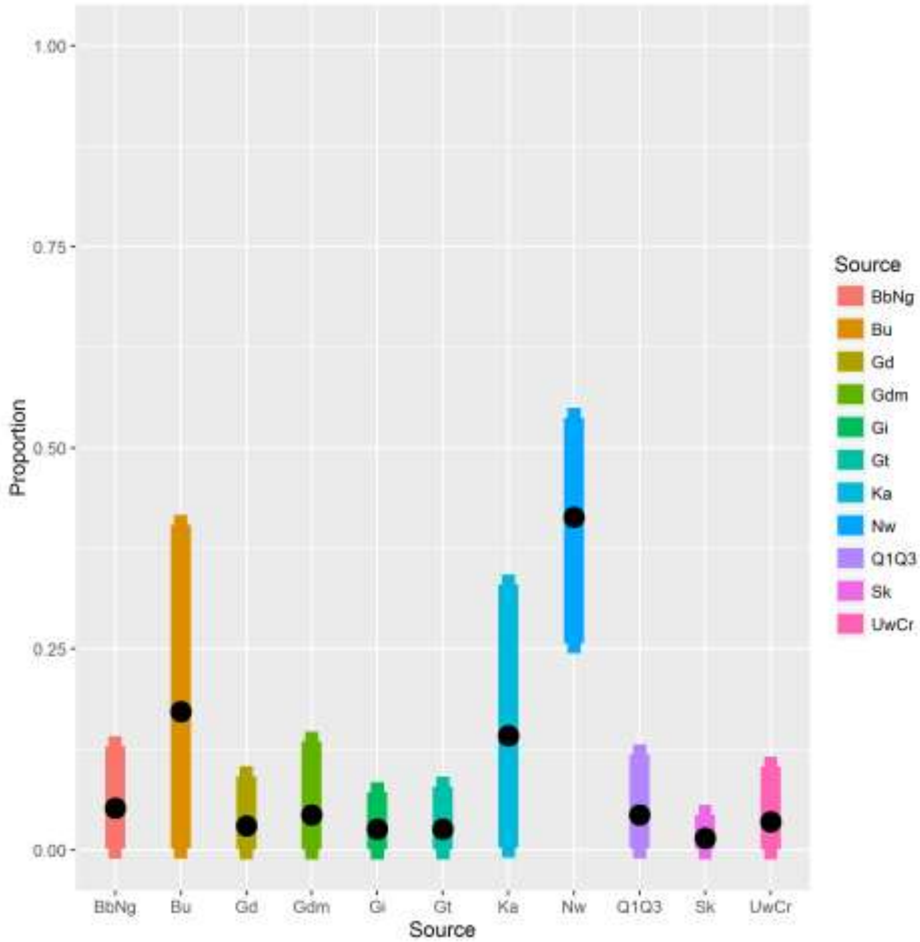


Figure 27: Source proportions in sediment samples pooled into a composite

Table 7 : Mean, standard deviation and confidence intervals of the sediment composition proportion of each geological type

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Nw	0.414	0.079	0.257	0.28	0.364	0.417	0.47	0.537	0.56
Bu	0.172	0.141	0.002	0.004	0.032	0.155	0.296	0.404	0.434
Ka	0.142	0.109	0.003	0.006	0.039	0.124	0.23	0.33	0.365
BbNg	0.052	0.04	0.002	0.004	0.022	0.045	0.072	0.129	0.155
Gdm	0.044	0.044	0.001	0.002	0.011	0.03	0.06	0.135	0.166
Q1Q3	0.044	0.037	0.002	0.003	0.015	0.035	0.063	0.119	0.139
UwCr	0.035	0.035	0.001	0.001	0.01	0.024	0.049	0.104	0.131
Gd	0.03	0.032	0.001	0.002	0.008	0.02	0.042	0.092	0.117
Gi	0.026	0.024	0.001	0.002	0.008	0.02	0.038	0.072	0.085
Gt	0.026	0.027	0.001	0.001	0.007	0.017	0.035	0.079	0.099
Sk	0.015	0.015	0.001	0.001	0.005	0.011	0.021	0.044	0.057

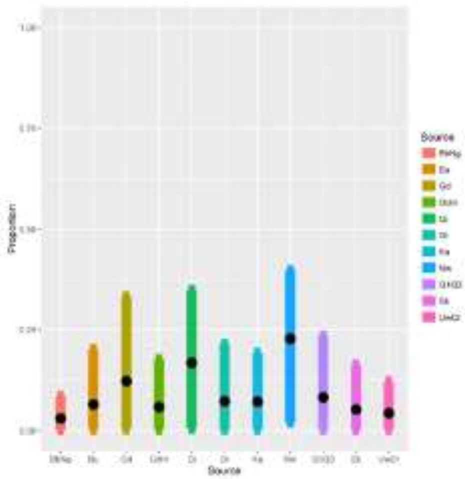
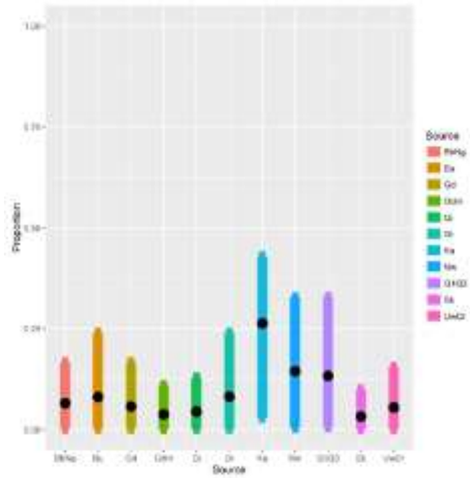
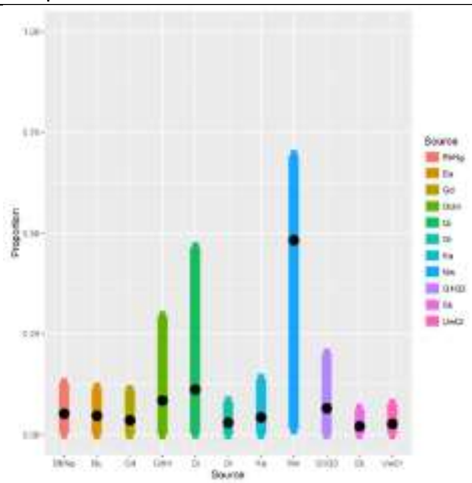
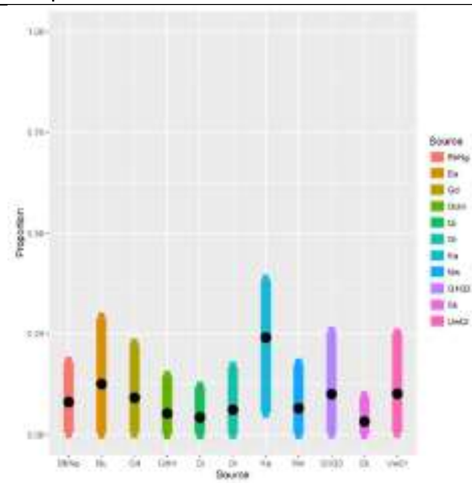
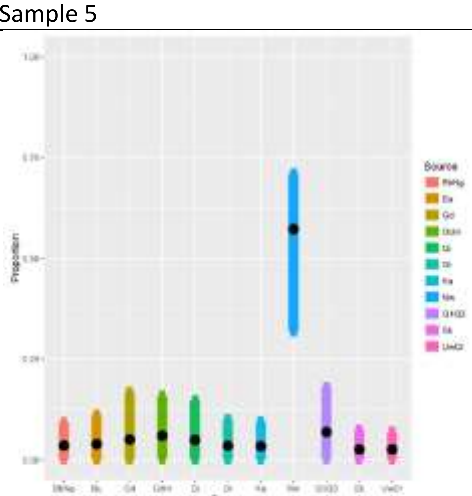
Sample 1	Sample 2
	
Sample 3	Sample 4
	
Sample 5	
	

Figure 28: Source proportions for sediment in the Nyabarongo river headwaters, that is the confluence of the Mwogo and the Mbirurume (bottom right).

3.2.5 Nyabarongo Upper sub catchment

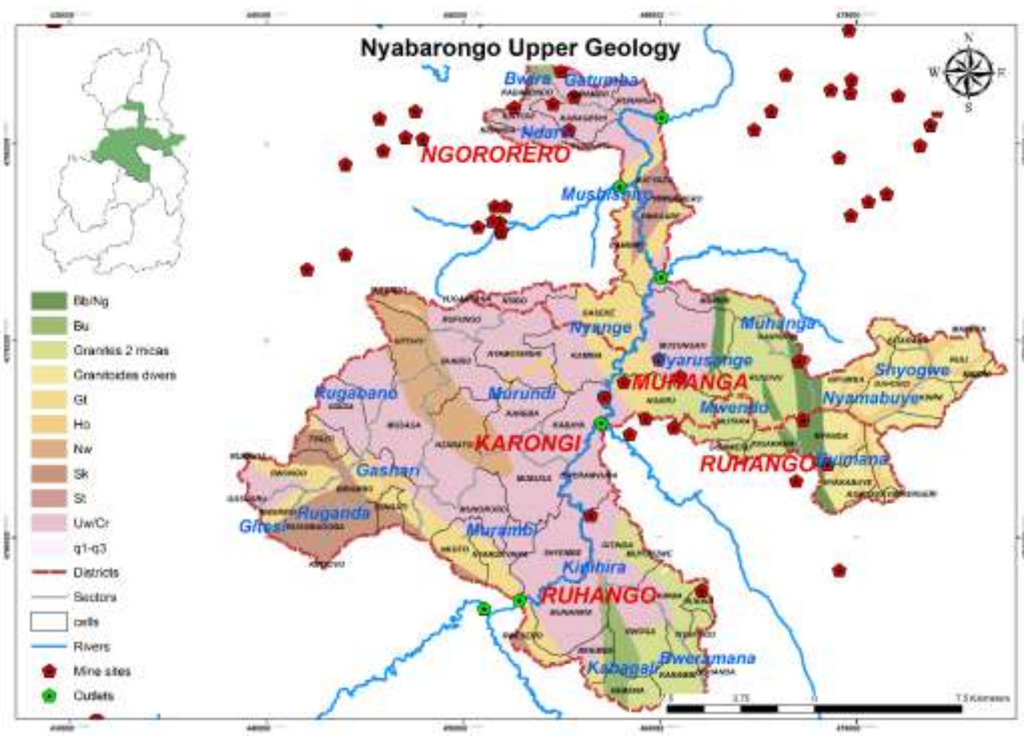


Figure 29: Geological formations in the Nyabarongo Upper Catchment

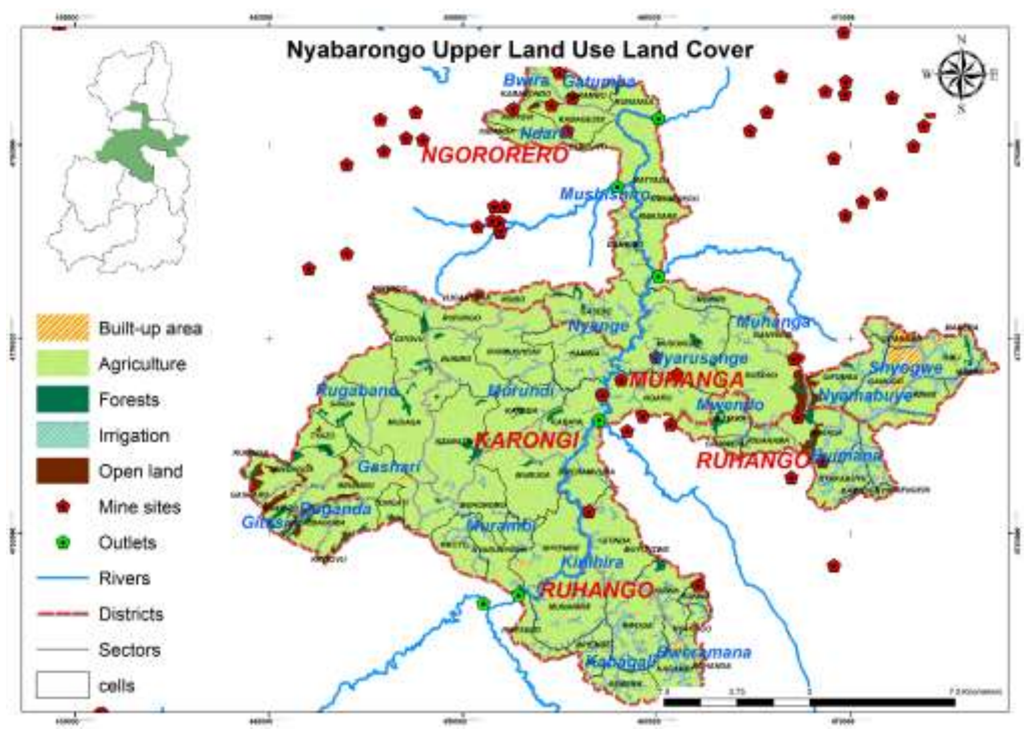


Figure 30: Land use in the Nyabarongo Upper Catchment

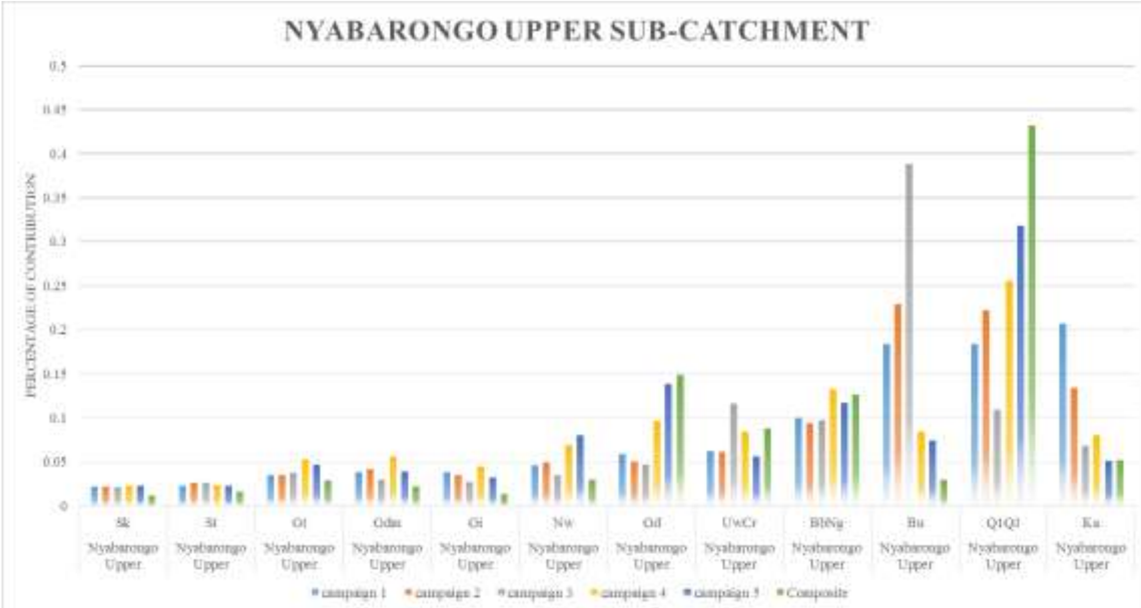


Figure 31: Source proportions of sediment sampled on 5 individual events as well as the composite of all 5 events.

Nyabarongo Upper sub catchment sediment major geological units contributors are q1-q3 with 12% to 33% followed by Bu geological unit with 18% - 38 % for the first three sampling campaign. Q1-Q3 is dominant in other tributaries of Nyabarongo upper (Mwogo upper, Rukarara and Mbirurume sub catchment) where mining and open agriculture have identified as major land use activities. Bu is dominant in Kabagali sector in Ruhango district with open agriculture as land use and Gatumba sector in Ngororero District with mining as land use activities .

3.2.6 Kiryango sub catchment

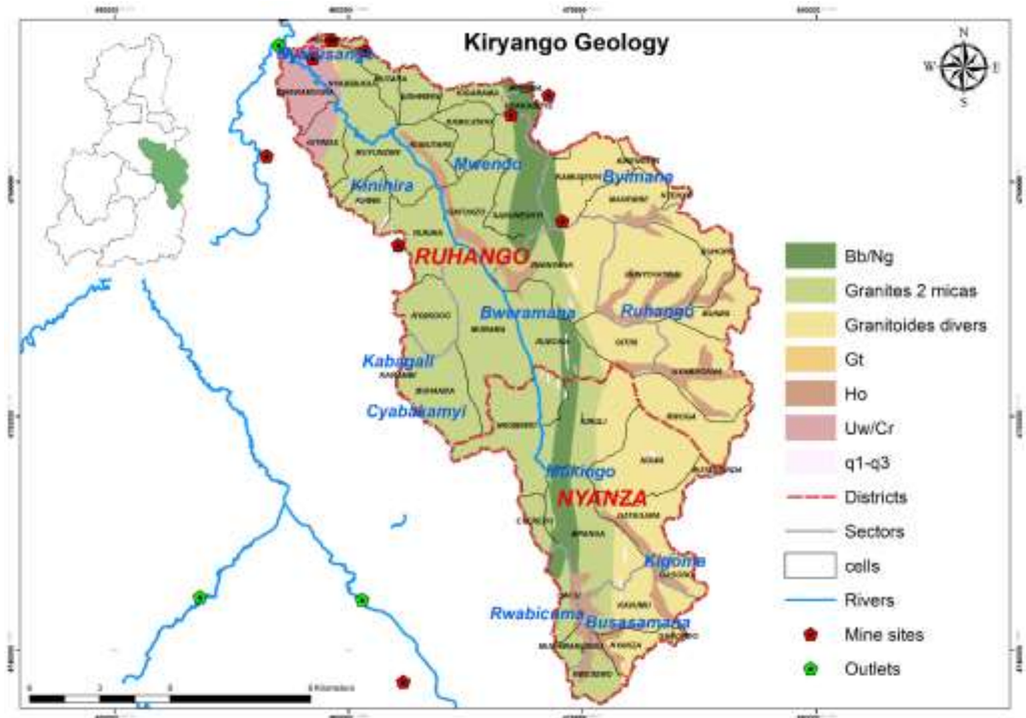


Figure 32: Geological Formations in the Kiryango catchment

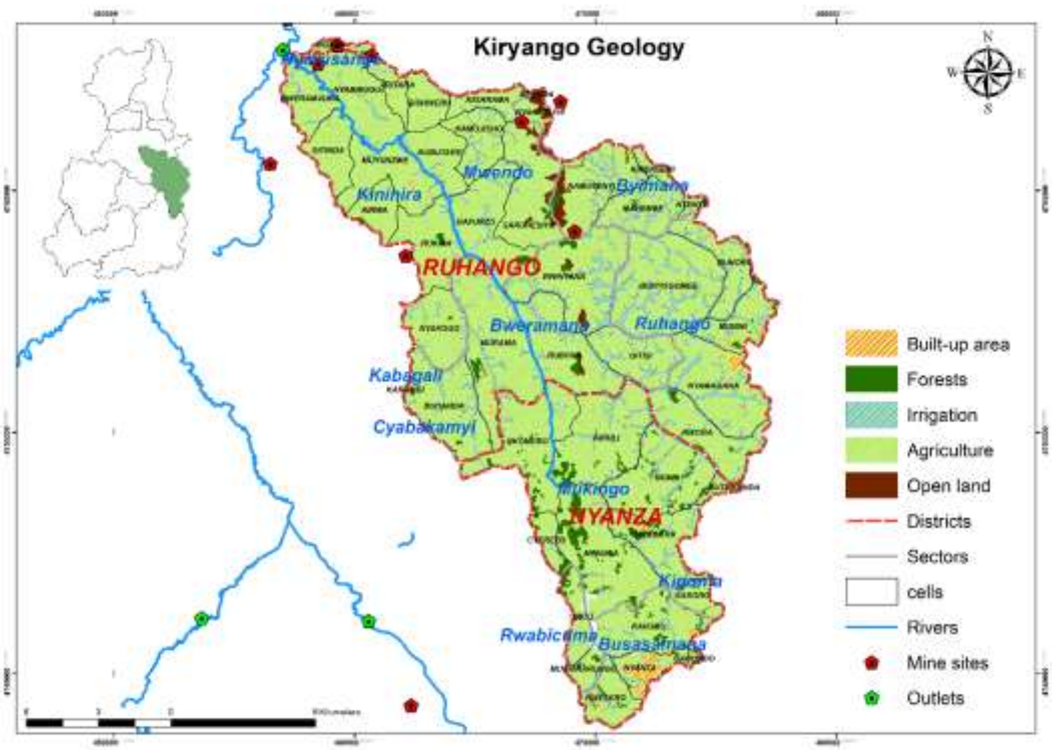


Figure 33: Land use in the Kiryango atchmemt

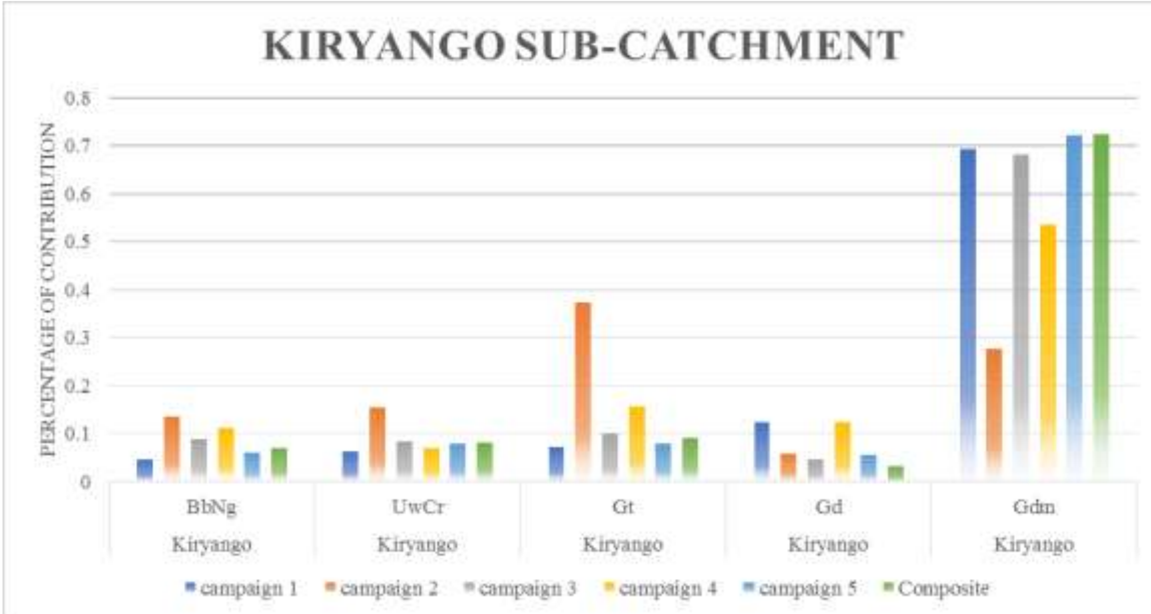


Figure 34: Source contributions to sediment composition sampled five times; the last bar represents the composite over the 5 samplings.

In the Kiryango sub catchment, the major geological unit sediment contributor was Gdm (Granite de mica) with 28% to 72% . This geological unit is dominant in Rwabicuma, Busasamana and Mukingo sector in Nyanza District as well as in Nyarusange , Mwendo, Kinihura, Kabagari, Cyabakamyi and Bweramana sectors in Ruhango distric. The major activities contributing to those sediment are open agriculture and mining on that geological units. The other geological unit that contributed up to 38% is Gt but it was only for one sampling campaign.

Kiryango Catchment

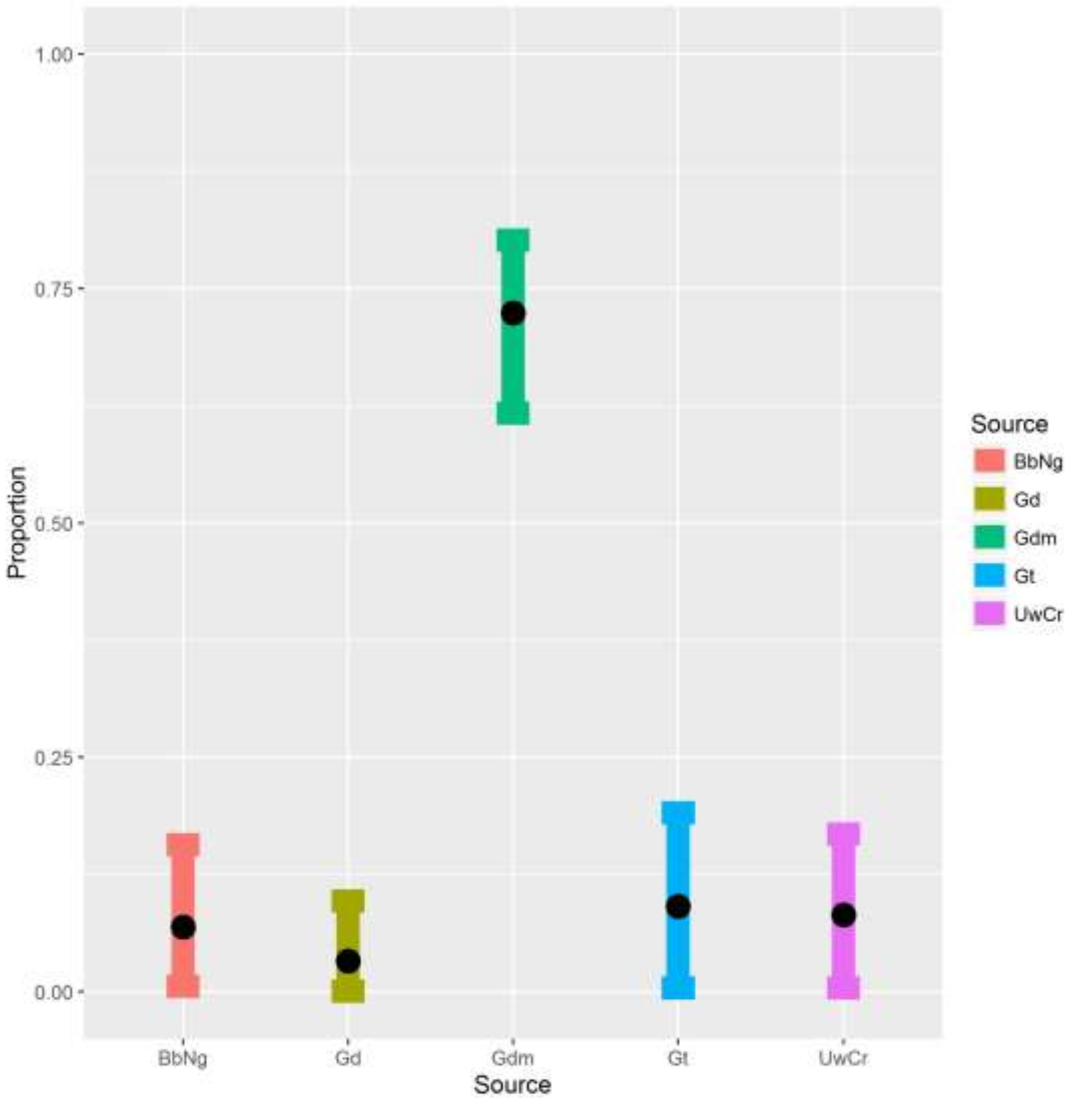
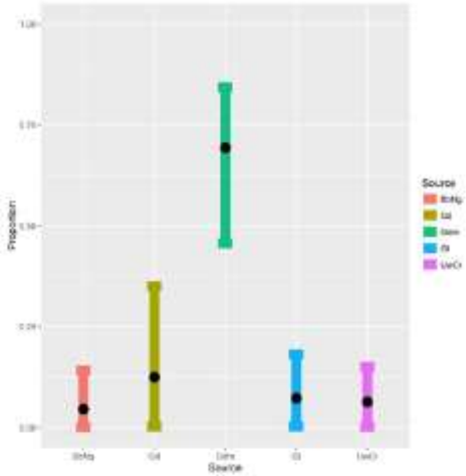


Figure 35: Source proportions of sediment composition of the composite of 5 individual sampling events.

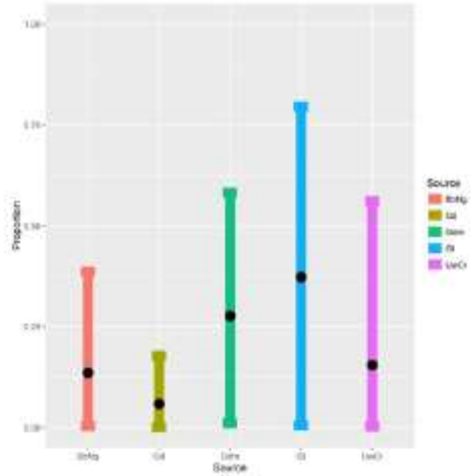
Table 8: Mean, standard deviation and confidence intrervals of diferent constituent geologivcal types in the Iryango catchment

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Gdm	0.724	0.05	0.617	0.638	0.692	0.727	0.758	0.801	0.812
Gt	0.091	0.058	0.004	0.008	0.044	0.086	0.131	0.191	0.216
UwCr	0.082	0.05	0.004	0.008	0.041	0.081	0.119	0.168	0.184
BbNg	0.069	0.045	0.006	0.011	0.039	0.062	0.09	0.157	0.183
Gd	0.033	0.031	0.001	0.002	0.01	0.024	0.048	0.097	0.115

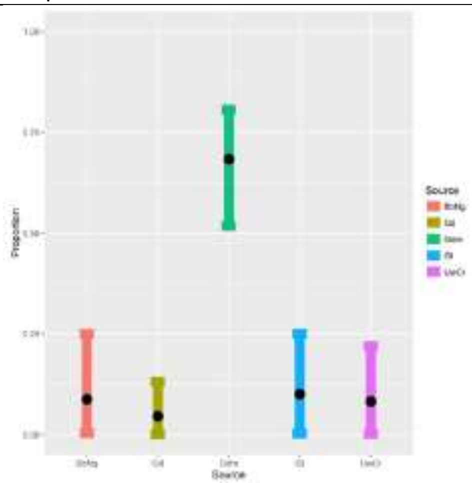
Sample 1 - Jan 21



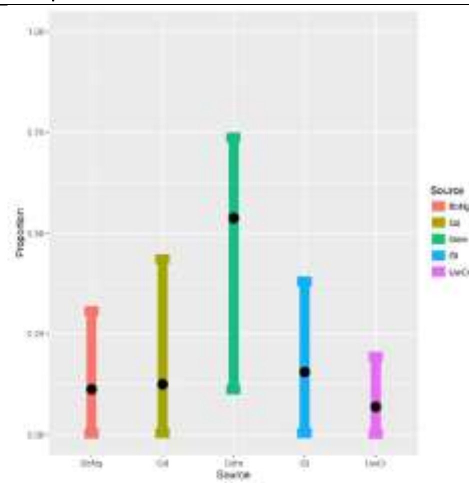
Sample 2 – Feb 10



Sample 3 – March 7



Sample 4 – March 28



Sample 5 – April 21

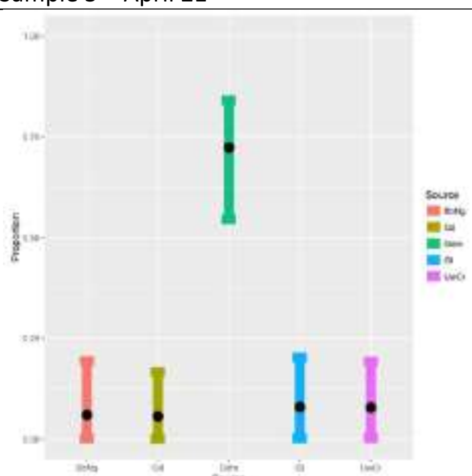


Figure 36: Source proportions in sediment sampled in the Kiryango catchment.

3.2.7 Nyagako subcatchment

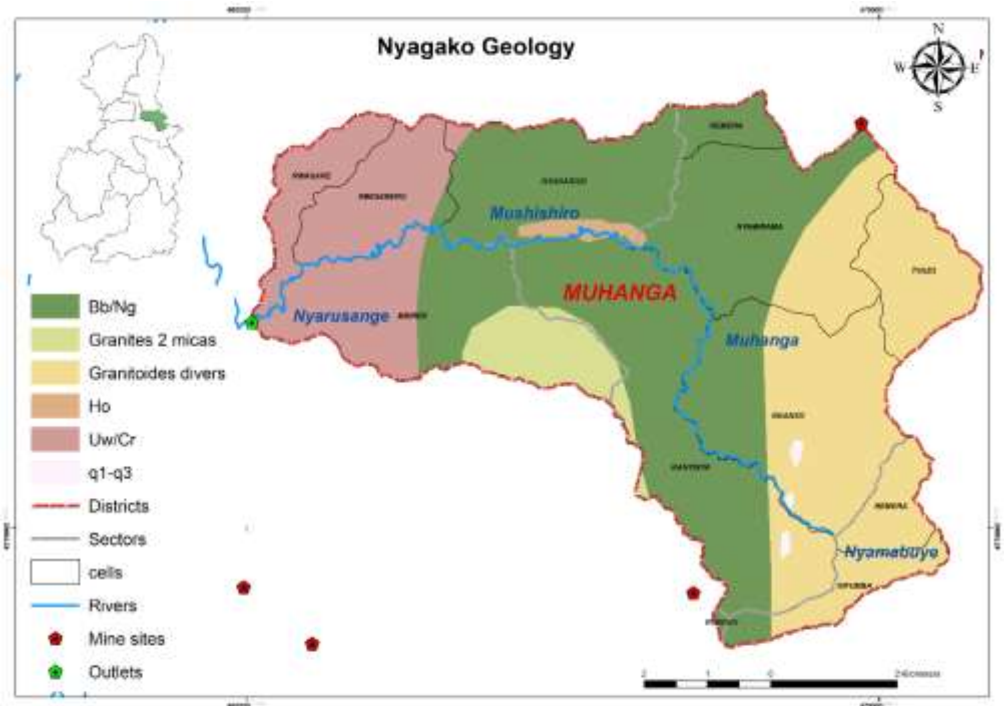


Figure 37: Geological formations in Nyagako catchment

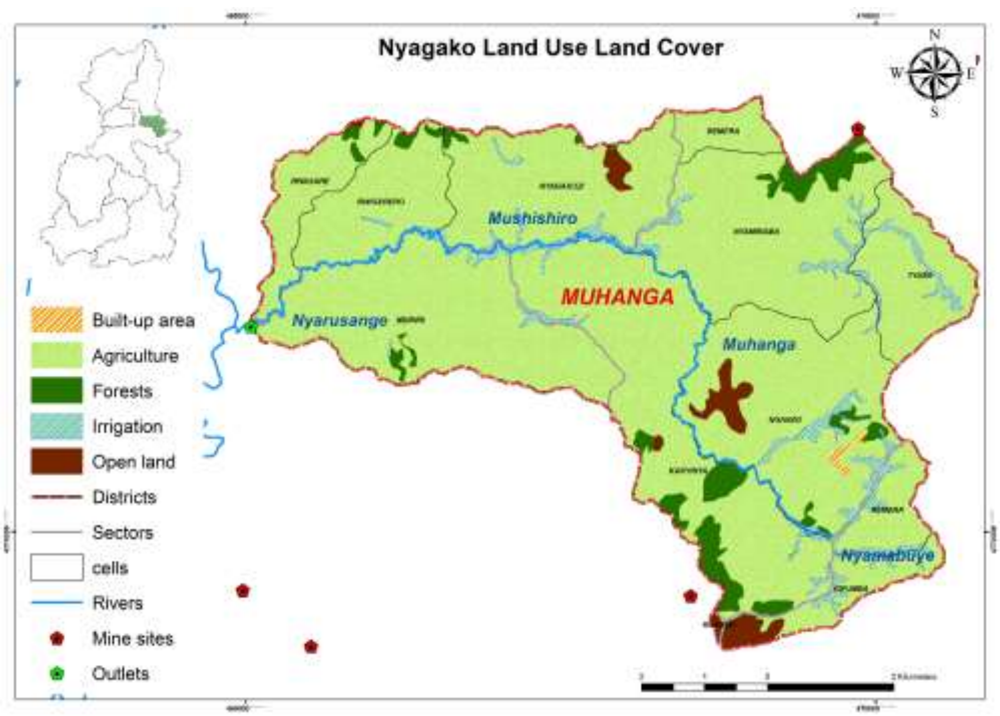


Figure 38: Land use in Nyagako catchment

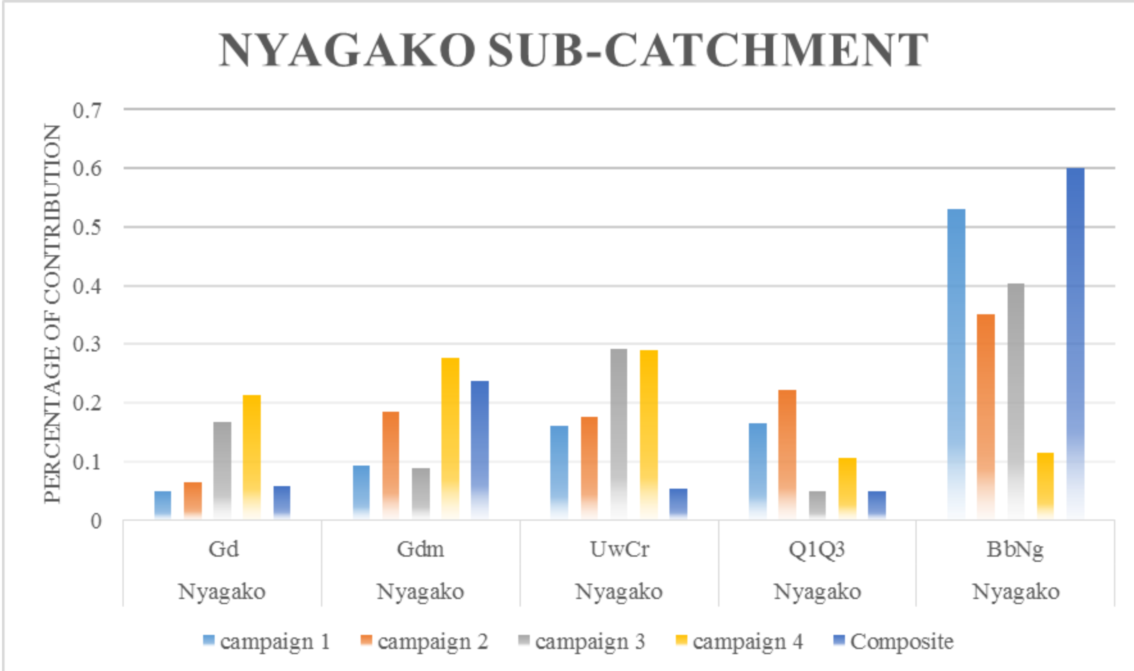


Figure 39: Source proportions in individual sediment sampling events as well as in the composite obtained by pooling all 5 events.

Nyagako sub catchment sediment major geological unit contributor was Bb/Ng with 36% - 60% for the first three sampling campaign. This Bb/Ng geological unit is dominant in Mushishiro, Muhanga and Nyarusange sectors in Muhanga District. The land use activity for Bb/Ng is mainly open agriculture. Gdm and Uw/Cr geological units contributed each with 9-29% and are dominant in Nyarusange sector in Muhanga District with open agriculture as land use major activity. Gd and q1-q3 geological units contributed each with less than 22%. Again open agriculture is the major activities in those geological units.

Nyagako Catchment

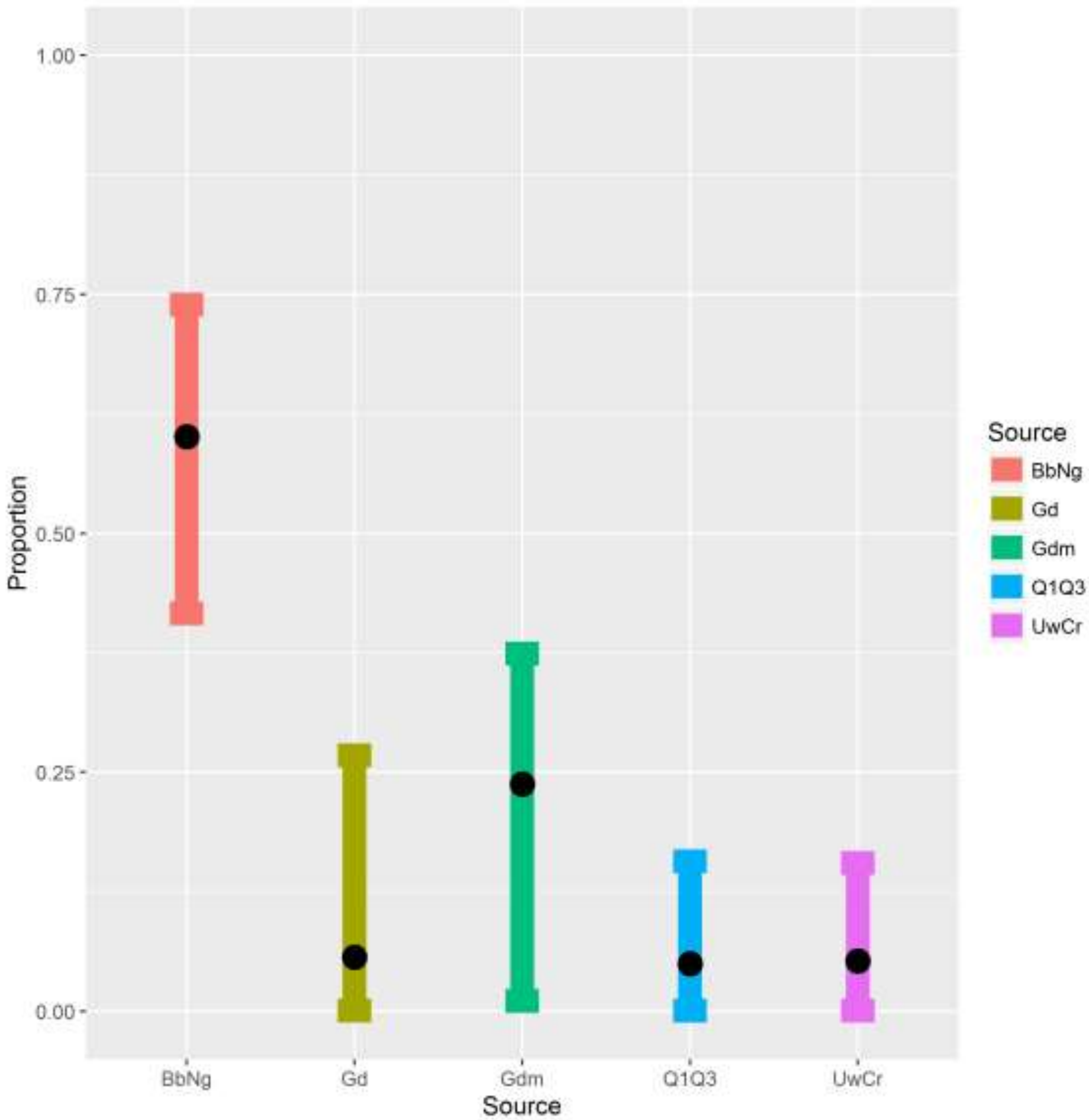
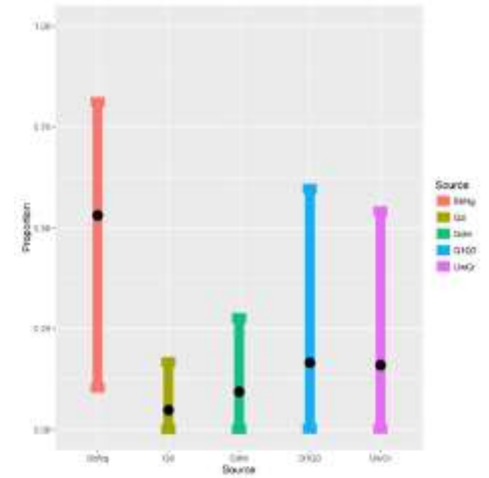


Figure 40: Source proportions in ssdiment composite

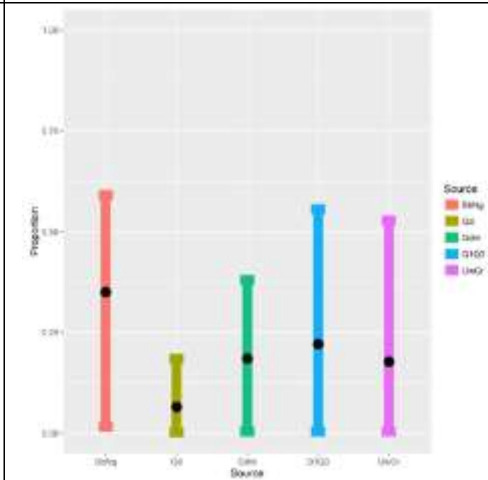
Table 9: Means, standard deviation and confidence intervals of source proportions in the sediment composite sample.

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
BbNg	0.601	0.09	0.416	0.448	0.548	0.606	0.659	0.739	0.764
Gdm	0.238	0.097	0.011	0.029	0.19	0.251	0.308	0.374	0.393
Gd	0.057	0.083	0.001	0.002	0.011	0.028	0.057	0.268	0.344
UwCr	0.053	0.05	0.001	0.003	0.015	0.038	0.078	0.155	0.184
Q1Q3	0.05	0.07	0.001	0.002	0.013	0.029	0.061	0.157	0.229

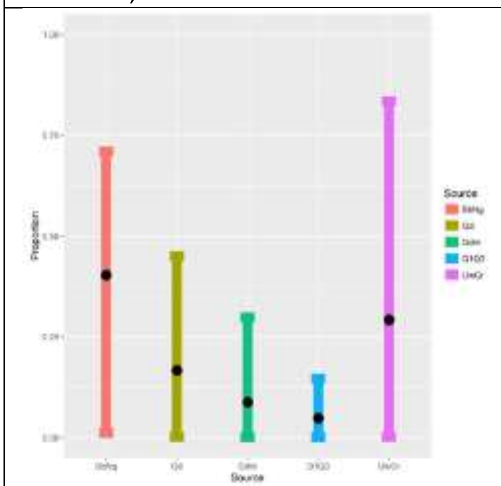
January 21-25, 2016



February 7-11, 2016



March 3-7, 2016



April 21-25, 2016

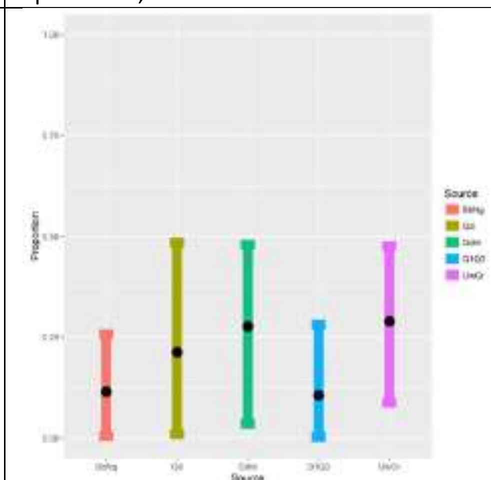


Figure 41: Source proportions in sediment present in the Nyagako river.

3.2.8 Secoko subcatchment

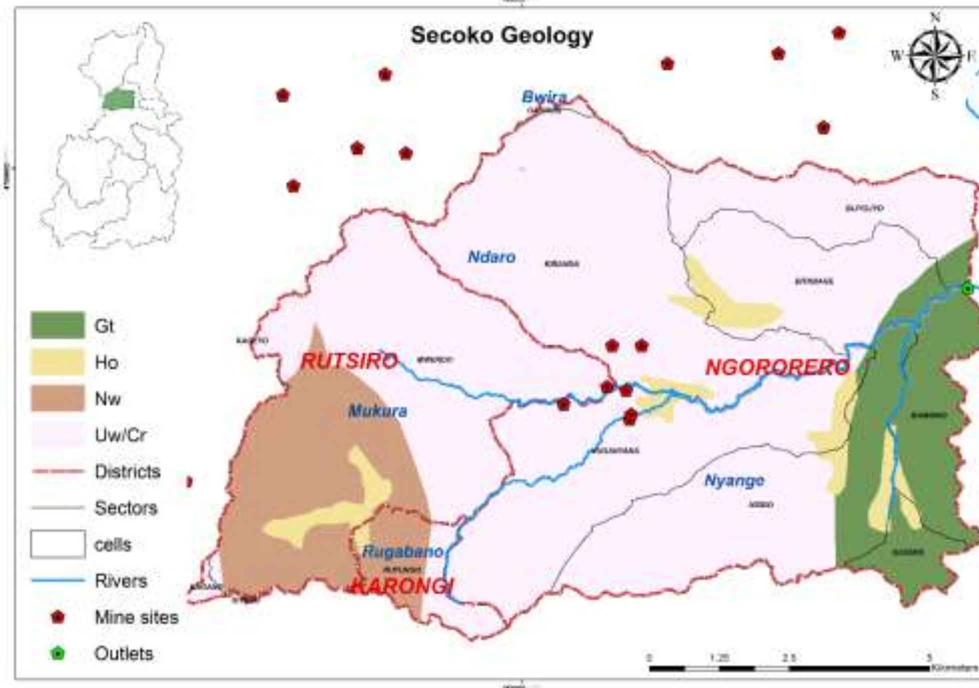


Figure 42: Geological formations in Secoko catchment

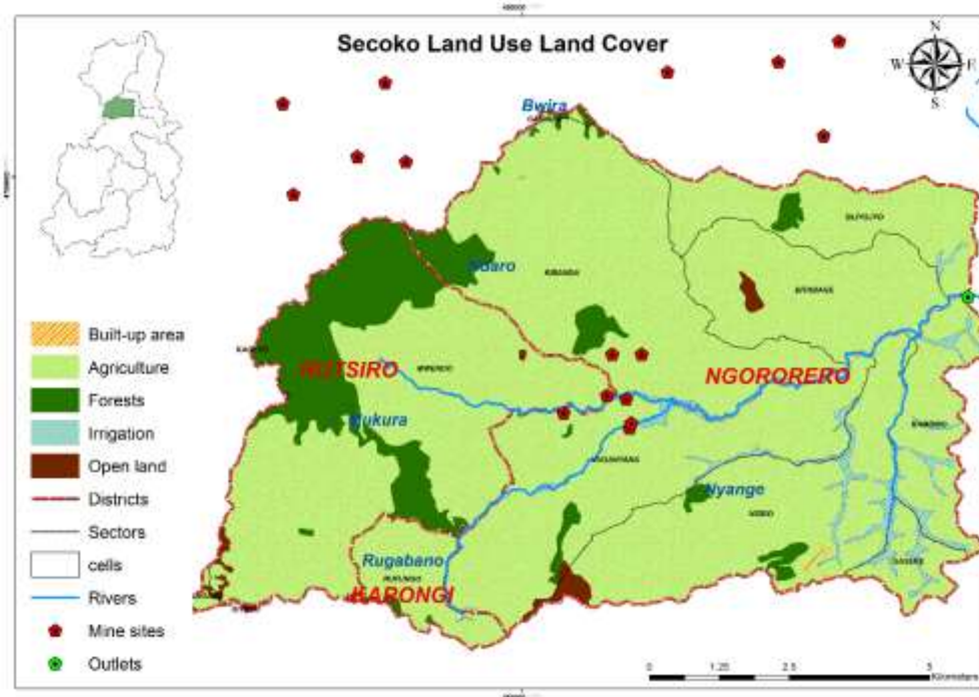


Figure 43: Land use in Secoko catchment

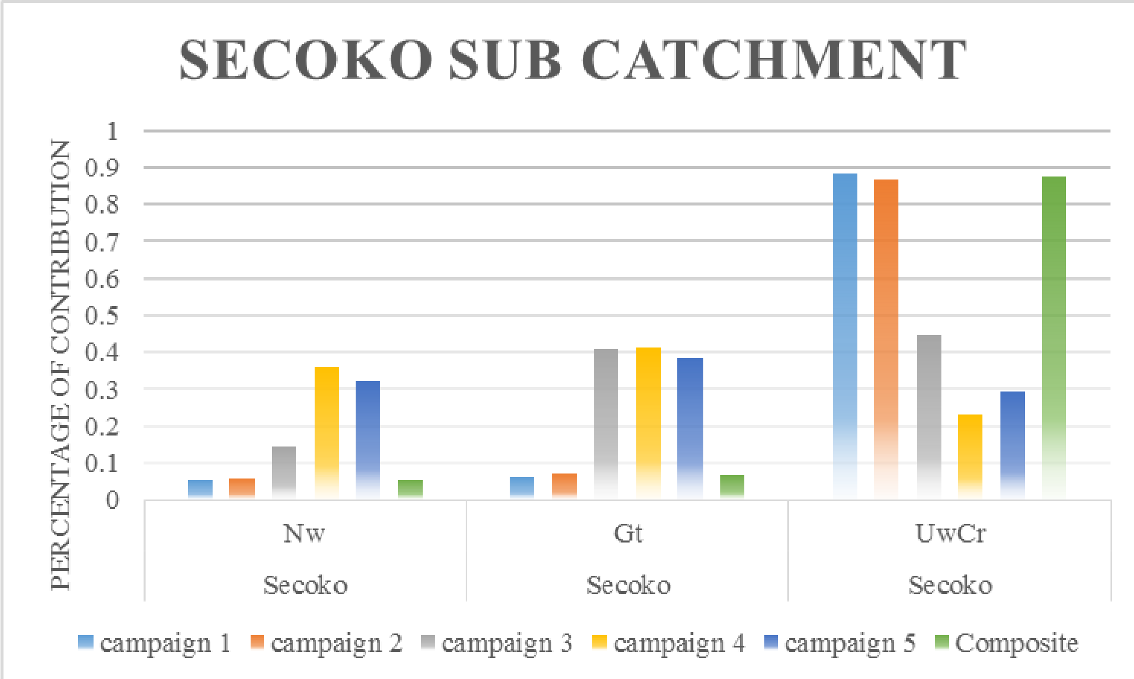


Figure 44: Source proportions in sediment sampled in 5 indivudual events; last bar shows composite acorss pooled samples.

Secoko sub catchment sediment major contributor was Uw/Cr with 22% to 89 %. This geological unit is dominant in Ndoro, Mukura sector in Rutsiro District and Nyange, Rugabano in Ngororero district. Major activities are mining and open agriculture. Nw and Gt geological units contributed each 5% to 40 % of sediments and are dominant in Mukura sector in Rutsiro district, Nyange sector in Ngororero District and Rugabano sector in Karongi District. Open agriculture land was found to be the major activities in these geological units. The Secoko river was seen over the period January-April to be carrying extremely high sediment loads into the Nyabarongo, with heavy deposits on the river bed and banks.

Secoko Catchment

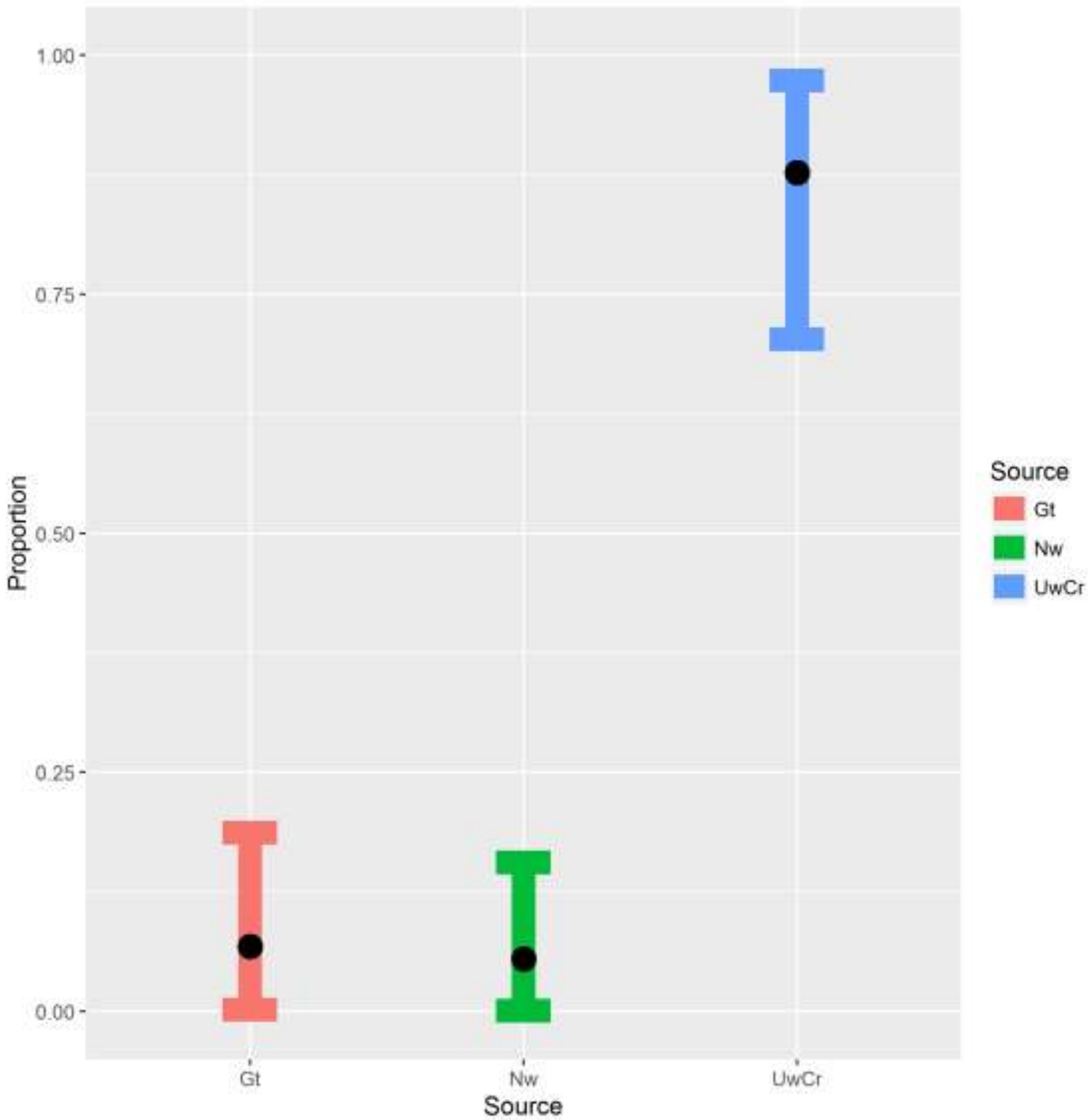
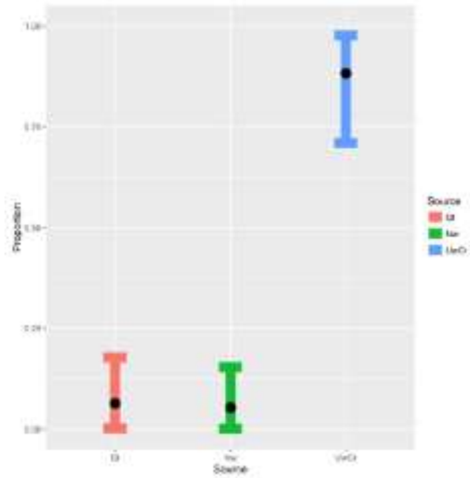


Figure 45: Source proportions in the composite of all 5 sediment samples , Jan- April

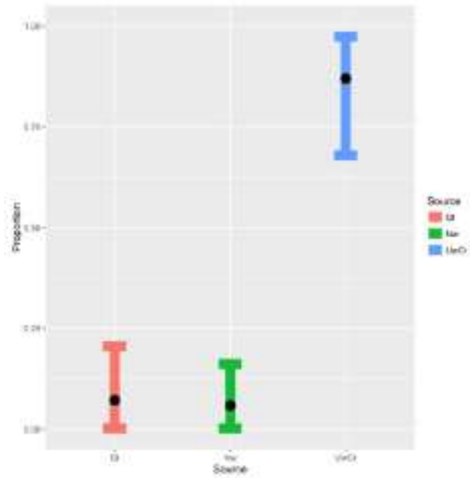
Table 10: Mean, standard deviation and confidence intervals of source proportions in composite sediment samples.

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
UwCr	0.877	0.074	0.703	0.737	0.833	0.889	0.934	0.973	0.981
Gt	0.068	0.061	0.002	0.004	0.021	0.05	0.1	0.187	0.226
Nw	0.055	0.049	0.001	0.003	0.018	0.041	0.079	0.156	0.181

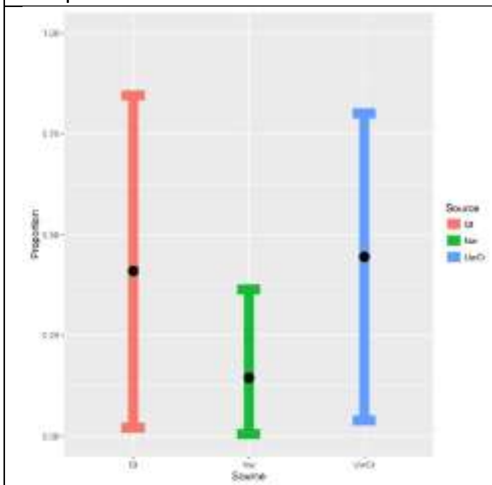
Sample 1



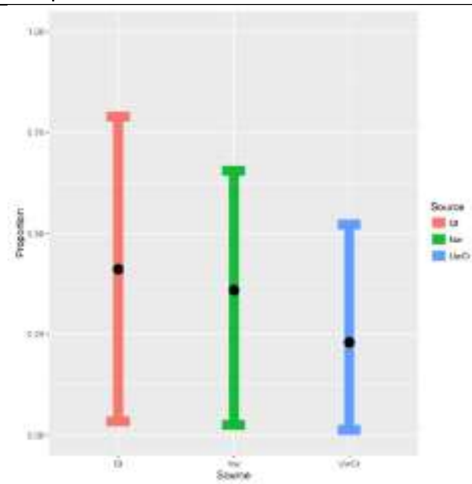
Sample 2



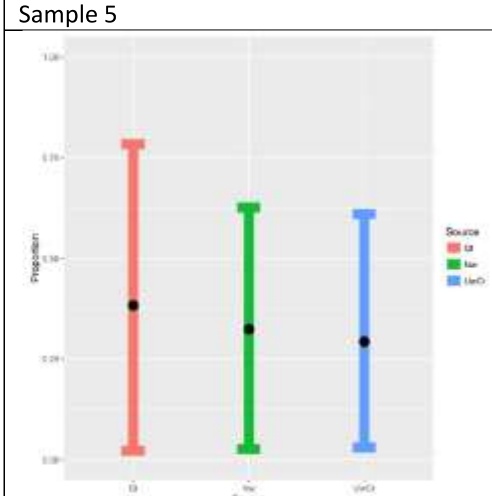
Sample 3



Sample 4



Sample 5



Sample 5

Figure 46: Source proportions in sediment sampled in five individual events. Bottom right – view of sediment laden Secoko river

3.2.9 Nyabarongo Hydropower subcatchment

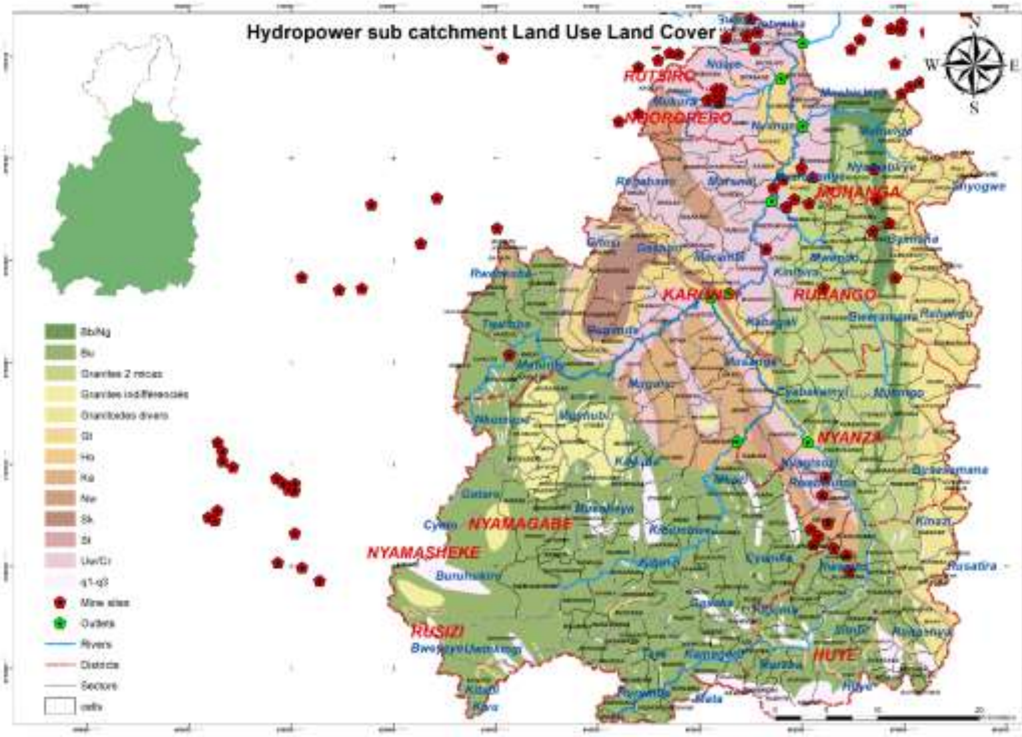


Figure 47: Geologival types in the Hydropower catchment

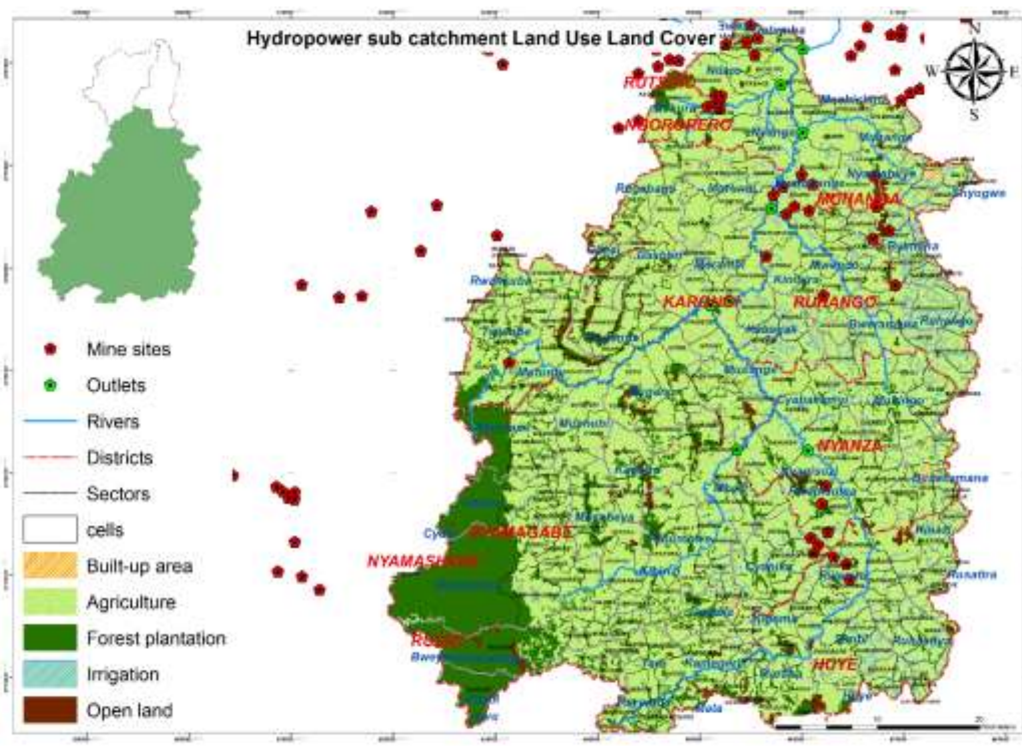


Figure 48: Land use in the HYdropower catchment

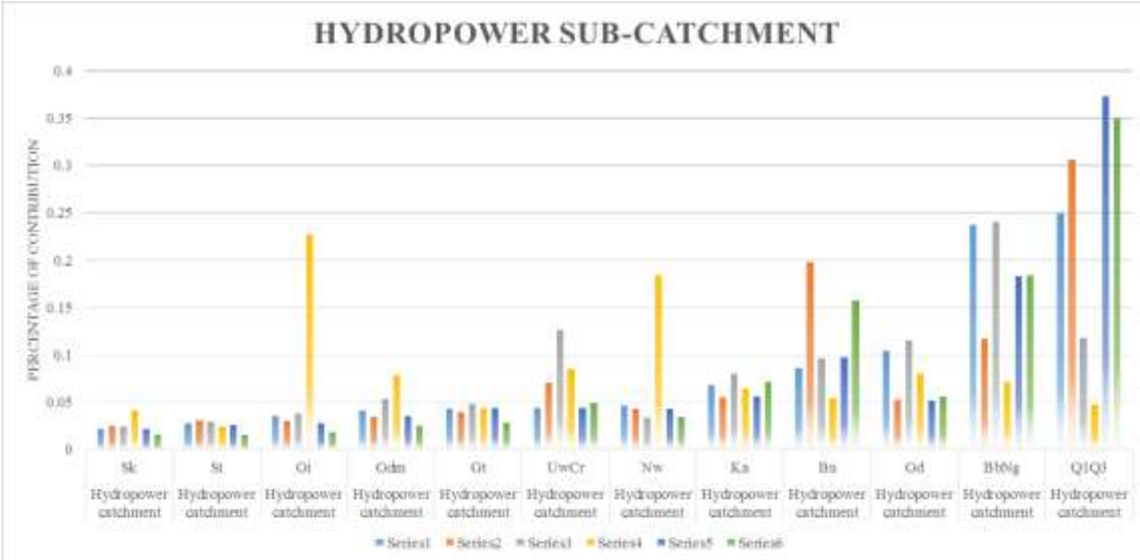


Figure 49: Source proportions in sediment sampled in 5 individual events,; also shown is the composite

The Nyabarongo Hydropower subcatchment is a much larger region that includes many subcatchments, namely those of the rivers Kiryango, Nyagako, Secoko catchments and the catchment Nyabarongo upstream of the Hydropower reservoir) The results indicate that while Q1-Q3 is the largest contributor, there is no clear dominance of any one geological type in the sediments flowing into the reservoir. Thus the sediment in the river between January-April came from many parts of the catchment.

Hydropower sub catchment sediment major geological unit were Q1-Q3 with 5% to 37%, Bb/Ng and Bu with 7% to 24% and 5% 20 %. This sub catchment cover the all sub catchments mentioned above and mining and open agriculture remain the major activities contributing largely to sediment load at hydropower reservoir.

Nyabarongo Hydropower Subcatchment

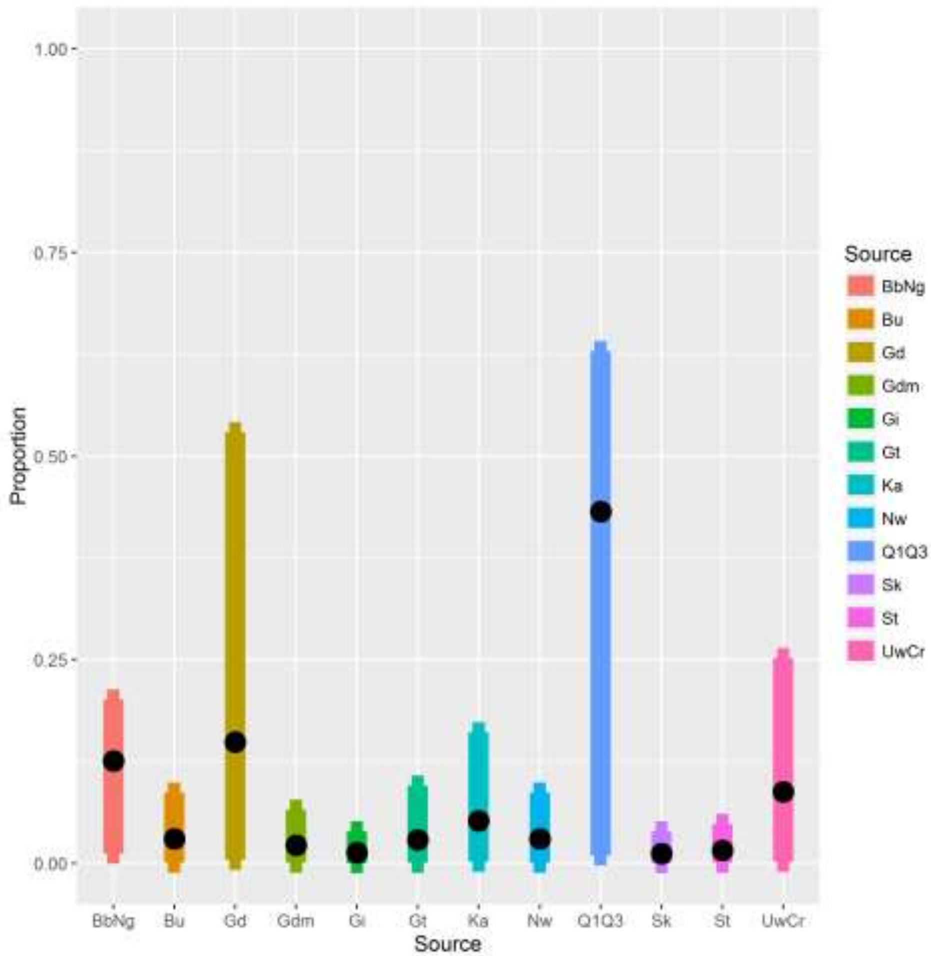
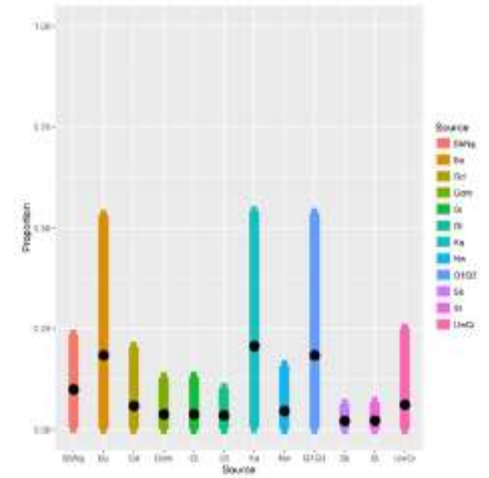


Figure 50: Source proportions in the composite sediment pooling analysis from all 5 sampling events.

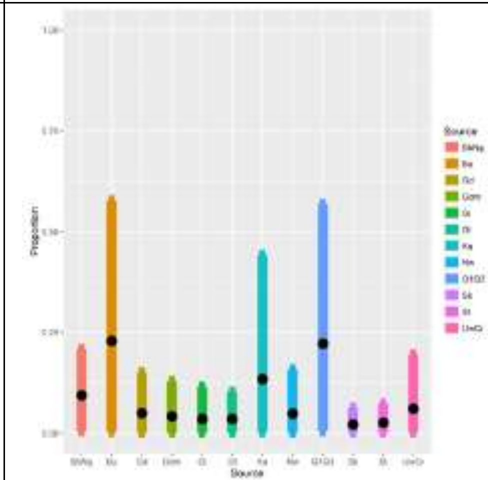
Table 11: Mean, standard deviation and confidence intervals of source proportions of composite sediment.

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Q1Q3	0.432	0.19	0.01	0.025	0.382	0.501	0.563	0.629	0.647
Gd	0.149	0.176	0.004	0.006	0.025	0.068	0.192	0.529	0.558
BbNg	0.126	0.05	0.012	0.025	0.099	0.132	0.159	0.201	0.216
UwCr	0.088	0.078	0.002	0.004	0.03	0.066	0.121	0.252	0.29
Ka	0.052	0.051	0.002	0.003	0.015	0.035	0.073	0.161	0.191
Bu	0.03	0.028	0.001	0.001	0.009	0.022	0.043	0.087	0.105
Nw	0.03	0.033	0.001	0.002	0.009	0.021	0.04	0.087	0.118
Gt	0.029	0.03	0.001	0.002	0.009	0.019	0.038	0.095	0.11
Gdm	0.022	0.023	0.001	0.001	0.006	0.014	0.03	0.066	0.081
St	0.016	0.017	0.001	0.001	0.005	0.011	0.023	0.048	0.064
Gi	0.013	0.013	0	0.001	0.004	0.009	0.018	0.039	0.048
Sk	0.012	0.013	0	0.001	0.003	0.008	0.017	0.039	0.047

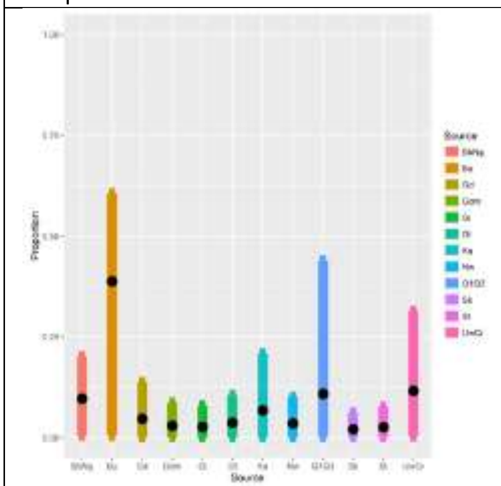
Sample 1



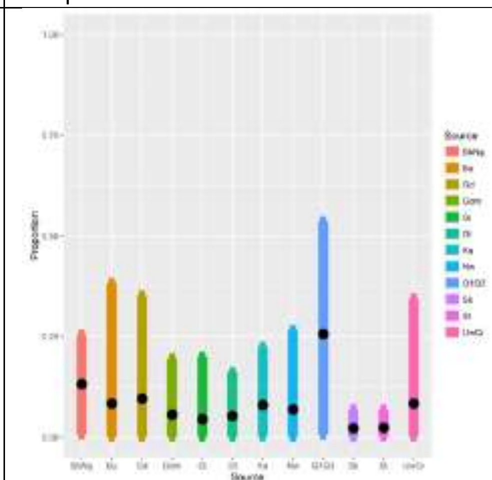
Sample 2



Sample 3



Sample 4



Sample 5

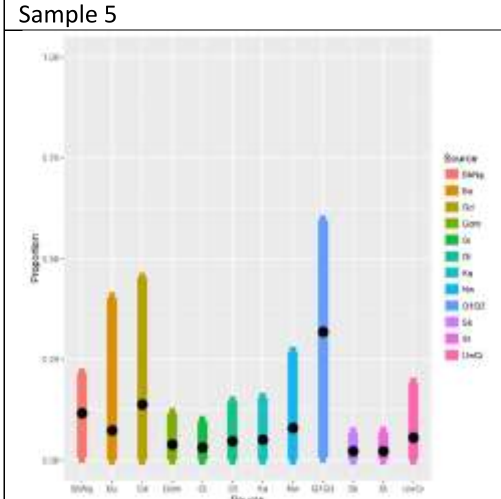


Figure 51: source proportions of sediment in each of the five sampling events (Table 1). Bottom right – turbid reservoir

3.2.10 Satinsyi sub catchment

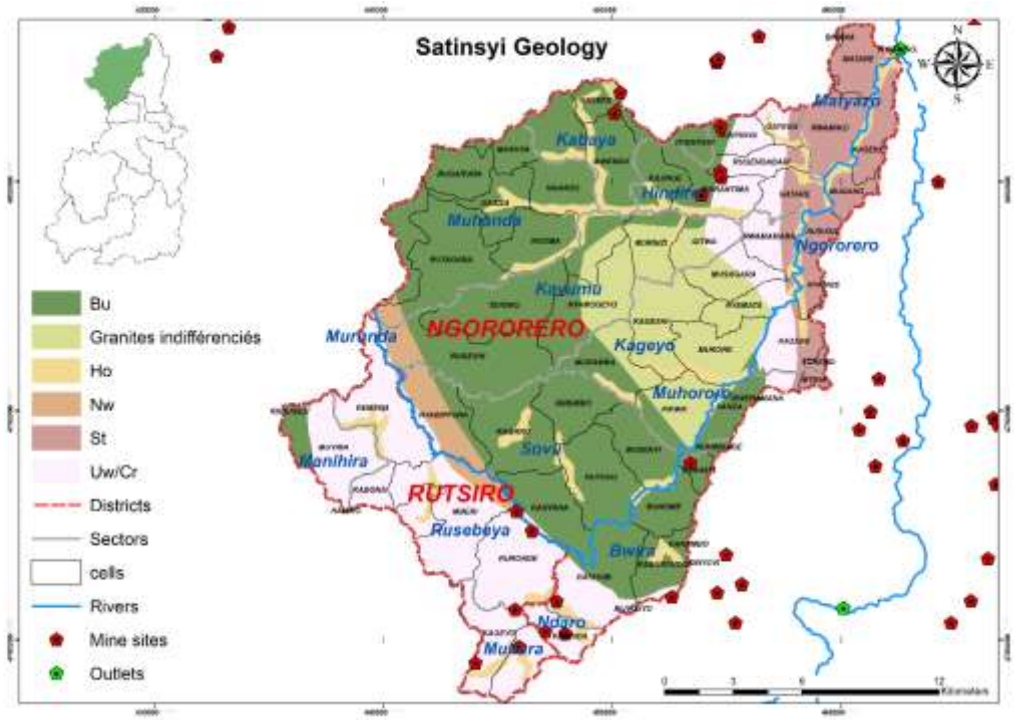


Figure 52: Geological formations in Satinsyi Catchment

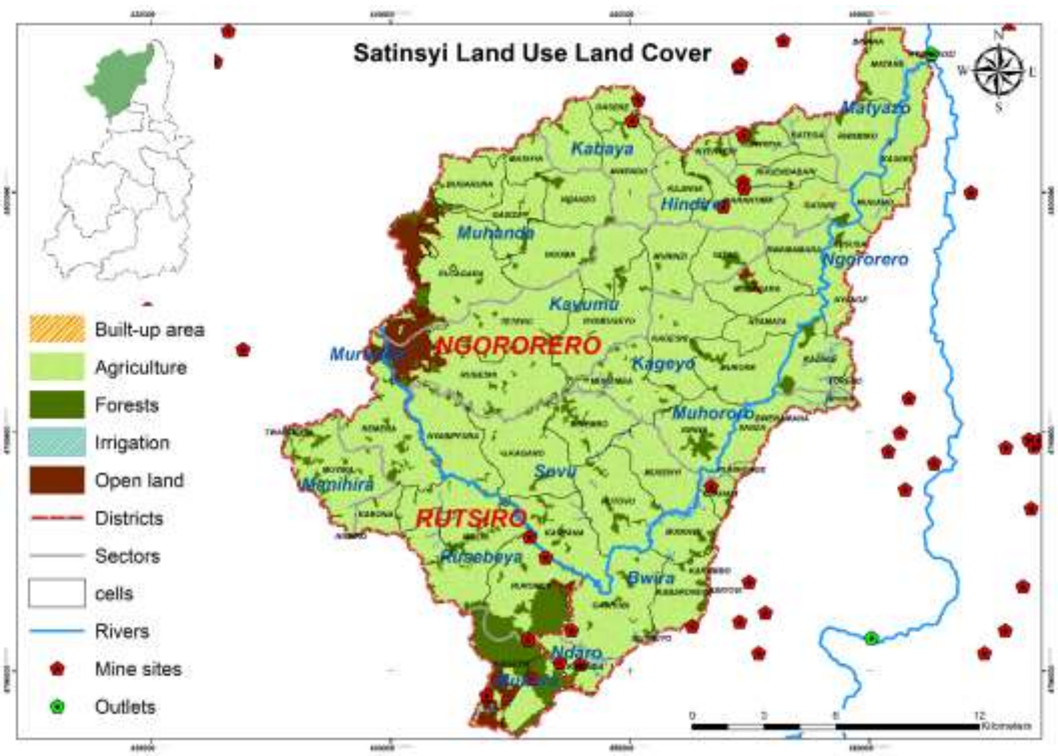


Figure 53: Land use in Satinsyi catchment

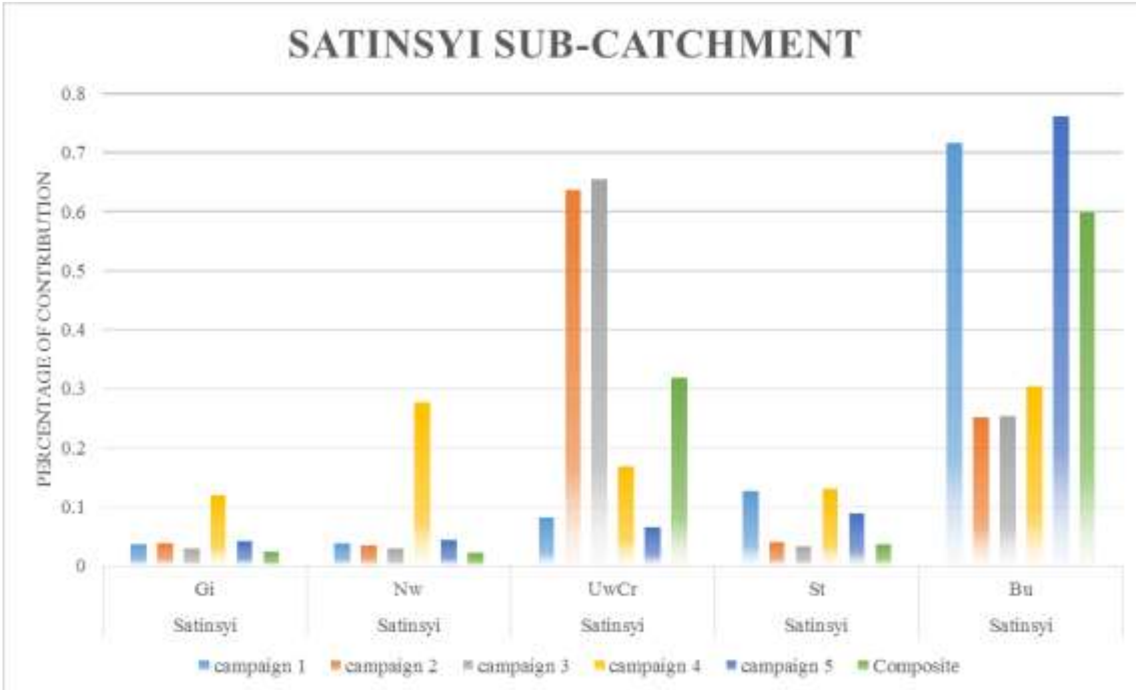


Figure 54: Source proportions in sediment sampled five times as well as the composite

Satinsyi sub catchment sediment major geological unit contributor was Bu with 25 % to 75% . This geological unit is dominant in Kabaya, Hindiro, Kavumu, Sovu and Bwira sectors in Ngororero District. Open agriculture and mining are the major activities land use. UwCr geological unit contributed largely to sediment from 5% to 65% and this Uw/Cr is dominant in Rusebeya, Ndaro, Mukura, Manihura sector in Rutsiro district. Major activities on Uw/Cr geological unit are open agriculture and mining.

Satinsyi Catchment

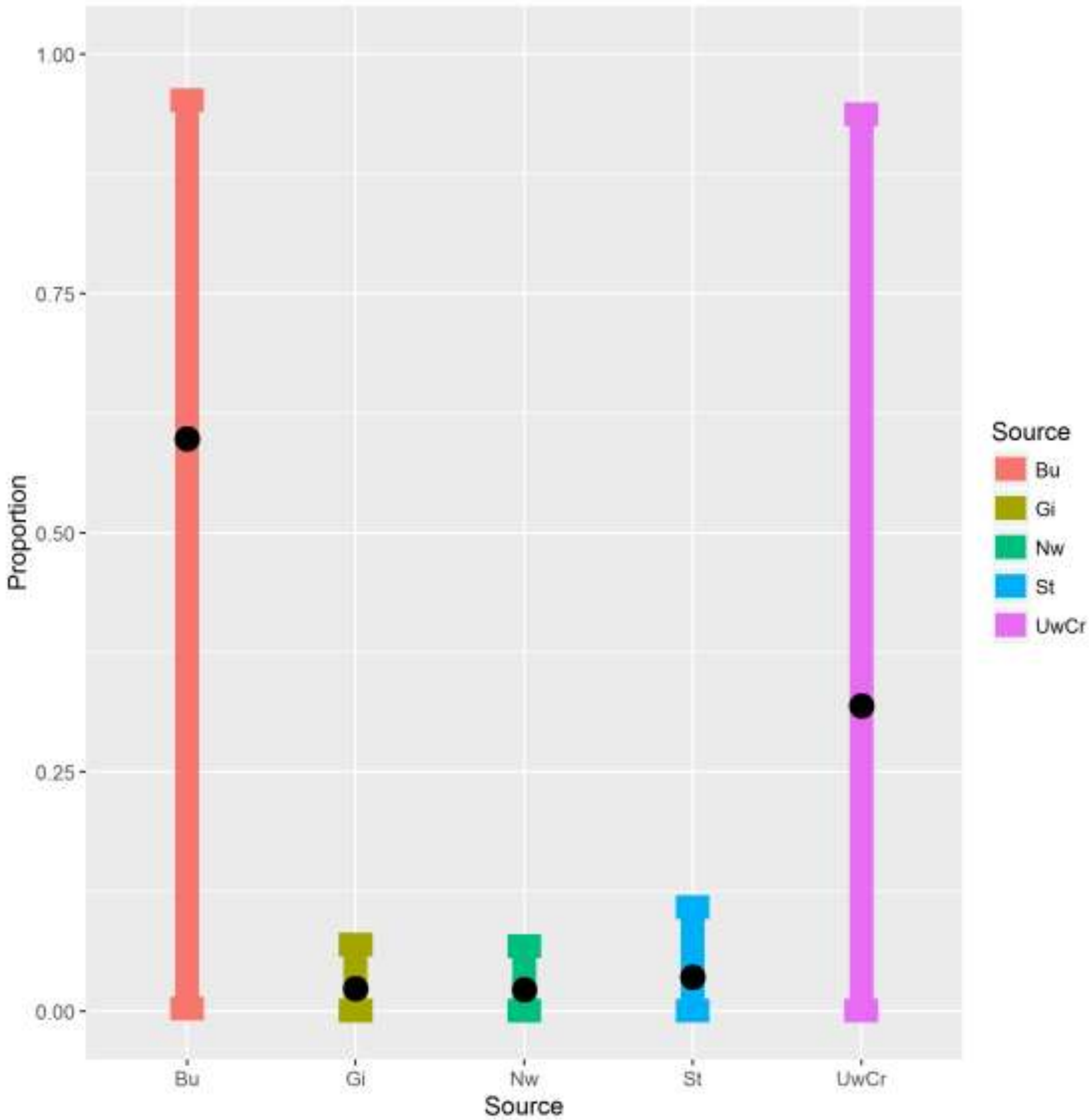
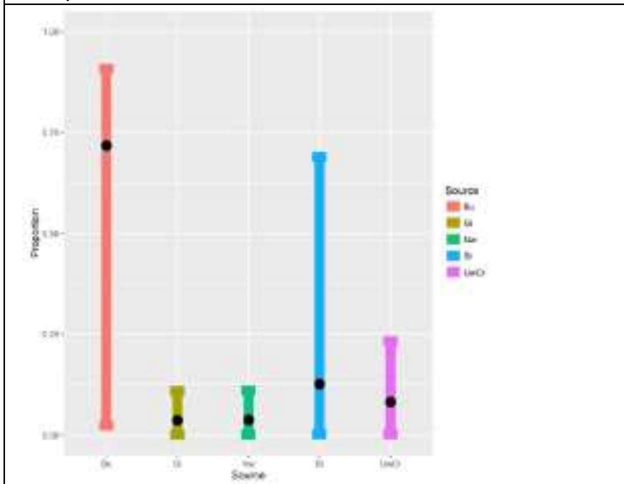


Figure 55: Source proportions in sediment - composite

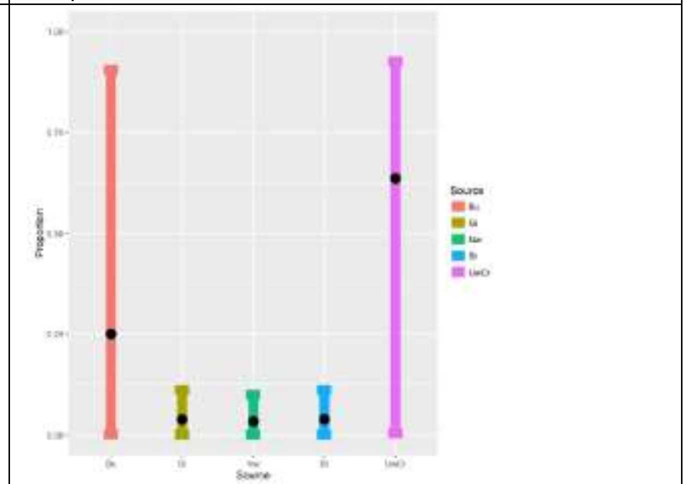
Table 12: Mean, standard deviation and confidence intervals for source proportions in sediment - composite

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
Bu	0.598	0.401	0.003	0.006	0.05	0.845	0.904	0.952	0.96
UwCr	0.319	0.402	0.001	0.002	0.016	0.05	0.858	0.937	0.95
St	0.036	0.036	0.001	0.002	0.01	0.024	0.05	0.109	0.135
Gi	0.024	0.023	0.001	0.001	0.007	0.017	0.033	0.07	0.083
Nw	0.023	0.022	0.001	0.001	0.007	0.016	0.032	0.068	0.083

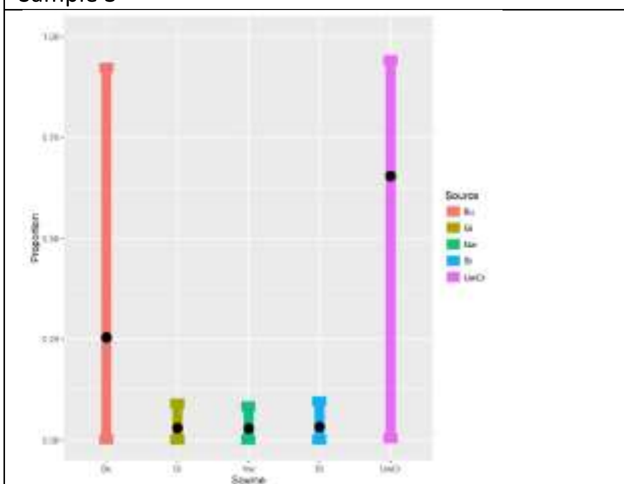
Sample 1



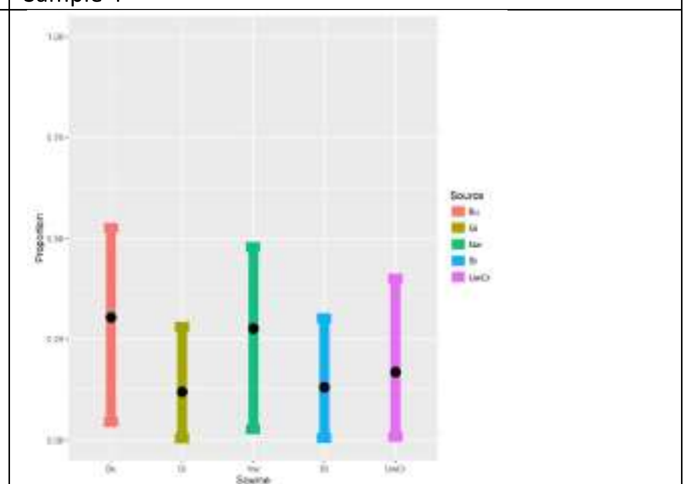
Sample 2



Sample 3



Sample 4



Sample 5

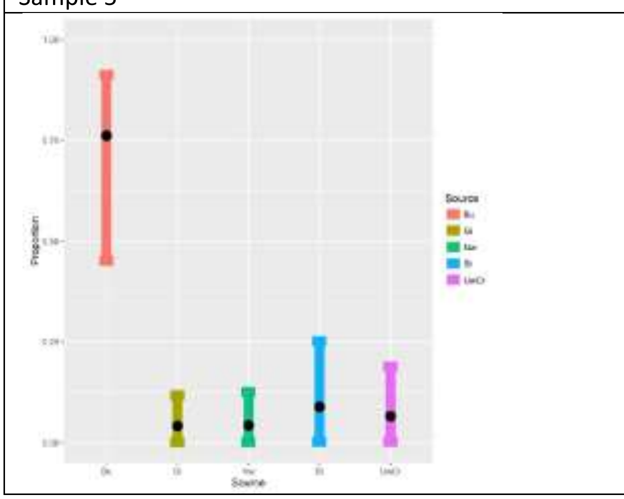


Figure 56: Source proportions in sediment sampled in the five individual events (Table 1)

3.2.11 NNYU outlet

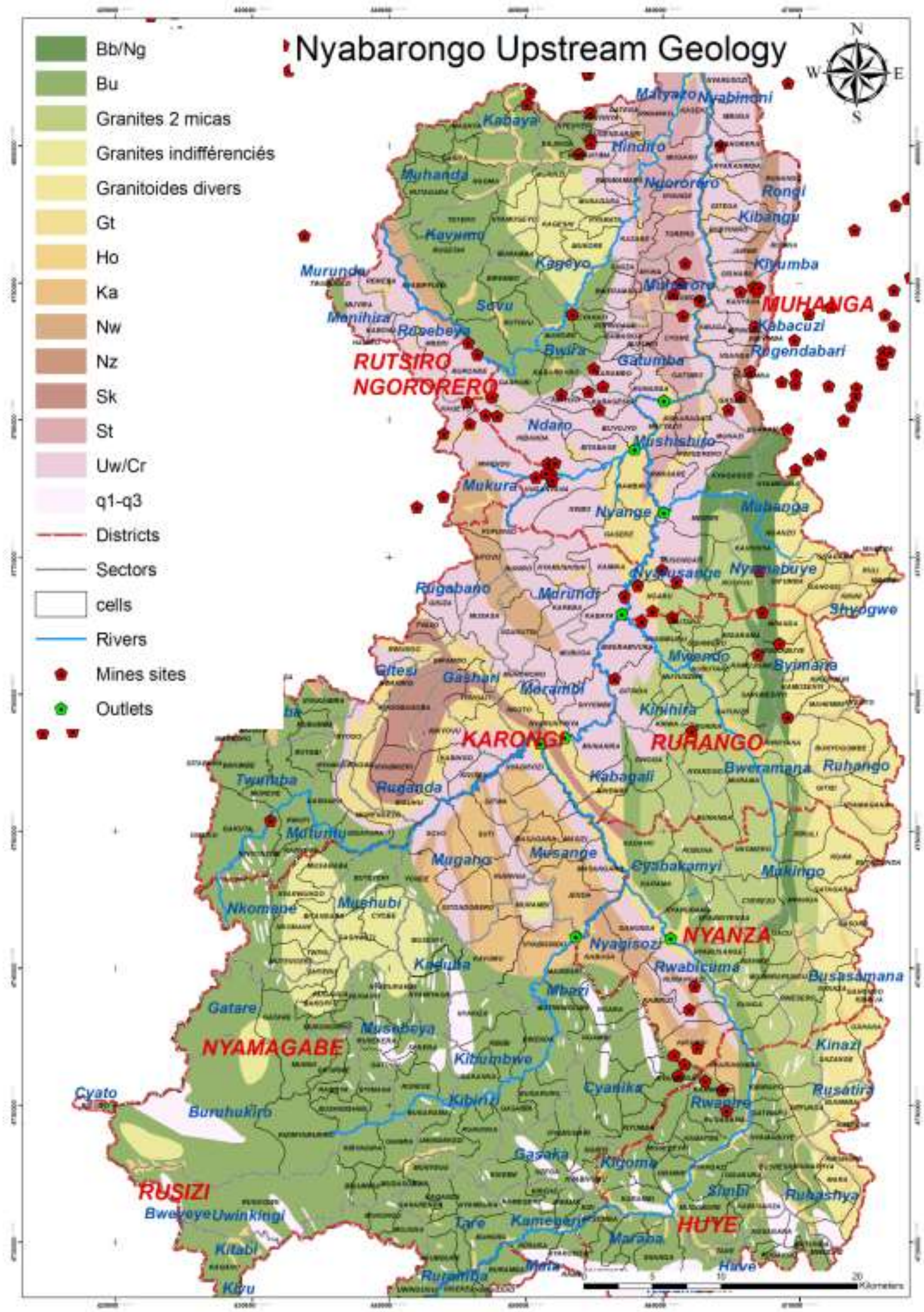


Figure 57: Geological formations in NNYU

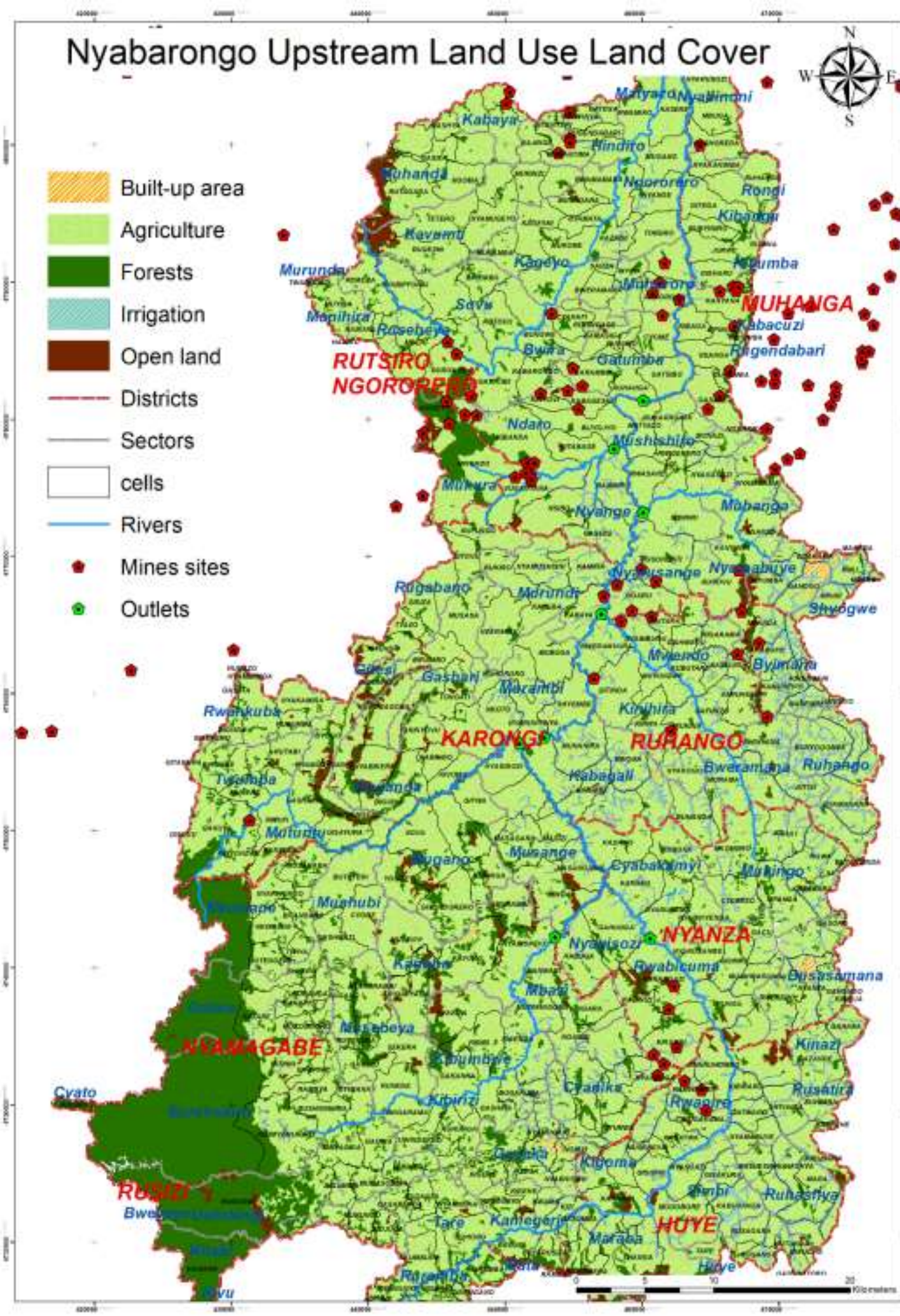


Figure 58: Land cover in NNYU

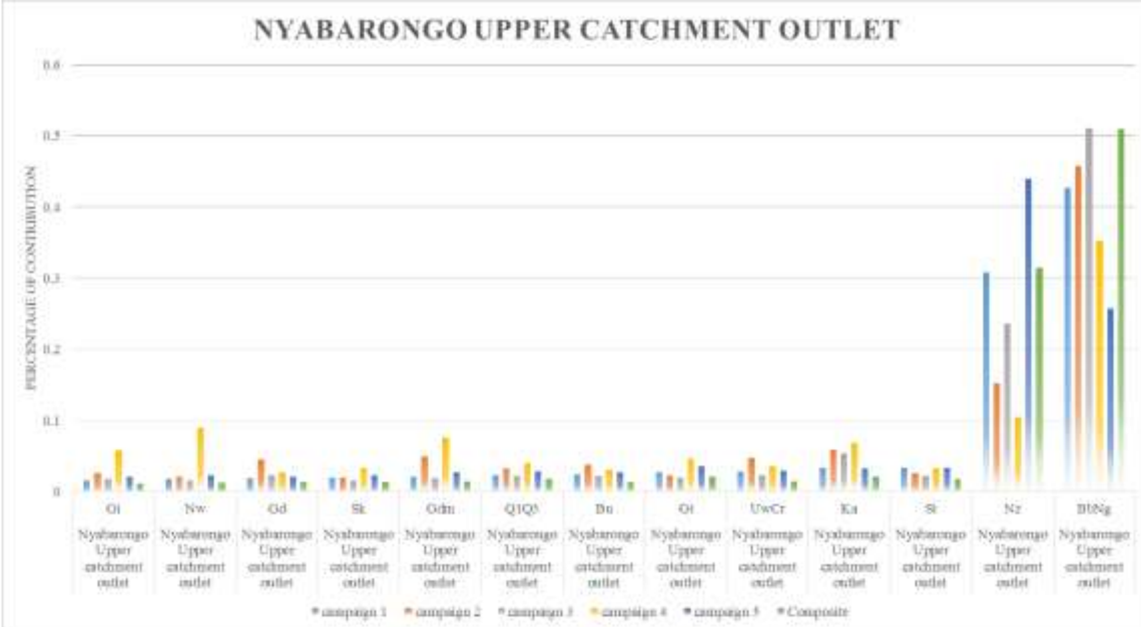


Figure 59: Source proportions in sediment sampled in the 5 events; also showing the composite

Nyabarongo upper catchment outlet is found with Bg/Ng and Nz geological units with 25% to 51% and 10% to 44% of sediments respectively. Bg/Ng was found as major contributor in Nyagako and Nyabarongo hydropower sub catchments while Nz was found to be major contributor in Nyabarongo lower. Again mining and open agriculture have been found as majors activities covering the big area of entire Nyabarongo Upper outlet subcatchment.

NNYU Catchment

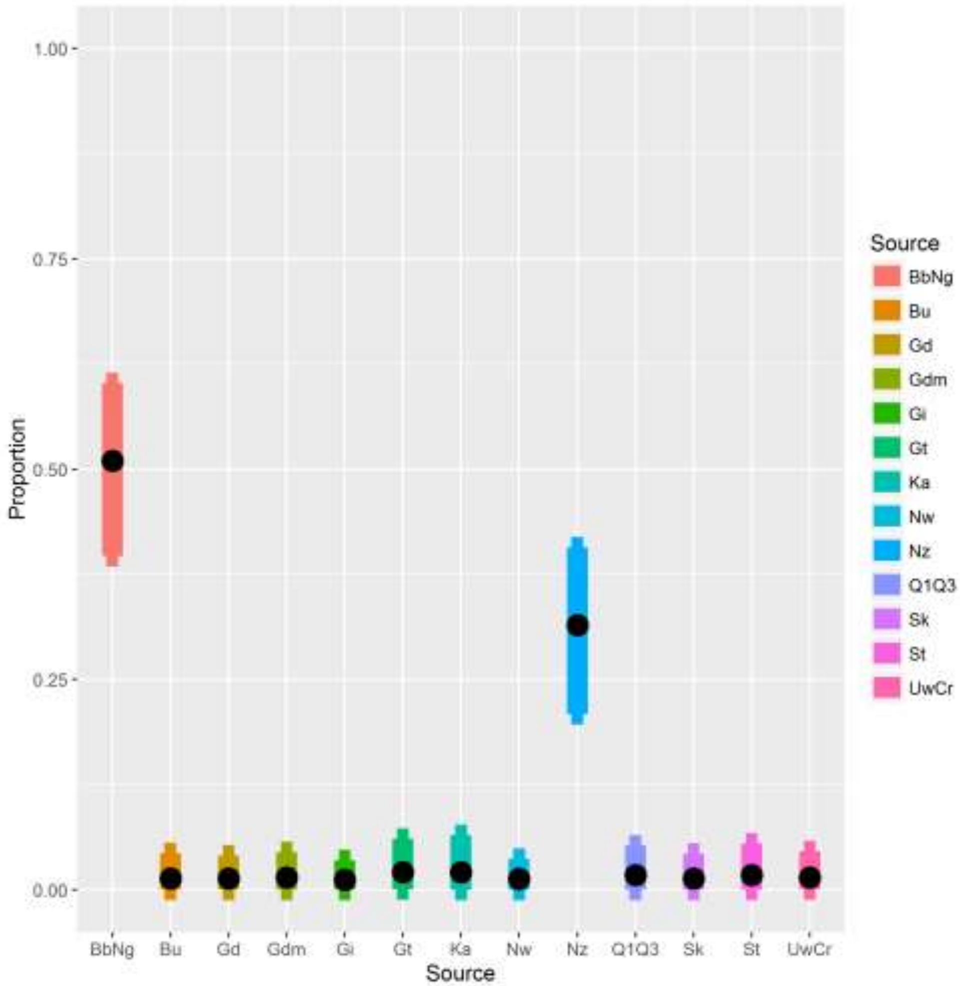
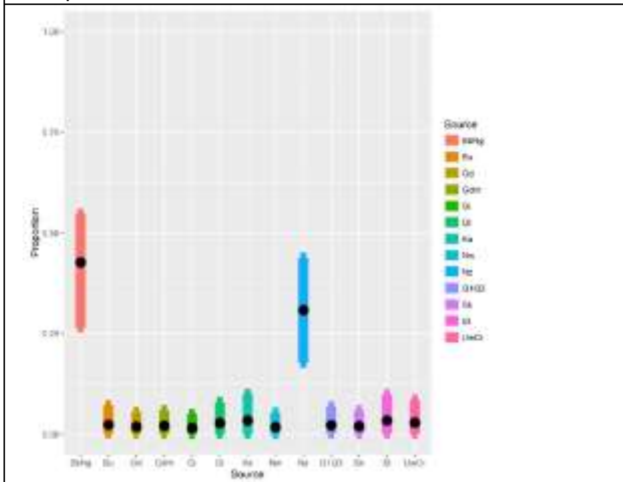


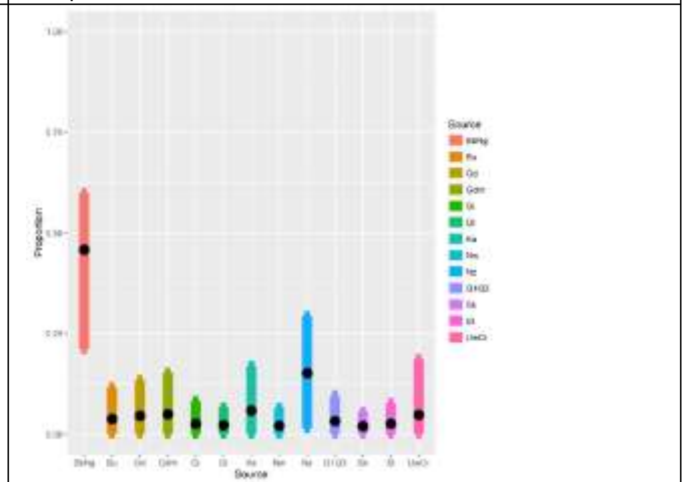
Figure 60: Source proportions in sediment - composite

Source	Mean	SD	2.50%	5%	25%	50%	75%	95%	97.50%
BbNg	0.51	0.057	0.397	0.415	0.472	0.51	0.549	0.602	0.621
Nz	0.315	0.055	0.209	0.224	0.277	0.315	0.351	0.407	0.424
Gt	0.021	0.02	0.001	0.001	0.006	0.014	0.028	0.061	0.073
Ka	0.021	0.022	0	0.001	0.006	0.015	0.029	0.065	0.081
Q1Q3	0.018	0.018	0	0.001	0.005	0.013	0.025	0.053	0.065
St	0.018	0.019	0	0.001	0.004	0.012	0.025	0.055	0.069
UwCr	0.015	0.016	0.001	0.001	0.005	0.011	0.021	0.046	0.057
Gdm	0.015	0.015	0	0.001	0.004	0.011	0.022	0.045	0.055
Sk	0.014	0.014	0	0.001	0.004	0.01	0.019	0.043	0.054
Bu	0.014	0.015	0	0.001	0.004	0.009	0.019	0.044	0.056
Gd	0.014	0.014	0	0	0.004	0.01	0.019	0.041	0.051
Nw	0.013	0.012	0	0.001	0.004	0.009	0.018	0.037	0.046
Gi	0.012	0.011	0	0.001	0.003	0.008	0.016	0.035	0.043

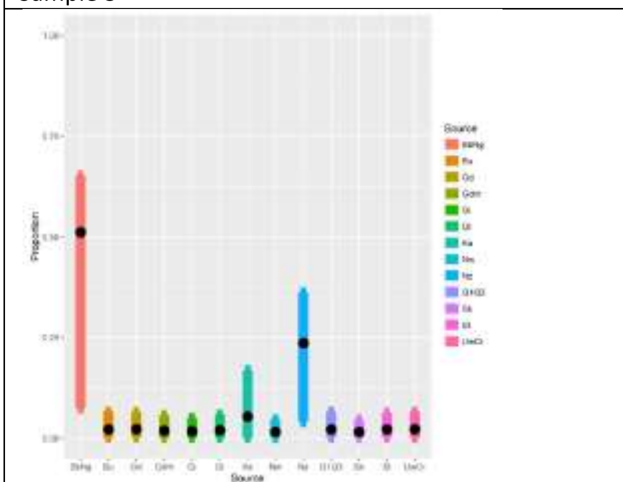
Sample 1



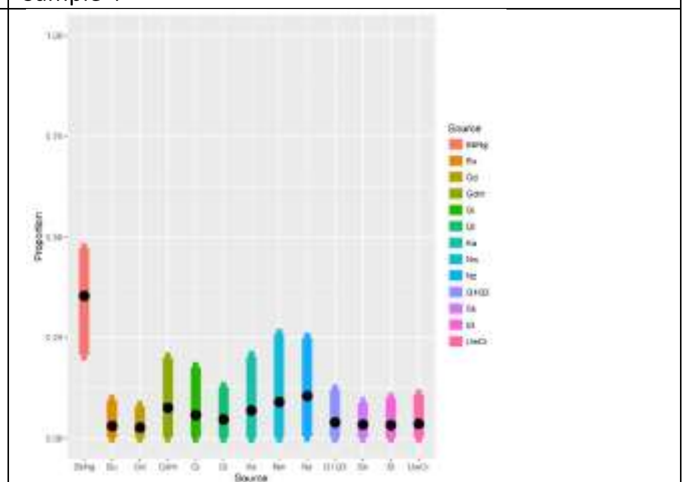
Sample 2



Sample 3



Sample 4



Sample 5

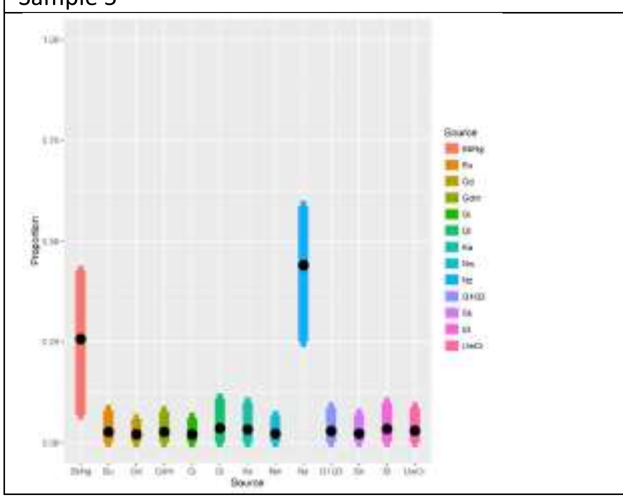


Figure 61: Source proportions in sediment from the five individual samplings. Confluence of Karonga with Nyabarongo as the latter leaves the NNYU.

3.3 Sediment concentration differences across NNYU

Sediment concentrations were obtained from weighing the sediments obtained by filtering 250 ml of river water in each sampling campaign. On average, the Secoko river (Figure 64) has by far the highest sediment concentration as seen in every sampling campaign, followed by Satinsyi (Figure 65). This accompanies the visual impression of highly turbid waters flowing between heavily sedimented riverbanks in these two rivers. Reservoir concentration values are low because the water is stationary, allowing settling down of sediment. It should be noted that these are sediment concentrations in milligrams of sediment per liter of river water, and do not signify sediment loads. For that, river discharge information is necessary in addition.

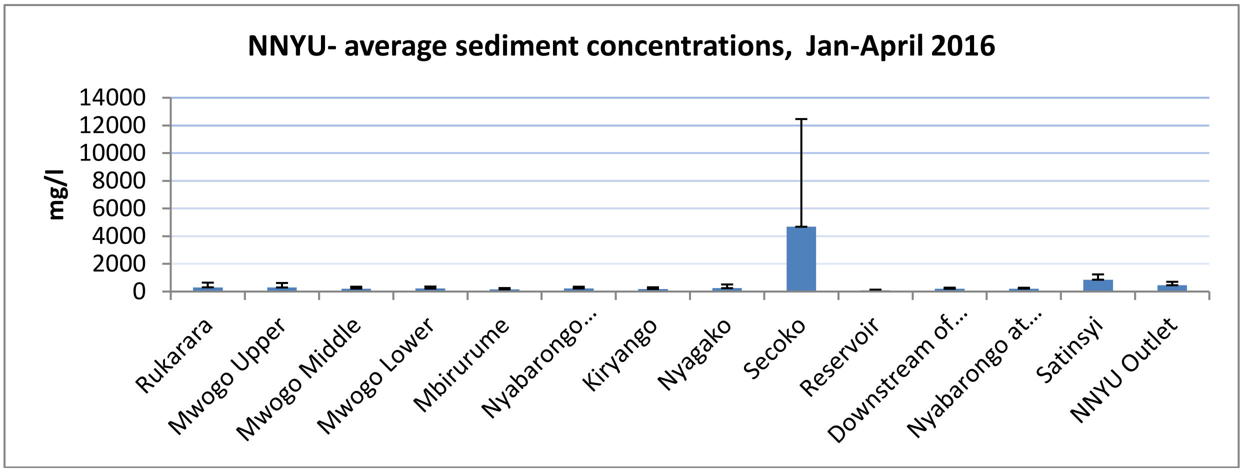


Figure 62: Average sediment concentration at the sediment sampling stations averaged over January-April 2016.

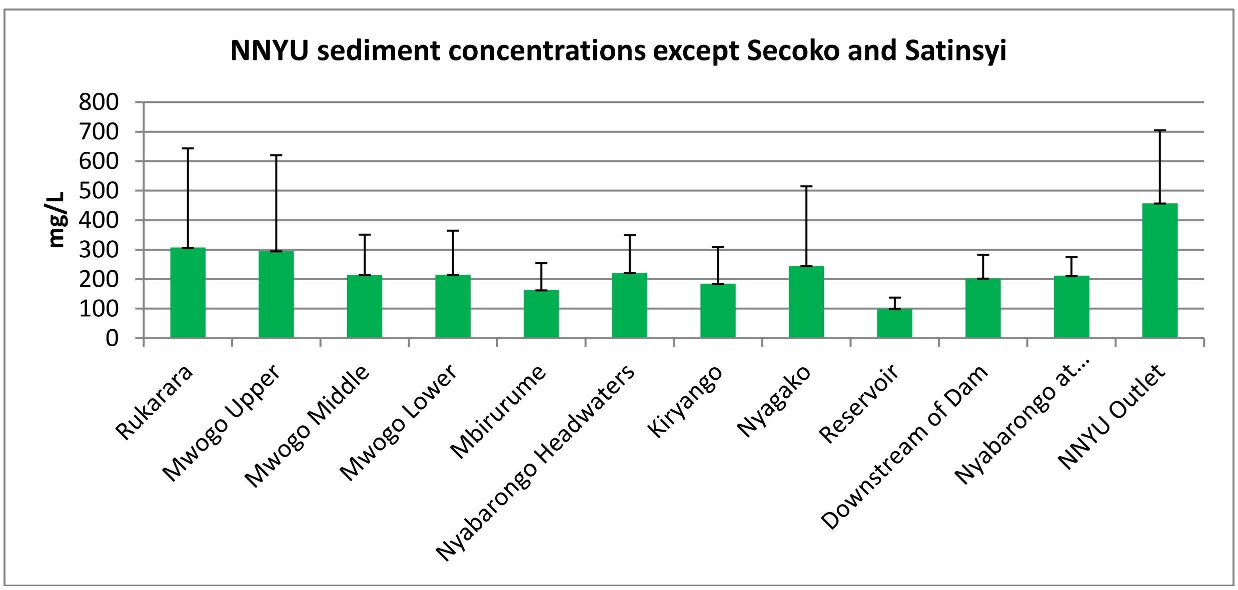


Figure 63: Average sediment concentrations in all sampling points on the Nyabarongo drainage except Secoko and Satinsyi, as these latter are of a higher order of magnitude.


Figure 64: Muddy banks of the Secoko


Figure 65: Satinsyi laden with sediment just before confluence with Nyabarongo

4. Priority rehabilitation focal areas in NNYU

4.1 From Results to Priority Locations – the approach

Results identify the geological types in each subcatchment that contributed the highest levels of sediment over the sampling period. Locating these geological types on an administrative map then indicates the cells (and their sectors and districts) that are the likely areas subject to the highest levels of erosion. These areas should then be visited to verify erosion, ascertain the reasons of erosion and thereby define catchment rehabilitation to control erosion and sediment runoff.

The prioritization analysis was done for each subcatchment, starting with the headwaters subcatchments – Rukarara, Upper Mwogo, Mwogo and Mbirurume. The potential sediment sources in each subcatchment as presented in Chapter 3 were analyzed with respect to the hydrological flowpath (ie. from headwaters to the catchment outlet) of the Nyabarongo river drainage. This means that the suspended sediments sampled at any point in the Nyabarongo river system have entered the river as runoff at various points in the catchment upstream of the sampling point.

4.2 Prioritization process

The headwater subcatchments were considered first in the analysis, to look at the sediment sources right at the very beginnings of the river drainage. The initial prioritization was as follows:
Level 1: geological types that contributed 40% or more sediment.
Level 2: 20-40%
Level 3: 10-20%
Geological types contributing less than 10% were not assigned any priority level.

Now, as a river flows and joins other tributaries downstream, each tributary comes in with its own sediment load. Furthermore, as a river flows, some sediment settles out on slow flowing zones, such as river bends or flow obstructions, while new sediment comes in. Hence the sediment composition changes with space and time as one goes downstream. Its possible that a sediment source that may have been a major contributor in an upstream catchment is no longer as dominant downstream. To account for this dynamic change in sediment composition as one goes downstream, a further prioritization strategy is taken as follows:
Level 1: assigned to a geological type that retains its dominance in sediment contribution downstream, as seen from the sediment composition results at a downstream point on the river
Level 2: geological types that were Level 1 in a headwater catchment but decrease in contribution level downstream.
Level 3: geological types that were Level 2 in a headwater catchment and decrease to Level 3 or less.

This process is repeated for results from each downstream sampling point, until the requisite region is covered. A map of the NNYU catchment has being created (Figure 63) with three levels of intervention priority – 1, 2 and 3. It is important to note that areas other than identified as Levels 1-3 also do contribute sediment, on account of the loss of native forest. However, areas under Levels 1-3 contribute anywhere between 50-80% of the sediment. Such maps greatly help focus limited resources on rehabilitating areas with the gravest levels of soil erosion and sediment generation. The list of cells with prioritization levels are included in the Annex.

4.3 The next step - Validation of Potential Hotspots

The next step is field validation of the sediment fingerprinting results. This has two purposes – to confirm whether there is high erosion in these areas, and if confirmed, note the causes. Field visits targeted to these villages and areas can provide information to determine the causes of local soil erosion, which will be of value for the development of appropriate rehabilitation approaches.

A similar exercise can be carried out for the Nyabarongo Hydroelectric Project Reservoir to discern the major sources of the sediment entering the reservoir. Once these sources are attended to by means of effective rehabilitation measures, a fresh set of suspended sediment samples can then indicate other sources of sediment via the sediment fingerprinting process. As erosion and sediment runoff processes are dynamic and changeable in nature, sediment fingerprinting can thus become a part of overall longterm watershed management.

Mining activities heavily produce sediment with localized accentuation during particular rainfall events on the site. The contribution of open agriculture was also observed to be important as it was related to the fact that large areas contribute sediment. The latter combined with specific localized rainfall events could accentuate the sediment contribution. A determination of the administrative entities up to the level of the villages within the identified most contributing locations was made and this can serve as basis for the prioritization of affected area and therefore guide the implementation strategy of the existing Nyabarongo Upstream rehabilitation plan.

In general, in areas where primary multi-canopy forests are the natural form of vegetation on the landscape, such as much of NNYU, are highly prone to soil erosion once the forest cover is removed. Unfortunately the thin soils and steep slopes pose challenges to the rate of recovery of forest cover. Plantation forestry, while being a useful socioeconomic activity still do not possess a dense multi-layered canopy to break the impact of rainfall upon the soil, as do native primary forest. The prevalence of agriculture in NNYU requires continuation of existing soil conservation efforts such as terracing, mulching and contour trenching. Road building and mining pose special challenges as these actively excavate and destabilize large areas of soil; hence need to be managed with remediation programs. Given the tremendous logistical challenges of undertaking these activities at the huge spatial scale of the NNYU catchment, the sediment fingerprinting process can indicate the potential hotspots of erosion, and thereby help undertake catchment rehabilitation in an effective and tiered manner.

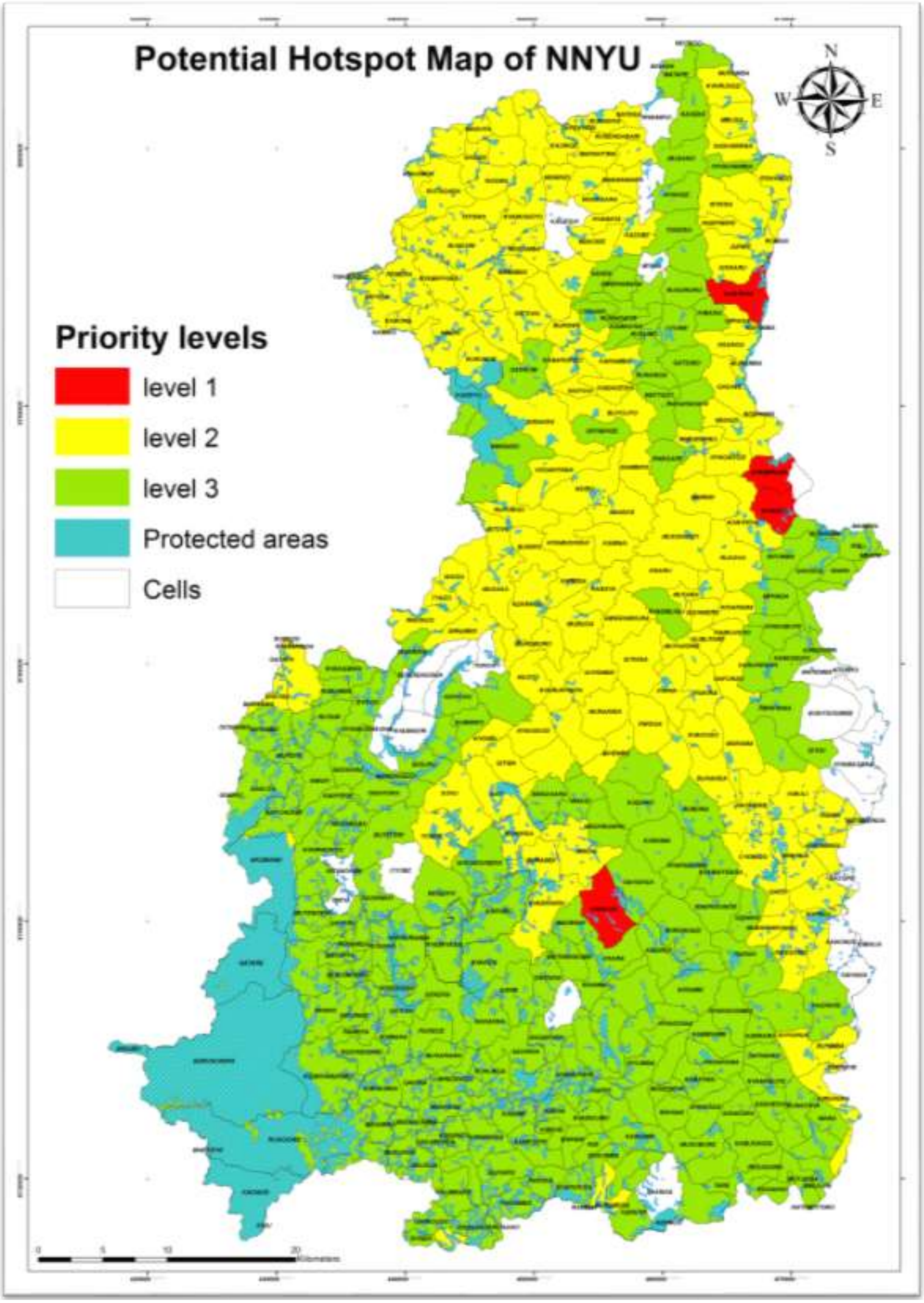


Figure 66: Potential hotspots in the Nyabarongo Headwaters region with a 3-level scale of intervention.

References

Byiringiro F, Reardon T. 1996. Farm productivity in Rwanda: effects of farm size, erosion, and soil conservation investments Agricultural Economics Volume 15, Issue 2, November 1996, Pages 127–136

Clay DC, Lewis LA. 1990. Land use, soil loss, and sustainable agriculture in Rwanda, Human Ecology , June 1990, Volume 18, Issue 2, pp 147-161

Collins AL, Walling DE, Leeks GJL. 1997. Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. Catena 29 (1997) 1-27.

Collins AL, Walling DE. 2002. Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. Journal of Hydrology 261:218–244.

Davis CM, Fox JF. 2009. Sediment Fingerprinting : Review of the Method and Future Improvements for Allocating Nonpoint Source Pollution. Journal of Environmental Engineering 135 :490-504

Dutton C, Anisfeld S, Ernstberger H. 2013. A novel sediment fingerprinting method using filtration: application to the Mara River, East Africa. Journal of Soils and Sediments: 1-16. Doi: 10.007/S11368-013-0725-z.

Evrard, O., Poulenard, J., Némery, J., Ayrault, S., Gratiot, N., Duvert, C., Prat, C., Lefèvre, I., Bonté, P., Esteves, M., 2013. Tracing sediment sources in a tropical highland catchment of central Mexico by using conventional and alternative fingerprinting methods. Hydrol. Processes 27, 911–922.

Fenn CR, Gomez B. 1989. Particle size analysis of the sediment suspended in a proglacial stream: Glacier de Tsidjiore Nouve, Switzerland. Hydrological Processes, 1989

Fox, J., Papanicolaou AN. 2007. The use of carbon and nitrogen isotopes to study watershed erosion processes. Journal of American Water Resources Association. 43(4):1047-1064.

Fox, J., Papanicolaou AN. 2008. An un-mixing model to study watershed erosion processes. Advances in Water Resources. 31:96-108.

GLOWS-FIU. 2014. Sediment Source Determination by fingerprinting in the Ruvu River Basin, Tanzania. Global Water for Sustainability Program, Florida International University. 58 pp.

Gurgen PT. 2003 Global peculiarities and tendencies in river discharge and wash-down of the suspended sediments — The earth as a whole, Elsevier Research paper, Journal of Hydrology, 107:1-4, 113-131.

Klages MG, Hsieh YP. 1975. Suspended Solids Carried by the Gallatin River of Southwestern Montana: II. Using Mineralogy for Inferring Sources. Journal of Environmental Quality.Vol. 4 No. 1, p. 68-73

Koiter et al (2014): Sediment fingerprinting: A methodological framework Workshop Summary July 7 –

11, 2014 University of Manitoba, Winnipeg, MB

Legout, C., Poulenard, J., Nemery, J., Navratil, O., Grangeon, T., Evrard, O., Esteves, M., 2013. Quantifying suspended sediment sources during runoff events in headwater catchments using spectrocolorimetry. J. Soil Sediments 13, 1478–1492.

Olago, D. O. & E. O. Odada (2007) Sediment impacts in Africa's transboundary lake/river basins: Case study of the East African Great Lakes, Aquatic Ecosystem Health & Management, 10:1, 23-32.

Oldfield F, Maher BA, Donoghue J and Pierce J. 1985. Particle-size related, mineral magnetic source sediment linkages in the Rhode River Catchment, Maryland, USA. J.Geol Soc (London), 142, 1035-1046.

Olley J and Caitcheon G. 2000. Major element chemistry of sediments from the Darling-Barwon Roiver and its tributaries : Implications for sediment and phosphorus sources. Hydrological Processes 14 :1159-1175.

Poulenard et al 2009. Infrared spectroscopy tracing of sediment sources in a small rural watershed (French Alps). SCIENCE OF THE TOTAL ENVIRONMENT 407 (2009) 2808–2819

Poulenard et al 2012. Tracing sediment sources during floods using Diffuse Reflectance Infrared Fourier Transform Spectrometry (DRIFTS): A case study in a highly erosive mountainous catchment (Southern French Alps) Journal of Hydrology 414–415 (2012) 452–462

Probst, J. L. & P. AMIOTTE SUCHET (1992) Fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa), Hydrological Sciences Journal, 37:6, 621-637.

REMA (2009): Rwanda State of Environment and Outlook Report" Rwanda Environment Management Authority P.O. Box 7436 Kigali, Rwanda. http://www.rema.gov.rw/soe/chap3.php

SHER Ingenieurs-Conseils s.a. (2014) Catchment master plan – NNYU. Master Plan Report – Appendix03NNYU. Consultancy services for development of Rwanda National Water Resources Master Plan. Tender No. 021/RNRA/2011-2012. 68pp.

Tiecher et al 2015. Tracing sediment sources in a subtropical rural catchment of southern Brazil by using geochemical tracers and near-infrared spectroscopy. Soil and Tillage Research. In press.

Twagiramungu, F. (2006). Environmental Profile of Rwanda. European Commission, Kigali.

Walling DE, Woodward JC, Nicholas AP.1993. A multi-parameter approach to fingerprinting suspended sediment sources. In : NE Peters, E Hoehn, Ch Leibundgut, N Tase and DE Walling (editors) : Tracers in Hydrology. IAHS Publ No. 215, IAHS Press, Wallingford, UK. Pp.329-337.

Yanda, P.Z. & P. K.T. Munishi PKT (2007) Hydrologic and land use/cover change analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) Watersheds. Report for WWF/CARE Dar es Salaam, Tanzania.

Annex 1: DESCRIPTION OF THE LABORATORY ELEMENTAL ANALYSIS

2.1. Instrumental parameters

The ICP-MS used in this study was a Perkin Elmer Sciex, model ELAN DRC II, coupled to a laser ablation unit (Applied Spectra J200, 266nm). Helium was used as the carrier gas of the ablated particles. "Spot" was used as the ablation mode with a spot size of 200 µm for 75 seconds of ablation. Table 13 lists the instrumental parameters used for the analysis.

Table 13. Instrumental parameters used for the LA-ICP-MS analysis.

Parameter	Value
Laser Wavelength	266 nm
Ablation mode	Spot
Spot size	200 µm
Power	30 % E
Repetition rate	3 Hz
Ar flow after the cell	0.8 L/min
He flow through cell	0.8 L/min
Time of gas blank	20 s
Time of ablation	75 s

2.2. Samples

The following specimens were received by DHL at Dr. Jayachandran's laboratory in ECS on 19 February, 2016, and picked up on 22 February, 2016, inside a sealed box:

1. Small plastic tubs containing a total of 69 Ziploc® baggies, each containing 50 - 150 g dry soil, labeled with locations and dates. These will be referred to as "soils" in the report.
2. A small plastic tub containing a Ziploc® bag containing 5 plastic Petri dishes, each containing a single blank filter. These will be referred to as "blank filters" in the report.
3. In the same Ziploc® bag, a total of 14 plastic Petri dishes, each containing a single filter with sediment, labeled with a weight, a date, and/or a location. These will be referred to as "sediment filters" in the report.

The following specimens were received by Fed-Ex at Dr. Jayachandran's laboratory in ECS on 3 March, 2016, and picked up on 4 March, 2016 inside a sealed box:

1. A small plastic tub containing a total of 4 Ziploc® baggies, each containing 150 - 200 g dry soil, labeled with locations and dates. These will be referred to as "soils" in the report.
2. A small plastic tub containing a Ziploc® bag containing 5 plastic Petri dishes, each containing a single blank filter. These will be referred to as "blank filters" in the report.
3. In the same Ziploc® bag, a total of 14 plastic Petri dishes, each containing a single filter with sediment, labeled with a weight, a date, and/or a location. These will be referred to as "sediment filters" in the report.

2.3 Sample preparation and analysis

Soils

Each of the 73 soil specimens was oven-dried for at least 24 hours at 60 °C in open bags. Some formed hard clay-like rolls, which were broken up by hitting them with a pestle while still in the bag. Most of the rest of the soils were coarse aggregates that were broken up by shaking in a plastic centrifuge tube. Sieving was performed in a plastic Buchner funnel fitted with disposable nylon mesh (Miami Aquaculture) of 64 µm pore size. A 0.5 g sub-sample of the <64 µm fraction was accurately weighed and spiked with internal standards and mixed thoroughly with a vortex touch mixer (Fisher Scientific, Pittsburg, PA, USA). Duplicate sub-samples were taken from three specimens. The internal standards consisted of 175 µL of a 1000 µg/g scandium ICP-MS standard solution (Ricca Chemical Company, Pocomoke City, MD, USA), and 150.0 µl of a 1000 µg/g indium ICP-MS standard solution (Ricca Chemical Company, Pocomoke City, MD, USA), for a final concentration of 349.6 µg/g scandium and 299.8 µg/g indium in each soil sample. Samples were dried at 80 °C overnight. Each sample was milled and homogenized using a high speed ball mill mixer with a tungsten carbide jar and ball (Retsch, Newtown, PA, USA), and then the powder was pressed into a pellet of 13 mm diameter and approximately 2 mm thickness using stainless steel dies (Carver, Wabash, IN, USA). Each soil pellet was mounted onto an adhesive backing, packaged in weighing paper, and labeled with a unique identifier.

LA-ICP-MS analysis was performed using the ablation parameters described in Table 13. Each soil pellet was analyzed in four independent replicate measurements. Each replicate was acquired during the continuous ablation of a single location 200 µm in diameter after a gas blank. Two soil pellets were randomly selected as duplicates, and an additional four replicate measurements of each were performed at the end of the day.

The sediment reference material (RM) NIST SRM 2704 ("Buffalo River Sediment", National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA) was used as the calibrator[a]. The soil and sediment reference materials NIST SRM 2710 ("Montana Soil"; "Highly Elevated Trace Element Concentrations", NIST, Gaithersburg, MD, USA) and PACS-2 ("Marine Sediment Reference Material", National Research Council (NRC) of Canada, Ottawa, Canada) were used as the control standards to check for accuracy of the measurements. Pellets of 13 mm diameter were made of each of the RMs using the same procedure described for the soil pellets, above. These "standard pellets" were used for the LA-ICP-MS analysis of the soil pellets. Four replicate measurements were acquired per each standard pellet at the beginning and end of each day, and sets of two to four replicate measurements were acquired periodically throughout the day. A set of in-house calibration standard pellets, containing known amounts of a sub-set of the elements in the element menu, were also analyzed to confirm linearity of the measurement response.

The data acquired with the LA-ICP-MS instrument was processed with GLITTER software (GEMOC, Macquarie University, Australia). This software integrates the signal, subtracts the gas blank signal, and normalizes the data using scandium as the internal standard. It also calculates the concentration of the samples based on the certified concentration values in the database of RMs. Minimum detection limits (MDL) for each element are calculated at the 99 % confidence level for each replicate.

Sediments

The sediments could not be effectively removed from the filter paper, so they were processed with the filters. Sediment filters were spiked with internal standard. The internal standards consisted of a 1000 µg/g scandium ICP-MS standard solution (Ricca Chemical Company, Pocomoke City, MD, USA), and a 1000 µg/g indium ICP-MS standard solution (Ricca Chemical Company, Pocomoke City, MD, USA). The volume of scandium and indium added was calculated based on each individual sediment weight supplied, for a final concentration of 349.6 µg/g scandium and 299.8 µg/g indium in the sediment. Specimens were dried at 50 °C for 1-2 hours. Each spiked sediment filter was milled and homogenized (including filter) using a high speed ball mill mixer with a tungsten carbide jar and ball (Retsch, Newtown, PA, USA), and then the powder was pressed into one or more (see **Error! Reference source not found.**) pellets of 6 mm diameter and 2 m m thickness using stainless steel dies (Carver, Wabash, IN, USA). Pellets were mounted onto an adhesive backing, packaged in weighing paper and labeled with a unique identifier.

The sediment reference material (RM) NIST SRM 2704 ("Buffalo River Sediment", National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA) was used as the calibrator[a]. The soil and sediment reference materials NIST SRM 2710 ("Montana Soil"; "Highly Elevated Trace Element Concentrations", NIST, Gaithersburg, MD, USA) and PACS-2 ("Marine Sediment Reference Material", National Research Council (NRC) of Canada, Ottawa, Canada) were used as the control standards to check for accuracy of the measurements. For each RM, a blank filter was selected, and a mass of the RM equal to the mass of the blank filter was added with the appropriate amount of the internal standards (calculated based on the mass of RM). Each spiked RM with filter was milled and homogenized as above. Pellets of 6 mm diameter were pressed as above. These "standard filter pellets" were used for the LA-ICP-MS analysis of the sediment filter pellets.

LA-ICP-MS analysis was performed on pellets from specimens #2 through #13 using the ablation parameters described in Table 13. Each pellet was analyzed in four independent replicate measurements. Each replicate was acquired during the continuous ablation of a single location 200 µm in diameter after a gas blank. One pellet was randomly selected as a duplicate, and an additional four replicate measurements were performed at the end of the analysis. Four replicate measurements were acquired per each standard filter pellet at the beginning and end of each day, and sets of four replicate measurements were acquired periodically throughout the analysis.

The data acquired with the LA-ICP-MS instrument was processed with GLITTER software (GEMOC, Macquarie University, Australia). This software integrates the signal, subtracts the gas blank signal, and normalizes the data using scandium as the internal standard. It also calculates the concentration of the samples based on the certified concentration values in the database of RMs. Minimum detection limits (MDL) for each element are calculated at the 99 % confidence level for each replicate.

Notes:
a. NIST SRM 2704 does not have certified values for Y, Mo, Ag, Nd, or Au, and therefore NIST SRM 2710 was used as the calibrator for these elements.

3. RESULTS:

Elemental data is reported in µg/g (ppm) for all elements (whether or not they passed the quality control criteria, as was requested for the previous project in Tanzania) : ^{7}Li, ^{23}Na, ^{25}Mg, ^{27}Al, ^{29}Si, ^{31}P, ^{39}K, ^{47,49}Ti, ^{51}V, ^{52,53}Cr, ^{56,57}Fe, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{69}Ga, ^{75}As, ^{85}Rb, ^{88}Sr, ^{89}Y[a], ^{95}Mo[a], ^{91}Zr, ^{107}Ag[a], ^{111}Cd, ^{118}Sn, ^{121}Sb, ^{137}Ba, ^{139}La, ^{140}Ce, ^{146}Nd[a], ^{147}Sm, ^{153}Eu, ^{163}Dy, ^{172}Yb, ^{175}Lu, ^{178}Hf, ^{197}Au[a], ^{205}Tl, ^{206}Pb, ^{232}Th, ^{238}U. Quality data are summarized in Table 14 for soil and Table 15 for sediments. Recoveries (% Rec.) for each isotope of each RM are reported as a percent of the certified concentration values. Recoveries between 75 and 125 % were considered acceptable. Reproducibility for each duplicate run is reported as a percent difference (Dup. % Diff.) in the measured concentration of each set of four replicates, for each isotope. The overall MDL (MDL Avg) for each isotope was calculated by averaging the MDL over all replicates. Variability (Var.) for each isotope was assessed by calculating the relative standard deviation (RSD) of the four replicate measurements on each sample, then averaging the RSDs of all samples.

Table 14. Quality Data for Soils. Calibrator: NIST SRM 2704 (except Y, Mo, Ag, Nd, Au)[a].

Isotope	PACS-2 % Recovery (n=24)	2710 % Recovery (n=55)	Duplicate % Difference 58-44	Duplicate % Difference 58-63	Duplicate % Difference 58-59 & 58-75	Duplicate % Difference 58-61 & 58-76	MDL (Avg, µg/g)	Variation (Avg of RSDs, %)
Li7	121		1	2	5	1	0.195	5
Na23	137	94	20	7	12	9	0.443	4
Mg25	84	97	0.0	3	1	2	0.791	3
Al27	58	99	2	0.3	2	2	0.546	2
Si29	79	110	17	0.1	6	18	220.5	6
P31	118	89	13	3	4	4	8.97	5
K39	94	94	16	2	4	1	0.836	4
Ca42	49	93	1	0.4	8	0.5	35.2	
Ti47	76	101	0.3	4	6	3	1.53	4
Ti49	76	101	1	3	6	3	0.983	4
V51	97	92	15	3	6	2	0.146	3
Cr52	98	84	25	1	2	3	0.525	6
Cr53	98	83	9	4	2	3	1.08	6
Mn55	78	112	8	2	5	3	0.159	3
Fe56	96	96	7	1	5	4	1.66	3
Fe57	92	97	5	2	3	2	4.12	3
Ni60	108	132	8	2	17	3	0.222	5
Cu63	128	86	9	2	2	1	0.130	4
Zn66	116	88	10	0.3	3	8	0.574	7
Ga69		86	0.4	0.5	6	4	0.099	4
As75	107	94	20	14	3	4	0.803	NA(<dl)
Se82	286		28	NA(<dl)	NA(<dl)	181	49.1	NA(<dl)
Rb85		97	19	3	4	1	0.051	4
Sr88	41	98	3	1	7	4	0.027	3
Y89[a]		101	12	6	18	29	0.023	10

Zr91			17	14	59	47	0.376	25
Mo95[a]	121	101	17	0.2	3	0.1	0.148	10
Ag107[a]	126	100	32	16	19	4	0.085	
Cd111	154	67	26	13	23	8	0.452	NA(<dl)
Sn118	124		25	5	4	3	0.096	8
Sb121	90	84	NA(<dl)	12	5	8	0.093	NA(<dl)
Ba137		99	9	6	5	2	0.160	2
La139		83	1	0.2	6	2	0.020	5
Ce140		112	9	3	7	0	0.024	5
Nd146[a]		101	2	3	9	2	0.102	6
Sm147		65	4	8	5	3	0.146	7
Eu153		103	4	10	10	13	0.038	8
Dy163		79	1	8	7	10	0.127	11
Yb172		174	29	7	2	1	0.107	19
Lu175		NA(<dl)	25	15	27	27	0.046	17
Hf178		185	15	7	63	48	0.181	25
Au197[a]		105	100	NA(<dl)	43	145	0.142	NA(<dl)
Tl205	128	97	15	6	8	1	0.045	8
Pb206	130	86	18	2	8	2	0.129	5
Th232		112	2	2	8	2	0.042	6
U238	86	96	19	5	7	2	0.035	8

Blank cells indicate no certificate value available. Red text indicates failed QC criteria. NA(<dl) indicates values not detected (below the detection limits).

Table 15. Quality Data for Soils. Calibrator: NIST SRM 2704 (except Y, Mo, Ag, Nd, Au)[a]

Isotope	PACS-2 % Recovery (n=8)	2710 % Recovery (n=12)	Duplicate % Difference 50-05	MDL (Avg, µg/g)	Variation (Avg of RSDs, %)
Li7	122		2	0.103	2
Na23	127	115	0.5	0.353	3
Mg25	108	95	0.2	0.809	1
Al27	73	84	1	1.31	1
Si29	129	125	2	131.1	4
P31	116	96	1	2.31	2
K39	109	98	0.9	0.682	2
Ca42	61	70	8	14.7	2
Ti47	119	129	0.3	1.09	2
Ti49	119	130	1	1.10	2
V51	101	100	0.8	0.055	2

Cr52	97	113	0.5	0.257	2
Cr53	99	106	0.4	0.397	3
Mn55	94	100	0.1	0.128	2
Fe56	114	106	0.5	1.25	2
Fe57	106	111	3	6.47	2
Ni60	106	162	4	0.110	3
Cu63	110	96	2	0.110	3
Zn66	119	100	8.7	0.416	3
Ga69		99	0.8	0.033	2
As75	103	110	1	0.369	4
Se82			NA(<dl)	6.04	NA(<dl)
Rb85		102	1	0.055	2
Sr88	70	83	7	0.030	3
Y89 [a]		100	0.1	0.019	7
Zr91			4	0.376	7
Mo95 [a]	107	100	6	0.062	4
Ag107 [a]	58	100	19	0.040	17
Cd111	87	94	4	0.301	NA(<dl)
Sn118	101		3	0.041	6
Sb121	87	60	23	0.028	73
Ba137		91	2	0.158	2
La139		74	7	0.019	5
Ce140		102	2	0.028	4
Nd146 [a]		101	0.6	0.065	5
Sm147		60	4	0.076	8
Eu153		91	0.3	0.019	8
Dy163		74	4	0.092	7
Yb172		146	6	0.062	17
Lu175			3	0.031	11
Hf178		198	7	0.132	8
Au197 [a]		105	93	0.146	NA(<dl)
Tl205	126	114	2	0.037	4
Pb206	120	95	3	0.207	6
Th232		121	0.6	0.035	3
U238	90	112	2	0.025	5

Blank cells indicate no certificate value available. Red text indicates failed QC criteria. NA(<dl) indicates values not detected (below the detection limits).

Due to the large number of samples and elements, results for the samples are attached in a separate Excel file. Values are MDL-filtered, in which values below the MDL are denoted by a "<" followed by the MDL of that particular element for that particular replicate. For example, "<1.38" indicates that the measured concentration was below the MDL of 1.38 ppm for that replicate. The non-MDL-filtered values and the background-subtracted raw intensity data of the integrated ablation signals are also included in the file. A string of asterisks (**** or *****) denotes a non-detection.

Notes:
a. NIST SRM 2710 was used to calculate concentrations for Y, Mo, Ag, Nd, or Au.

4. REFERENCES:

Jantzi, SC, Almirall, JR. Characterization and forensic analysis of soil samples using laser-induced breakdown spectroscopy (LIBS), Anal Bioanal Chem, 2011, 400:3341-3351.

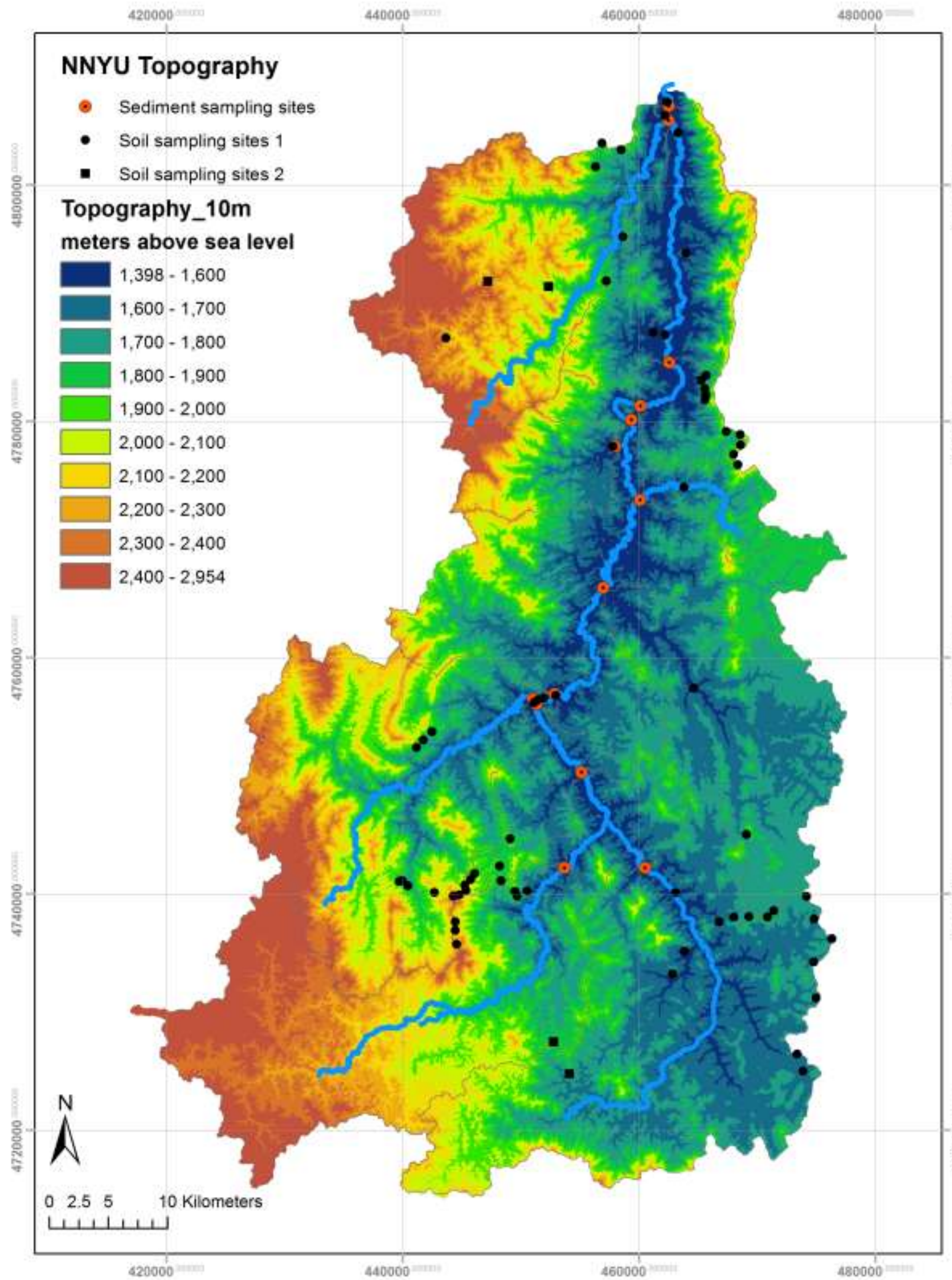
Arroyo, L, Trejos T, Gardinali P, Almirall JR. Optimization and Validation of a LA-ICPMS method for the routine analysis of soils and sediments, Spectrochim Acta B, 2009, 64:16-25.

Dutton, C, Anisfeld, SC, Ernstberger, H. A novel sediment fingerprinting method using filtration: application to the Mara River, East Africa, J Soils Sediments, 2013.

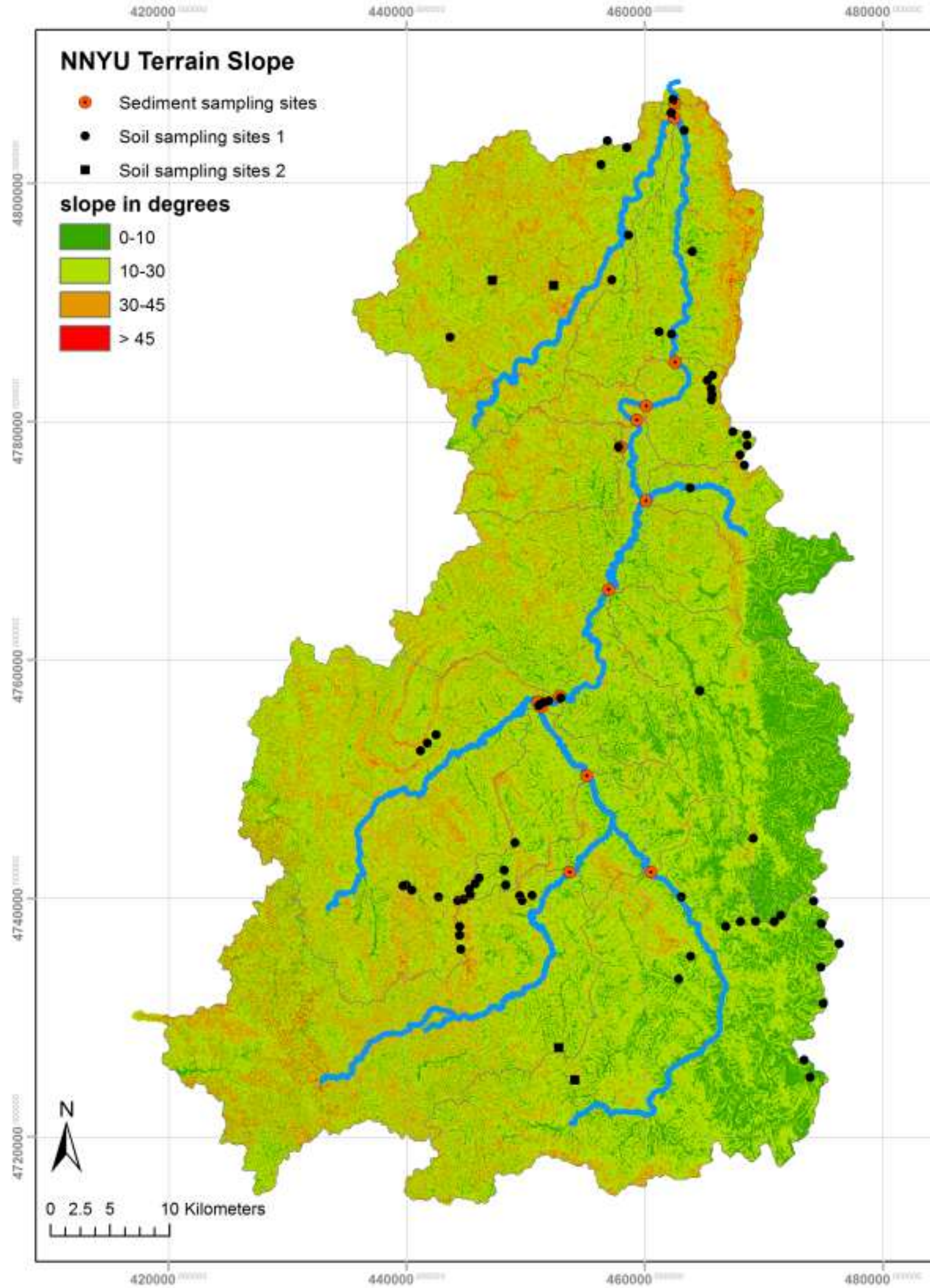
Jantzi, SC, Dutton, CL, Masikini, R, Novel "filter pellet" sample preparation strategy for quantitative LA-ICP-MS analysis of filter-bound sediments: Application to sediment source determination in Tanzania's Ruvu River Basin, J Soils Sediments, submitted.

ANNEX B: List of maps

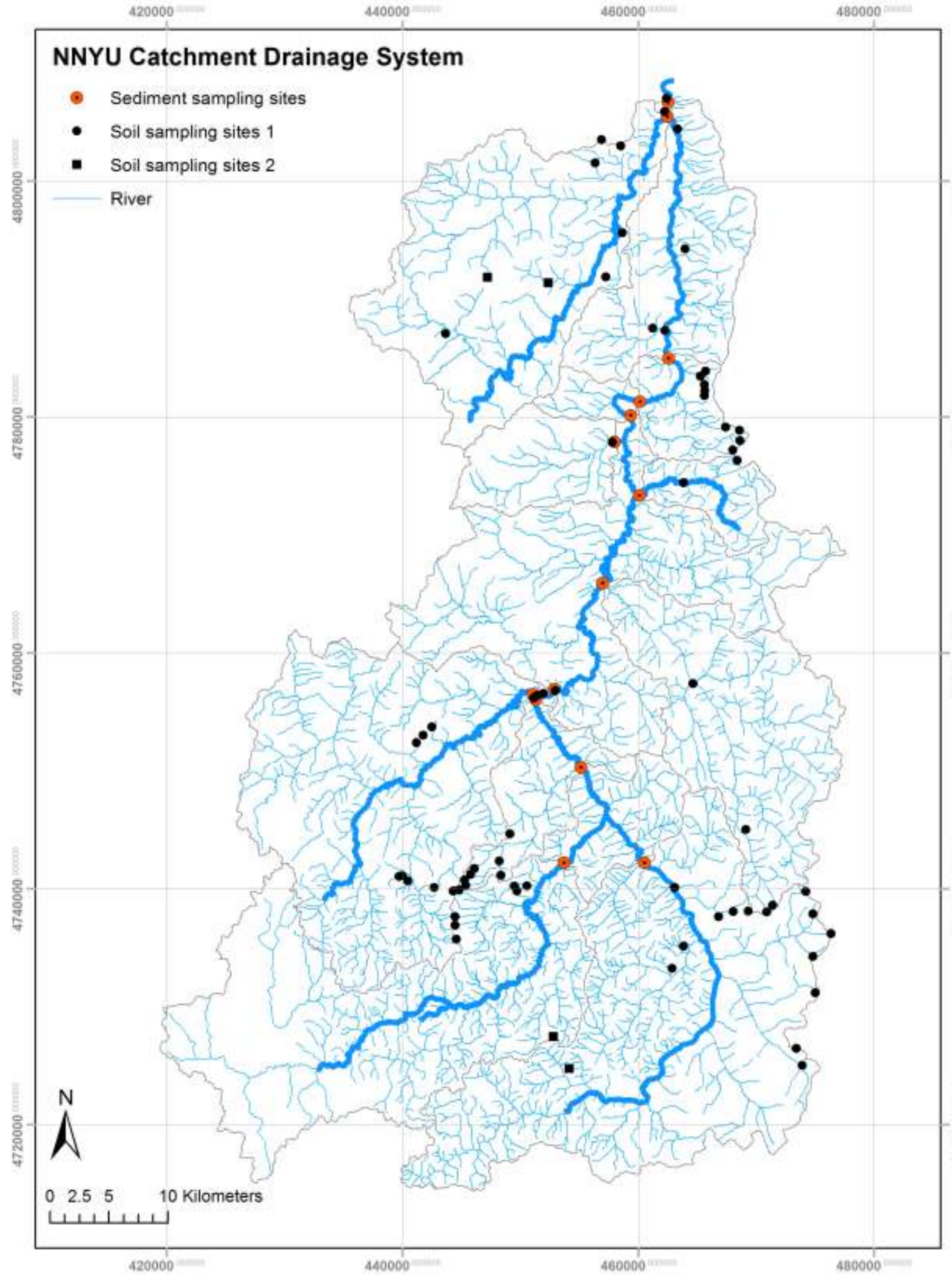
1. Map 1: Topography, river drainage, sediment and soil sampling sites in NNYU catchment.
2. Map 2: Slope of terrain in NNYU catchment; larger degrees indicate steeper slopes.
3. Map 3: River drainage network, sediment and soil sampling sites in NNYU catchment.
4. Map 4: Sediment and soil sampling sites within districts in NNYU catchment
5. Map 5: Model subcatchment areas, sediment and soil sampling sites in NNYU catchment
6. Map 6: Land cover map of the NNYU subcatchment
7. Map 7: Geological formations and sampling sites in NNYU catchment



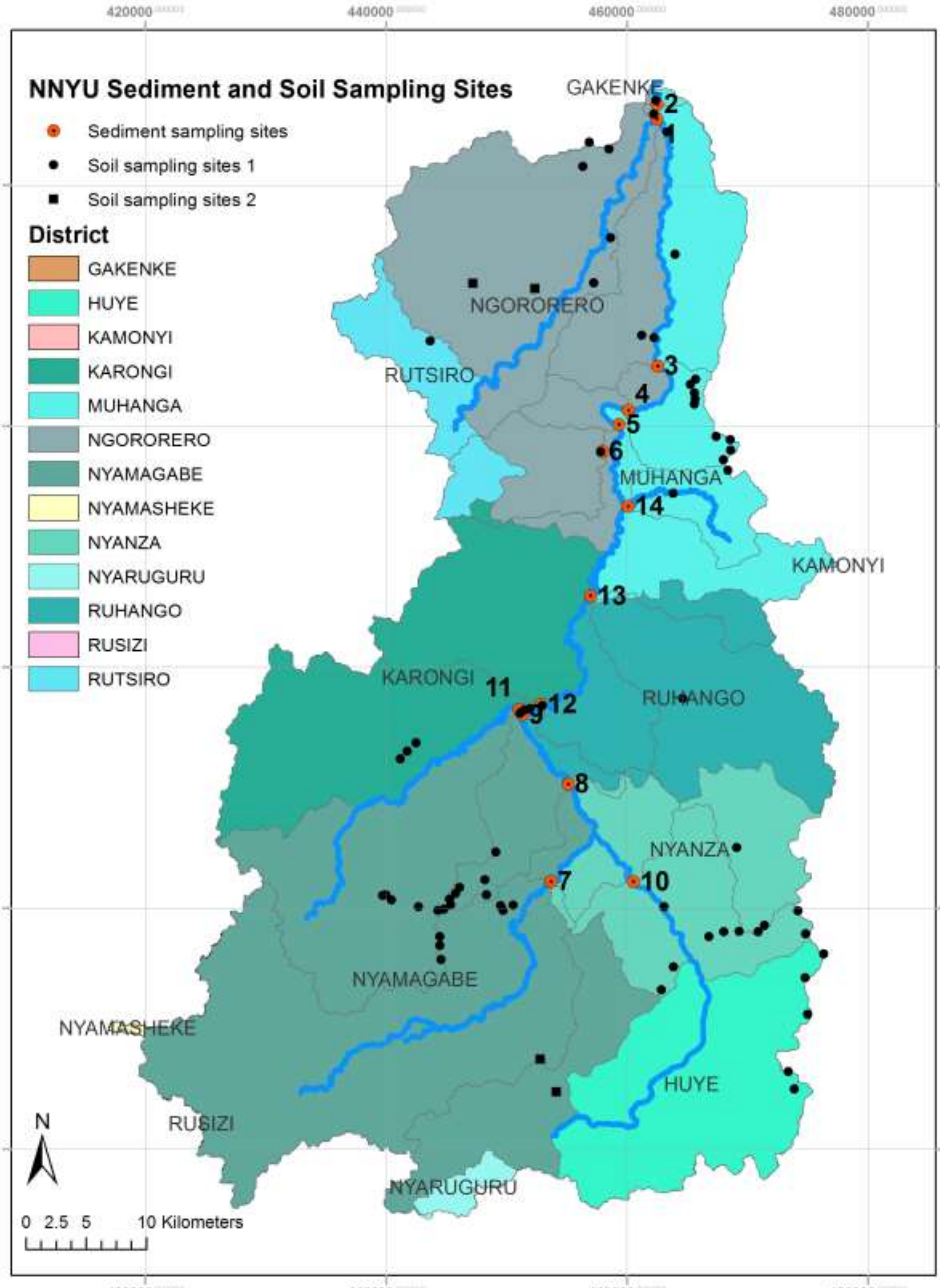
Map 1: Topography, river drainage, sediment and soil sampling sites in NNYU catchment.



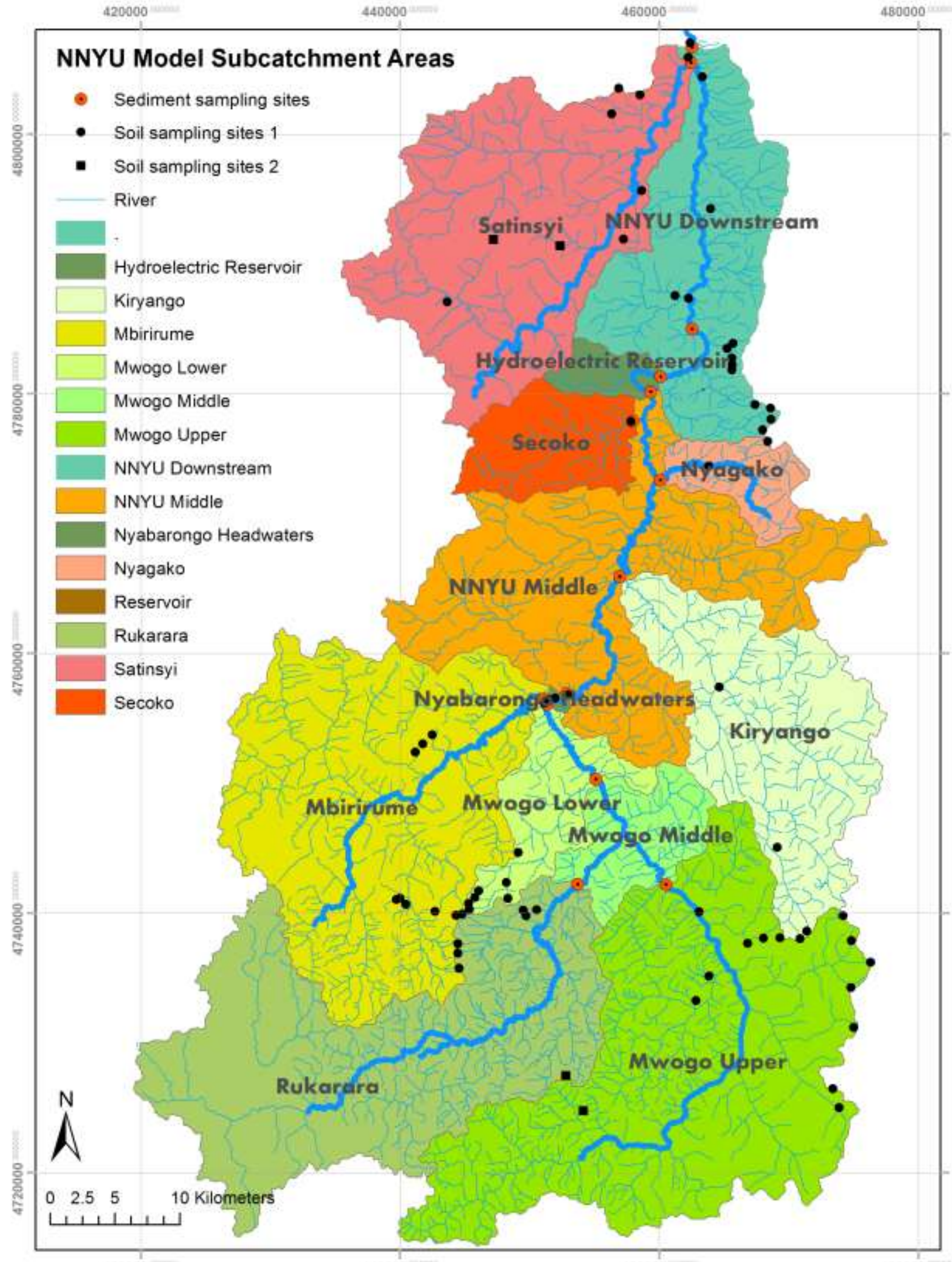
Map 2: Slope of terrain in NNYU catchment; larger degrees indicate steeper slopes.



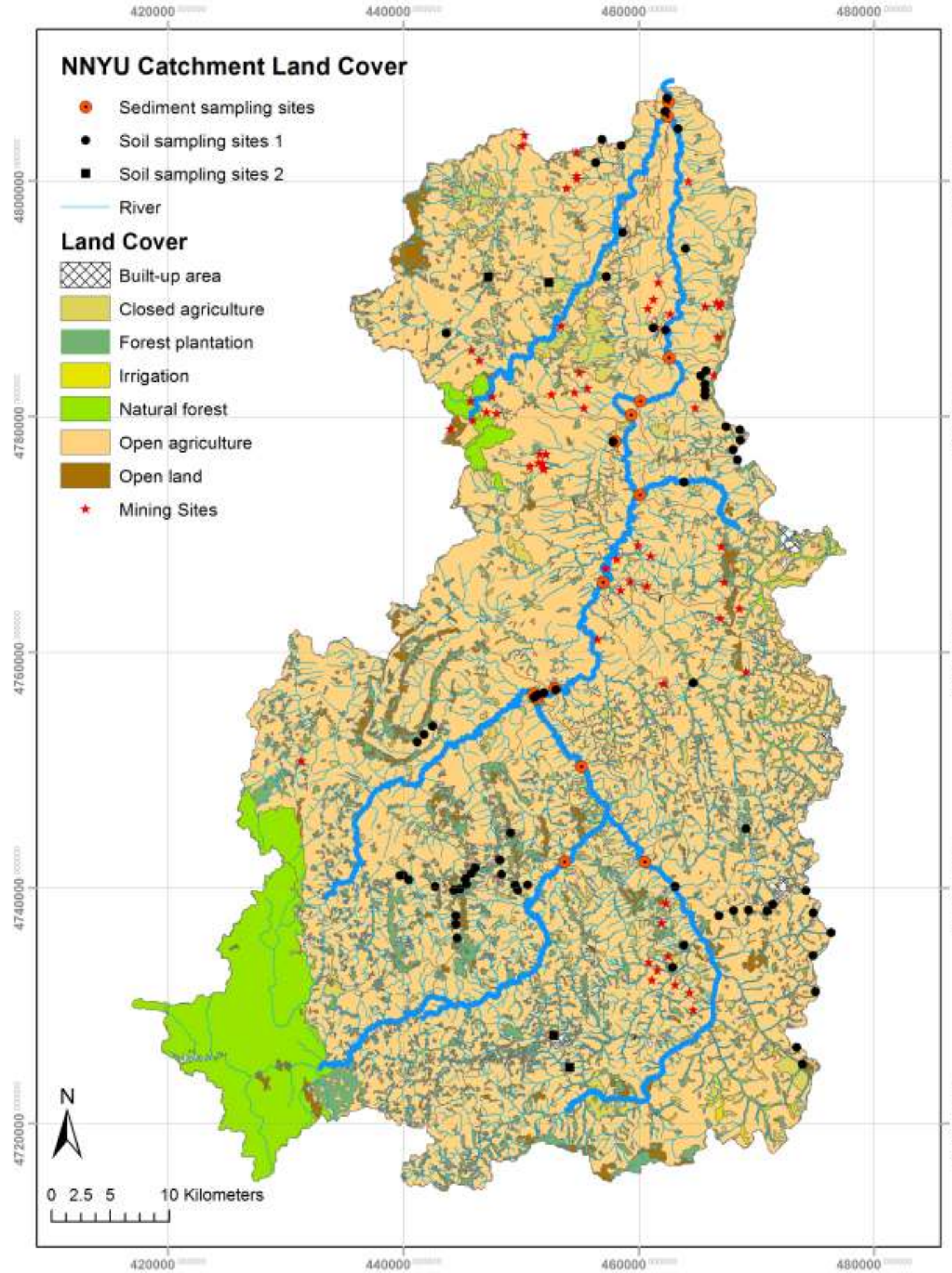
Map 3: River drainage network, sediment and soil sampling sites in NNYU catchment.



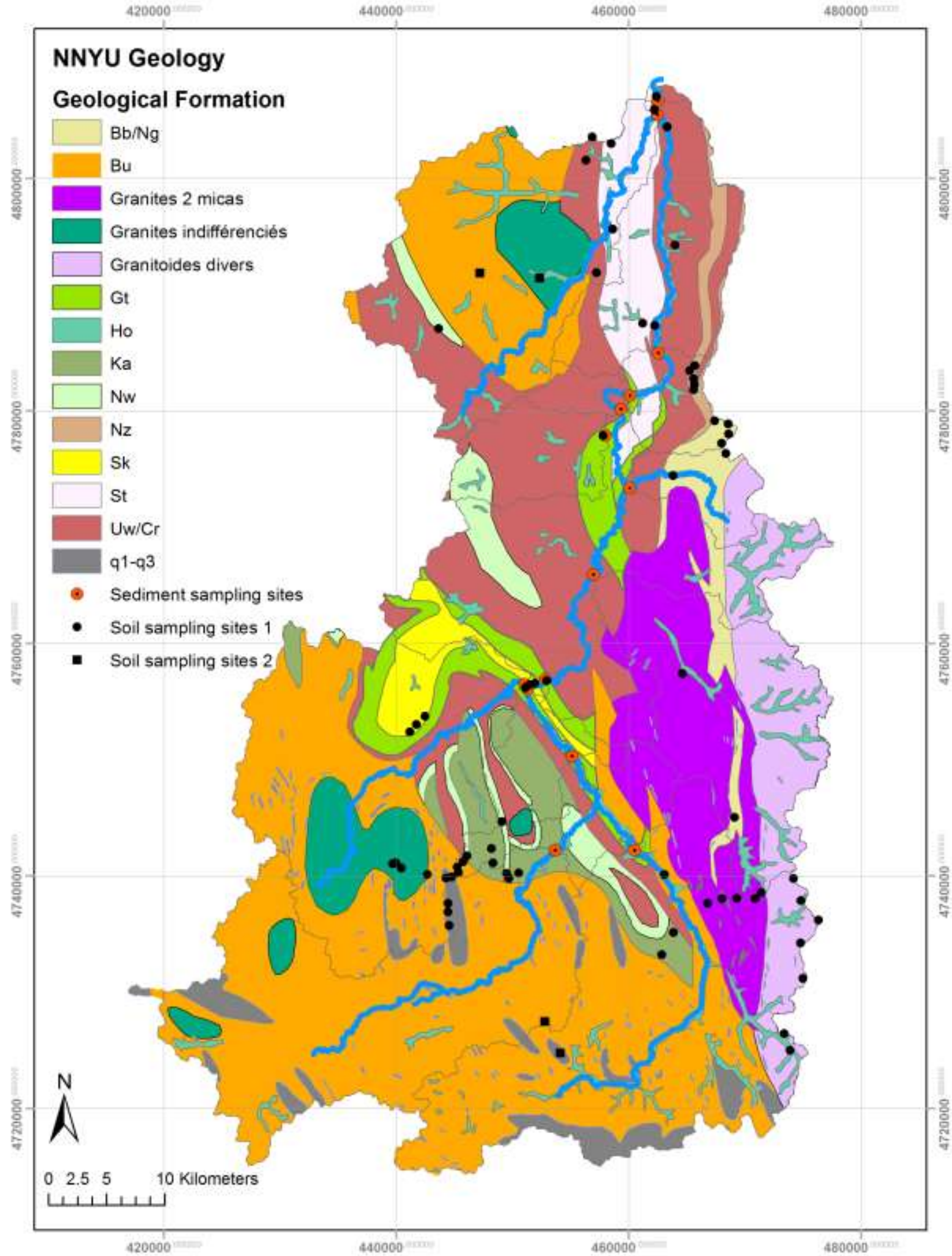
Map 4: Sediment and soil sampling sites within districts in NNYU catchment.



Map 5: Model subcatchment areas, sediment and soil sampling sites in NNYU catchment



Map 6: Land cover map of the NNYU subcatchment



Map 7: Geological formations and sampling sites in NNYU catchment

- (Granitoides divers) Nyabisindu/Kigali, generally follies. Presence of metasedimentary enclaves sometimes mylonites.
- (Granites indifferencies) All the terrains with granitical lithology in the Butare complex.
- (Ho) Alluvial of valley, lower & middle terraces, cones of dejection. Holocene & Pleistocene undifferentiated
- (Bb/Ng) Bumbogo formation. Alternation of sandstone or quartzite and schist to phylite with fine sandstone dominance in small benches. Nyabugogo formation. Benches of fine quartzite to very coarse and alternation of fine sandstone beds.
- (Bu) Butare complex. Alternation of granites, gneissic granites, quartzitic metasediments, micaschist and amphibolites.
- (Gt) Gatwaro superformation (700-900m). Mountain peak (Nyabidahe formation) with a pelitical dominant character finely laminated dark gray/light quartzophylite. Sandy base (Gatwaro formation) essentially clear motley quartzite.
- (q1-q3) Isolated outcrops, granitoide, basic rocks and pegmatoide.
- (Ka) Kaduha formation. Areno-pelitical: centimetric to decentimetric alternation of light gray quartzite and dark gray to black quartzophylite to phylite. Mountain peak with decimetric to metric levels of yellow quartzophylite.
- (Nz) Ndiza formation (120m). Benches of quartzite and fine to medium sandstone; regular bed alternation of sandstone and schist. Shyorongi formation (200m). Homogeneous schist and regular alternation of fine sandstone beds and schist beds.
- (Nw) Nyungwe formation (200-400m). Areno-pelitical: centimetric to metric sequentiel alternation of red quartzite and quartzophylite to black phylite; levels of probable volcanic heritage.
- (Granite 2 micas) Porphyric (Mutara, Bukora) or equigranular (Masango). Homogeneous massives essentially intrusive.
- (Sk) Sakinyaga formation (350-700m) with a sandy dominant character: Greenish to witish quartzite usually laminated and finely laminated dark gray/light quartzophylites: toward the mountain peak gravelly in the past.
- (St) Satinsyi complex. Phylite (Biotite, Chloritoid, Garnet), Chloritoschist, Quartzite, probable metavolcanic and numerous basic intrusions (Amphobilized).
- (Uw/Cr) Uwinka formation (500m). Pelitical dominance: bicolor banded quartzophylite, generally black/light gray or black/red. Cyurugeyo superformation (1100-1500m). Pelitical mountain peak (Kibuye formation) finely laminated with gray quartzophylite.

Table 3: Detailed description of the geological formation key used in the geological map (Map 7) and study.

Location	Easting	Adjusted Northing	District	Sector	Cell	River
Satinsyi outlet	462484.8359	4805510.364	Ngororero	Ngororero	Kaseke	Satinsyi
NNYU outlet	462537.5935	4806710.252	Ngororero	Matyazo	Matare	Nyabarongo
Nyabarongo at Ngororero bridge	462558.4935	4784997.252	Ngororero	Gatumba	Cyome	Nyabarongo
Nyabarongo hydro project - downstream of dam	460125.5935	4781308.652	Muhanga	Mushishiro	Matyazo	Nyabarongo
Nyabarongo hydro project - reservoir	459355.5935	4780149.252	Muhanga	Mushishiro	Matyazo	Nyabarongo
Secoko before Nyabarongo confluence	457974.9935	4777909.652	Ngororero	Ndaro	Bijyojyo	Secoko
Rukarara bridge, before confluence with Mwogo	453713.7935	4742201.452	Nyanza	Nyagisozi	Kabuga	Rukarara
Mwogo river floodplain - Mwogo Middle	455136.3935	4750289.252	Nyamagabe	Musange	Masizi	Mwogo
Mwogo before confluence with Mbirirume	451334.2935	4756038.352	Ruhango	Kabagali	Rwesero	Mwogo
Mwogo before confluence with Rukarara	460540.8935	4742187.652	Nyanza	Nyagisozi	Rurangazi	Mwogo
Mbirirume before confluence with Mwogo	451069.2985	4756481.793	Karongi	Murambi	Nyarunyinya	Mbirurume
Nyabarongo after confluence of Mwogo and Mbirirume	452873.9042	4756910.994	Ruhango	Kabagali	Rwesero	Nyabarongo
Kiryango river before confluence w Nyabarongo	456973.0985	4765906.512	Muhanga	Nyarusange	Ngaru	Kiryango
Nyagako river before joining Nyabarongo	460093.1026	4773339.825	Muhanga	Nyarusange	Mbiriri	Nyagako

Table 4: Locations of suspended sediment sampling points in NNYU; adjusted northing is obtained by subtracting 500,000 from the northing value of the Rwandan Geographical Coordinate System.

ANNEX 3: Prioritization Level for Rehabilitation – list of Cells

#	Provinces	Districts	Sectors	Cells	Priority
1	Western	NGORORERO	MUHANDA	MUHANDA	level 2
2	southern	NYAMAGABE	GATARE	GATARE	level 3
3	southern	NYAMAGABE	BURUHUKIRO	BURUHUKIRO	level 3
4	southern	NYAMAGABE	GATARE	BAKOPFU	level 3
5	Western	NGORORERO	NYANGE	BAMBIRO	Level 2
6	western	KARONGI	RWANKUBA	BIGUGU	level 2
7	Western	KARONGI	RUGANDA	BIGUHU	level 3
8	southern	NYAMAGABE	UWINKINGI	BIGUMIRA	level 3
9	Southern	RUHANGO	KABAGALI	BIHEMBE	Level 2
10	western	KARONGI	TWUMBA	BIHUMBE	level 3
11	Western	NGORORERO	NDARO	BIJYOJYO	level 2
12	Western	KARONGI	GASHARI	BIRAMBO	Level 2
13	Western	NGORORERO	SOVU	BIREMBO	level 2
14	Western	NGORORERO	KAVUMU	BIREMBO	level 2
15	western	KARONGI	RWANKUBA	BISESERO	level 3
16	western	NYAMASHEK	CYATO	BISUMO	level 3
17	Western	NGORORERO	NDARO	BITABAGE	level 3
18	southern	NYAMAGABE	KIBIRIZI	BUGARAMA	level 3
19	Western	NGORORERO	MUHANDA	BUGARURA	level 2
20	southern	NYAMAGABE	KIBIRIZI	BUGARURA	level 3
21	Southern	RUHANGO	BWERAMANA	BUHANDA	Level 2
22	southern	HUYE	RUSATIRA	BUHIMBA	level 2
23	southern	HUYE	KARAMA	BUHORO	level 2
24	southern	NYAMAGABE	TARE	BUHORO	level 3
25	Western	KARONGI	MURUNDI	BUKIRO	Level 2
26	Western	NGORORERO	BWIRA	BUNGWE	level 2
27	southern	MUHANGA	KABACUZI	BURAMBA	level 1
28	southern	HUYE	MARABA	BUREMERA	level 3
29	southern	HUYE	RUHASHYA	BUSHESHI	level 3
30	southern	NYAMAGABE	BURUHUKIRO	BUSHIGISHIGI	level 3
31	southern	NYAMAGABE	MUSHUBI	BUTETERI	level 3
32	southern	NYAMAGABE	KAMEGERI	BWAMA	level 3
33	southern	NYAMAGABE	KIBUMBWE	BWENDA	level 3
34	Western	NGORORERO	MUHORORO	BWERAMANA	level 3
35	Southern	RUHANGO	KINIHIRA	BWERAMVURA	Level 2
36	southern	NYAMAGABE	BURUHUKIRO	BYIMANA	level 3
37	western	KARONGI	MUTUNTU	BYOGO	level 3
38	Western	NGORORERO	BWIRA	CYAHAFI	level 3
39	southern	NYANZA	MUKINGO	CYEREZO	level 2
40	Western	NGORORERO	GATUMBA	CYOME	level 3
41	southern	NYANZA	RWABICUMA	GACU	level 2
42	Southern	RUHANGO	MWENDO	GAFUNZO	Level 2
43	southern	NYAMAGABE	UWINKINGI	GAHIRA	level 3
44	Southern	MUHANGA	NYAMABUYE	GAHOGO	level 3
45	southern	NYANZA	NYAGISOZI	GAHUNGA	level 3

46	southern	NYAMAGABE	KIBUMBWE	GAKANKA	level 3
47	western	KARONGI	TWUMBA	GAKUTA	level 3
48	southern	NYAMAGABE	TARE	GASARENDA	level 3
49	western	KARONGI	RWANKUBA	GASATA	level 2
50	Western	MUHANGA	RUGENDABARI	GASAVE	level 2
51	southern	NYAMAGABE	MUSANGE	GASAVE	level 2
52	Western	NGORORERO	KABAYA	GASEKE	level 2
53	Western	NGORORERO	NYANGE	GASEKE	Level 2
54	Western	KARONGI	GITESI	GASHARU	Level 2
55	western	KARONGI	MUTUNTU	GASHARU	level 3
56	southern	NYAMAGABE	KIBIRIZI	GASHIHA	level 3
57	southern	MUHANGA	NYABINONI	GASHORERA	level 1
58	Western	MUHANGA	NYABINONI	GASHORERA	level 3
59	Western	NGORORERO	BWIRA	GASHUBI	level 3
60	southern	NYAMAGABE	MUSHUBI	GASHWATI	level 3
61	Western	NGORORERO	MUHANDA	GASIZA	level 2
62	southern	HUYE	MARABA	GASUMBA	level 3
63	Southern	NYANZA	MUKINGO	GATAGARA	Level 2
64	Western	NGORORERO	HINDIRO	GATARE	level 2
65	southern	NYAMAGABE	GATARE	GATARE	level 3
66	Western	NGORORERO	HINDIRO	GATEGA	level 2
67	southern	HUYE	MBAZI	GATOBOTOBO	level 3
68	southern	NYAMAGABE	MUSEBEYA	GATOVU	level 3
69	southern	HUYE	RUHASHYA	GATOVU	level 3
70	southern	NYAMAGABE	TARE	GATOVU	level 3
71	Western	NGORORERO	GATUMBA	GATSIBO	level 3
72	southern	HUYE	RWANIRO	GATWARO	level 3
73	Southern	MUHANGA	NYAMABUYE	GIFUMBA	level 3
74	southern	NYAMAGABE	BURUHUKIRO	GIFURWE	level 3
75	southern	HUYE	SIMBI	GISAKURA	level 3
76	western	KARONGI	MUTUNTU	GISAYURA	level 3
77	southern	NYARUGURU	RURAMBA	GISEKE	level 3
78	Western	MUHANGA	KIBANGU	GISHARU	level 2
79	southern	HUYE	KIGOMA	GISHIHE	level 3
80	southern	NYANZA	RWABICUMA	GISHIKE	level 3
81	Southern	RUHANGO	MWENDO	GISHWERU	Level 2
82	Western	KARONGI	RUGABANO	GISIZA	Level 2
83	western	KARONGI	TWUMBA	GISOVU	level 3
84	western	KARONGI	TWUMBA	GITABURA	level 3
85	Southern	MUHANGA	NYAMABUYE	GITARAMA	level 3
86	Southern	KAMONYI	NYARUBAKA	GITARE	level 3
87	Western	MUHANGA	KIBANGU	GITEGA	level 2
88	southern	NYAMAGABE	CYANIKA	GITEGA	level 3
89	southern	NYAMAGABE	CYANIKA	GITEGA	level 3
90	Southern	RUHANGO	KINIHIRA	GITINDA	Level 2
91	Southern	RUHANGO	BWERAMANA	GITISI	level 3
92	southern	NYAMAGABE	MUGANO	GITONDORERO1, 2	level 3
93	Western	KARONGI	RUGABANO	GITOVU	Level 2
94	Western	NGORORERO	KAVUMU	GITWA	level 2
95	southern	NYAMAGABE	MUGANO	GITWA	level 2
96	Western	RUTSIRO	MANIHIRA	HANIRO	level 2

97	Southern	NYAMAGABE	MUSANGE	JENDA	level 3
98	Western	MUHANGA	KIBANGU	JURWE	level 2
99	Western	NGORORERO	NDARO	KABAGESHI	Level 2
100	Western	NGORORERO	BWIRA	KABARONDO	level 2
101	southern	HUYE	KIGOMA	KABATWA	level 3
102	Western	KARONGI	MURUNDI	KABAYA	Level 2
103	western	KARONGI	RUGANDA	KABINGO	level 3
104	southern	NYANZA	NYAGISOZI	KABIRIZI 2	level 3
105	Western	RUTSIRO	RUSEBEYA	KABONA	level 2
106	southern	NYANZA	NYAGISOZI	KABUGA	level 1
107	southern	HUYE	KIGOMA	KABUGA	level 3
108	southern	NYANZA	NYAGISOZI	KABUGA	level 3
109	southern	HUYE	SIMBI	KABUSANZA	level 3
110	southern	HUYE	MARABA	KABUYE	level 3
111	Southern	NYANZA	CYABAKAMYI	KADAHO	level 3
112	Western	NGORORERO	SOVU	KAGANO	level 2
113	Western	RUTSIRO	MUKURA	KAGANO	level 3
114	southern	NYAMAGABE	KITABI	KAGANO	level 3
115	southern	NYAMAGABE	TARE	KAGANZA	level 3
116	Western	RUTSIRO	MUKURA	KAGEYO	level 3
117	Western	NGORORERO	HINDIRO	KAJINGE	level 2
118	Western	NGORORERO	GATUMBA	KAMASIGA	level 3
119	southern	NYAMAGABE	KAMEGERI	KAMEGERI	level 3
120	Western	KARONGI	MURUNDI	KAMINA	Level 2
121	Southern	RUHANGO	MWENDO	KAMUJISHO	Level 2
122	Southern	RUHANGO	BYIMANA	KAMUSENYI	level 3
123	southern	HUYE	RWANIRO	KAMWAMBI	level 3
124	southern	MUHANGA	RUGENDABARI	KANYANA	level 1
125	Western	NGORORERO	SOVU	KANYANA	level 2
126	Western	MUHANGA	RUGENDABARI	KANYANA	level 3
127	western	KARONGI	MUTUNTU	KANYEGE	level 3
128	Southern	MUHANGA	MUHANGA	KANYINYA	level 2
129	southern	HUYE	MARABA	KANYINYA	level 3
130	southern	HUYE	RUHASHYA	KARAMA	level 3
131	southern	NYAMAGABE	CYANIKA	KARAMA	level 3
132	southern	NYANZA	CYABAKAMYI	KARAMA	level 3
133	southern	NYAMAGABE	CYANIKA	KARAMA	level 3
134	Southern	RUHANGO	KABAGALI	KARAMBI	Level 2
135	southern	HUYE	KIGOMA	KARAMBI	level 3
136	Western	NGORORERO	GATUMBA	KARAMBO	level 2
137	southern	NYAMAGABE	KIBIRIZI	KARAMBO	level 3
138	Western	KARONGI	MURUNDI	KAREBA	Level 2
139	Western	NGORORERO	NGORORERO	KASEKE	level 3
140	Southern	NYANZA	BUSASAMANA	KAVUMU	Level 2
141	western	KARONGI	TWUMBA	KAVUMU	level 3
142	southern	NYAMAGABE	KADUHA	KAVUMU	level 3
143	Western	NGORORERO	NGORORERO	KAZABE	level 2
144	Western	MUHANGA	RUGENDABARI	KIBAGA	level 3
145	Western	NGORORERO	NDARO	KIBANDA	level 2
146	southern	NYAMAGABE	KIBUMBWE	KIBIBI	level 3
147	southern	HUYE	KARAMA	KIBINGO	level 2

148	southern	HUYE	RWANIRO	KIBIRARO	level 3
149	southern	NYAMAGABE	UWINKINGI	KIBYAGIRA	level 3
150	southern	MUHANGA	KABACUZI	KIBYIMBA	level 1
151	Southern	RUHANGO	MWENDO	KIGARAMA	Level 2
152	southern	NYAMAGABE	GASAKA	KIGEME	level 3
153	Southern	MUHANGA	SHYOGWE	KININI	level 3
154	western	KARONGI	MUTUNTU	KINYONZWE	level 3
155	Western	NGORORERO	NDARO	KINYOVI	Level 2
156	western	KARONGI	RUGANDA	KINYOVU	level 3
157	southern	NYANZA	NYAGISOZI	KIRAMBI	level 3
158	southern	NYAMAGABE	KAMEGERI	KIREHE	level 3
159	Southern	RUHANGO	BYIMANA	KIRENGERI	level 3
160	southern	HUYE	RUSATIRA	KIRUHURA	level 2
161	Southern	NYANZA	MUKINGO	KIRULI	Level 2
162	Western	RUTSIRO	MURUNDA	KIRWA	level 2
163	Western	NGORORERO	KAGEYO	KIRWA	level 2
164	Southern	RUHANGO	KINIHIRA	KIRWA	Level 2
165	Western	KARONGI	RUGANDA	KIVUMU	level 2
166	southern	NYAMAGABE	CYANIKA	KIYUMBA	level 3
167	southern	NYAMAGABE	KAMEGERI	KIZI	level 3
168	southern	NYAMAGABE	BURUHUKIRO	KIZIMYAMURIRO	level 3
169	Southern	RUHANGO	MWENDO	KUBUTARE	Level 2
170	Southern	MUHANGA	CYEZA	MAKERA	level 3
171	southern	NYAMAGABE	MBAZI	MANWARI	level 3
172	southern	HUYE	RUHASHYA	MARA	level 3
173	Western	NGORORERO	HINDIRO	MARANTIMA	level 2
174	southern	NYAMAGABE	MUSANGE	MASAGARA	level 3
175	southern	NYAMAGABE	MUSANGE	MASANGANO	level 3
176	Western	NGORORERO	MUHANDA	MASHYA	level 2
177	southern	NYAMAGABE	MUSANGE	MASIZI	level 3
178	Western	NGORORERO	MATYAZO	MATARE	level 3
179	Western	MUHANGA	MUSHISHIRO	MATYAZO	level 3
180	Southern	MUHANGA	SHYOGWE	MBARE	level 3
181	Western	RUTSIRO	RUSEBEYA	MBERI	level 2
182	Southern	MUHANGA	NYARUSANGE	MBIRIRI	level 2
183	Western	MUHANGA	NYABINONI	MBUGA	level 2
187	southern	NYARUGURU	KIVU	KIVU	level 3
188	western	RUSIZI	BWEYEYE	BWEYEYE	level 3
189	southern	NYAMAGABE	NKOMANE	NKOMANE	level 3
191	Southern	RUHANGO	BYIMANA	MPANDA	level 3
192	Southern	NYANZA	MUKINGO	MPANGA	Level 2
193	Western	MUHANGA	RUGENDABARI	MPINGA	level 2
194	Western	NGORORERO	MUHORORO	MUBUGA	level 3
195	Western	MUHANGA	KIBANGU	MUBUGA	level 2
196	Western	KARONGI	MURAMBI	MUBUGA	Level 2
197	Western	KARONGI	RUGABANO	MUBUGA	Level 2
198	Southern	MUHANGA	SHYOGWE	MUBUGA	level 3
199	southern	NYANZA	RWABICUMA	MUBUGA	level 3
200	southern	NYAMAGABE	UWINKINGI	MUDASOMWA	level 3
201	Western	NGORORERO	NGORORERO	MUGANO	level 3
202	southern	HUYE	SIMBI	MUGOBORE	level 3

203	Western	KARONGI	MURAMBI	MUHORORO	Level 2
204	Southern	RUHANGO	BYIMANA	MUHORORO	level 3
205	southern	HUYE	RUHASHYA	MUHORORO	level 2
206	southern	NYAMAGABE	KITABI	MUJUGA	level 3
207	southern	NYAMAGABE	GATARE	MUKONGORO	level 3
208	Western	NGORORERO	KAGEYO	MUKORE	level 2
209	southern	NYAMAGABE	KITABI	MUKUNGU	level 3
210	Southern	RUHANGO	KABAGALI	MUNANIRA	Level 2
211	southern	MUHANGA	MUSHISHIRO	MUNAZI	level 2
212	western	KARONGI	RWANKUBA	MUNINI	level 2
213	southern	NYAMAGABE	BURUHUKIRO	MUNINI	level 3
214	southern	NYAMAGABE	UWINKINGI	MUNYEGE	level 3
215	Southern	RUHANGO	BWERAMANA	MURAMA	Level 2
216	Western	NGORORERO	KAGEYO	MURAMBA	level 2
217	southern	NYAMAGABE	KADUHA	MURAMBI	level 2
218	southern	NYARUGURU	MATA	MURAMBI	level 2
219	southern	NYAMAGABE	KADUHA	MURAMBI 1	level 2
220	western	KARONGI	TWUMBA	MUREHE	level 3
221	western	KARONGI	MUTUNTU	MURENGEZO	level 3
222	Western	NGORORERO	KAVUMU	MURINZI	level 2
223	Western	NGORORERO	KAGEYO	MUSAGARA	level 2
224	southern	NYAMAGABE	NKOMANE	MUSARABA	level 3
225	Western	KARONGI	GASHARI	MUSASA	Level 2
226	southern	HUYE	KIGOMA	MUSEBEYA	level 3
227	Western	NGORORERO	SOVU	MUSENYI	level 2
228	southern	NYAMAGABE	KADUHA	MUSENYI	level 3
229	Southern	NYANZA	RWABICUMA	MUSHIRARUNGU	Level 2
230	Southern	MUHANGA	NYARUSANGE	MUSONGATI	level 2
231	Southern	RUHANGO	MWENDO	MUTARA	Level 2
232	southern	NYAMAGABE	NKOMANE	MUTENGERI	level 3
233	southern	NYAMAGABE	MBAZI	MUTIWINGOMA	level 3
234	southern	HUYE	MBAZI	MUTUNDA	level 3
235	Western	MUHANGA	NYABINONI	MUVUMBA	level 2
236	Western	RUTSIRO	MANIHIRA	MUYIRA	level 2
237	Southern	RUHANGO	KINIHIRA	MUYUNZWE	Level 2
238	Western	NGORORERO	KABAYA	MWENDO	level 2
239	Western	RUTSIRO	MUKURA	MWENDO	level 3
240	Western	KARONGI	GASHARI	MWENDO	level 3
241	southern	HUYE	RWANIRO	MWENDO	level 3
242	western	KARONGI	GASHARI	MWENDO	level 3
243	southern	HUYE	MBAZI	MWULIRE	level 3
244	southern	NYAMAGABE	MBAZI	NGAMBI	level 3
245	Western	NGORORERO	MUHANDA	NGANZO	level 2
246	Southern	MUHANGA	MUHANGA	NGANZO	level 1
247	southern	NYAMAGABE	MBAZI	NGARA	level 3
248	southern	MUHANGA	KABACUZI	NGARAMA	level 1
249	Southern	MUHANGA	NYARUSANGE	NGARU	Level 2
250	southern	NYAMAGABE	GASAKA	NGIRYI	level 3
251	Western	NGORORERO	MUHANDA	NGOMA	level 2
252	Western	NGORORERO	KABAYA	NGOMA	level 2
253	southern	NYAMAGABE	CYANIKA	NGOMA	level 3

254	Southern	NYANZA	MUKINGO	NGWA	Level 2
255	southern	NYAMAGABE	NKOMANE	NKOMANE	level 3
256	southern	NYANZA	MUKINGO	NKOMERO	level 2
257	Western	KARONGI	MURAMBI	NKOTO	Level 2
258	southern	NYAMAGABE	TARE	NKUMBURE	level 3
259	Western	MUHANGA	RUGENDABARI	NSANGA	level 2
260	Western	NGORORERO	NYANGE	NSIBO	Level 2
261	Southern	RUHANGO	MWENDO	NYABIBUGU	level 3
262	southern	NYANZA	CYABAKAMYI	NYABINYENGA	level 3
263	Western	NGORORERO	SOVU	NYABIPFURA	level 2
264	Southern	NYAMAGABE	KADUHA	NYABISINDU	level 2
265	southern	HUYE	KIGOMA	NYABISINDU	level 3
266	southern	NYAMAGABE	KADUHA	NYABISINDU	level 3
267	southern	NYAMAGABE	GASAKA	NYABIVUMU	level 3
268	southern	MUHANGA	MUSHISHIRO	NYAGASOZI	level 2
269	Southern	NYAMAGABE	MUSANGE	NYAGISOZI	level 2
270	Southern	RUHANGO	BYIMANA	NYAKABUYE	level 3
271	Western	KARONGI	RWANKUBA	NYAKAMIRA	level 3
272	southern	NYAMAGABE	KIBUMBWE	NYAKIZA	level 3
273	Southern	RUHANGO	KINIHIRA	NYAKOGO	Level 2
274	southern	HUYE	RWANIRO	NYAMABUYE	level 3
275	Western	NGORORERO	KAGEYO	NYAMATA	level 2
276	southern	NYAMAGABE	TARE	NYAMIGINA	level 3
277	Southern	MUHANGA	MUHANGA	NYAMIRAMA	level 1
278	western	KARONGI	GITESI	NYAMIRINGA	level 2
279	southern	NYAMAGABE	KADUHA	NYAMIYAGA	level 3
280	southern	NYAMAGABE	KADUHA	NYAMIYAGA	level 3
281	southern	NYAMAGABE	GASAKA	NYAMUGARI	level 3
282	Western	NGORORERO	KAVUMU	NYAMUGEYO	level 2
283	Western	KARONGI	MURUNDI	NYAMUSHISHI	Level 2
284	southern	HUYE	SIMBI	NYANGAZI	level 3
285	Western	NGORORERO	NGORORERO	NYANGE	level 3
286	Southern	NYANZA	BUSASAMANA	NYANZA	Level 2
287	southern	NYAMAGABE	CYANIKA	NYANZA	level 3
288	southern	NYAMAGABE	CYANIKA	NYANZOGA	level 3
289	southern	NYARUGURU	RURAMBA	NYARUGANO	level 3
290	southern	HUYE	RWANIRO	NYARUHOMBO	level 3
291	Western	KARONGI	MURAMBI	NYARUNYINYA	Level 2
292	southern	NYANZA	CYABAKAMYI	NYARURAMA	level 3
293	southern	NYAMAGABE	MUSEBEYA	NYARURAMBI	level 3
294	southern	NYANZA	RWABICUMA	NYARUSANGE	level 3
295	southern	NYAMAGABE	KAMEGERI	NYARUSIZA	level 3
296	southern	MUHANGA	NYABINONI	NYARUSOZI	level 2
297	southern	NYAMAGABE	NKOMANE	NYARWUNGO	level 3
298	Western	NGORORERO	KABAYA	NYENYERI	level 2
299	Western	KARONGI	MURUNDI	NZARATSI	Level 2
300	southern	NYAMAGABE	GASAKA	NZEGA	level 3
301	southern	NYARUGURU	MATA	RAMBA	level 2
302	southern	NYAMAGABE	BURUHUKIRO	RAMBYA	level 3
303	southern	MUHANGA	KIYUMBA	REMERA	level 1
304	Western	RUTSIRO	RUSEBEYA	REMERA	level 2

305	Southern	MUHANGA	MUHANGA	REMERA	level 2
306	Southern	MUHANGA	NYAMABUYE	REMERA	level 3
307	southern	RUHANGO	KABAGALI	REMERA	level 3
308	southern	NYAMAGABE	GASAKA	REMERA	level 3
309	western	KARONGI	RWANKUBA	RUBAZO	level 2
310	Southern	NYANZA	CYABAKAMYI	RUBONA	Level 2
311	Southern	RUHANGO	BWERAMANA	RUBONA	level 3
312	Western	KARONGI	RUGANDA	RUBONA	level 3
313	southern	NYANZA	CYABAKAMYI	RUBONA	level 3
314	western	KARONGI	RWANKUBA	RUBUMBA	level 3
315	Western	MUHANGA	KIBANGU	RUBYINIRO	level 2
316	Western	KARONGI	RUGABANO	RUFUNGO	Level 2
317	southern	NYAMAGABE	GATARE	RUGANDA	level 3
318	southern	HUYE	MBAZI	RUGANGO	level 3
319	southern	NYAMAGABE	MUSEBEYA	RUGANO	level 3
320	southern	HUYE	KIGOMA	RUGARAMA	level 3
321	Western	NGORORERO	HINDIRO	RUGENDABARI	level 2
322	Western	NGORORERO	KAVUMU	RUGESHI	level 2
323	Western	NGORORERO	MUHORORO	RUGOGWE	level 3
324	southern	NYARUGURU	RURAMBA	RUGOGWE	level 2
325	southern	HUYE	RUHASHYA	RUGOGWE	level 3
326	southern	NYAMAGABE	UWINKINGI	RUGOGWE	level 3
327	southern	NYARUGURU	RURAMBA	RUGOGWE	level 3
328	Western	NGORORERO	GATUMBA	RUHANGA	level 3
329	Western	MUHANGA	RONGI	RUHANGO	level 2
330	southern	HUYE	RUHASHYA	RUHASHYA	level 3
331	southern	MUHANGA	KIYUMBA	RUHINA	level 1
332	Western	NGORORERO	BWIRA	RUHINDAGE	level 3
333	Western	KARONGI	GITESI	RUHINGA	Level 2
334	southern	NYAMAGABE	MUGANO	RUHINGA	level 2
335	southern	NYAMAGABE	KIBIRIZI	RUHUNGA	level 3
336	Western	MUHANGA	MUSHISHIRO	RUKARAGATA	level 3
337	Southern	RUHANGO	KINIHIRA	RUKINA	Level 2
338	Southern	MUHANGA	SHYOGWE	RULI	level 3
339	southern	NYAMAGABE	MUSEBEYA	RUNEGE	level 3
340	southern	NYANZA	RWABICUMA	RUNGA	level 3
341	Western	NGORORERO	HINDIRO	RUNYINYA	level 2
342	southern	NYARUGURU	RURAMBA	RURAMBA	level 3
343	southern	NYANZA	NYAGISOZI	RURANGAZI	level 3
344	Western	RUTSIRO	RUSEBEYA	RURONDE	level 2
345	southern	HUYE	MBAZI	RUSAGARA	level 3
346	southern	NYAMAGABE	MUSEBEYA	RUSEKERA	level 3
347	Western	NGORORERO	MUHORORO	RUSORORO	level 3
348	Southern	MUHANGA	NYARUSANGE	RUSOVU	level 2
349	Western	NGORORERO	GATUMBA	RUSUMO	level 3
350	southern	NYAMAGABE	KAMEGERI	RUSUSA	level 3
351	western	KARONGI	TWUMBA	RUTABI	level 3
352	Western	NGORORERO	MUHANDA	RUTAGARA	level 2
353	Western	NGORORERO	SOVU	RUTOVU	level 2
354	Western	NGORORERO	KAGEYO	RWAMAMARA	level 2
355	western	KARONGI	GITESI	RWARIRO	level 3

356	Western	MUHANGA	MUSHISHIRO	RWASARE	level 3
357	Southern	RUHANGO	KABAGALI	RWESERO	Level 2
358	southern	NYANZA	BUSASAMANA	RWESERO	level 2
359	Southern	MUHANGA	MUSHISHIRO	RWIGERERO	Level 2
360	Southern	RUHANGO	BWERAMANA	RWINYANA	level 3
361	Southern	RUHANGO	KABAGALI	RWOGA	Level 2
362	western	KARONGI	MUTUNTU	RWUFI	level 3
363	Western	KARONGI	RUGABANO	RWUNGO	Level 2
364	Western	MUHANGA	KIBANGU	RYAKANIMBA	level 3
365	Western	NGORORERO	MUHORORO	SANZA	level 3
366	Southern	RUHANGO	MWENDO	SARUHESHYI	Level 2
367	southern	HUYE	KINAZI	SAZANGE	level 2
368	southern	NYAMAGABE	MUSEBEYA	SEKERA	level 3
369	southern	NYAMAGABE	KITABI	SHABA	level 3
370	southern	HUYE	KIGOMA	SHANGA	level 3
371	Western	KARONGI	MURAMBI	SHYEMBE	Level 2
372	southern	HUYE	MARABA	SHYEMBE	level 3
373	southern	NYAMAGABE	GATARE	SHYERU	level 3
374	southern	HUYE	RWANIRO	SHYUNGA	level 2
375	southern	NYAMAGABE	MUGANO	SOVU	level 2
376	southern	HUYE	HUYE	SOVU	level 3
377	southern	NYAMAGABE	MUGANO	SOVU	level 3
378	Southern	NYAMAGABE	MUGANO	SUTI	level 2
379	southern	HUYE	MBAZI	TARE	level 3
380	Western	NGORORERO	KAVUMU	TETERO	level 2
381	Western	NGORORERO	NGORORERO	TORERO	level 3
382	Western	RUTSIRO	MURUNDA	TWABUGEZI	level 2
383	Western	KARONGI	RUGABANO	TYAZO	Level 2
384	southern	NYAMAGABE	KIBIRIZI	UWINDEKEZI	level 3
385	southern	NYAMAGABE	KITABI	UWINGUGU	level 3
386	Western	NGORORERO	NYANGE	VUGANYANA	Level 2
387	southern	NYAMAGABE	MUGANO	YONDE	level 2

ANNEX 4: The Sediment Fingerprinting Team

Dr. Christopher Dutton, RIWSP/Yale University
Dr. Amartya Saha, RIWSP/Florida International University
Dr. Sylvere Sirikare, RIWSP/Rwanda Agricultural Board
Engr. Marc Manifica, Rwanda Ministry of Natural Resources
Dr Maria Donoso, RIWSP/Florida International University
Mr Egide Nkuranga, RIWSP
Mr Boniface Mahirwe, Rwanda Ministry of Natural Resources
Mr Ignace Mpundu, Rwanda Ministry of Natural Resources
Mr Emmanuel Nkuduma, University of Rwanda
Mr Yusuf, RIWSP
Mr Madjaliwa, RIWSP

Figure 67: Participants at the Statistical Training Workshop in the Sediment Fingerprinting Workshop Series at Kigali, April 2016.

Le Fin