EWMR
Embedding IWRM in Rwanda

ASSESSING THE CONTRIBUTION OF MINING TO SEDIMENT LOADS IN THE UPPER NYABARONGO CATCHMENT

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EXECUTIVE SUMMARY

Globally, the construction of impoundments and reservoirs adjacent to or on waterways highly reduces sediment loads to the rivers and lakes, while agricultural, deforestation and surface mining activities, mineral exploitation, building construction and infrastructure development can accelerate soil erosion, with subsequent increases in sediment loads of rivers. Rwanda, like other developing countries in the world, relies on traditional uses of land and water (including mining activities) for its social and economic cohesion. Despite the contribution 0of mining on foreign exchange for the country; approximately 80% of mining activities are artisanal or unregulated and practised on a small scale. This negatively impacts on land, soil and water resources quality.

The aim of this study was to assess the contribution of mining to sediment loads in the Upper Nyabarongo Catchment,with focus on the Secoko sub-catchment. It consisted of assessing the spatial and temporal variability of water quality in the streams of the sub-catchment; assessing contribution of mining to sediment load by using the fingerprinting methodology and developing the sediment rating curve at the outlet of Secoko sub-catchment. The 14 sampling locations were selected across the sub-catchment. Through 8 campaigns, 112 water samples were collected to assess the variability of water quality.The 20 Soil samples, and 112 suspended sediment samples were collected across the study area for fingerprinting analysis to identify different levels of erosion hotspots and sedimentation in Secoko sub-catchment.

-The assessment of spatio-temporal variability of Water quality in the streams of Secoko sub-catchments was conducted through laboratory analysis of physico-chemical and metallic parameters in water samples collected . Most of physico-chemical parameters were found to be in acceptable range compared to RSB standards for surface water, except the turbidity which was found to be above the acceptable range . Furthermore, some metallic parameters such as Iron, Manganese, Magnesium, Copper, Arsenic, Antimony, Tin, Cadmium, Cobalt, Tantalum and Lead, exceeded the acceptable values for surface water quality compared to RSB standards, and the high concentration is likely attributed to land use activities.

-The assessment of sediment load by fingerprinting technique was carried out through different activities. Laboratory Analysis of the source and downstream samples were done at the Rwanda Bureau of Standards (RBS) on a standard suite of elements using a XRF and both soil and

sediment samples were taken to the Trace Evidence Analytical Facility Laboratory for elemental analysis via mass spectrometry. The Statistical results were interpreted based on conceptualizing the catchment of interest in order to track sedimentation from upstream to downstream with control of source location. Box plots were utilized to show the modeling results for each individual suspended sediment sample and composite sample for the all the campaigns. The results identify the geological types in each sub catchment that contributed the highest levels of sediment over the sampling period.The prioritization analysis was done for each sub catchment and the potential sediment sources in each sub catchment were analyzed with respect to the hydrological flow path.

The mixing model of only the geologic types within the entire Secoko sub-catchment showed that the Ho geologic type contributes the majority of the suspended sediments and the second highest amount of sediments was coming from either the Granites (Gt), or Nw geologic types. The model found with high certainty that the Uw/Cr type does not contribute much suspended sediments to the outlet. On the another side , it was discovered that the degraded part of Secoko sub-catchment is devastated by mining activities and another part of it is covered by landslide and agriculture of the seasonal crops; and these activities expose the total land to erosion leading to causing sediment load in streams of the Secoko sub-catchment

-The development of Sediment rating curve at the outlet of Secoko was achieved through various stages. The data collection was conducted once per month in one year with 8 hours on the sampling day . The stream flow was measured together with water samples collection for TSS analysis at the outlet of Secoko river. The current meter was used to measure the flow rate,and water samples collected were analysed for TSS in the IPRC Kigali laboratory. The Sediment Rating Curve (SRC) at the outlet of Secoko sub-catchment was developed by plotting the River discharges in different measurements for various periods to the Total Suspended Solids (TSS) abtained from water samples analyzed. It was found that the concentration of Total Suspended Solids (TSS) is high in Secoko River with the increase in discharge that imposes high concentration of total suspended solids. Furthermore, the high concentration of TSS at the outlet of Secoko sub-catchment is directly linked to the soil erosion influenced by rainfall, soil type, topography , and land use and management practice .

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1. GENERAL INTROCUCTION

1.1. Background

Rwanda, like other developing countries in the world, relies on traditional uses of land and water (including mining activities) for its social and economic cohesion. Despite the fact that the mining sector was ranked in 2014 as the second largest exporter, generating over $200 million of foreign exchange for the country; approximately 80% of mining activities are artisanal or unregulated and practised on a small scale. The latter has negative environmental impacts on the land, soil and water resources of the country. Activities at the mining sites include clearance of land; the introduction of new transportation, construction and sector support infrastructure; the consolidation and management of wastes; all of which have consequences for human settlements (McIntyre et al. 2016). These land-use activities, with water abstraction and discharge from mining activities may have significant impacts on water quality and quantity for downstream users.

It is globally acknowledged that anthropogenic activities alter the water cycle and hydrological processes in particular. For example, the construction of impoundments and reservoirs adjacent to or on waterways highly reduces sediment loads to the rivers and lakes, while agricultural, deforestation and surface mining activities, mineral exploitation, building construction and infrastructure development can accelerate soil erosion, with subsequent increases in sediment loads of rivers (Pietroń et al. 2017; Walling 2008). Globally, there is variability in rates of erosion and sediment transport in water-bodies and sediment loading has positive and negative impacts to aquatic habitants and ecosystems (Walling 2008). For example, excessive sediment inputs to water bodies can accelerate the rate of sedimentation in rivers, reservoirs and water conveyance systems, which cause problems for water resource development, not least opportunities to exploit the potential for hydro-power in fluvial systems. In contrast, the decline in sediment loading can result in scouring of river channels, erosion of delta and shorelines, and reduced flow of nutrients to aquatic ecosystems, which in turn results in changes to global bio-geochemical cycles of carbon and other chemical elements (ISI 2011; Walling 2008).

Studies on the relationships between land use and management, including mining and water quality variables at different catchment scales, showed complex and site-specific relationships, which cannot lead to a firm conclusion (Hobbs et al. 2008; McIntyre et al. 2016; Namugize et al. 2018). It is well documented that urban, forest and agricultural land uses are associated with increases in suspended sediments (Bostanmaneshrad et al. 2018). Therefore, rivers have immediate contact with their surroundings, their water quality is highly influenced by micro-scale parameters, i.e. land use, population density, geology and erosion properties.

Better environmental management is associated with larger-scale industrial mining projects. However, in Rwanda, the mining sector is primarily comprised of small–scale and artisanal operations. Generally, few mining companies follow good mining practices to manage known risks in order to comply with the country’s regulations related to rehabilitation of mining sites and post-closure management, but enforcement of mining regulations and environmental requirements is weak. High sediment loads have been identified as a problem, often due to poor management of sediments (Cordy et al. 2011).

Rwanda is known globally for its production of tin/cassiterite, tungsten/wolframite and tantalum/coltan ores (REMA 2015). In the Gatumba area of Ngororero District, tin and tantalum deposits of pegmatitic types are exploited, tin is often the dominating ore, which is a tantalum-rich-columbite mineral. Extraction of these minerals is often associated with minor and trace minerals which include pyrite, arsenopyrite, sulfides, sulfisalts (lead, zinc, cadmium, copper etc.), fluorides and elevated traces of uranium (Flügge et al. 2009; REMA 2015). In areas where small-scale mining is practiced, often changes in the hydrological behavior (mostly affecting the processes of infiltration, transpiration and runoff generation), water quality deterioration and sedimentation of rivers are attributed to poor soil residue management, lack of awareness amongst mining companies and cooperatives regarding the extent and consequences of environmental impacts,abandonment of mining sites, inadequate enforcement of green mining regulations, potential corruption, and a lack of concern for reputational harm associated with environmental neglect on the part of the mining companies and cooperatives.

An exploratory geochemical assessment of water and sediment carried out in the Gatumba area located in the Upper Nyabarongo catchment in 2008 indicated low levels of most inorganic elements derived from pegmatite rocks relative to World Health Organisation (WHO) thresholds for human consumption of water. However, high concentrations of uranium and arsenic exceeding their normal crustal abundance were attributed to hydrothermal and supergene dispersion and mobilisation caused by intensive agricultural activities in the area (Flügge et al. 2009). In contrast, a geochemical fingerprint evaluation of soil, plant, water (surface water and spring) and sediment reported high levels of Li, Rb, Cr and Cs and opposite results for uranium and arsenic in the same area (Nieder et al. 2014), demonstrating the potential impact of sample location and sampling methods on the outcome of such studies, where enrichment of certain elements can be localised according to geological and mineralogical factors.

A sediment fingerprint assessment undertaken in the Upper Nyabarongo catchment indicated, among others, that Secoko catchment had the largest source of sediments negatively impacting the Nyabarongo I hydroelectricity prower plant (FIU 2016). In Secoko catchment alone, approximately 15 mining sites were identified; this number may be supplemented by unknown illegal mining sites (refer to Figure 1). The major sources of sediment were ascribed to inadequate agriculture and mining activities. Heavy deposits of sediment were noted on the riverbed and river banks.

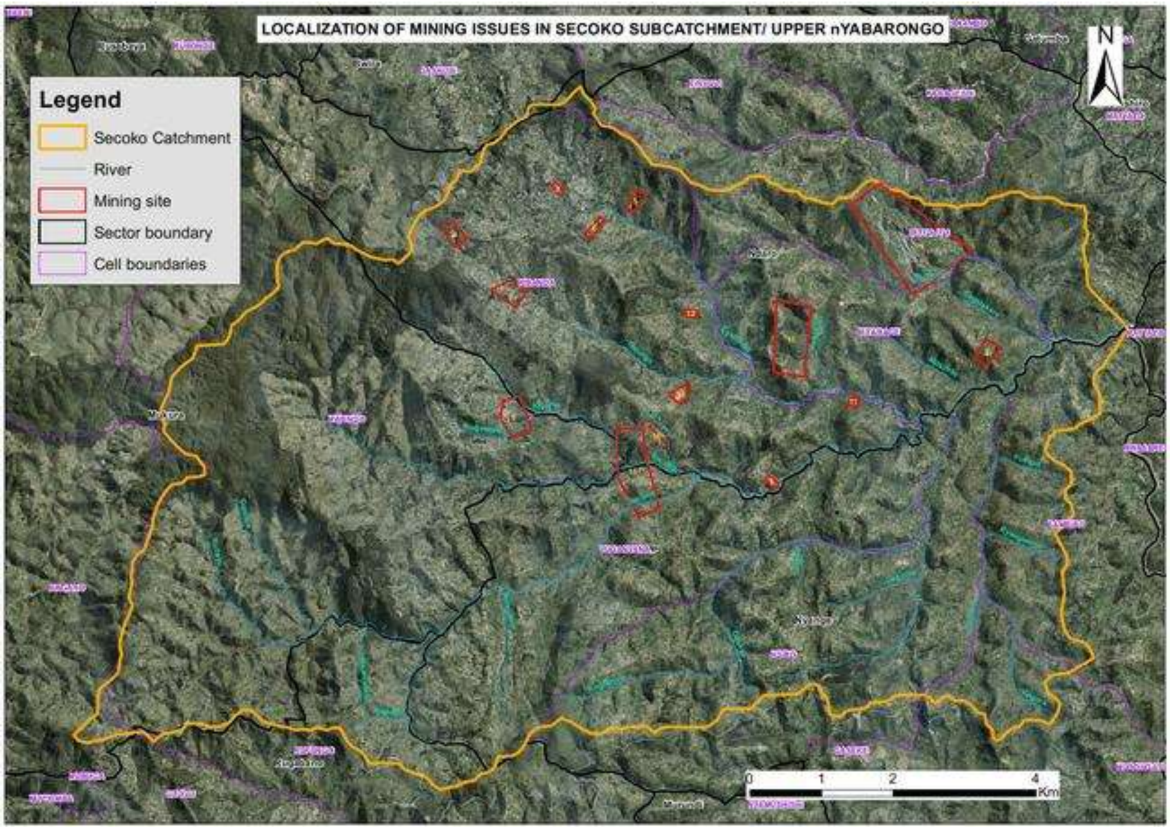

Figure 1: Location of mining sites in Secoko Sub-catchment, in the Upper Nyabarongo catchment (Source: RWFA, 2018).

In the Upper Nyabarongo catchment, siltation of rivers is a major issue, impacting in particular the potential for hydropower generation, but also the use of water resources by local communities. Poorly managed mining and associated waste disposal activities are significant causes of siltation and water pollution, but the relative contribution of mining and agriculture in mixed land use areas, in Secoko Catchment, has not been assessed. Therefore, it is not clear which land use should be the primary target for interventions to manage river siltation in different areas and thereby reduce impacts on water quality and downstream use, including hydropower exploitation/investment, which is currently restricted due to problems of chronic siltation/sedimentation in the Upper Nyabarongo catchment.

In this context, this research was undertaken in order to understand the contribution and effects of mining activities and mineral exploitation on sediment loads and transport in the Secoko sub-catchment of the Upper Nyabarongo catchment in Western Rwanda. The results of this study can be used to benchmark, at impact level, the past and ongoing sustainable mining and Integrated Water Resource Management (IWRM) and Landscape Restoration (LR) initiatives.

1.2. Project objectives

1.2.1. Main objective

The main objective of this study was to evaluate the contribution of mining activities to the sediment load and water quality deterioration in the river network of the Secoko catchment. This was achieved through a combination of scientific approaches and laboratory assessments aiming at relating spatially the sources of sediments in the rivers, their types and spatio-temporal variability in the catchment. The spatial relation of sediments and their sources was assessed using the sediment fingerprinting approach, and the spatio-temporal variability of sediments and their types, in the rivers of Secoko catchment, was assessed using detailed laboratory analysis. To facilitate monitoring of the sediment load exiting Secoko catchment, a sediment rating curve was developed at its outlet.

1.2.2. Specific objectives

To achieve the main objective of this study, the following were done:

- Delineation of Secoko catchment into sub-catchments for each of its tributaries to facilitate sediment sourcing assessment;
- Spatial analysis of sediment and their sources using the sediment fingerprinting approach;
- Spatio-temporal variability anaylisis of water quality across the catchment;
- Quantification of sediment loads from ore extraction and mineral processing;
- Development of an outcome level monitoring mechanism by developing a sediment rating curve of Secoko Catchment.

1.3. Research questions

In order to get a better understanding on sediment loading in the Secoko Catchment and respond to the research objectives, the following research questions are formulated:

- What is the current status of water quality deterioration of Secoko Catchment?
- Can the sources of sediments be linked, in space and time, with sediment loads in the Secoko River using the available geomorphological data?
- Are the estimated sediment loads emanating from mining activities higher than those from other anthropogenic activities or natural processes (such as erosion in steep terrain)?
- What are the appropriate recommended monitoring mechanisms for water/sediment loading and delivery in Secoko catchment that could improve enforcement against under- and unregulated mining play?

1.4. Challenges

During the study, accessing mining sites to carry out sampling activity turns out to be difficult to implement as access was not granted to the sites. To address this issue, the study area was conceptualized in such a way that all tributaries of Secoko River were delineated to facilitate a spatial relationship assessment between tributaries outlets and mining sites’ locations. Based on the circumstances raised, this report does not include activities planned to be carried out to quantify sediment loads resulting directly from ore extraction and mineral processing at mining sites.

2. AREA DESCRIPTION OF THE PROJECT

Secoko catchment is comprised between three districts known as Rubavu, Rutsiro and Karongi. It is located in the Northwestern part of the country. The approximate area of Secoko catchment is 94.78 square kilometers. The catchment is considered to have a high erodibility factor, as Secoko River was observed, during periods of rainfall, to be carrying extremely high sediment loads into the Nyabarongo River, with heavy deposits on the river bed and banks.

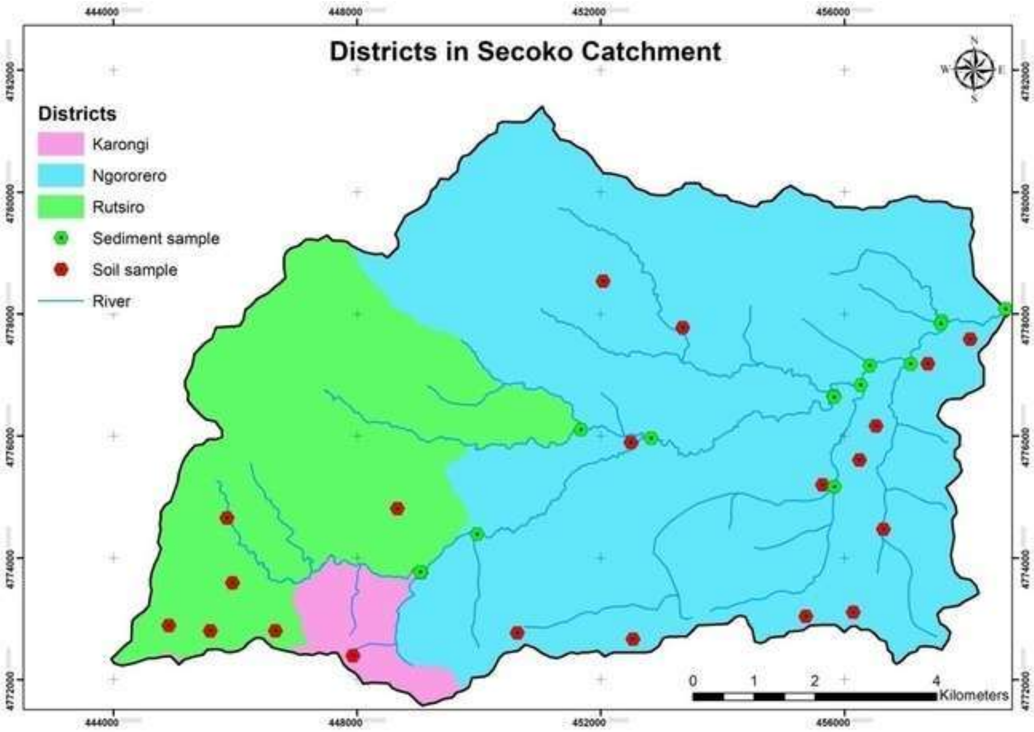

Figure 2: Localization of Secoko catchment in districts.

2.1. Topography

To analyze the topography of the project area, high resolution data were used. The dataset used is the 10 m resolution digital elevation model (DTM) that was produced in 2010, within the framework of the first Rwanda land use and development masterplan project (Swedesurvey, 2010).

Using the available DTM, the altitude variation in the study area was assessed. A variation from 1,474 m to 2,622 m a.s.l was observed. The topography of the area was considered as complex because of abrupt changes of altitude on small distances resulting in a distribution of very steep slopes all over the study area.

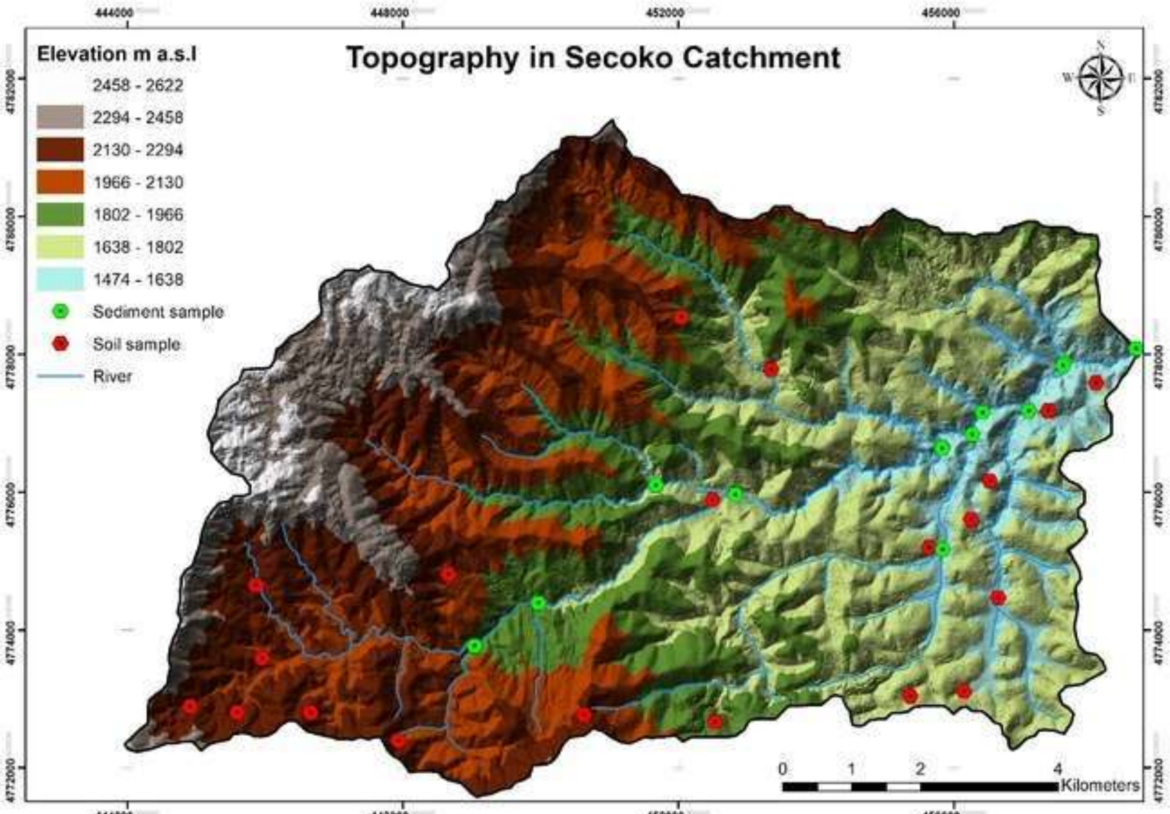

Figure 3: Topography of Secoko Catchment.

2.2. Land use land cover

The land use land cover (LULC) dataset used in this study was the 2018 LULC map of Rwanda, a dataset that was produced by combining optical satellite imagery (Landsat 8) and Synthetic Aperture Radar (SAR) data (Sentinel 1) taken at regular time intervals over all seasons (time series), to ensure representativeness for the whole year (RLMUA, 2018).

The observed major land use land cover classes in Secoko Catchment are agriculture (64.2%) used for cropping and open grass land used for grazing (5.2%). The catchment has planted sparse forests on approximately 29.9% of its total area while the remaining 0.1% is settlements and 0.6% is surface water (Secoko River outlet section). On top of that, in the catchment, intensive mining is practiced.

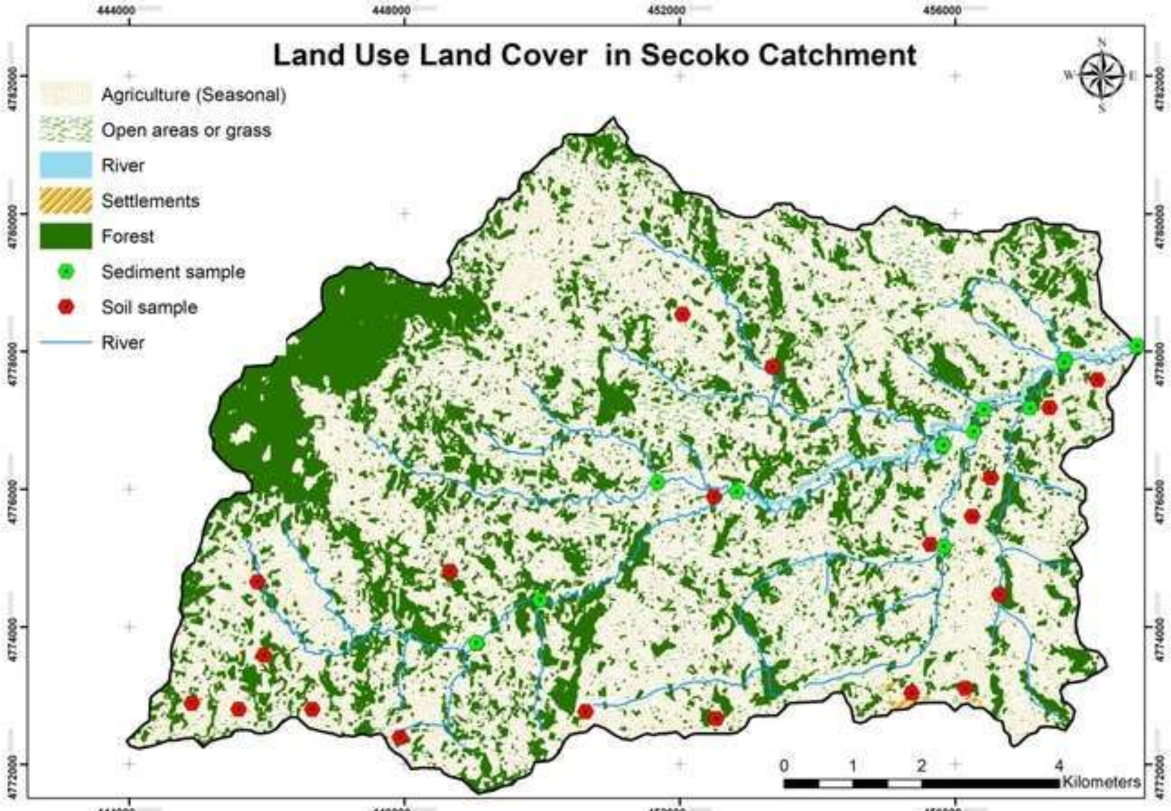

Figure 4: Land use land cover of Secoko Catchment.

2.2.1. Land use related economic activities in Secoko catchment

The identification of major land economic activities in the study area was done using a combination of satellite imageries (obtained from google earth engine) and intensive field investigation (during fieldwork). The identified activities are illustrated in Figure 5.

The land use related economic activities in Secoko Catchment are dominantly mining activities and open/rainfed agriculture. Unplanned settlements at the hilltop near agriculture farms, which also increases runoff from the upstream areas, is also observed in the catchment. Mining activities are scattered in all the sub-catchments of Secoko catchment. Most of mining sites are located in the vicinity of outlets of Secoko tributaries, causing extreme siltation of the river.

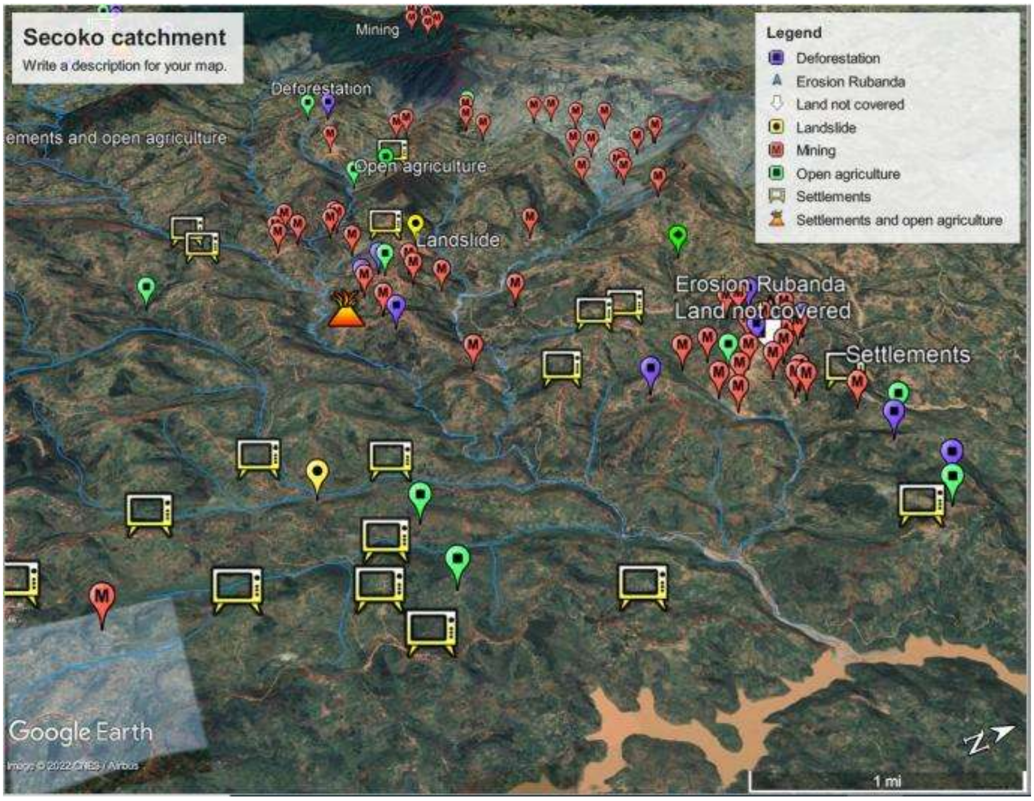

Figure 5: Land use related economic activities in Secoko catchment.

2.3. Geology

The geological formations, within the Secoko Catchment, are of four types. The dominant geological type is the Uw/Cr with an estimated 72.17 % of the catchment area, followed by the Nw, Gt and Ho with 12.05%, 11.07% and 4.71% respectively, as indicated in Figure 6 and Table 1.

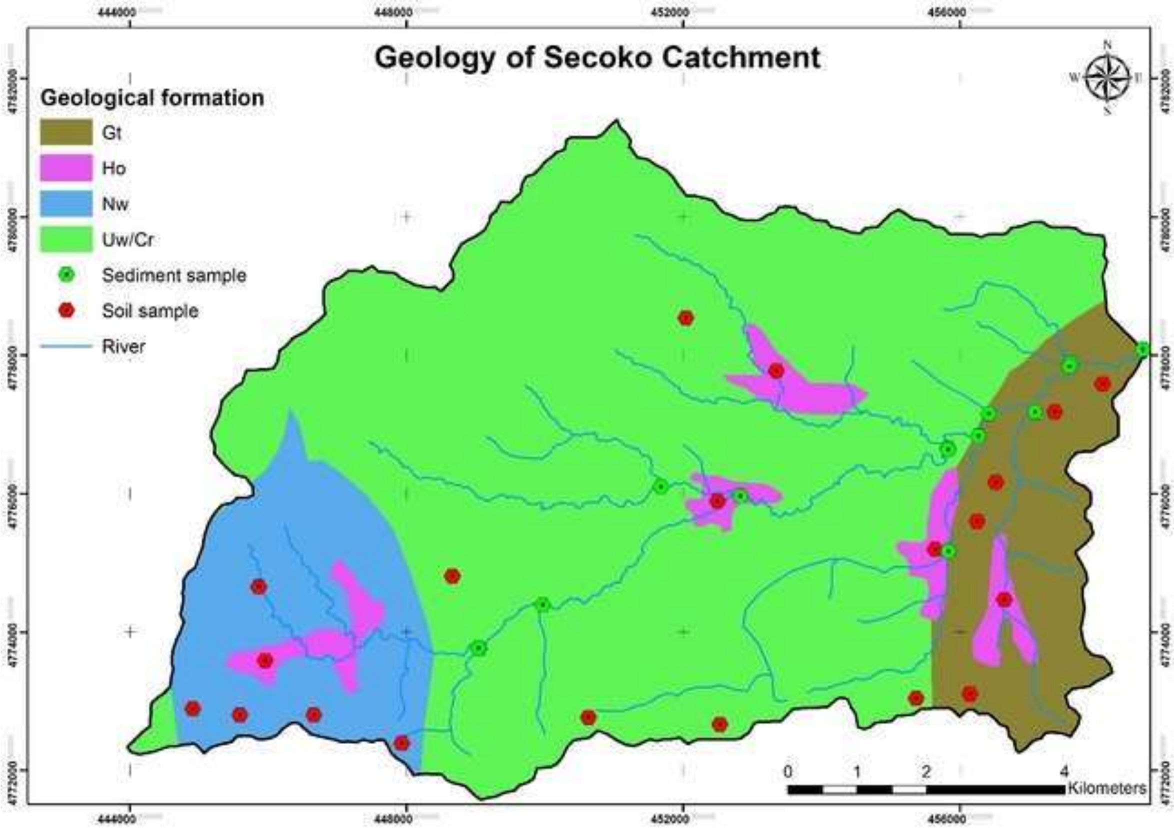

Figure 6: Geological formations of Secoko Catchment.

Table 1: Geological formation distribution.

#	**Geological formation**	**Area (Ha)**	**Percentage(%)**	**Details**
1	Ho	446.18	4.71	Alluvial of valley, lower & middle terraces, cones of dejection. Holocene & Pleistocene undifferentiated
2	Uw/Cr	6840.46	72.17	Uwinka formation (500m). Pelitical dominance: bicolor banded quartzophylite, generally black/light gray or black/red. Cyurugeyo super formation (1100-1500m). Pelitical mountain peak (Kibuye formation) finely laminated with gray quartzophylite.
3	Nw	1141.95	12.05	Nyungwe formation (200-400m). Areno-pelitical: centimetric to metric sequential alternation of red quartzite and quartzophylite to

				black phyllite; levels of probable volcanic heritage.
4	Gt	1049.22	11.07	Gatwaro super formation (700-900m). Mountain peak (Nyabidahe formation) with a pelitical dominant character finely laminated dark gray/light quartzophylite. Sandy base (Gatwaro formation) essentially clears motley quartzite.
Total		**9477.81**	**100.00**	

2.4. Soil

The soil classes are predominantly Typic Humitropept, Typic Tropohumult, and Oxic Humitropept as shown in the Table 2. In other soil mapping systems, Typic Humitropept soils are also called umbrisols generally developed in cool and humid climates, where precipitation considerably exceeds evapotranspiration. They are usually associated with acid parent materials. Umbrisols are characterized by a surface layer that is rich in humus but not in calcium available to plants, owing to high rainfall and extensive leaching that lead to acidic conditions. Most Umbrisols are moderately deep to deep, medium-textured, permeable and well-drained soils. Gravel, stones and boulders may occur throughout the profile. Base saturation is less than 50 percent in the umbric horizon and normally also deeper down.

Umbrisols are associated with Reference Soil Groups that occur under cool-temperate, moist, free-draining conditions. Linkages with the age of the landscape and local conditions. Umbrisols in cool and/ or wet areas are associated with Regosols and Leptosols, and in places with Histosols. In low-lying areas with a fluctuating water table, Umbrisols on lower slopes are found adjacent to Gleysols and Histosols (in depressions) and Cambisols, Podzols, Regosols and Leptosols (at higher elevation). Infiltration rates of these soils are generally high, except for the case for the clay and mineral soils on flat topography encountered in the catchment. The combination of the geological formation and soil data characterizes the Secoko catchment as a fragile ecosystem susceptible to heavy erosion if not well managed.

Table 2: Soil taxonomy within Secoko Catchment

#	Soil class	Area (Ha)	Percentage (%)
1	Lithic Troporthent	734.36	7.75
2	Typic Tropohumult	1591.68	16.79
3	Typic Humitropept	3392.53	35.80
4	Orthoxic Tropohumult	80.54	0.85
5	Fluventic Humitropept	244.37	2.58
6	Orthoxic Tropudult	658.07	6.94
7	Typic Paleudalf	770.74	8.13
8	Typic Dystropept	14.80	0.16

9	Humoxic Sombrihumult	748.10	7.89
10	Humoxic Tropohumult	149.71	1.58
11	Oxic Humitropept	1063.90	11.23
12	Aeric Tropaquept	0.08	0.00
13	Aeric Umbric Tropaqult	28.76	0.30
Total		**9477.65**	**100.00**

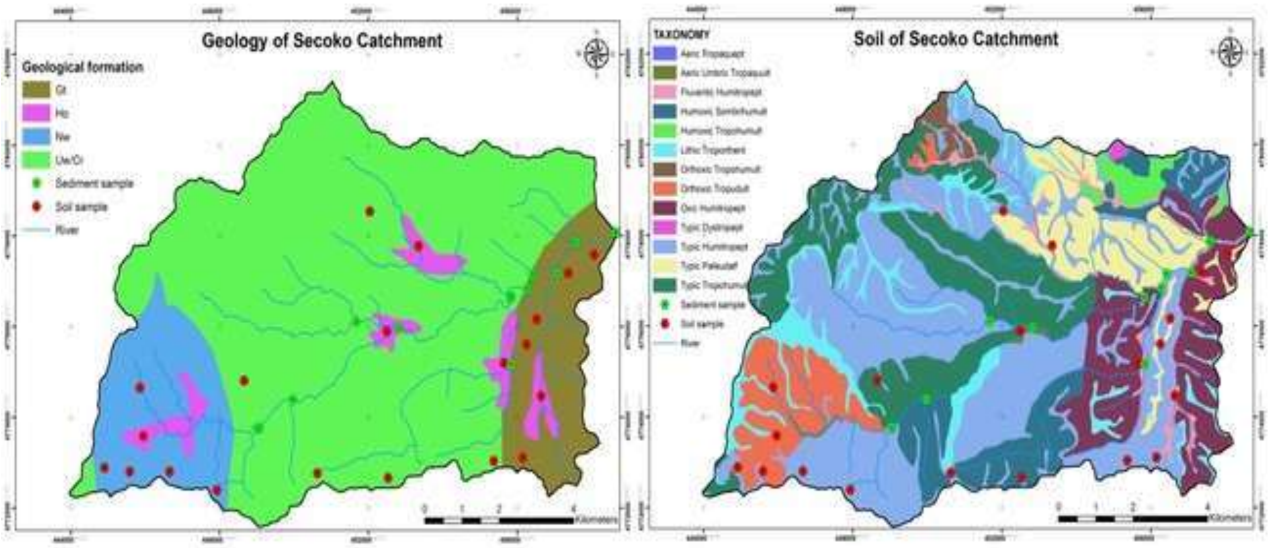

Figure 7: Geology and soil of the Secoko Catchment.

2.5. Climate

The rainfall data used in this study were collected from Meteo-Rwanda database, in a gridded form. These were done to address the temporal and spatial gaps in the Rwandan meteorological observations, by using the ENACTS (Enhancing National Climate Services) initiative reconstructed rainfall data by combining station data with satellite rainfall estimates. Bias correction factors were applied to the satellite data to produce a merged final product, which is spatio-temporally complete from the early 1980s to 2017 at a high spatial resolution (4–5 km) (Siebert et al., 2019).

The rainfall distribution in the Secoko Catchment varies between 1,343 mm to 1,464 mm per year, indicating very wet conditions. The downstream of the catchment recieves high amount of rainfall compared to the upstream.

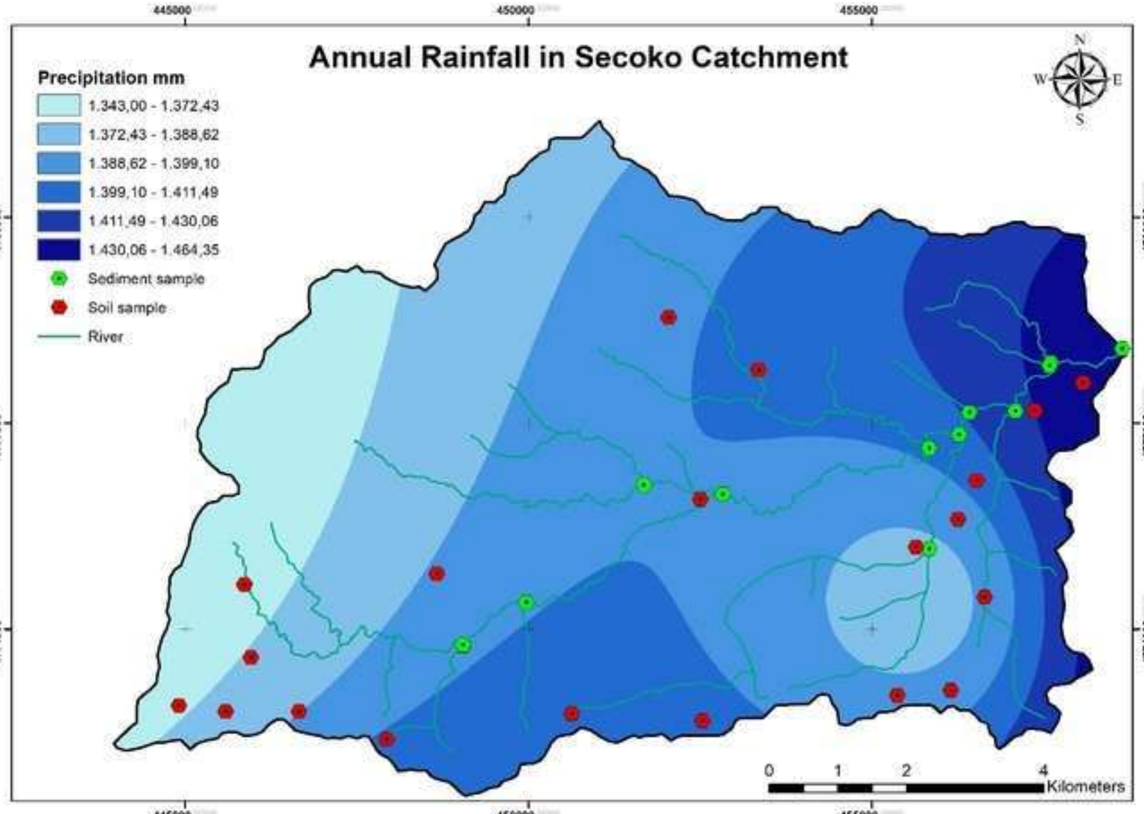

Figure 8: Annual Rainfall in Secoko Catchment.

3. MATERIALS AND METHODS

As described in the previous sections, this study had three components building up towards assessing the contribution of mining activities to sedimentation in Secoko River and setting up a monitoring mechanism to track the outcomes of all the landscape restoration efforts implemented in Secoko Catchment. The first component focused on understating the quality status of Secoko River, the second one focused on determining the sources and their contribution to sedimentation in Secoko River, using the sediment fingerprinting approach and the last focused on setting up a practical monitoring mechanism to track the changes in the degradation status of Secoko River. In this section, the methodology applied to achieve the objective of the study is provided.

3.1. Sub-catchment delineation

A sub-catchment delineation using DEM hydro-processing (Maathuis & Wang, 2006), was conducted, within a GIS platform (ArcMap 10.1), using tributaries confluence as sub-catchment outputs. Tributaries outlets were selected to facilitate sampling at known locations and spatial correlation between the source and sediment in the river, using the hydrological connectivity of Secoko River and its tributaries. 14 confluences (including the catchment outlet) were identified in Secoko catchment and were used to delineated 14 sub-catchments (refer to Table 3 and Figure 9). This delineation allowed the analysis to estimate with high accuracy the sediment sources and contribution of each sub-catchment.

Table 3: Sub-catchments in Secoko and their respective hydrological connectivity.

#	Name	Area (sq.km)	Percentage (%)	Upstream catchment(s)	Downstream catchment
1	Rubanda	7.04	7.46	N/A	Secoko Lower
2	Sagatekere	0.87	0.92	N/A	Secoko Lower
3	Mitsimbi	1.20	1.27	N/A	Secoko Lower
4	Cyajongo	17.03	18.05	N/A	Secoko Lower
5	Kagera	7.14	7.57	N/A	Secoko Lower
6	Gasesa Upper	9.26	9.81	N/A	Gasesa
7	Gasesa	4.59	4.87	Gasesa Upper	Secoko Lower
8	Secoko Upper	12.20	12.93	N/A	Kiguhu
9	Kiguhu	6.25	6.62	Secoko Upper	Secoko Middle
10	Rubayu	11.68	12.37	N/A	Secoko Middle
11	Kagogo	2.72	2.89	N/A	Secoko Middle
12	Ruhumira	1.19	1.26	N/A	Secoko Middle
13	Secoko Middle	10.16	10.77	Kiguhu, Rubayu, Kagogo, Ruhumira	Secoko Lower
14	Secoko Lower	3.03	3.21	Rubanda, Sagatekere, Mitsimbi, Cyajongo, Kagera, Secoko Middle	N/A
Total		**94.36**	**100**		

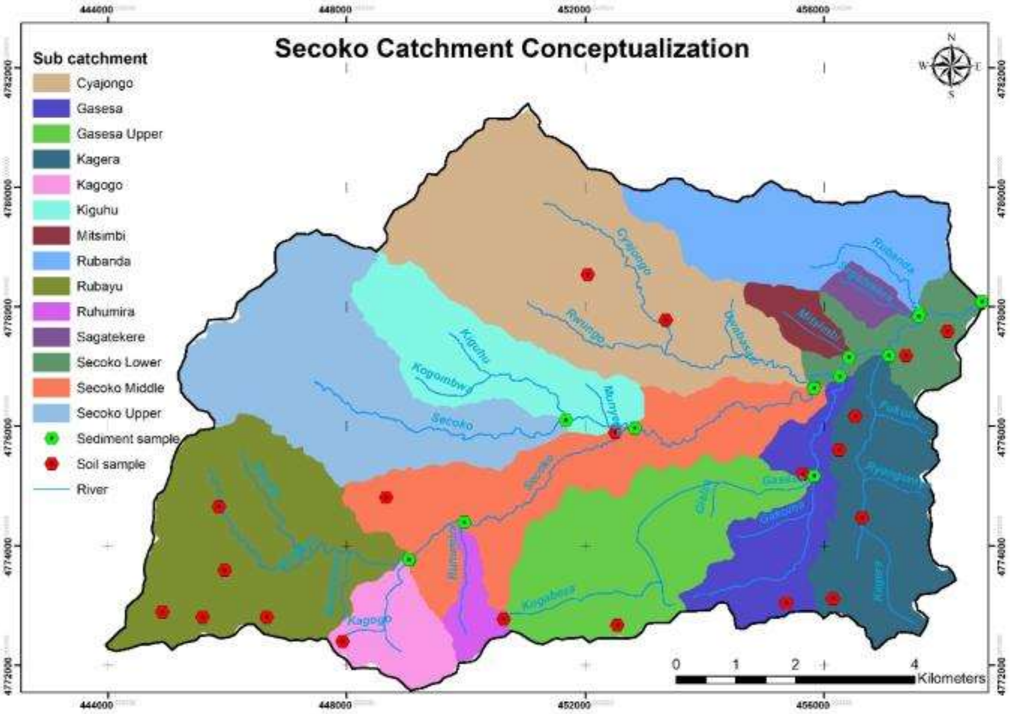

Figure 9: Secoko catchment conceptualization.

3.2. Sampling

3.2.1. Water quality sampling

International standards and protocols were applied to collect water samples as well as prepare the needed instrumentations. The samples were upstream the confluences at adequate distance to avoid backwater flow and then were sealed in such a way to maintain their raw quality. During field investigations, all physico-chemical parameters namely pH, temperature, salinity, conductivity and turbidity were immediately measured on the spot.

3.2.2. Soil sampling

Soil samples were collected throughout the catchment. Each soil sample collected was a composite sample collected at 50 cm depth within a 50 meter radius, in each geological unit of Secoko catchment. 5 composite samples were collected from each lithographic group. Soil samples were air dried in the field then sealed using a ziploc style bag. The location of the soil samples are provided in Table 4.

Table 4: Soil samples locations.

#	Type of sample	X	Y	District	Sector	Cell	Village
1	Soil	458064	4777586	Ngororero	Nyange	Bambiro	Rwasankuba
2	Soil	457368	4777179	Ngororero	Nyange	Bambiro	Butare
3	Soil	456519	4776161	Ngororero	Nyange	Nsibo	Murambi
4	Soil	456247	4775600	Ngororero	Nyange	Nsibo	Murambi

5	Soil	456145	4773105	Ngororero	Nyange	Nsibo/Gaseke	Zegenya/Birambo
6	Soil	456638	4774463	Ngororero	Nyange	Bambiro	Nyarushubi
7	Soil	455636	4775193	Ngororero	Nyange	Vuganyana	Nyamyungo
8	Soil	452496	4775888	Ngororero	Nyange	Vuganyana	Mbobo
9	Soil	453345	4777773	Ngororero	Ndaro	Bitabage	Gasharu
10	Soil	445954	4773587	Rutsiro	Mukura	Mwendo	Nyove
11	Soil	455365	4773037	Ngororero	Nyange	Gaseke	Cyambogo
12	Soil	452530	4772664	Ngororero	Nyange	Nsibo	Nyange
13	Soil	450629	4772766	Ngororero	Nyange	Vuganyana	Kakinyoni
14	Soil	448659	4774803	Rutsiro	Mukura	Mwendo	Nyarusongati
15	Soil	452037	4778537	Ngororero	Ndaro	Kibanda	Kimirehe
16	Soil	447930	4772392	Karongi	Rugaba	Rufungo	Bitenga
17	Soil	446656	4772800	Rutsiro	Mukura	Mwendo	Gako
18	Soil	445587	4772800	Rutsiro	Mukura	Mwendo	Nyarubande
19	Soil	444908	4772884	Rutsiro	Mukura	Mwendo	Nyarubande
20	Soil	445859	4774650	Rutsiro	Mukura	Mwendo	Kagogo

3.2.3. Sediment sampling

Two types of sediment sampling were conducted in this study. The first one focused on collecting samples at confluences for trace element analysis and the second one was specifically collecting total suspended solid at the outlet of Secoko catchment to develop a sediment rating curve. both these sampling were conducted as follows:

- **The first type:**

Similarly to water quality samples, suspended sediment samples were collected upstream the confluences at adequate distance to avoid backwater flow. Sampling was done by taking one liter sample of water per tributary of the Secoko River, in a Nalgene 1-Liter sample bottle rinsed three times with distilled water. A sub-sample of the water was then filtered in the field through a pre-cleaned, pre-dried, pre-weighed 0.45 µm Whatman Cellulose Nitrate (CN) filter; and sealed accordingly. The location of the first type of sediment samples collected is provided in Table 5.

Table 5: First type sediment samples locations.

#	Type of sample	X	Y	District	Sector	Cell	Village
1	Sediment	458636	4778082	Ngororero	Ndaro	Bijyojyo	Birima
2	Sediment	457598	4777881	Ngororero	Ndaro	Bitabage	Gituza
3	Sediment	457581	4777838	Ngororero	Ndaro	Bitabage	Kamuyobora
4	Sediment	457084	4777176	Ngororero	Ndaro/Nyange	Bitabage/Bambiro	Kamuyobora/Butare
5	Sediment	456413	4777154	Ngororero	Ndaro	Bitabage	Ngugu
6	Sediment	456263	4776833	Ngororero	Nyange	Nsibo	Murambi
7	Sediment	455825	4776655	Ngororero	Ndaro/Nyange	Bitabage/Kibanda /Vuganyana	Ngugu/Nyamugari /Nyamyungo
8	Sediment	455829	4776632	Ngororero	Ndaro/Nyange	Bitabage/Kibanda /Vuganyana	Ngugu/Nyamugari /Nyamyungo
9	Sediment	455831	4775165	Ngororero	Nyange	Vuganyana/Nsibo	Nyamyungo/Murambi

10	Sediment	452826	4775962	Ngororero	Ndaro/Nyange	Kibanda/Vuganyana	Rwambogo/Nyagatama
11	Sediment	451673	4776098	Ngororero/ Rutsiro	Ndaro/Mukura /Nyange	Kibanda/Mwendo /Vuganyana	Rwambogo/Mataba /Mbobo
12	Sediment	449966	4774386	Ngororero	Nyange	Vuganyana	Kazenga/Kakinyoni
13	Sediment	449047	4773754	Rutsiro/Karongi/Ngororero	Mukura/Rugaba/Nyange	Mwendo/Rufungo /Vuganyana	Nyarusongati/Bitenga/ Kamuriza
14	Sediment	449041	4773767	Rutsiro/Karongi/Ngororero	Mukura/Rugaba/Nyange	Mwendo/Rufungo /Vuganyana	Nyarusongati/Bitenga/ Kamuriza

- **The second type:**

Sediment sampling was carried out at the outlet of Secoko River. By using well cleaned sampling bottles, water samples were collected once per month, in a period of 1 year. Samples were taken on hourly-basis during 8 hours on the day on field, then conserved in a cooler box and transported to IPRC Kigali Water Laboratory for total suspended solids (TSS) analysis. During laboratory analysis a well-mixed, measured volume of a water sample was filtered through a pre-weighed filter paper. The filter paper was dried in an oven at 104 ± 1ºC for 24 hours and then weighed again.

The mass increase divided by the water volume filtered expressed TSS in mg/L as per formula:

$$\frac{Weight_{final}(g) - Weight_{initial}(g) \times 1{,}000{,}000}{Sample\ Volume\ (mL)} = mgTSS/L \qquad (1)$$

3.3. Flow measurement

The measurement of stream flow was conducted in parallel with the second type of sediment sampling to characterize the behavior of Secoko River at its outlet both on flow and the sediment load. A current meter was used to measure the flow rate (refer to Figure 10). The measurements were taken once a month over a year, where eight (8) measurements were made at the interval of one hour from nine (9:00) in the morning up to (16:00) in the evening, in the same day.

The measuring site was carefully selected to ensure accurate flow measurements. As Secoko River has many tributaries, the site was selected to the most downstream location where all water are connected and measured together, eventhough it was a bit challenging because of the high deposition of sediments.

A current meter was used to measure the stream flow and to know the profile of the river. A water level gauge was installed on the river. The river was divided into equal sections to take representative samples. Secoko River discharge was calculated using the continuity formula below:

$$Q = V * A \qquad \textbf{(2)}$$

Where: Q is the stream discharge (flow) in m^3/s, V is the average stream velocity in m/s, and A is the stream's cross-sectional area (perpendicular to the predominant flow direction) in m^2.

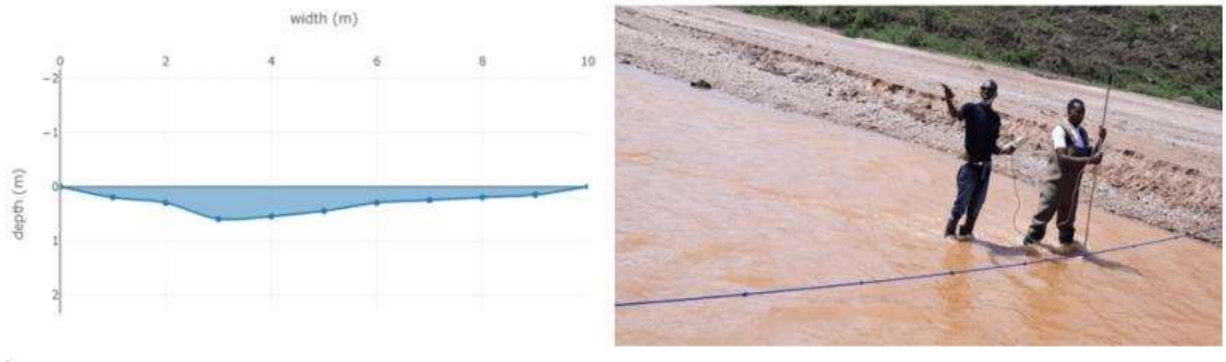

Figure 10: Secoko River Cross Section during field measurement, July 2021.

3.4. Analysis

3.4.1. Water quality analysis

Table 6 summarizes the category of individual parameters measured, the measurement method and equipment used.

Table 6: Parameters measured and applied methods.

Category of parameter Measured	**Method used**	**Parameters measured**	**Equipment used**
Parameters measured directly on the field	Electrochemical method	pH and Conductivity	pH meter, Conductivity meter
Physical-Chemical parameters	Titration method	Calcium, Fluoride, Magnesium and Chlorides	Turbid meter, DR3900 spectrophotometer, AA spectrophotometer, watch glass, cooler box, analytical balance, wash bottles and laboratory glassware
	Spectrophotometric method	Sulfate, Manganese, Iron	
	Atomic Absorption spectroscopy	Arsenic, Cadmium, Chromium, Cobalt, lead, Antimony, Tantalum, Tin	
	Electrochemical	Turbidity	

3.4.2. Trace Element Analysis

Soil and sediment samples were taken to the Trace Evidence Analytical Facility Laboratory at RBS 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. The mass spectrometer data was then assessed for quality control, and pre-processed using the appropriate software.

Figure 11: Laboratory instrumentation.

3.4.3. Statistical analysis

All statistical analyses were done in R 4.1.2. for windows (R Core Team, 2016). The Kruskal-Wallis H test was first used to identify tracers that showed significant differences between source types (kruskal.test function) (Kruskal & Wallis, 1952). A default p-value of 0.05 was used to determine significance. For several of the models, the default p-value did not provide enough tracers for use in the mixing model so the p-value was adjusted up in 0.05 increments until a minimum of three tracers were identified that could be used in the mixing model. The identification and use of tracers using higher p-values from the Kruskal-Wallis test ultimately will be reflected in the greater 95% confidence intervals in the mixing model.

A step-wise discriminant function analysis based on the minimization of Wilks' lambda was then used to determine which parameters were capable of discriminating between source types (greedy.wilks function in the klaR package and the lda function in the MASS package) (Weihs, Ligges, Luebke, & Raabe, 2005). A jackknifed discriminant function analysis was also used to assess the discriminatory power of the tracers through a cross-validation procedure (lda function in the MASS package). With the jackknifed procedure, the discriminant function analysis is run multiple times, leaving a different sample out each time. The procedure then provides a value of the success in the reclassification of the source samples that is often more conservative than a discriminant function analysis utilizing all source samples (Borcard, Gillet, & Legendre, 2011).

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

A mixing model with Bayesian Inference was used to determine the likely sources of sediments. The MixSIAR mixing model was originally developed for inferring diet composition from stable isotope analysis of consumers and sources (Stock et al., 2018; Stock & Semmens, 2013). MixSIAR allows for all sources of uncertainty to be propagated through the model. The model is fit via a Markov Chain Monte Carlo (MCMC) routine. MCMC produces a simulation of the plausible values of the posterior distribution given the data provided.

The MCMC routine ran through a user specified number of iterations and attempt to determine plausible values, or the proportion of each source in a sample, given the data input into the model. This information was then used to create the confidence intervals of the model sources.

The model was run for 500,000 iterations with the first 50,000 iterations discarded (burn-in). An uninformative prior distribution was specified in the models. The mixing model assumes the contribution of the sources add up to 100%. The means of all potential sources within the model will not necessarily add up to exactly 100% due to the different distributions for each source.

There are many potential sources of uncertainty with using mixing models with sediment data throughout a large catchment. Differences in organic matter and particle size within samples can differentially affect the concentration of geochemical elements. A number of different correction factors have been used in the past to normalize concentration data between different samples and if necessary will be applied in this analysis as well.

3.5. Spatial assessment approach from statistical results

The interpretation of the statistical results was based on the conceptualization of Secoko catchment in order to track sedimentation from upstream to downstream with control of source location. Sources of sediment usually vary with time due to a number of reasons; therefore, the analysis was done at sub catchment level on each individual set of samples as well as over the pool of samples (composite) across sampling campaigns. Results yielded the proportion of sediment arising from each geological type.

Box plots were utilized to show the modeling results for each individual suspended sediment sample and composite sample for the all the campaigns. The box plot indicates the likely geological sources of sediments over the sampling period. These plots provide suspended sediment sources in the river at the time the sample was taken. The range of each sample in the box plot represents the 95% confidence intervals and the line for each source represents the most likely value for that source (mean). The variations in the source of sediment per samples indicate changes in sediment sources over time in a sub catchment, due to differences in rainfall and/or human activities.

3.6. Prioritization approach of highly degraded areas (biggest sediment sources)

Results identify the geological types in each sub catchment 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 were then be visited to verify erosion, ascertain the reasons of erosion. The prioritization analysis was done for each sub catchment. The potential sediment sources in each sub catchment were analyzed with respect to the hydrological flow path (i.e. from upstream to downstream). This means that the suspended sediments sampled at any point in the river system have entered the river as runoff at various points in the catchment upstream of the sampling point. Models were run independently for each possible combination of geologic sources as well as for each combination of sub catchments that could be used as a potential source.

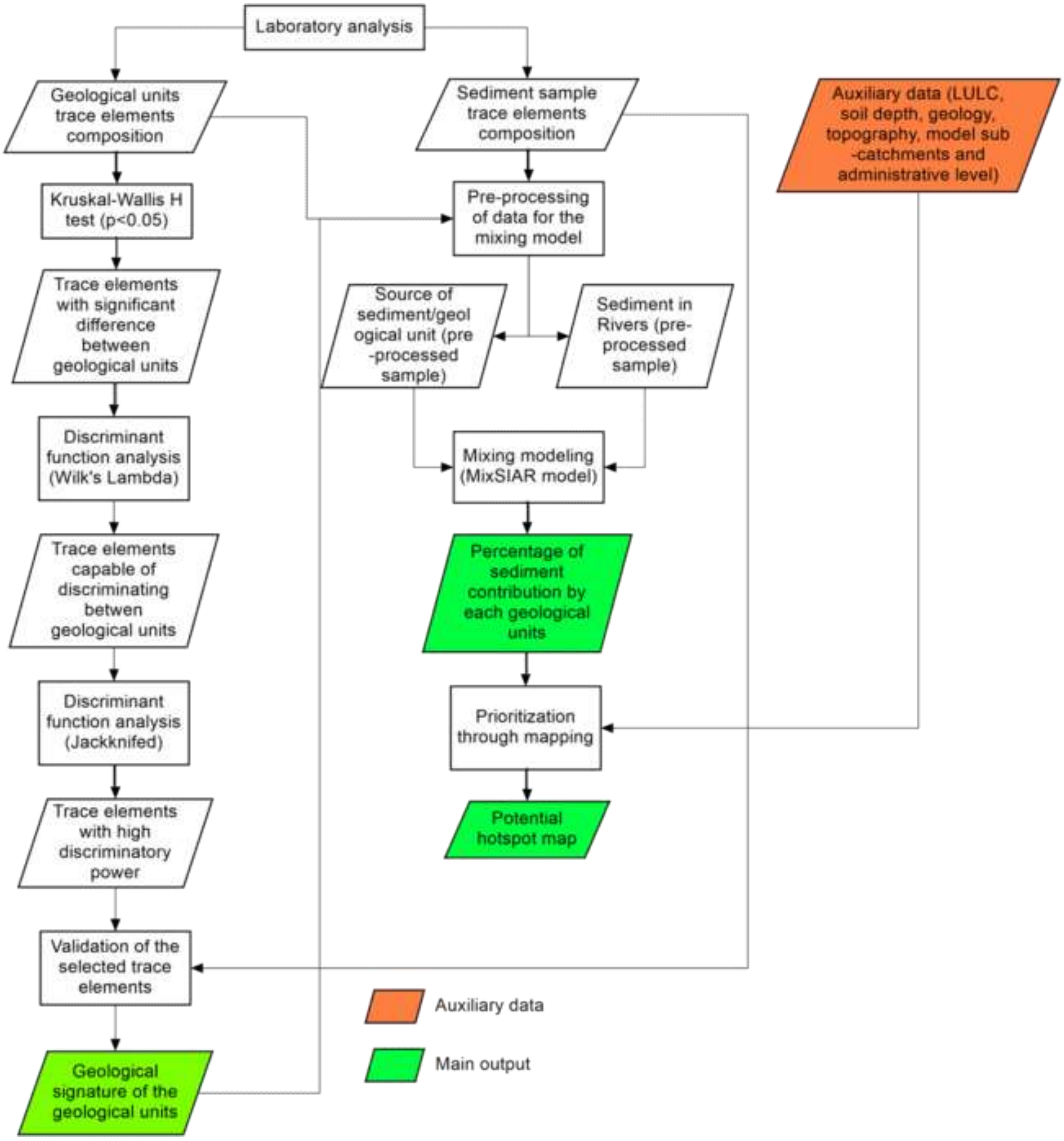

Figure 12: Conceptual framework of the spatial assessment of sources and sediments.

- **Prioritization process**

The upstream sub-catchments were considered first in this analysis, to look at the sediment sources right at the very beginnings of the river drainage. A multi-step prioritization was adopted in this study as follows:

Stage 1: Rating of individual upstream sub-catchment, from level 1 to level 3 for high to low priority respectively.

- Level 1: geological types that contributed sediment more than 40%;
- Level 2: geological types that contributed sediment between 20-40%;
- Level 3: geological types that contributed sediment between 10-20%.

Note that geological types that contributed less than 10% were not assigned any priority level, as they were considered not degraded.

Stage 2: Incorporating downstream sediment load into the rating of upstream sub-catchments. 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. This phenomenon is more pronounced for large watersheds. It is 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 an upstream catchment but decrease in contribution level downstream;
- Level 3: geological types that were Level 2 in an upstream catchment and decrease to Level 3 or less.

This process is repeated for results from each downstream sampling point, until the requisite study area is covered.

3.7. Sediment Rating Curve

Sediment Rating Curve (SRC) at the outlet of Secoko catchment was developed by plotting the river discharges obtained in different measurements for various periods to the Total Suspended Solids (TSS) obtained from water samples analyzed. The logic is in accordance with the literature which define the Sediment rating curve as fitted relationships between river discharge (Q) and suspended-sediment concentration (C), which are commonly used to assess patterns and trends in river water quality. The assumption is that rating curves have a power form (i.e. $C= aQ^b$, where a and b are fitted parameters).

4. RESULTS AND DISCUSSIONS

4.1. Spatial and temporal variability of water quality across Secoko catchment

The spatial and temporal water quality across Secoko catchment was assessed from laboratory analysis. The physico-chemical parameters, trace and metallic elements were analysed at sub-catchment level and the results are presented below.

4.1.1. Physico-chemical parameters of rivers in Secoko catchment

The physical and chemical parameters were analysed for pH, Total Dissolved Salts(TDS), Electrical conductivity (EC), Turbidity, Chlorides, Fluorides and Sulfates. The results are presented in Table 7 below.

Table 7: Physical and chemical parameters in Secoko catchment streams.

Sampling location	**Physico-chemical parameters**							
	pH		**TDS**	**E.C**	**Turbidity**	**Chlorides**	**Fluorides**	**Sulfates**
Rubanda	Min	5.6	18.9	31.2	678.0	8.6	0.1	2.0
	Max	8.1	51.3	76.5	3519.0	218.0	1.1	5.0
	Aver	7.4	32.6	49.1	1741.0	84.9	0.7	3.8
	SD	1.1	10.0	14.3	1064.4	72.2	0.5	1.3
Segatekere	Min	6.0	24.4	37.9	1620.0	0.2	0.3	0.0
	Max	7.7	34.2	51.1	13660.0	199.9	0.5	8.0
	Aver	7.2	29.2	43.8	5707.0	74.1	0.4	1.0
	SD	0.6	3.1	4.3	5125.2	69.6	0.1	3.2
Mitsimbi	Min	6.6	36.6	65.6	253.0	0.0	0.1	0.0
	Max	7.7	49.2	73.4	495.0	273.7	1.4	2.0
	Aver	7.2	45.6	68.1	329.0	51.5	0.8	1.0
	SD	0.4	4.3	6.4	101.1	93.1	0.6	0.9
Cyanjongo	Min	6.7	18.1	54.6	223.0	0.4	0.3	0.0
	Max	7.8	27.7	73.4	1956.0	336.9	0.8	6.0
	Aver	7.3	24.3	37.3	951.0	106.0	0.5	2.4
	SD	0.4	2.9	4.3	586.5	107.2	0.2	2.3
Kagere	Min	6.4	26.2	39.1	9.0	0.1	0.0	0.0
	Max	7.7	45.0	67.1	82.5	39.9	0.3	3.0
	Aver	7.0	38.9	58.0	36.9	7.0	0.1	1.0
	SD	0.5	6.4	9.5	31.9	13.5	0.1	0.9
Gasesa upper	Min	6.7	35.1	52.4	27.3	0.0	0.1	0.0
	Max	8.1	46.0	68.6	68.1	34.0	0.4	9.0
	Aver	7.4	39.1	58.4	35.6	5.8	0.2	3.0
	SD	0.4	3.8	5.6	13.8	11.6	0.1	3.1
Gasesa	Min	6.5	19.0	28.2	140.0	0.3	0.1	0.0
	Max	7.6	40.9	61.1	467.0	200.4	0.5	5.0

	Aver	7.0	27.9	41.6	303.0	38.7	0.3	3.4
	SD	0.5	6.3	9.4	115.6	66.0	0.2	1.5
Secoko upper	Min	6.5	19.0	28.4	175.0	3.5	0.7	3.0
	Max	7.8	22.7	33.8	2220.0	329.5	1.4	14.0
	Aver	7.1	20.2	30.1	853.1	79.5	1.0	7.1
	SD	0.4	1.2	1.9	772.7	104.8	0.3	3.5
Kiguhu	Min	6.2	27.7	41.3	10.5	0.8	0.1	0.0
	Max	7.6	37.9	56.5	62.4	113.7	0.8	1.0
	Aver	7.0	34.1	50.8	40.7	2.6	0.5	0.3
	SD	0.4	3.2	4.7	18.3	3.5	0.3	0.5
Rubayu	Min	5.6	18.9	28.2	865.0	2.1	1.9	1.0
	Max	6.4	34.5	36.6	7120.0	301.0	2.7	5.0
	Aver	5.2	23.3	33.0	2544.0	112.7	2.2	2.3
	SD	0.4	4.9	3.1	2315.8	113.7	0.3	1.4
Kagogo	Min	5.6	15.8	23.5	220.0	3.4	0.5	0.0
	Max	6.5	21.3	31.7	1336.0	76.1	0.8	4.0
	Aver	6.0	18.7	27.8	914.9	32.1	0.6	1.9
	SD	0.4	1.9	2.9	470.4	25.8	0.1	1.2
Ruhumira	Min	6.6	41.9	62.5	55.7	0.5	0.1	0.0
	Max	7.5	72.4	108.0	297.0	12.2	1.3	6.0
	Aver	7.0	56.8	84.8	136.9	4.5	0.8	2.6
	SD	0.3	9.9	14.7	97.6	4.6	0.1	2.7
Secoko middle	Min	5.6	23.9	35.6	67.9	0.5	0.0	1.0
	Max	6.3	30.6	45.7	234.0	9.2	0.7	3.0
	Aver	6.0	26.5	39.5	122.6	2.9	0.4	1.5
	SD	0.2	2.4	3.6	69.2	2.7	0.6	0.8
Secoko lower	Min	5.6	20.5	30.6	20.1	1.1	0.2	0.0
	Max	6.8	28.7	42.8	161.0	4.2	0.9	3.0
	Aver	5.9	23.4	35.0	77.6	2.1	0.6	1.6
	SD	0.4	2.9	4.3	58.3	0.9	0.3	1.2
RSB standards for natural surface water		5.5-9.5	1500.00	2500.0	25.0	250.0	1.5	400

The physical and chemical parameters concentrations were presented in accordance with their variability per sub-catchment level. The spatial and temporal variability of physico-chemical parameters in streams of Secoko sub-catchment are presented in Figures 13 – 19, respectively.

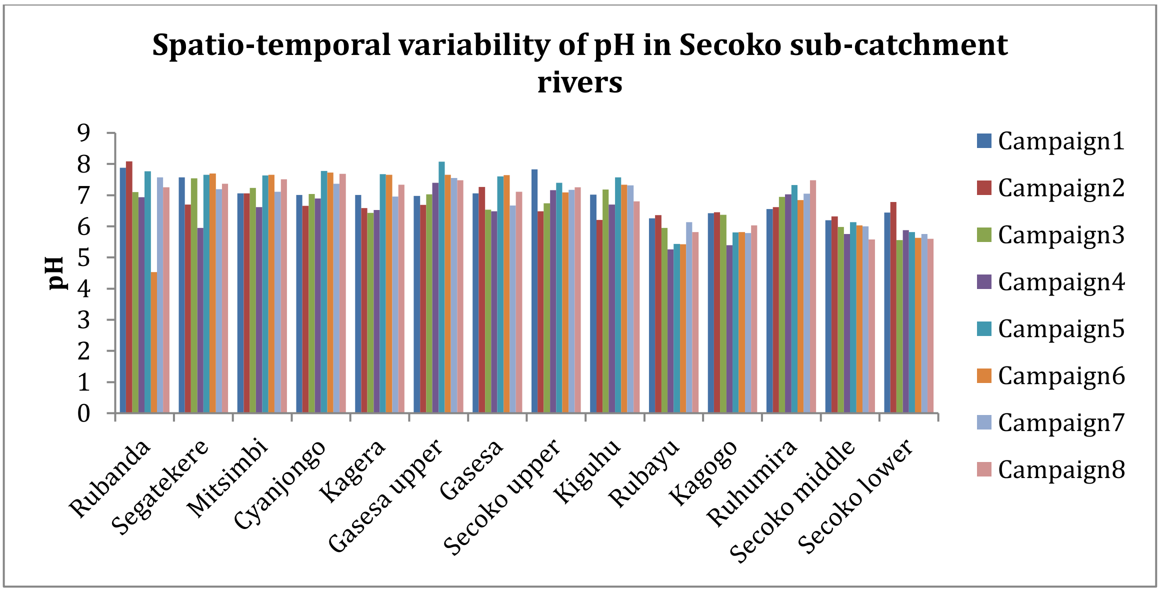

Figure 13: Variability of pH in sub-catchment streams.

The pH of water in the study area ranged between acidic (5.56) to basic (8.09). Results from this study showed a 100% compliance with the Rwandan standard of surface water quality in all monitoring sites.

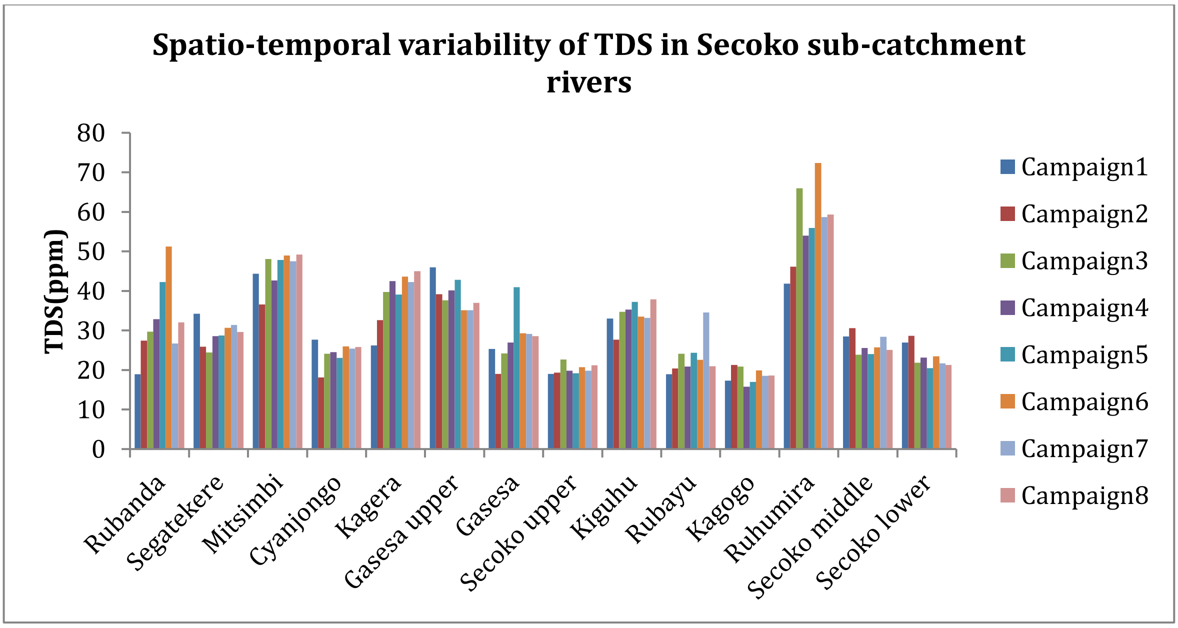

Figure 14: Variability of TDS in sub-catchment streams.

Recorded values were below the standard limit of 2,500 ppm in all monitoring sites, which is representing a 100 % compliance with the Rwandan standard.

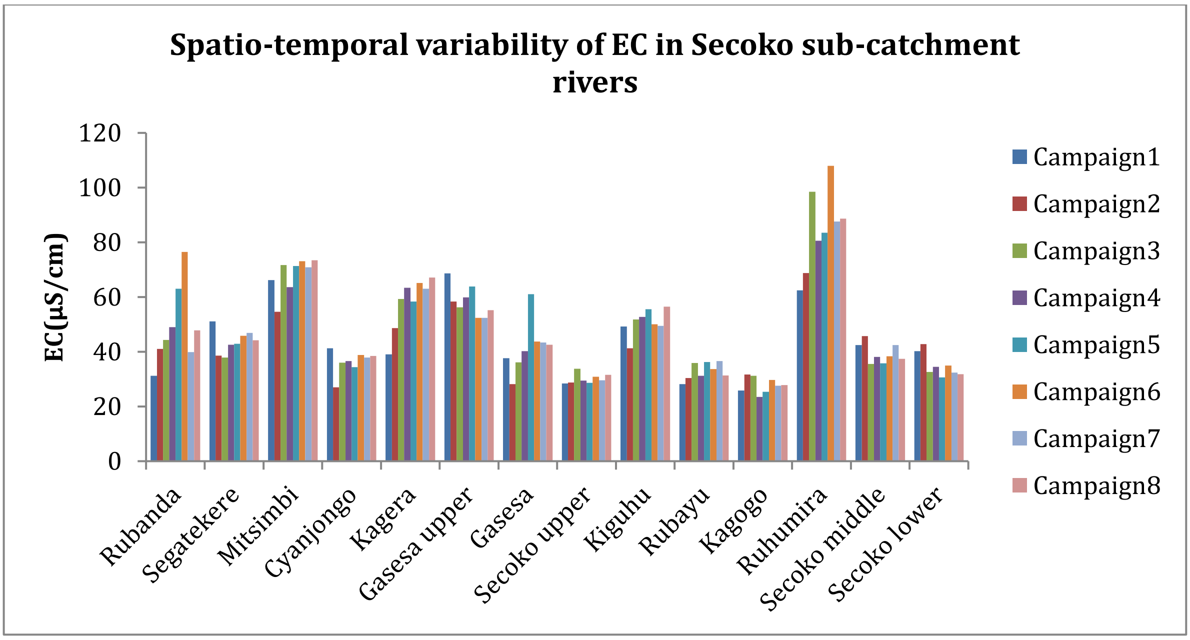

Figure 15: Variability of EC in Secoko sub-catchment streams.

Recorded values were below the standard limit of 2,500 ppm in all monitoring sites, which is representing a 100 % compliance with the Rwandan standard.

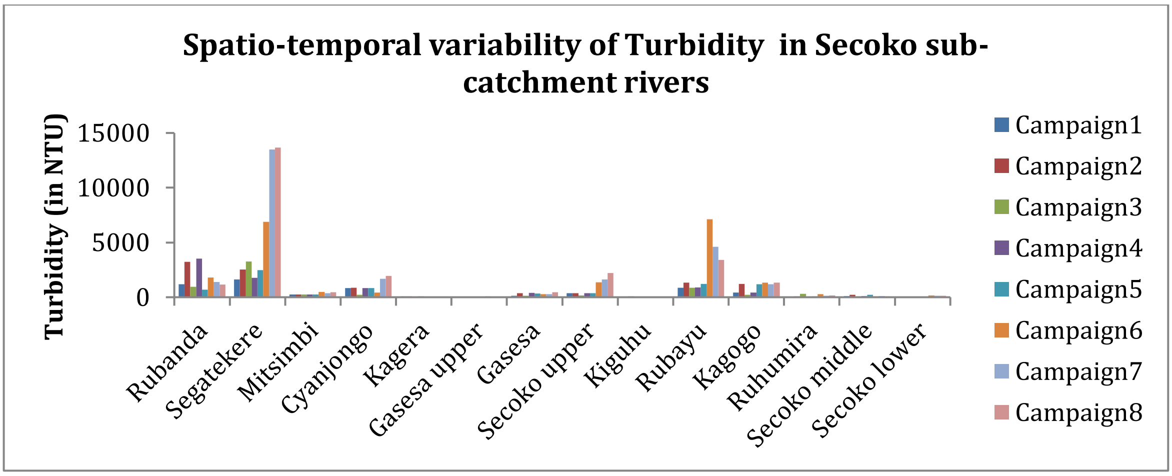

Figure 16: Variability of Turbidity in Secoko sub-catchment streams.

Results from this survey showed only one of monitored rivers presents higher turbidity value when compared to the standard limit of surface water quality. In general recorded turbidity values were varying between 9.01 and 13,660 NTU. Turbidity was high in most of areas during this water quality monitoring activity mainly due to soil erosion and illegal mining activities.

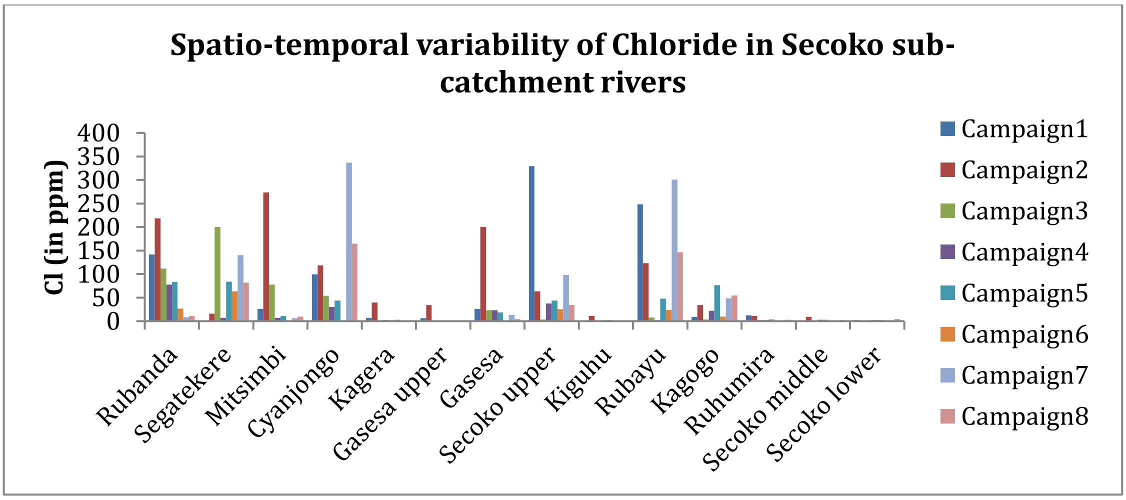

Figure 17: Variability of Chloride in Secoko sub-catchment streams.

In general, the main source for chloride contamination include septic tank effluent, animal waste, and agrichemicals. Chlorine enters surface waters through atmospheric deposition of oceanic aerosols, or weathering of some sedimentary rocks (mostly rock salt deposits), or from industrial and sewage effluents, or agricultural and road runoff. Results from this study showed compliance of chloride concentrations in most of the monitoring sites, since below the standard limit of 250 ppm.

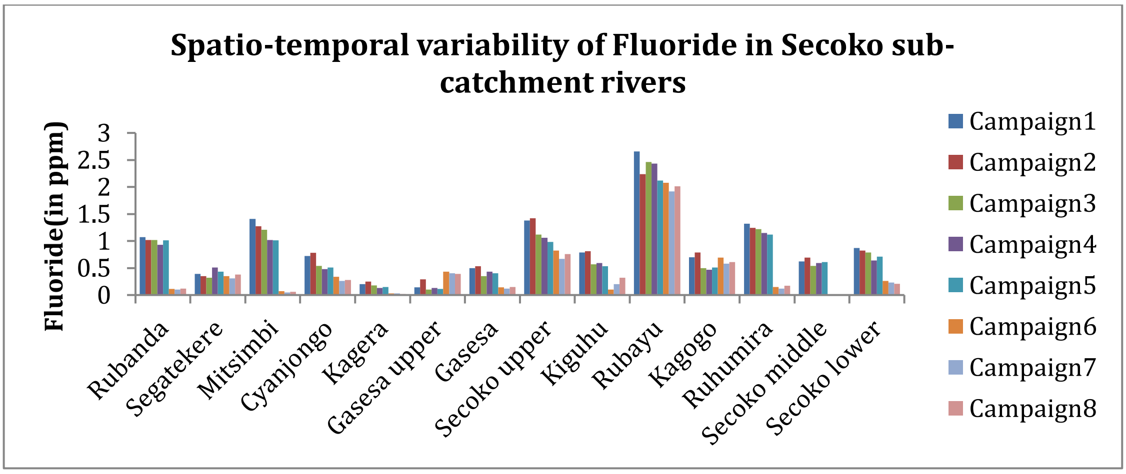

Figure 18: Variability of Fluoride in Secoko sub-catchment streams.

Results from this survey showed that only Rubayu sub-catchment had higher value of fluorides when compared to the standard limit. In general recorded fluorides values were varying between 0.01 and 2,66 mg/l.

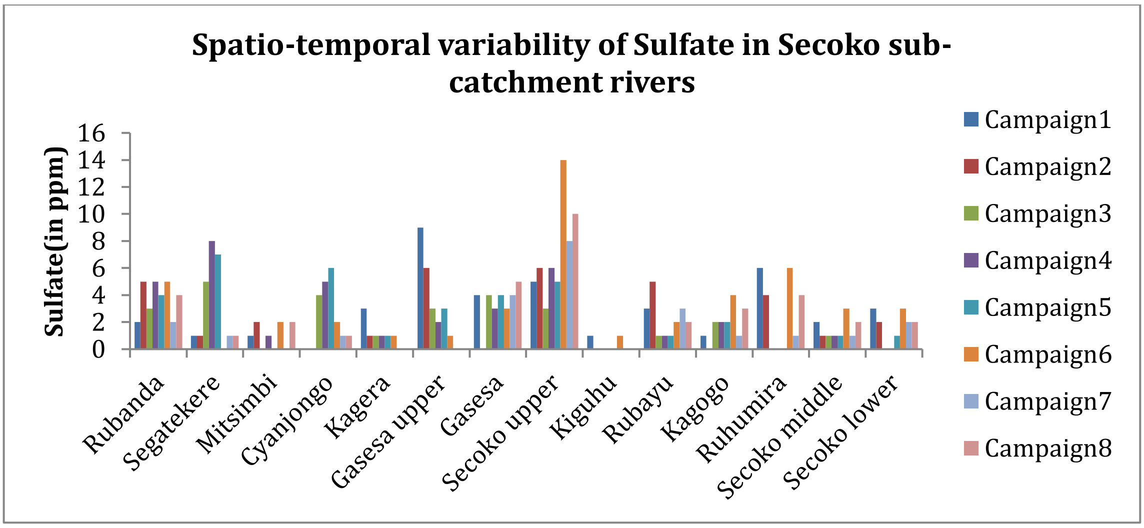

Figure 19: Variability of Sulfate in Secoko sub-catchment streams.

Results from this study showed a 100 % compliance of sulphate concentrations in all monitoring sites were below the standard limit of 400 ppm. Recorded concentrations were varying between 0 ppm and 14 ppm.

4.1.2. Trace and metallic elements in Secoko sub-catchment streams

Trace and metallic elements (Fe, Mn, Ca, Mg, Al, Cu, Zn, Sb, As, Cd, Co, Pb, Ta, Sn and W) were analysed in laboratory and the results are presented in Table 8.

Table 8: Trace and metallic elements in Secoko catchment streams.

Sampling location	**Trace and metallic elements**														
		Fe	**Mn**	**Ca**	**Mg**	**Al**	**Cu**	**Zn**	**Sb**	**As**	**Cd**	**Co**	**Pb**	**Ta**	**Sn**
Rubanda	Min	1.02	0.35	6.47	0.0	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.27
	Max	25.80	1.02	12.13	36.4	0.11	0.44	0.03	0.07	0.70	0.14	0.01	0.34	0.01	1.40
	AV	6.77	0.56	9.81	22.4	0.02	0.13	0.02	0.03	0.14	0.05	0.00	0.12	0.01	0.85
	STD	8.74	0.27	1.91	10.7	0.04	0.18	0.01	0.03	0.23	0.04	0.00	0.11	0.01	0.43
Segatekere	Min	0.44	0.48	8.00	0.0	0.02	0.02	0.01	0.00	0.13	0.05	0.00	0.00	0.00	1.07
	Max	23.20	3.22	14.33	43.5	0.08	0.72	0.11	0.13	0.33	0.70	1.00	0.27	0.01	1.87
	AV	4.67	1.05	10.21	24.1	0.04	0.21	0.04	0.04	0.23	0.15	0.22	0.14	0.01	1.29
	STD	7.57	0.89	2.15	12.3	0.02	0.25	0.04	0.05	0.07	0.22	0.34	0.10	0.01	0.25
Mitsimbi	Min	0.72	0.20	10.70	0.0	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.27
	Max	14.10	1.16	21.00	142.3	0.13	0.57	0.07	0.07	0.70	0.70	1.47	0.20	0.01	1.20
	AV	3.03	0.44	15.27	44.8	0.05	0.12	0.02	0.03	0.12	0.13	0.64	0.05	0.01	0.69
	STD	4.54	0.32	3.13	42.9	0.03	0.20	0.02	0.03	0.23	0.23	0.50	0.07	0.01	0.40
Cyanjongo	Min	1.34	0.24	5.06	16.2	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.20
	Max	22.50	1.21	11.00	39.5	0.10	0.63	0.70	0.07	0.60	0.70	0.47	0.67	0.01	1.30
	AV	9.46	0.67	7.38	25.7	0.05	0.13	0.15	0.02	0.09	0.11	0.06	0.16	0.00	0.71
	STD	7.76	0.40	2.18	7.6	0.03	0.24	0.26	0.03	0.20	0.24	0.16	0.22	0.01	0.43
Kagere	Min	0.18	0.02	9.54	23.0	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
	Max	4.85	0.16	35.80	50.3	0.05	0.03	0.03	0.05	0.60	0.06	1.60	0.14	0.01	0.87

	AV	1.05	0.11	17.49	30.7	0.03	0.02	0.02	0.03	0.10	0.03	0.55	0.07	0.01	0.54
	STD	1.60	0.06	10.17	9.3	0.02	0.01	0.01	0.03	0.20	0.03	0.56	0.04	0.01	0.38
Gasesa upper	Min	0.89	0.01	8.93	18.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27
	Max	4.26	0.27	22.87	32.7	0.06	0.22	0.03	0.07	0.70	0.07	0.34	0.14	0.01	1.27
	AV	1.61	0.11	13.03	27.3	0.04	0.04	0.01	0.03	0.11	0.04	0.08	0.08	0.01	0.71
	STD	1.17	0.09	4.47	5.2	0.02	0.07	0.01	0.03	0.24	0.03	0.16	0.06	0.01	0.35
Gasesa	Min	1.05	0.07	0.67	21.7	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.13
	Max	15.90	0.34	9.33	35.9	0.08	0.38	0.03	0.06	0.03	0.05	0.27	0.13	0.01	1.00
	AV	4.18	0.21	6.45	28.2	0.03	0.12	0.02	0.03	0.02	0.02	0.08	0.07	0.01	0.47
	STD	4.80	0.11	2.66	5.1	0.02	0.11	0.01	0.03	0.01	0.02	0.10	0.03	0.01	0.31
Secoko upper	Min	1.05	0.00	5.25	0.0	0.01	0.03	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.26
	Max	15.90	2.00	9.20	52.8	0.09	1.40	0.03	0.07	0.05	0.07	0.60	0.14	0.01	1.20
	AV	4.18	0.51	7.37	25.7	0.04	0.60	0.02	0.03	0.04	0.04	0.10	0.09	0.01	0.75
	STD	4.80	0.65	1.31	14.7	0.03	0.55	0.01	0.04	0.01	0.02	0.21	0.05	0.01	0.30
Kiguhu	Min	0.88	0.13	7.80	19.7	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	3.29	0.50	12.47	45.3	0.21	0.04	0.23	0.07	0.06	0.07	0.20	0.13	0.01	1.06
	AV	1.37	0.36	9.96	27.9	0.08	0.03	0.11	0.02	0.04	0.04	0.03	0.06	0.01	0.49
	STD	0.82	0.15	1.73	8.1	0.07	0.01	0.09	0.03	0.02	0.03	0.07	0.04	0.01	0.42
Rubayu	Min	0.23	0.50	4.06	17.7	0.00	0.05	0.01	0.00	0.02	0.04	0.00	0.01	0.00	0.94
	Max	21.00	1.19	9.54	32.8	0.08	0.47	0.36	0.08	0.04	0.14	0.00	0.40	0.01	1.47
	AV	6.22	0.68	7.25	22.9	0.03	0.26	0.10	0.04	0.03	0.09	0.00	0.21	0.01	1.23
	STD	7.19	0.23	2.05	5.7	0.03	0.17	0.12	0.04	0.01	0.04	0.00	0.12	0.01	0.17
Kagogo	Min	0.85	0.40	6.00	0.0	0.01	0.00	0.00	0.00	0.00	0.07	0.00	0.01	0.00	1.20
	Max	4.06	0.74	11.34	32.1	0.04	0.30	0.07	0.07	0.05	0.26	0.00	0.50	0.01	1.74
	AV	2.49	0.55	8.93	24.3	0.03	0.10	0.04	0.02	0.03	0.13	0.00	0.28	0.00	1.37
	STD	1.03	0.10	1.97	10.1	0.02	0.14	0.02	0.03	0.02	0.06	0.00	0.15	0.01	0.18
Ruhumira	Min	0.24	0.00	9.33	0.0	0.03	0.02	0.00	0.00	0.01	0.06	0.00	0.01	0.00	1.07
	Max	2.33	0.20	12.94	31.4	0.11	0.07	0.05	0.07	0.05	0.70	0.00	0.33	0.01	1.40
	AV	0.77	0.07	11.61	21.9	0.06	0.04	0.02	0.03	0.03	0.17	0.00	0.19	0.00	1.24
	STD	0.84	0.06	1.45	10.2	0.03	0.02	0.02	0.03	0.01	0.22	0.00	0.09	0.00	0.13
Secoko middle	Min	0.17	0.20	6.47	22.9	0.01	0.02	0.00	0.00	0.00	0.06	0.00	0.01	0.00	0.01
	Max	0.88	0.34	9.53	55.3	0.08	0.08	0.01	0.07	0.07	0.14	0.66	0.34	0.07	1.40
	AV	0.36	0.28	8.40	33.3	0.04	0.03	0.01	0.02	0.04	0.09	0.08	0.22	0.01	1.07
	STD	0.24	0.06	1.11	9.9	0.03	0.02	0.00	0.03	0.02	0.04	0.23	0.10	0.02	0.47
Secoko lower	min	0.23	0.14	7.40	20.2	0.00	0.01	0.00	0.00	0.03	0.01	0.00	0.01	0.00	1.13
	Max	3.57	0.45	12.80	61.6	0.12	0.03	0.02	0.07	0.06	0.14	0.00	0.50	0.01	1.67
	AV	1.16	0.28	10.80	35.0	0.03	0.02	0.01	0.03	0.04	0.09	0.00	0.26	0.01	1.30
	STD	1.34	0.10	2.05	14.7	0.04	0.01	0.01	0.03	0.01	0.05	0.00	0.14	0.01	0.18

The Concentration of trace and metallic element were presented in accordance with their variability in the whole sub-catchment. The spatial and temporal variability of trace and metallic elements in streams of Secoko sub-catchment are presented in Figures 20 – 33, respectively.

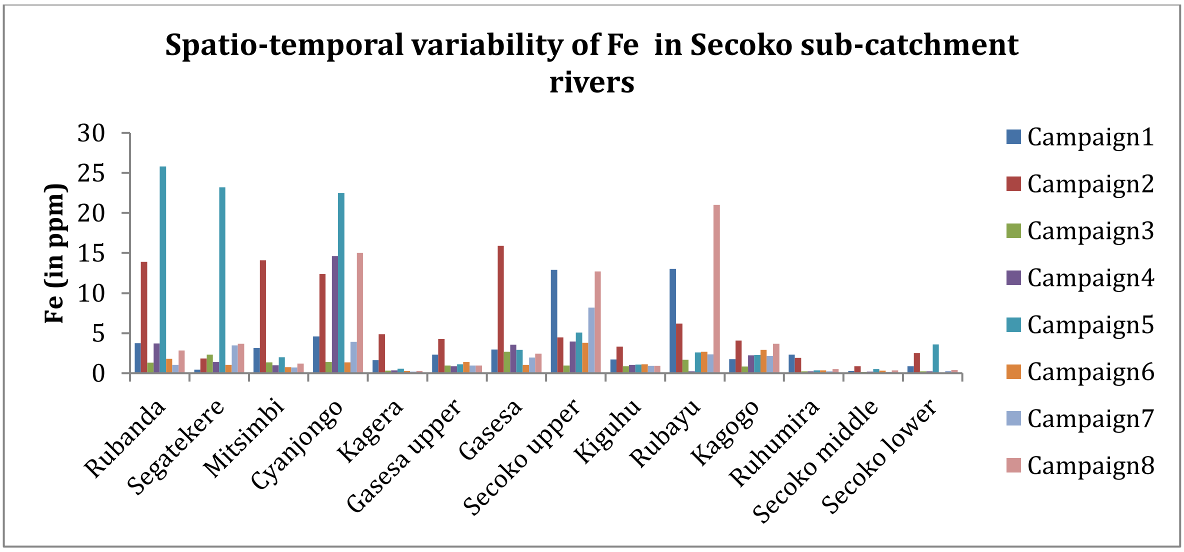

Figure 20: Variability of Iron in Secoko sub-catchment streams.

The findings showed that Iron concentration ranged from 0.17 mgL^{-1} (Secoko middle) to 25.8 mgL^{-1} (Rubanda). This largely exceeds acceptable value of 0.3 mgL-1. The high Iron values observed could be attributed to anthropogenic sources (land use activities) with low inputs from mine activities at the project site.

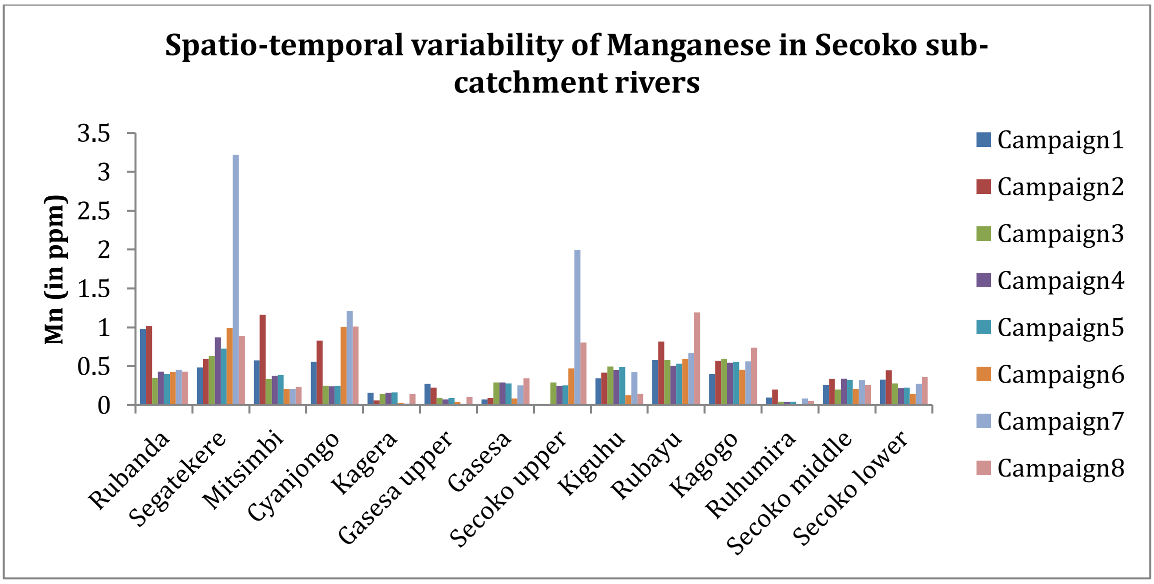

Figure 21: Variability of Manganese in Secoko sub-catchment streams.

For all sampling points Manganese concentrations ranged from 0.002 mgL^{-1} (Ruhumira) to 3.218 mgL^{-1} (Sagatekeri). This exceeds the maximum Manganese of 0.1 mgL^{-1}. The high manganese values observed could be attributed to anthropogenic sources (land use activities) with low inputs from mine activities at the project site.

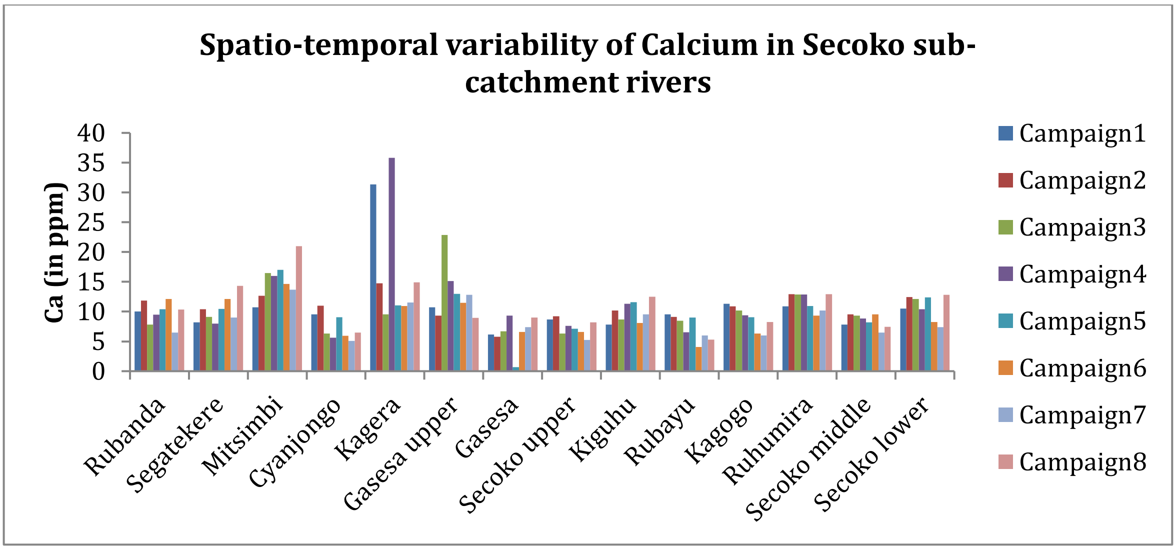

Figure 22: Variability of Calcium in Secoko sub-catchment streams.

The concentrations of Calcium for all sites water ranged from 0.67 mgL-1 (Gasesa) to 35.8mgL^{-1}(Kagera). A 100 % compliance with the Rwandan standard was observed in all monitoring sites, the recorded values were below the standard limit of 150 mg/L.

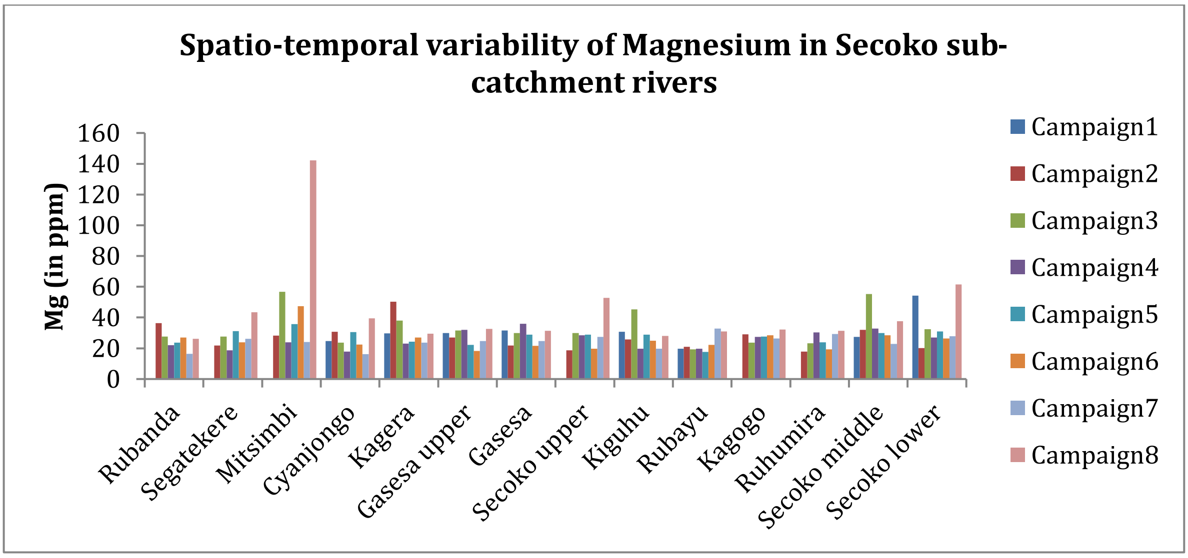

Figure 23: Variability of Magnesium in Secoko sub-catchment streams.

The concentrations of magnesium for all sites water ranged from 0.00 mgL-1 to 142.26 mgL-1(Mitsimbi). This value is greater that the acceptable value of 100 mg/L for Rwandan standard. This could be attributed to anthropogenic activities.

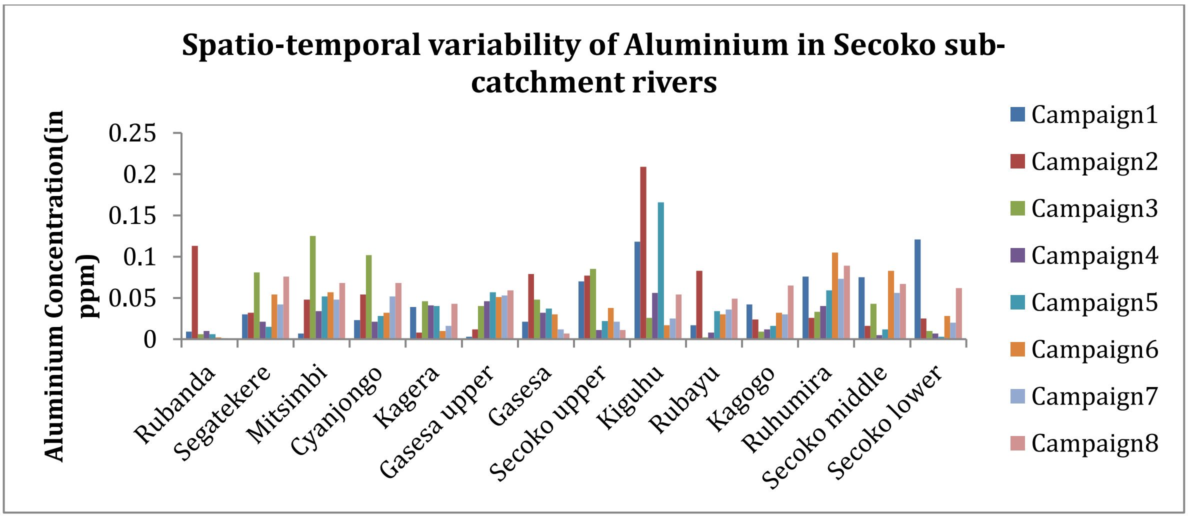

Figure 24: Variability of Aluminium in Secoko sub-catchment streams.

The concentrations of Aluminium for all sites water ranged from 0.000 mgL-1 to 3.218mgL-1(Kiguhu). The results showed that the highest concentration of Aluminium corresponds to acidic conditions (pH=5.96). It has been shown that the Aluminium sticks to soil particles and enters drinking water only if the water is acidic or soft. Metals tend to be more soluble and more reactive at lower pH.

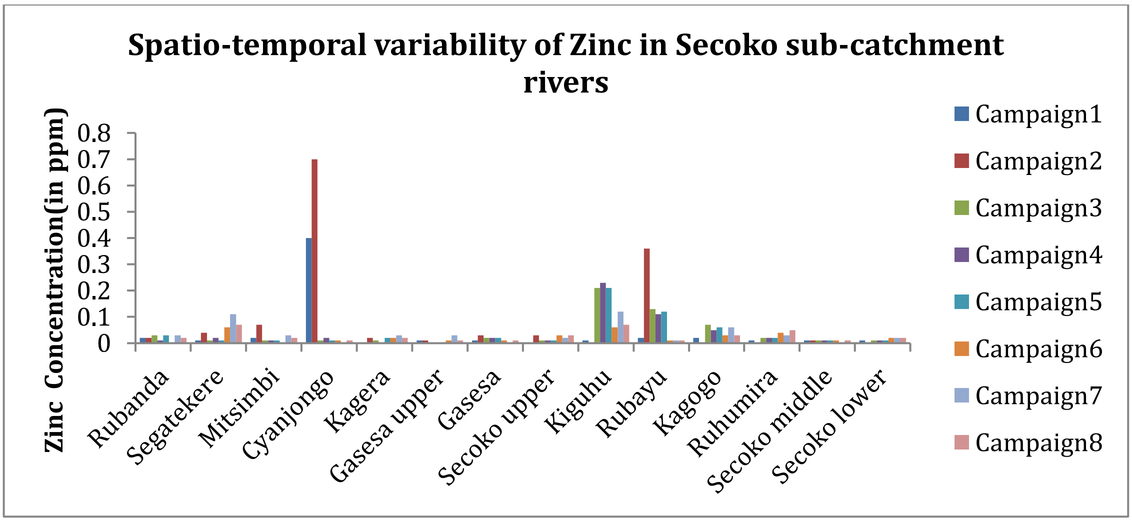

Figure 25: Variability of Zinc in Secoko sub-catchment streams.

Zinc is found in some natural waters, particularly in areas where zinc ore deposits have been mined. Zinc is not considered detrimental to health, but it will impart an undesirable taste to drinking water. The concentrations of zinc for all sites water ranged from 0.00 mgL-1 to 0.70 mgL-1(Kagera). A 100 % compliance with the Rwandan standard was observed in all monitoring sites, the recorded values were below the standard limit of 5 mg/L.

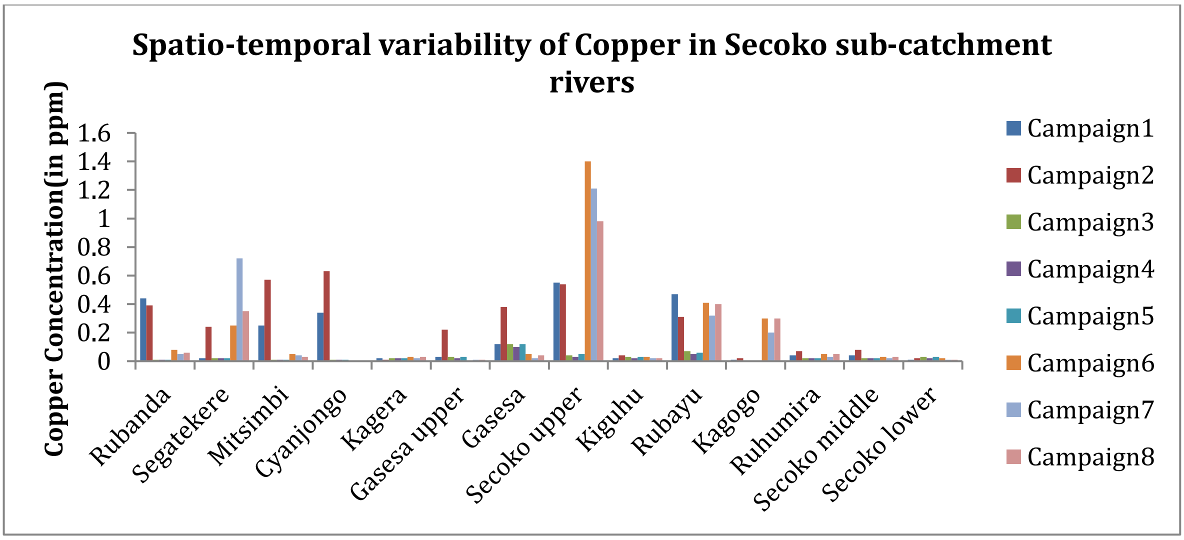

Figure 26: Variability of Copper in Secoko sub-catchment streams.

The concentrations of copper for all sites water ranged from 0.00 mgL-1 to 1.40 mgL-1(Secoko upper). This value is greater that the acceptable value of 1.00 mg/L for Rwandan standard. This high value could be attributed to the mining activities.

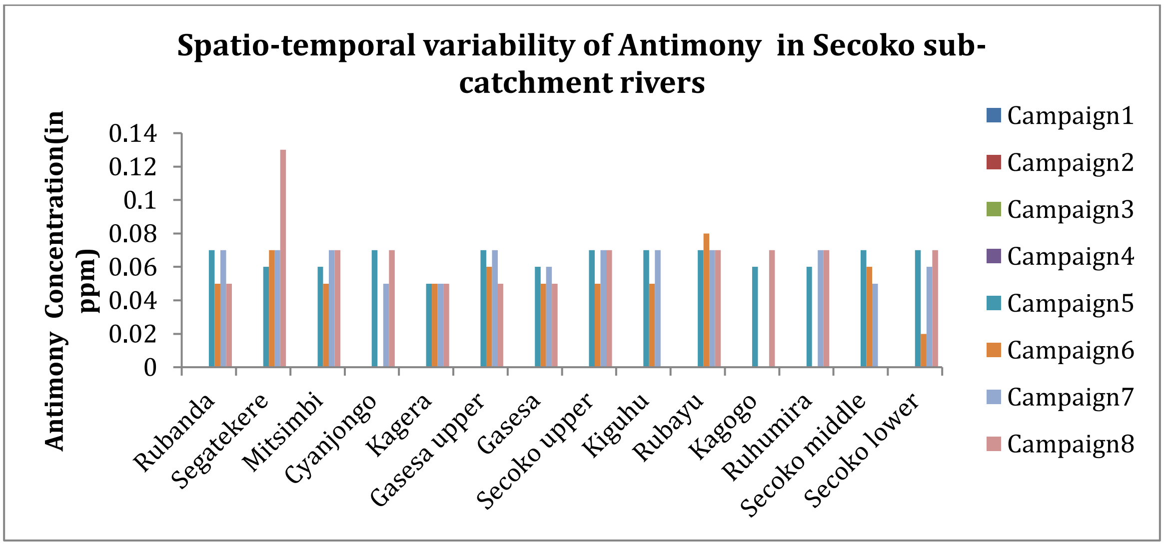

Figure 27: Variability of Antimony in Secoko sub-catchment streams.

Elemental antimony forms very hard alloys with copper, lead and tin. Antimony compounds have various therapeutic uses. Antimony is used in solders as a replacement for lead, but there is little evidence of any significant contribution to drinking-water concentrations from this source. Total exposure from environmental sources, food and drinking-water is very low compared with occupational exposure. The concentrations of antimony for all sites water ranged from 0.00 mgL-1 to 0.70 mgL-1(Segatekeri). This value is greater than the WHO standard of 0.003 mg/. This high value could be attributed to the mining activities.

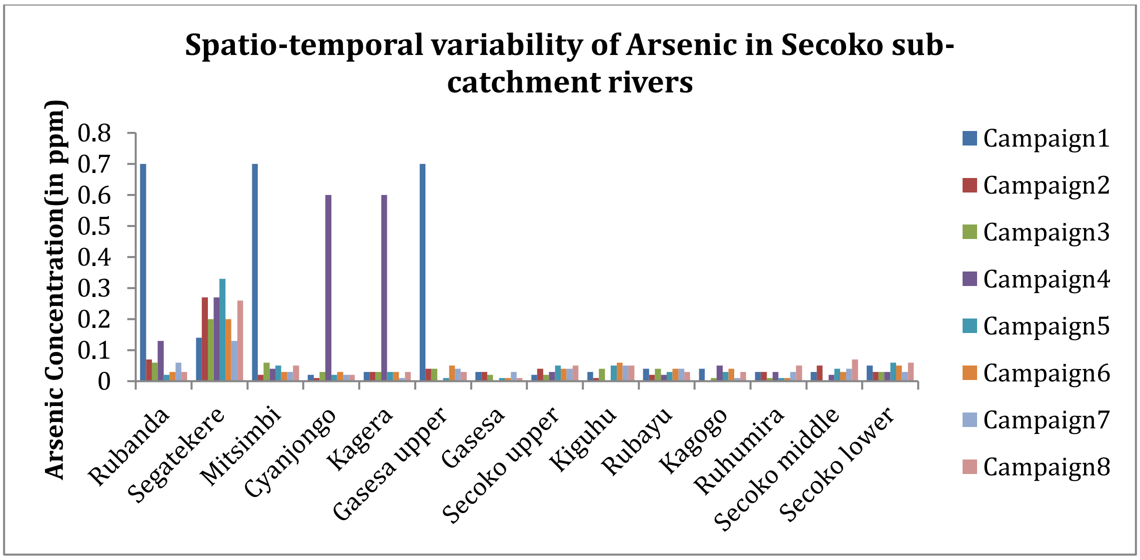

Figure 28: Variability of Arsenic in Secoko sub-catchment streams.

Arsenic occurs naturally in the environment, and it is also widely used in timber treatment, agricultural chemicals (pesticides), and manufacturing of Gallium arsenide wafers, glass and alloys. Arsenic in drinking water is associated with lung and urinary bladder cancer. The concentrations of arsenic for all sites water ranged from 0.00 mgL-1 to 1.40 mgL-1(Secoko upper). This value is greater than the Rwandan standard of 0.01 mg/L. This high value could be attributed to the mining activities.

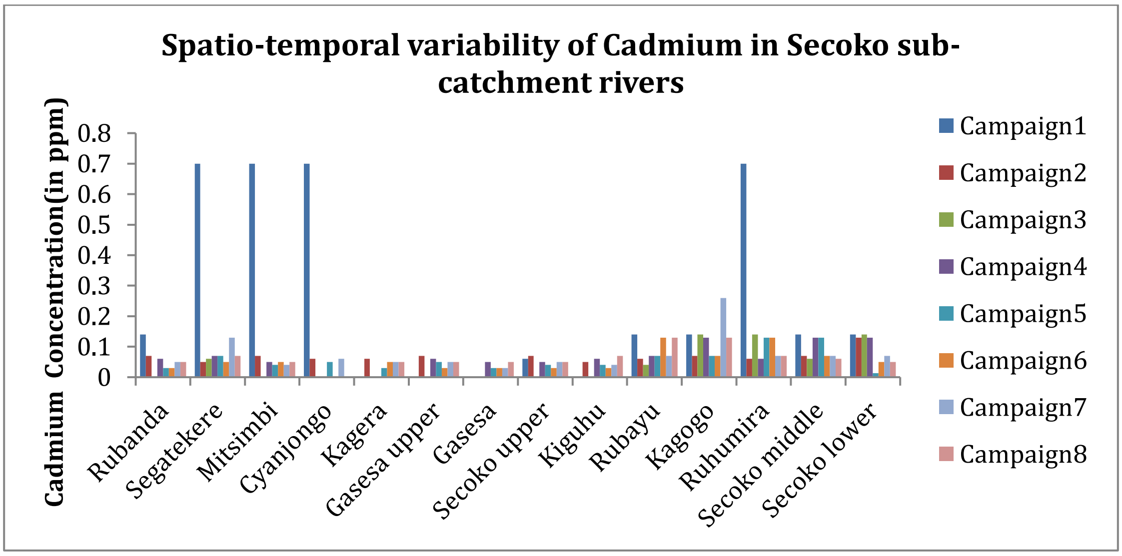

Figure 29: Variability of Cadmium in Secoko sub-catchment streams.

Cadmium metal is used in the steel industry and in plastics. Cadmium compounds are widely used in batteries. Cadmium is released to the environment in wastewater, and diffuse pollution is caused by contamination from fertilizers and local air pollution. Contamination in drinking-water may also be caused by impurities in the zinc of galvanized pipes and solders and some metal fittings. Food is the main source of daily exposure to cadmium. The daily oral intake is 10–35 µg. Smoking is a significant additional source of cadmium exposure. The concentrations of arsenic for all sites water ranged from 0.00 mgL-1 to 0.60 mgL-1(Kagogo). This value is greater than the Rwandan standard of 0.003 mg/L. This high value could be attributed to the mining activities.

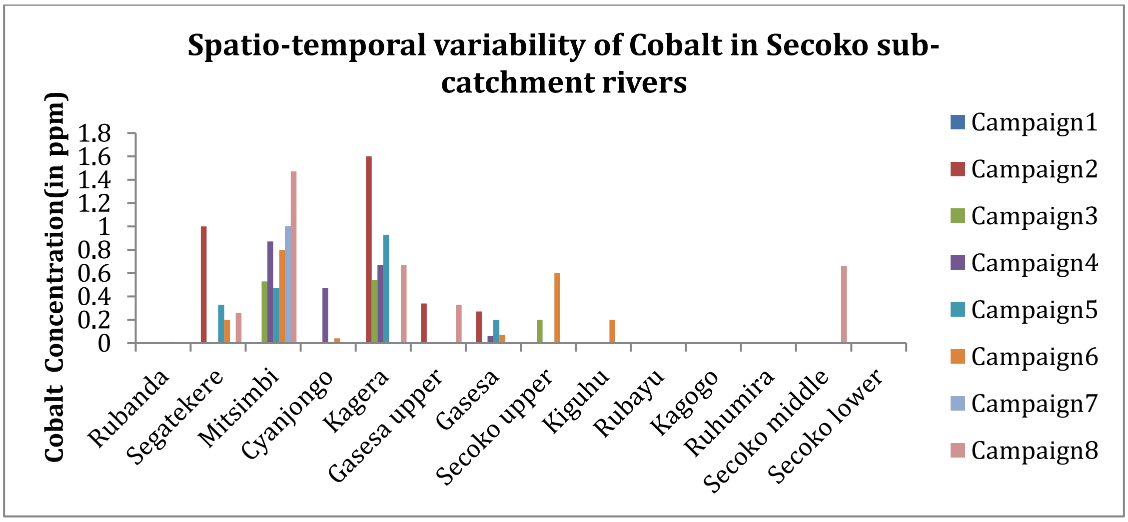

Figure 30: Variability of Cobalt in Secoko sub-catchment streams.

The concentrations of cobalt for all sites water ranged from 0.00 mgL-1 to 1.60 mgL-1(Kagogo). This value is greater than the Rwandan standard of 0.003 mg/L. This high value could be attributed to the mining activities.

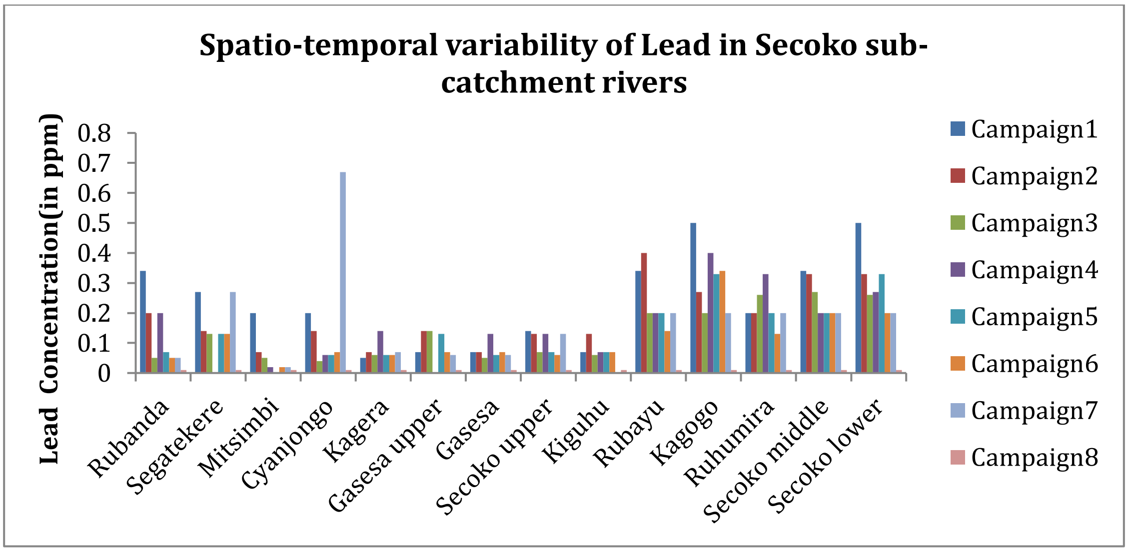

Figure 31: Variability of Lead in Secoko sub-catchment streams.

The concentrations of lead for all sites water ranged from 0.00 mgL-1 to 0.67 mgL-1(Cyanjongo). This value is greater than the Rwandan standard of 0.003 mg/L. This high value could be attributed to the mining activities.

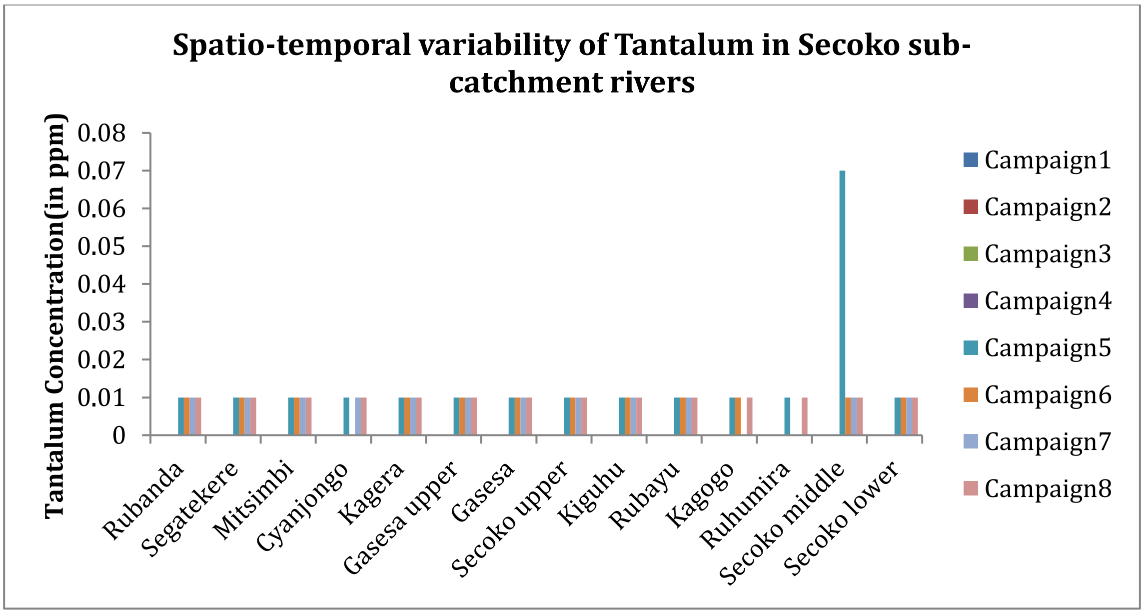

Figure 32: Variability of Tantalum in Secoko sub-catchment streams.

The concentrations of tantalum for all sites water ranged from 0.00 mgL-1 to 0.07 mgL-1(Kagogo). This value is greater than the Rwandan standard of 0.003 mg/L. This high value could be attributed to the mining activities.

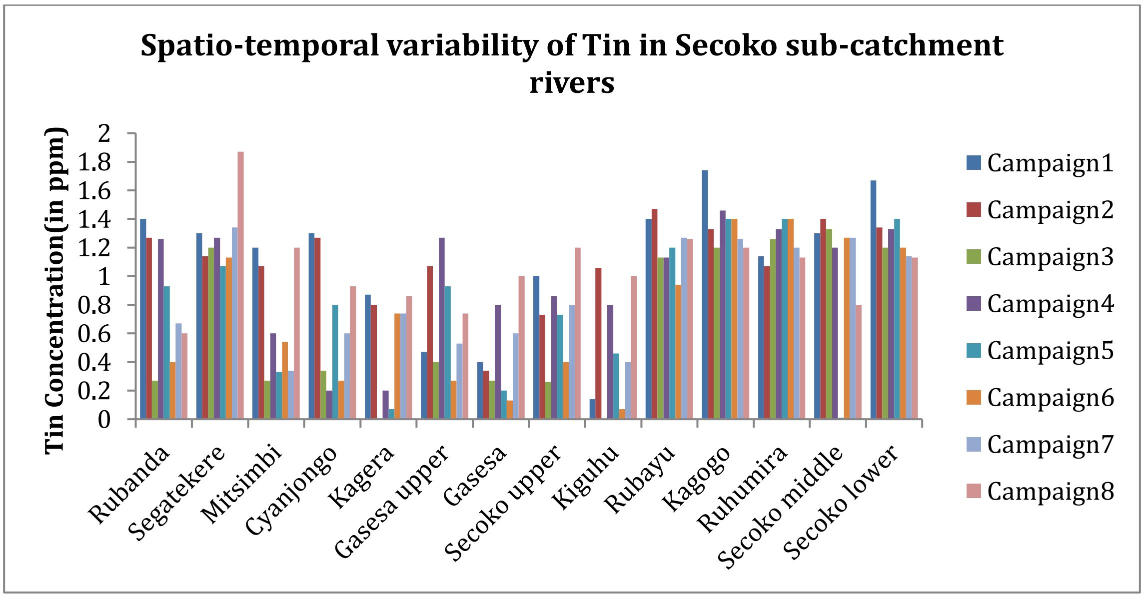

Figure 33: Variability of Tin in Secoko sub-catchment streams.

The concentrations of tin for all sites water ranged from 0.000 mgL-1 to 1.870 mgL-1(Sagatekeri). This value is greater than the Rwandan standard of 0.003 mg/L. This high value could be attributed to the mining activities.

4.2. Sediment sources and their contribution

4.2.1. Rubanda

In the Rubanda catchment, Granites indifferencies (Gt) is the largest source of suspended sediments, followed by Uw/Cr.

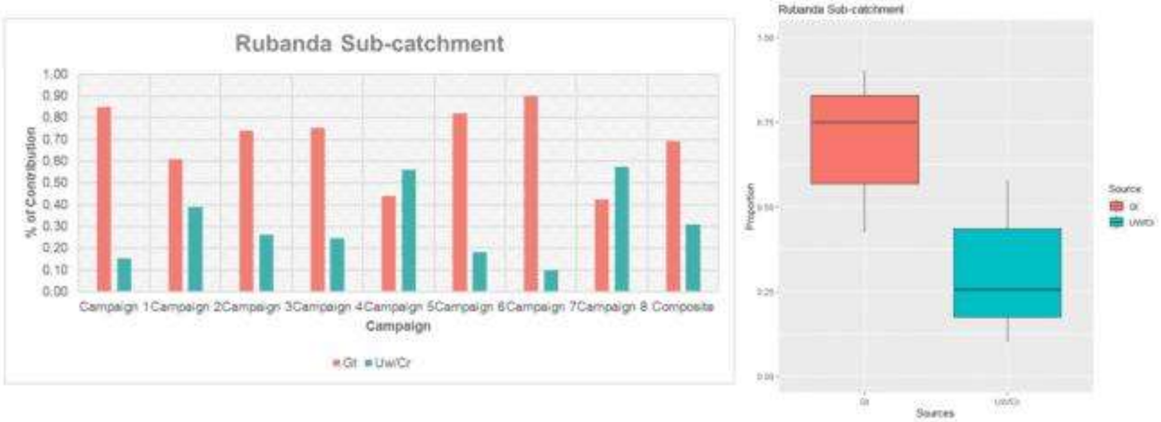

Figure 34: Rubanda sub-catchment sediment distribution.

Sediment sources proportions for all geologic types in the Rubanda sub-catchment is illustrated in Figure 34. Lines represent the mean. Colored boxes represent the 95% confidence intervals. Based on the illustrations and mapping, the most probable causes of the sediment sources distribution observed in this sub-catchment is related to mining activities near its outlet in the granite indifferencies formation (making it the highest contributor). The mining activities have weakened the sub-catchment and led to the successive degradation of land which exposed it to erosion. The effects of erosion due to mining and excessive deforestation might be the cause of Gt contributions observed in the sub-catchment; however the poor agriculture practices near its outlet may be the cause of Uw/Cr sediments.

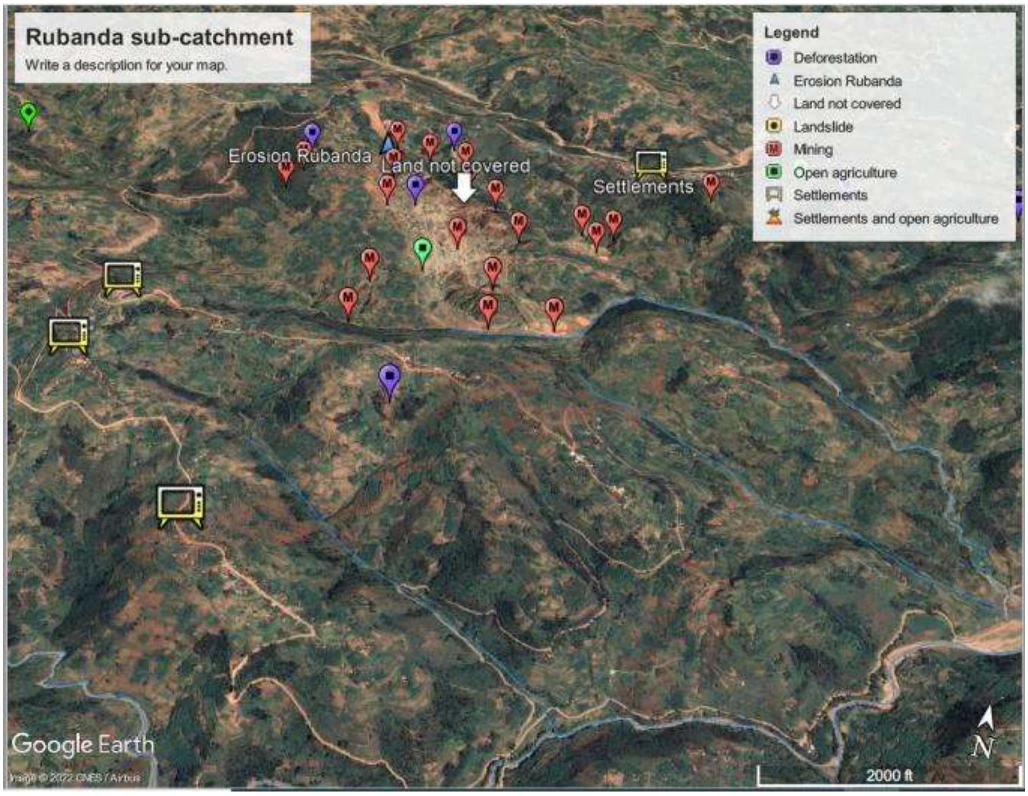

Figure 35: Land use and economic activities in Rubanda sub-catchment.

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4.2.2. Sagatekere

In the Sagatekere sub-catchment, Granites indifferencies (Gt) are the largest source of suspended sediments, followed by Uw/Cr.

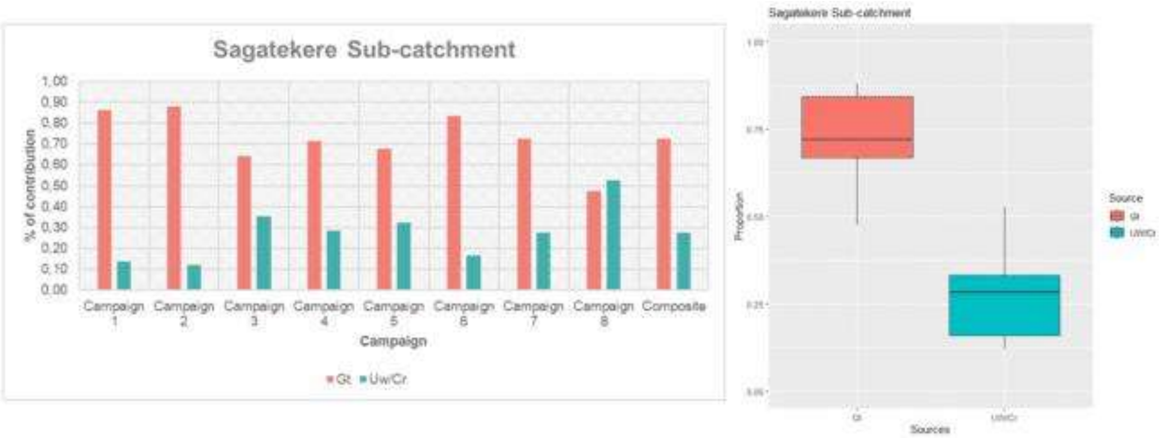

Figure 36: Sagatekere sub-catchment sediment distribution.

Based on the land use and ongoing economic activities in the catchment, the most probable causes of the sediment sources distribution observed in this sub-catchment is related to open and poor agriculture practices. The poor agriculture with no erosion control measures or practices are dominant in Sagatekere sub-catchment; which is one of the smallest sub-catchment in Secoko catchment. The effect of heavy rainfall on bare agriculture land with no erosion protection measures throughout the season may be the cause of Gt and Uw/Cr distributions in the Sagatekere sub-catchment.

Figure 37: Land use and economic activities in Sagatekere sub-catchment.

4.2.3. Mitsimbi

The Mitsimbi sub-catchment is made of one geological formation, the Uw/Cr. The situation in Mitsimbi sub-catchment is related to the deforestation and unplanned settlements mostly in degraded land with no measures of erosion control. However, due to limited sediment data, one can only relates the contribution from the Uw/Cr formation to a heavy rainfall event and or subsequently erosions on deforested lands that occurred prior to the sampling campaign.

Figure 38: Land use and economic activities in Mitsimbi sub-catchment.

4.2.4. Cyajongo

In the Cyajongo catchment, Ho was the largest source of suspended sediments, followed by Uw/Cr.

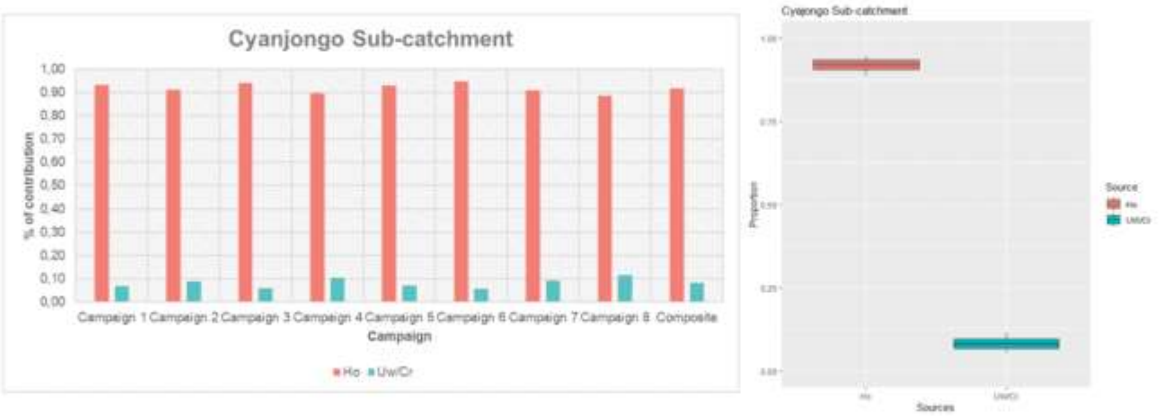

Figure 39: Cyanjongo sub-catchment sediment distribution.

The situation in Cyajongo sub-catchment is related to mining activities. The mining is heavily producing sediments in the floodplain of the river from top of the Ho formation. The high contribution of Ho sediments from this source may indicate poor mining practices in the area causing a loss of soil. In addition, the catchment is also covered with the Uw/Cr formation on top of which extensive and open agriculture is conducted. The sediment contribution from this formation may indicate poor agricultural practices with no sustainable protection from erosion in the area. Coupled with strong rainfall, poor agriculture in the middle of unplanned settlement made the main cause of especially Uw/Cr sediments in this area.

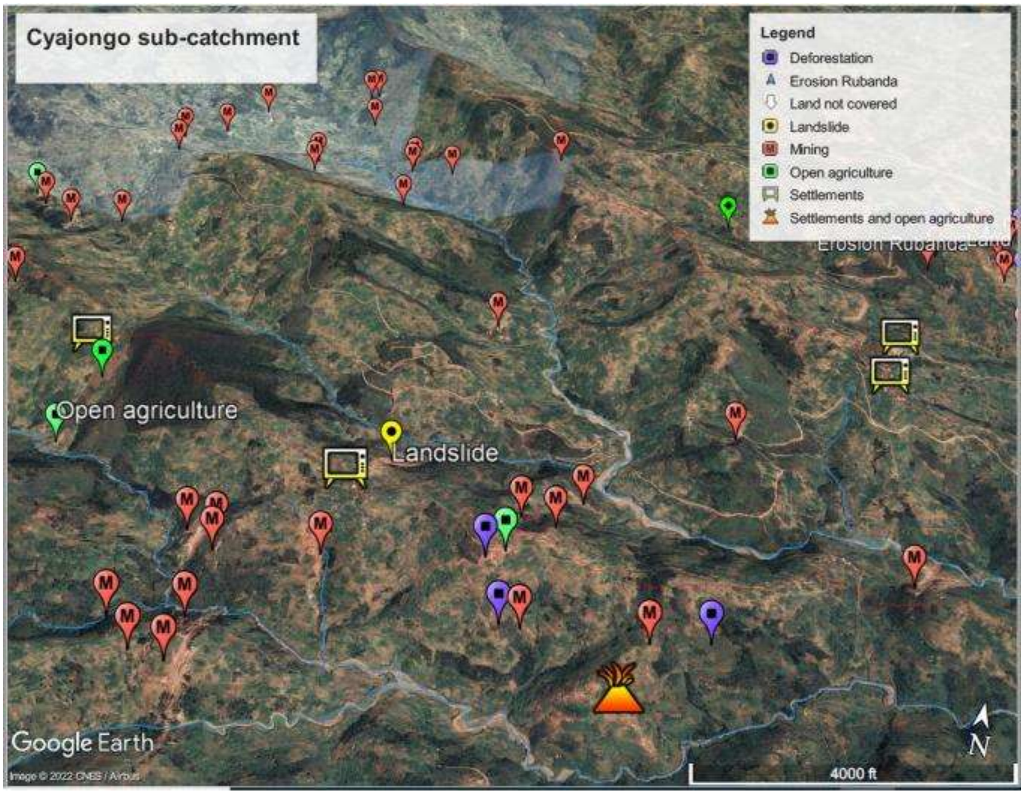

Figure 40: Land use and economic activities in Cyajongo sub-catchment.

4.2.5. Kagera

In the Kagera catchment, Ho is the larger source of suspended sediments followed by Gt.

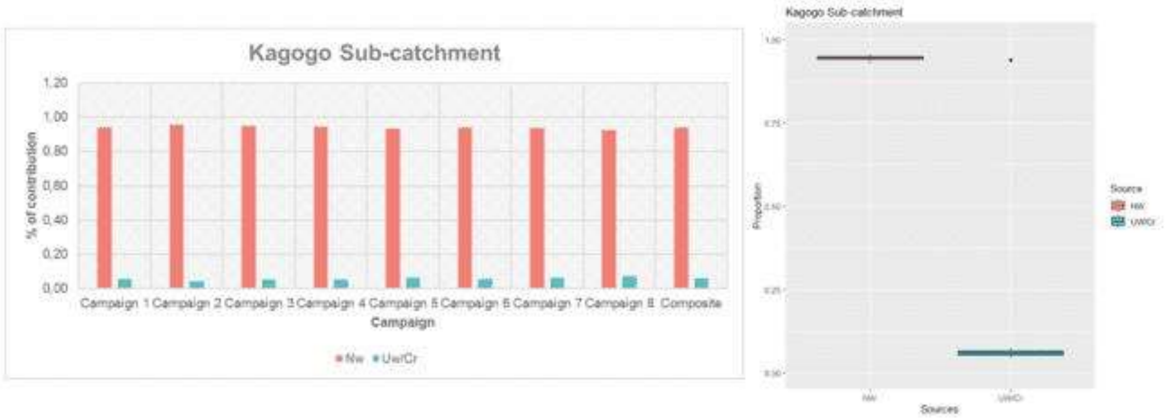

Figure 41: Kagogo sub-catchment sediment distribution.

In the Kagera sub-catchment, a combination of agriculture and unplanned settlements activities in a largely Ho formation explains the statistical results illustrated in Figure 20. In this sub-catchment, the land does not have terraces of any kind even though it has a high slope; the poor agriculture activities and erosion justify the existence of Ho and Gt formations.

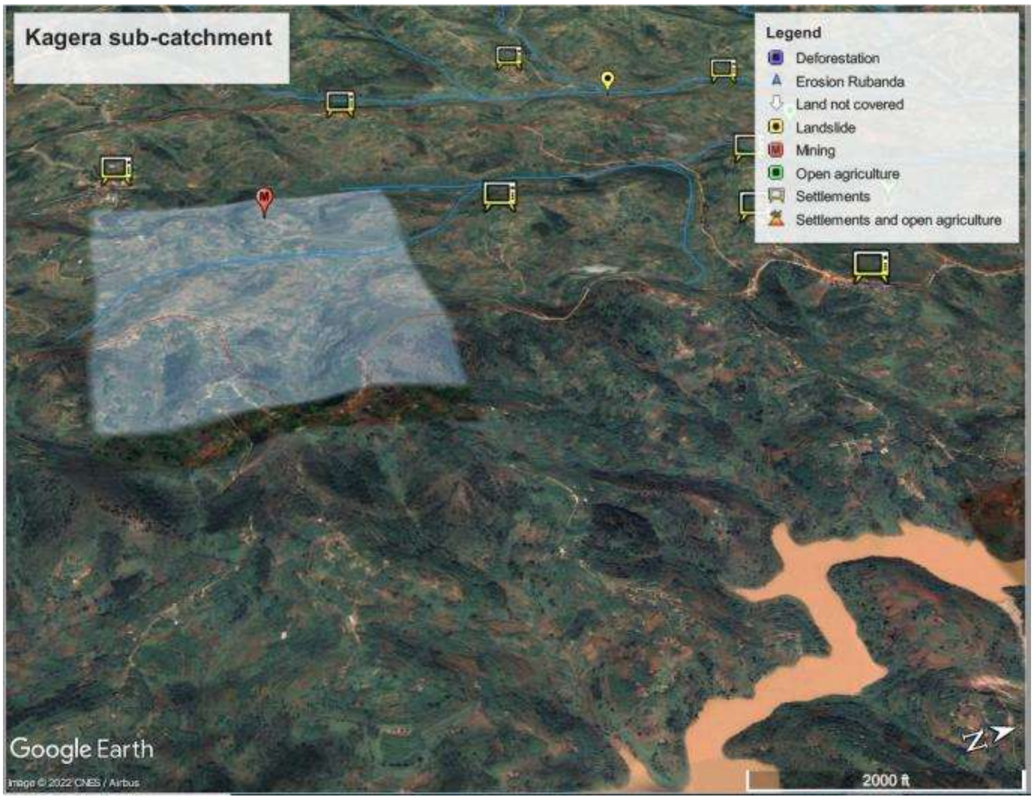

Figure 42: Land use and economic activities in Kagera sub-catchment.

The situation in Kagera sub-catchment shows that the catchment is very settled with different sorts of houses at the hill top. This may be the cause of erosion after heavy rains that can increase the runoff around Ho and Gt formations.

4.2.6. Gasesa Upper

In the Gasesa upper sub-catchment, Ho is the larger source of suspended sediments.

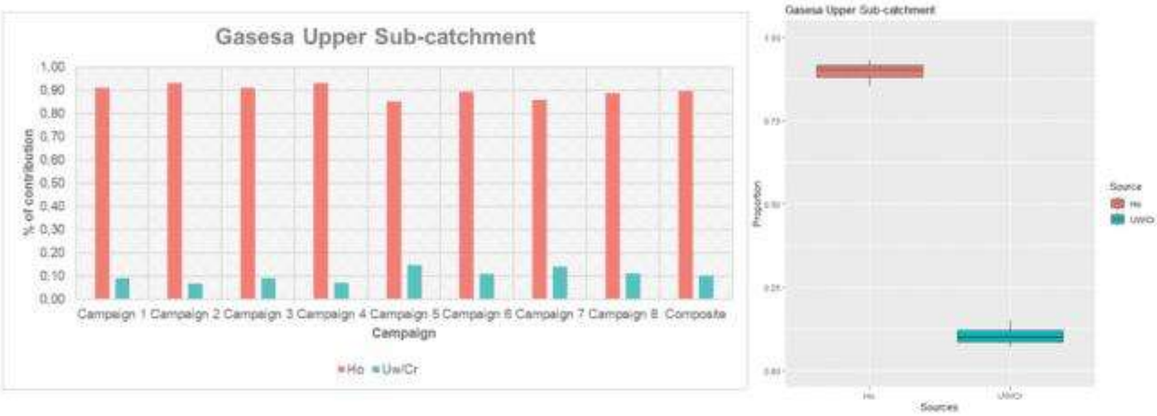

Figure 43: Gasesa upper sub-catchment sediment distribution.

The poor agriculture practices, tillage and unplanned settlements coupled with heavy rains in the Gasesa upper sub-catchment are the cause of erosion and Ho sediments. Uw/Cr is not heavily contributing to sedimentation because of most probably the land surrounded by forests.

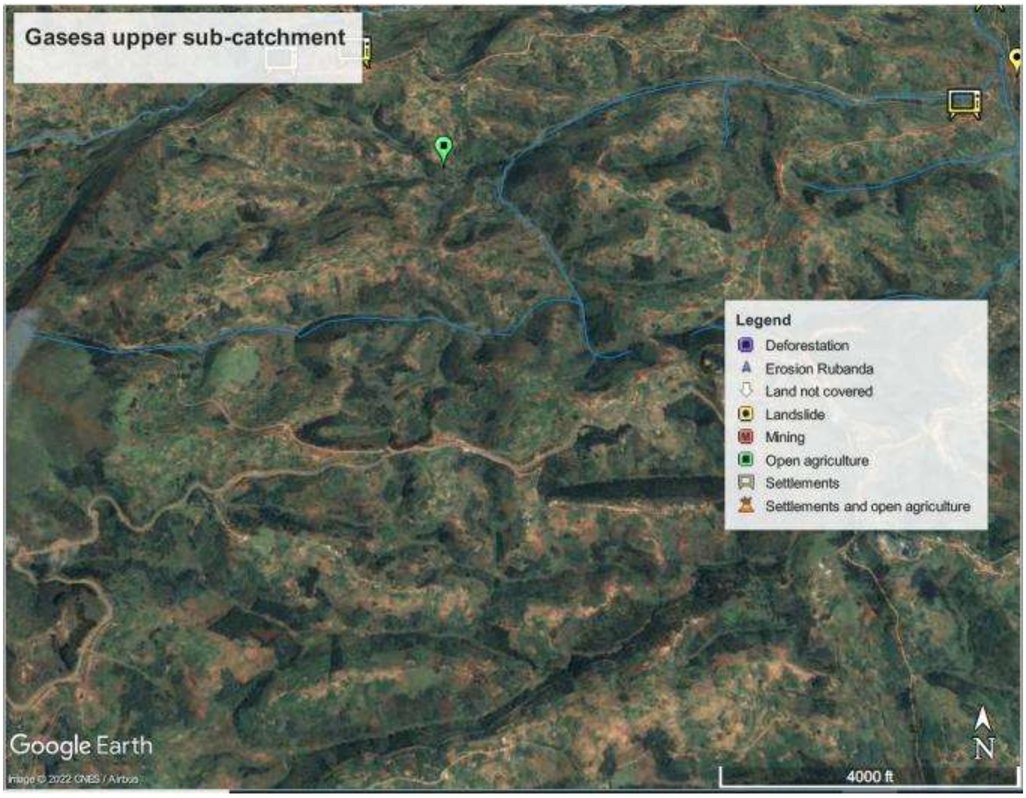

Figure 44: Land use and economic activities in Gasesa upper sub-catchment.

4.2.7. Gasesa

In the Gasesa catchment, Ho is the larger source of suspended sediments followed by Gt.

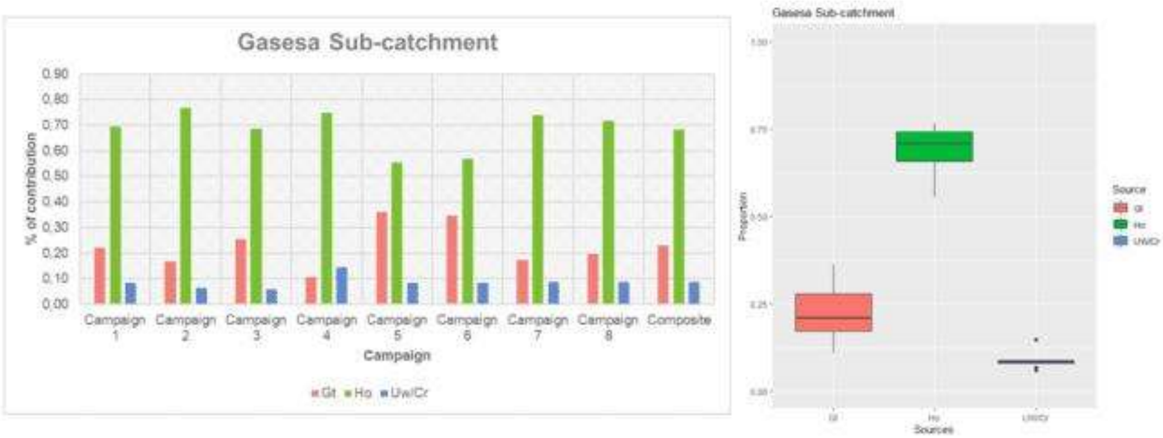

Figure 45: Gasesa sub-catchment sediment distribution.

The landslides in the Gasesa sub-catchment are the cause of erosion and sediments. This is justified by the dominance of Ho and Gt formations in the sediments. It is clear however, from the statistical results and geological formation in this catchment that, Uw/Cr is not heavily contributing to sedimentation because of most probably agriculture land surrounded by forests. The lack of erosion control measures such as terraces amplify contribution of Ho and Gt formations in floodplain of the river.

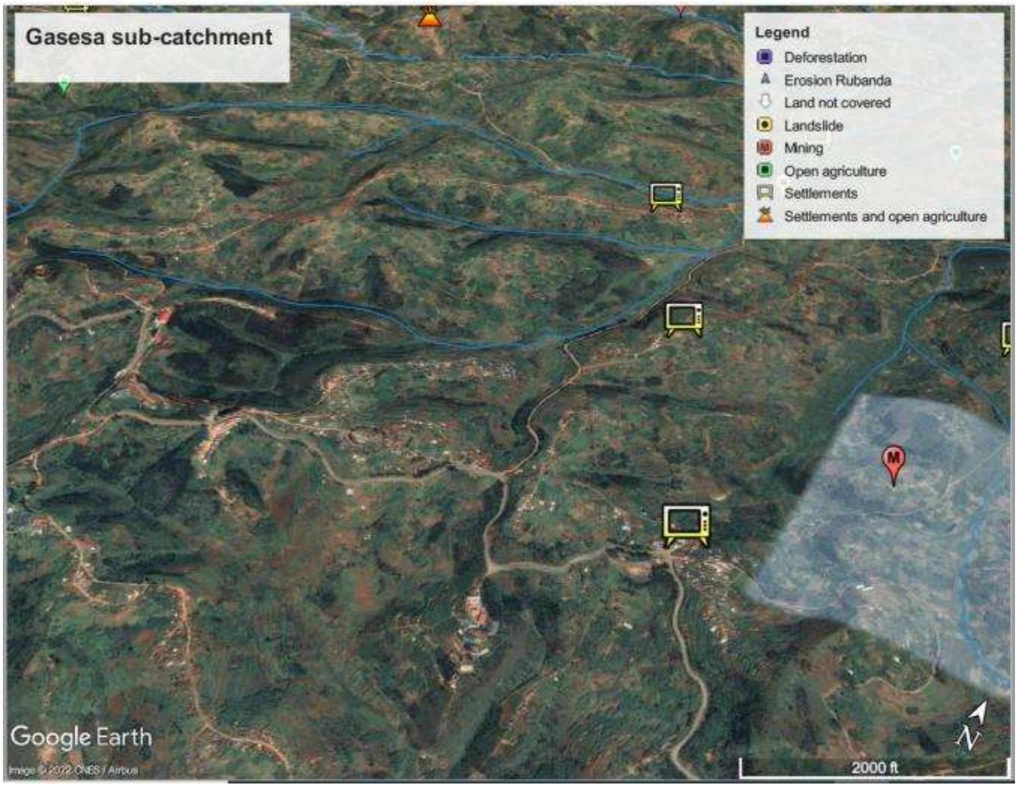

Figure 46: Land use and Economic activities in Gasesa sub-catchment.

In Gasesa, the agriculture and settlements activities are the major land uses. The contribution of the geological formation Uw/Cr is related to agriculture activity near the river course. However, the contribution of Ho and Gt is most probably related to landslide that occurred prior to sampling.

4.2.8. Secoko Upper

In the Secoko Upper-catchment, Nw appears to be larger source of suspended sediments and the contribution of Uw/Cr is not really significant.

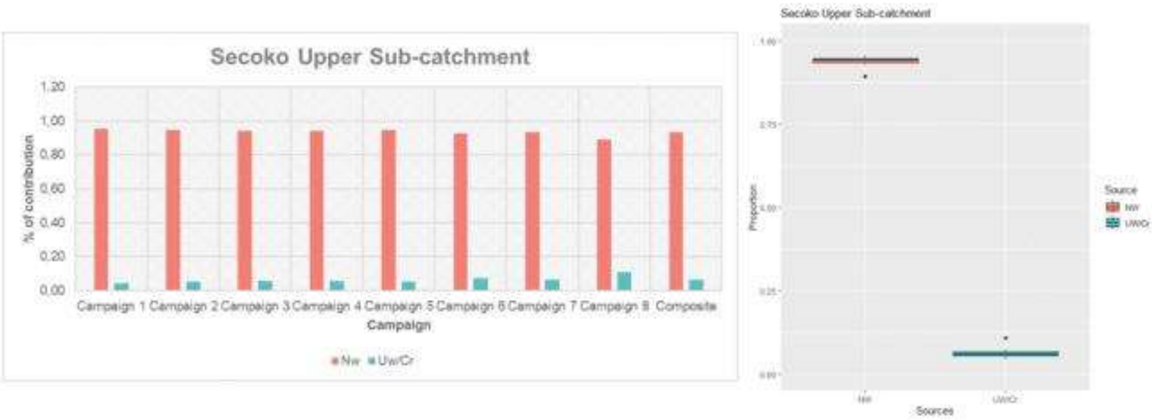

Figure 47: Secoko Upper sub-catchment sediment distribution.

The Mining activities in the secoko upper sub-catchment, within the Nw formation, is the most probable cause of high sediment contribution in the river. In addition, the limited contribution of Uw/Cr formation, located at the outlet of the catchment, indicates poor agriculture activity but its few sediments is due to the facts that the upstream is covered with forest which reduces velocity of erosion in the area.

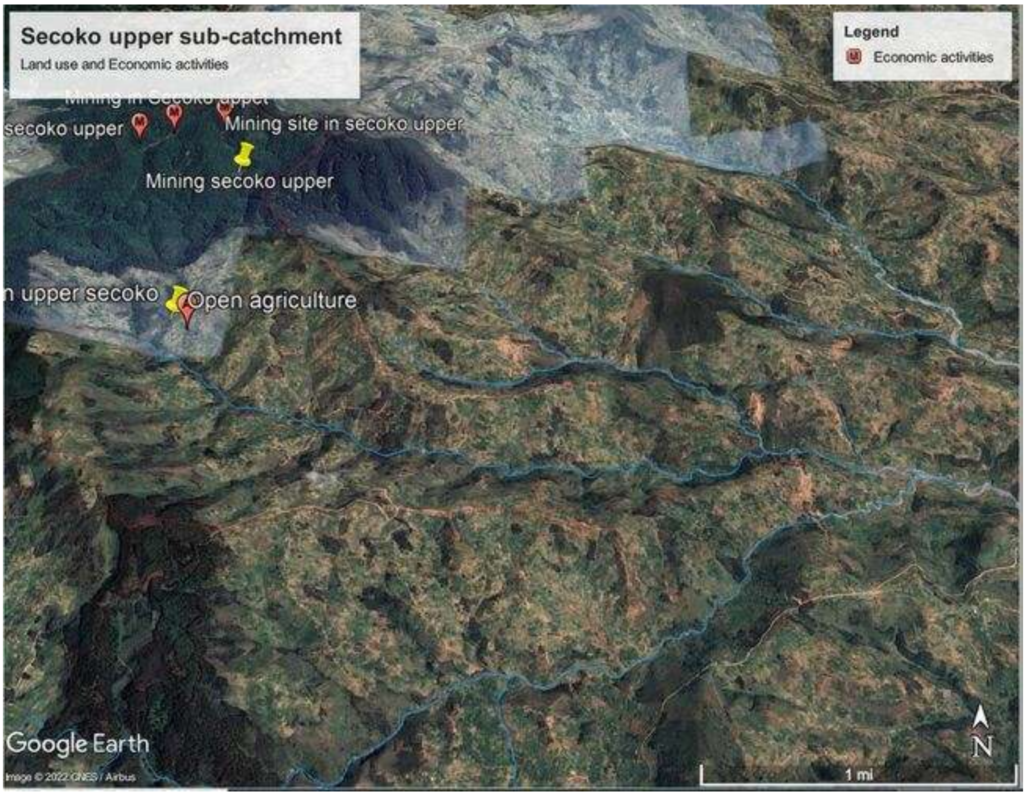

Figure 48: Land use and Economic activities in Secoko upper sub-catchment.

4.2.9. Kiguhu

In the Kiguhu sub-catchment, Ho is a larger source of suspended sediments followed by Nw.

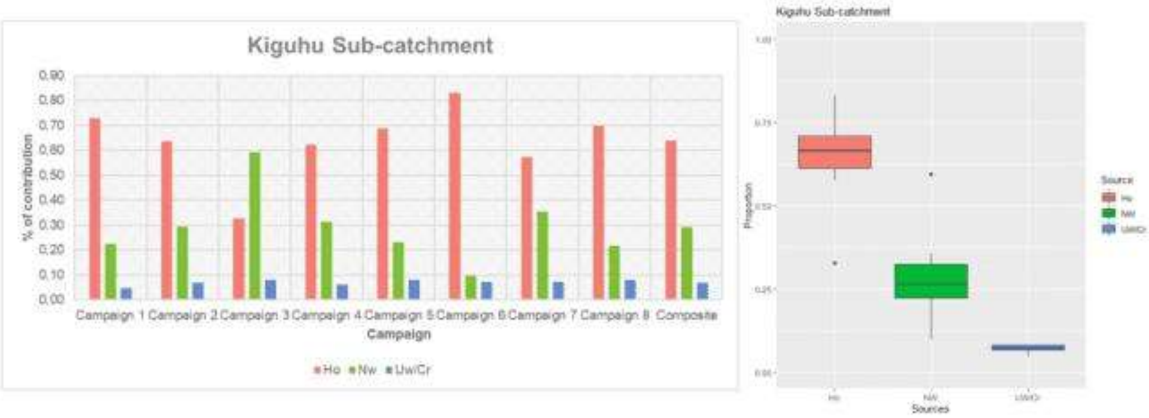

Figure 49: Kiguhu sub-catchment sediment distribution.

The main reason explaining the high sediment contribution of Ho formation in the Kiguhu sub-catchment is most probably due to mining activities near the river. In addition, poor agriculture practices and deforestation near the outlet of the river, in the Nw and Uw/Cr formations, may be behind the slightly higher contribution of Nw sediments depicted in the statistical results. The Kiguhu sub-catchment is very much affected by mining activities and deforestation, especially near Ho and Nw geological formations; thus the presence of Ho and Nw sediments at the outlet of the river. The erosion control measures are not in place despite its high slop and this may be cause of Uw/Cr contribution to outlet of the river.

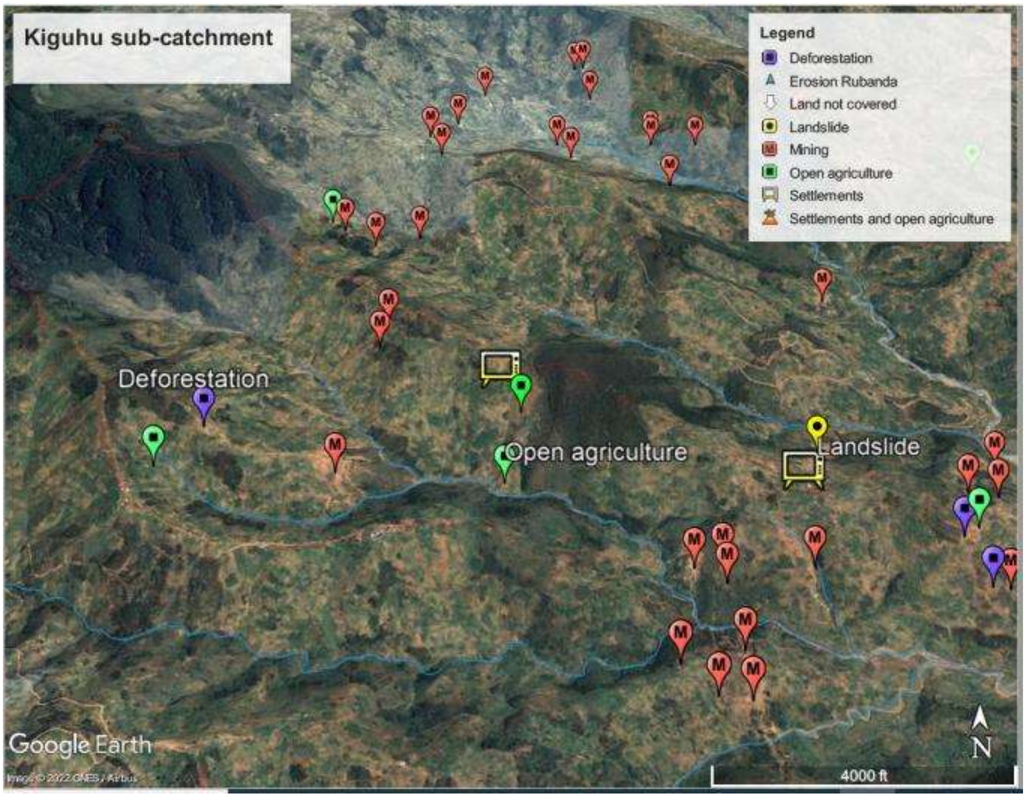

Figure 50: Land use and economic activities in Kiguhu sub-catchment.

4.2.10. Rubayu

In the Rubayu sub-catchment, Ho is a larger source of suspended sediments.

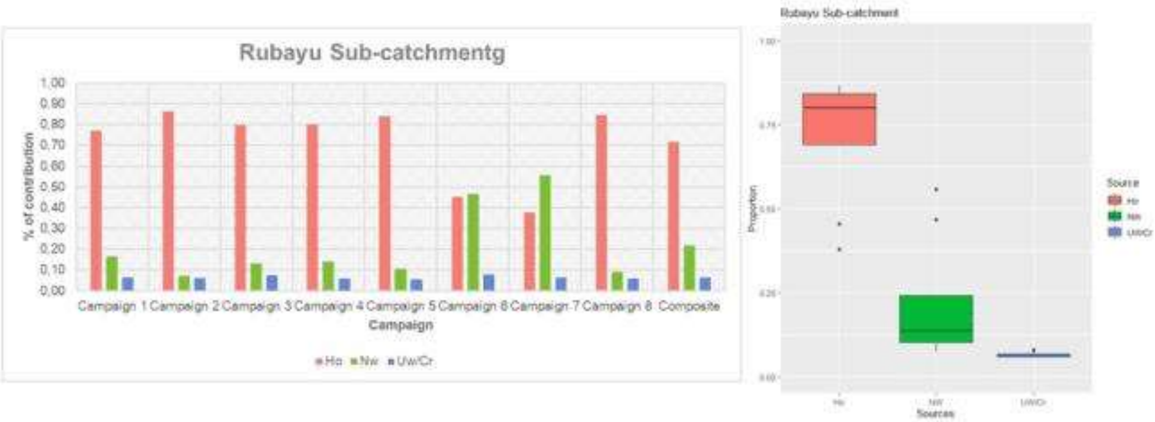

Figure 51: Rubayu sub-catchment sediment distribution.

In the Rubayu sub-catchment, the deforestation, poor agriculture activities and settlements are the major cause of high sediment contribution of the Ho formation. In addition, the Nw formation is slightly dominant to Uw/Cr due to poor land management which led to high land degradation and soil erosion. It was found that land is exposed to erosion and this is because of deforestation that took place in the area, or land degradation due to anthropogenic preference and open agriculture with no erosion control measures.

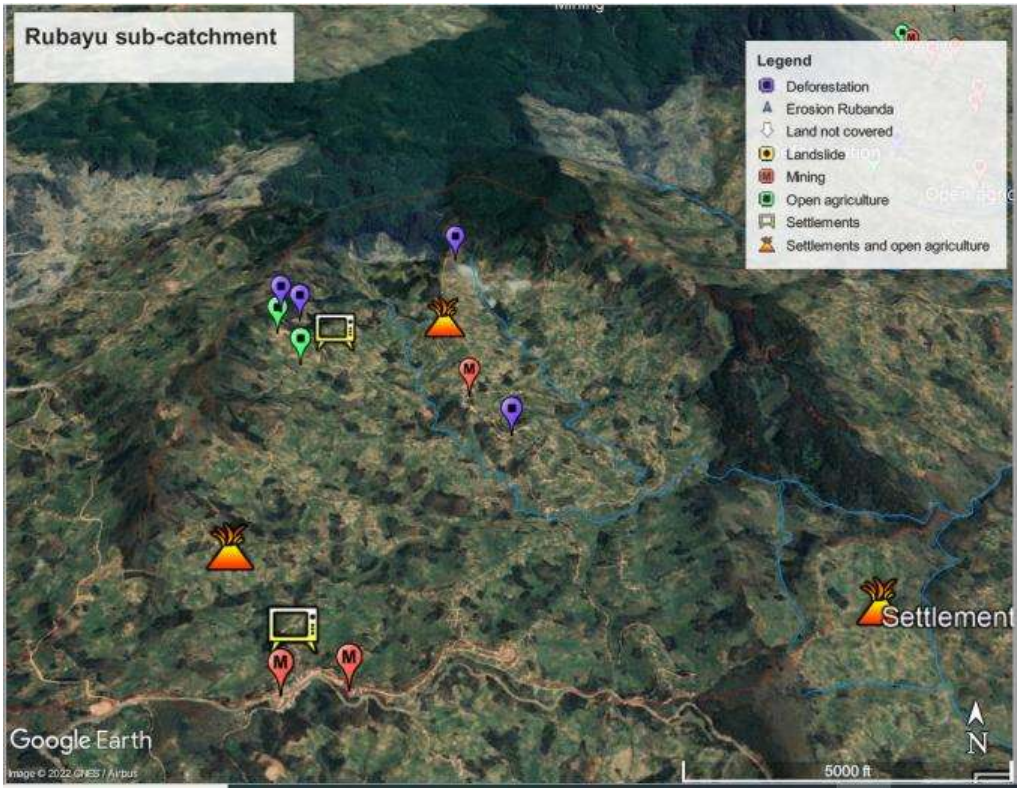

Figure 52: Land use and economic activities in Rubayu sub-catchment.

Figure 29 shows that Rubayu sub-catchment is a place where settlements and open agriculture are dominant. Deforestation was also found as the main cause of erosion and distribution of sediments in Ho and Nw formations.

4.2.11. Kagogo

In the Kagogo sub-catchment, Nw is a larger source of suspended sediments.

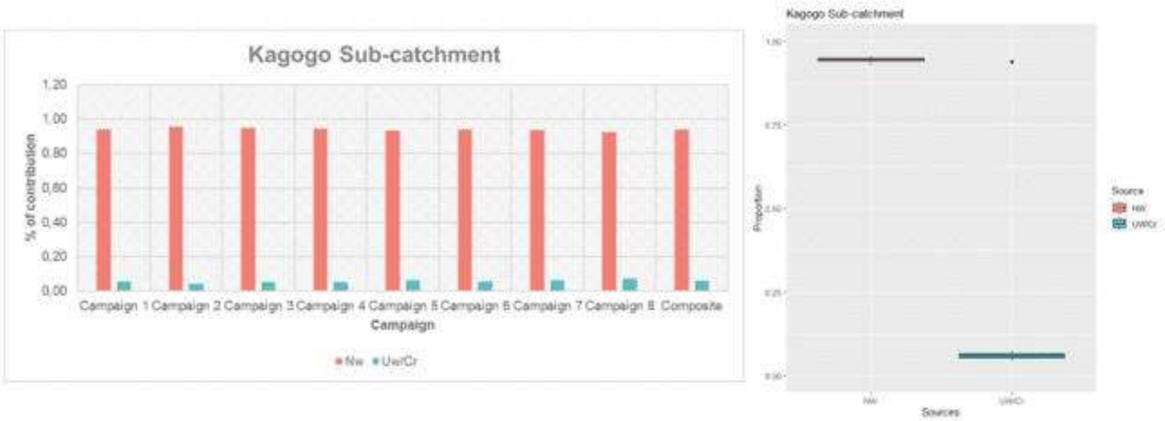

Figure 53: Rubayu sub-catchment sediment distribution.

The Kagogo sub-catchment is led by open agriculture activities with no protection measures against erosion. The poor agriculture practices and unplanned settlements may be the main cause of suspended Nw and Uw/Cr sediments in Kagogo sub-catchment.

Figure 54: Land use and economic activities in Kagogo sub-catchment.

The agriculture activities and poor designed settlements are dominant all over the sub-catchment. The contribution of Nyungwe (Uw/Cr) in the river even though the formation is very small, but a concentration of the poor agriculture sites is the cause the depicted contribution in the statistical results.

4.2.12. Ruhumira

The Ruhumira sub-catchment is made of one geological formation, the Uw/Cr. The situation in Ruhumira sub-catchment is related to poor agricultural practices with no measures of erosion control. However, due to limited sediment data, one can only relates the contribution from the Uw/Cr formation to a heavy rainfall event and or subsequently agriculture lands that occurred prior to the sampling campaign.

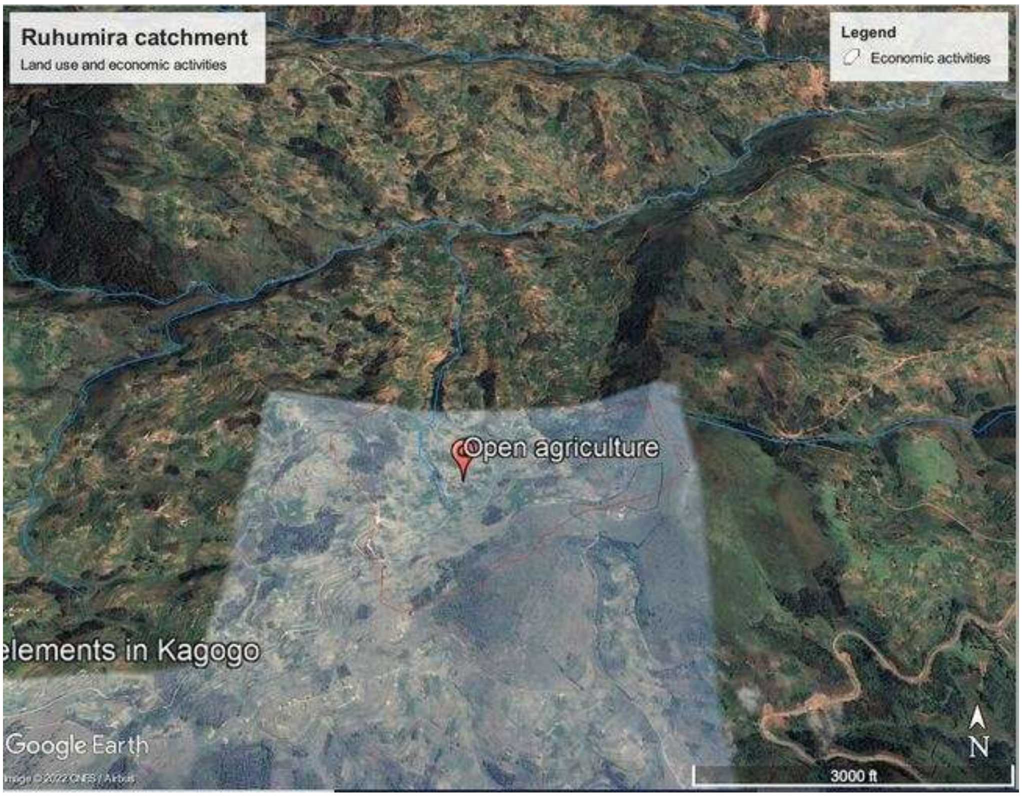

Figure 55: Land use and economic activities in Ruhumira sub-catchment.

The poor designed settlements and open agriculture are dominant all over the sub-catchment. The contribution of Uw/Cr sediments in the river is caused by the concentration of the poor agriculture activities in the area.

4.2.13. Secoko Middle

In the Secoko Middle sub-catchment, Ho is a larger source of suspended sediments, however there is also slightly high and significant contribution of Nw in the river.

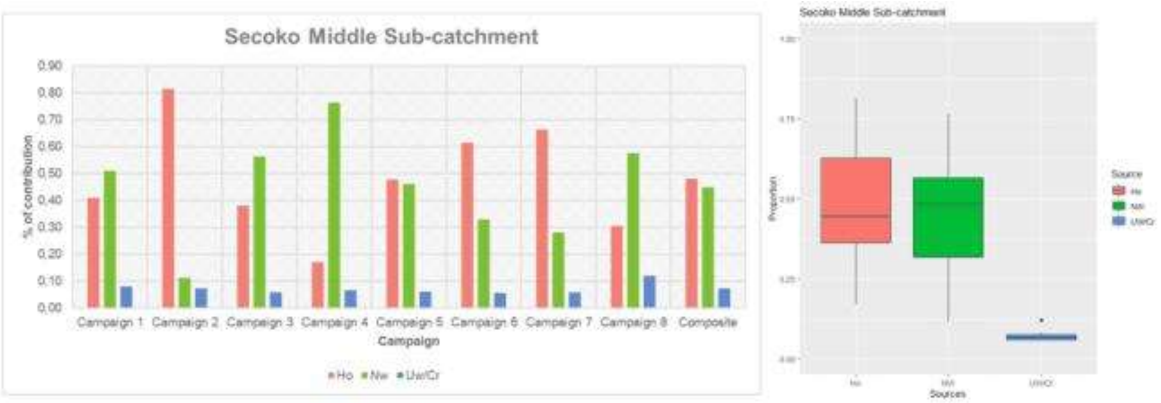

Figure 56: Secoko middle sub-catchment sediment distribution.

The Secoko Middle sub-catchment is dominated by mining, open agriculture with no protection measures against erosion. The Mining, deforestation, and poor agriculture practices may be the cause of high Ho suspended sediments in Secoko Middle sub-catchment. Among others, the deforestation which exposes land to erosion was also found as one else major challenge within the sub-catchment. The contribution of Uw/Cr in the river even though the formation is very small, but a concentration of the poor agriculture sites is also the cause the depicted contribution in the statistical results.

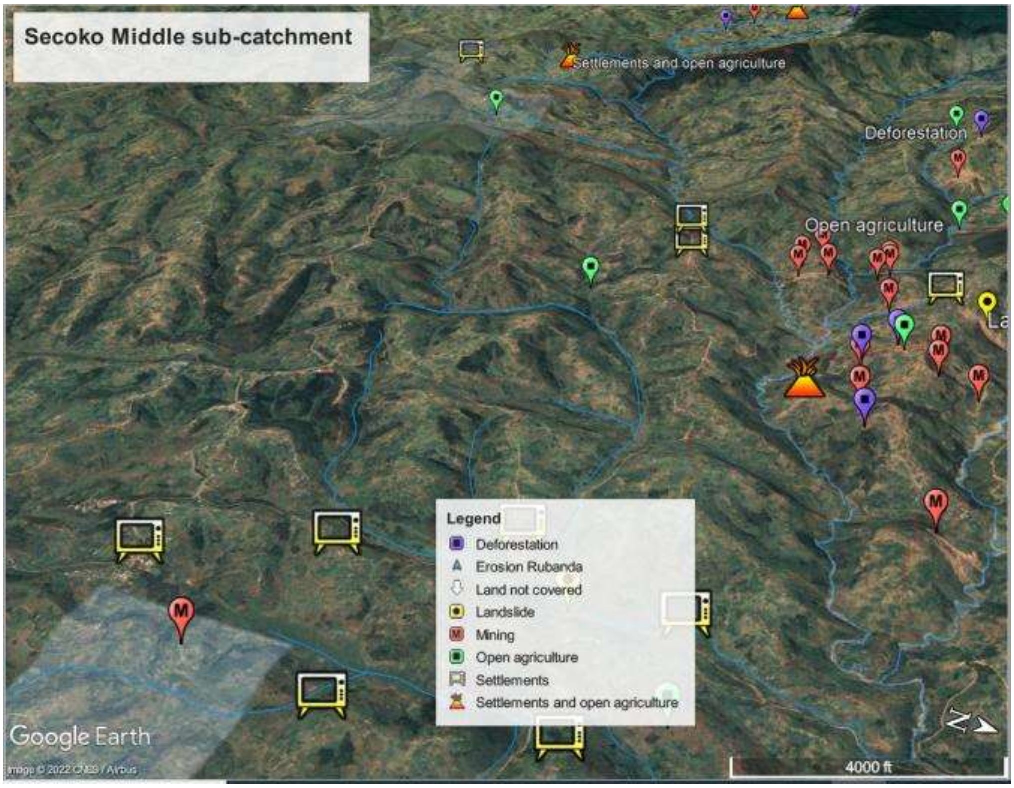

Figure 57: Land use and economic activities in Secoko middle sub-catchment.

The figure shows that Secoko middle sub-catchment is dominated by mining, deforestation, open agriculture and settlements.

4.2.14. Secoko Lower

In the Secoko Lower sub-catchment, Ho is a larger source of suspended sediments, however for the second contributors, there is much similarity in contribution between Nw and Gt. The composite of sediments of Secoko lower is made of all sources of secoko catchment because it is the only outlet of Secoko River; and all sediments from upstream are collected in secoko lower before they are channeled in the main river.

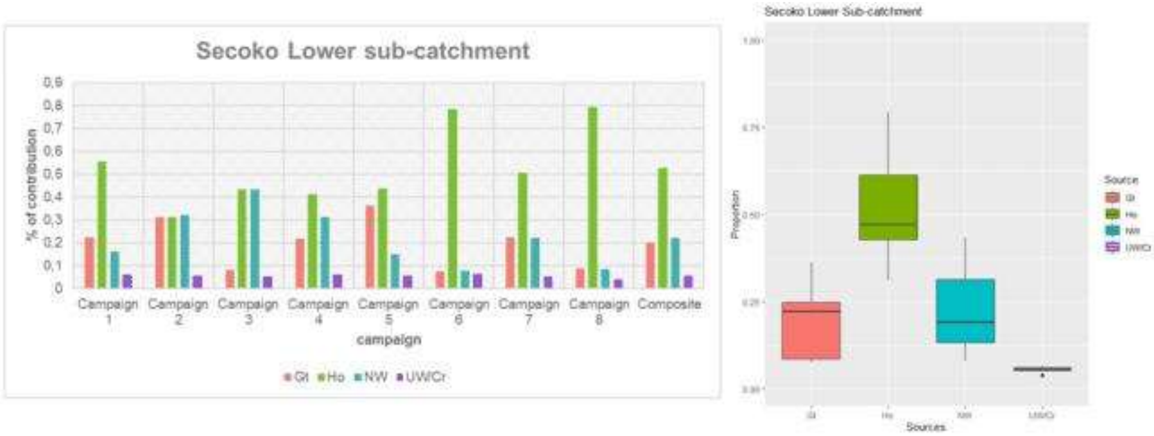

Figure 58: Secoko middle sub-catchment sediment distribution.

The mining, poor agriculture practices and settlements in the Secoko catchment, within the Ho and Gt formations, is the most probable cause of high sediment contribution at the outlet of secoko lower sub-catchment. The slightly equal contribution of Nw and Gt formations located at the outlet of the catchment, indicates poor agriculture activities and mining respectively.

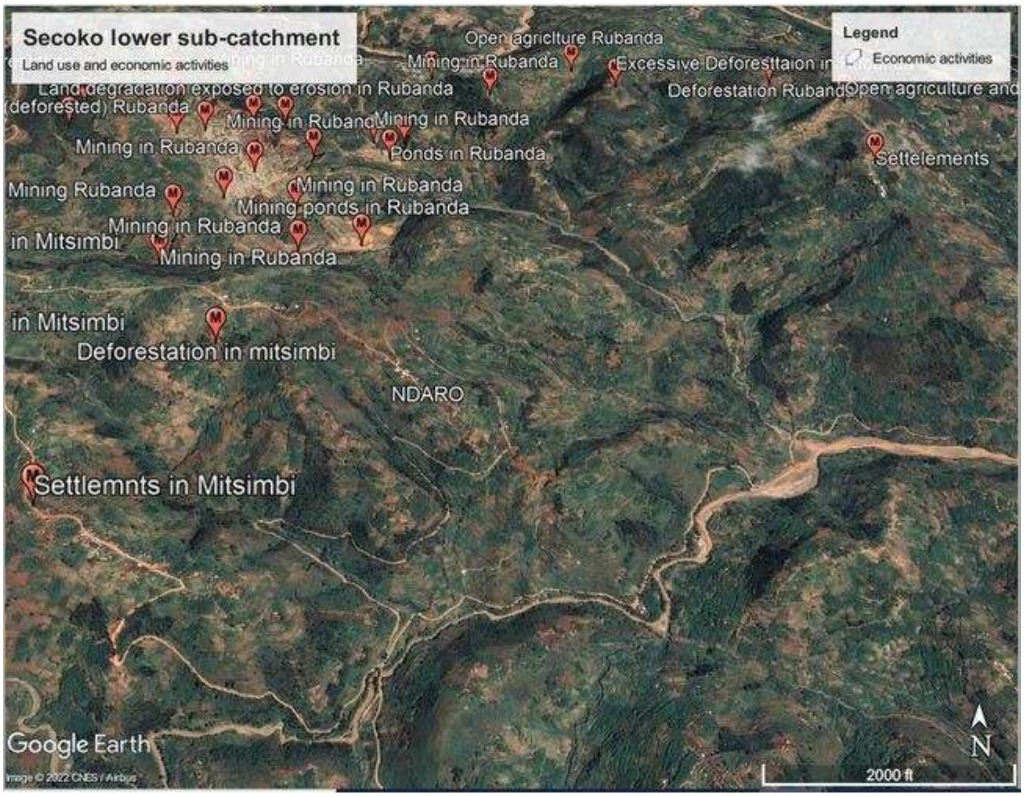

Figure 59: Land use and economic activities influencing sediments contribution in Secoko lower sub-catchment.

4.2.15. Prioritization of areas heavily affected by erosion

Results identify the geological types in each sub-catchment that contributed to the highest levels of sediment over the sampling period. Locating these geological types on an administrative map then indicated the villages that are the likely areas subject to the highest levels of erosion. Using observations from the fieldwork, during data collection, and updated high resolution satellite imageries of the area; the most erosive economic activities in the study area were identified and linked to villages. The prioritization analysis was done for each sub-catchment, starting with the upstream sub-catchments – Rubanda, Sagatekere, Cyanjongo, Kiguhu, Secoko Upper, Rubayu, Kagogo, Ruhumira, Gasesa Upper and Kagera. Then the analysis focused on intermediary sub-catchments – Secoko Middle and Gasesa – both receiving flow from the upstream catchment and discharge in the downstream catchment (i.e. the outlet of Secoko catchment). Finally, Secoko Lower, the overall outlet of the catchment was analysed as well. The potential sediment sources in each sub-catchment and their transport downstream were analysed with respect to the hydrological flow path (i.e. from upstream to the catchment outlet) of the Secoko River drainage. This means that the suspended sediments sampled at any point in the Secoko River system have entered the river as runoff at various points in the catchment upstream corresponding to the sampling points.

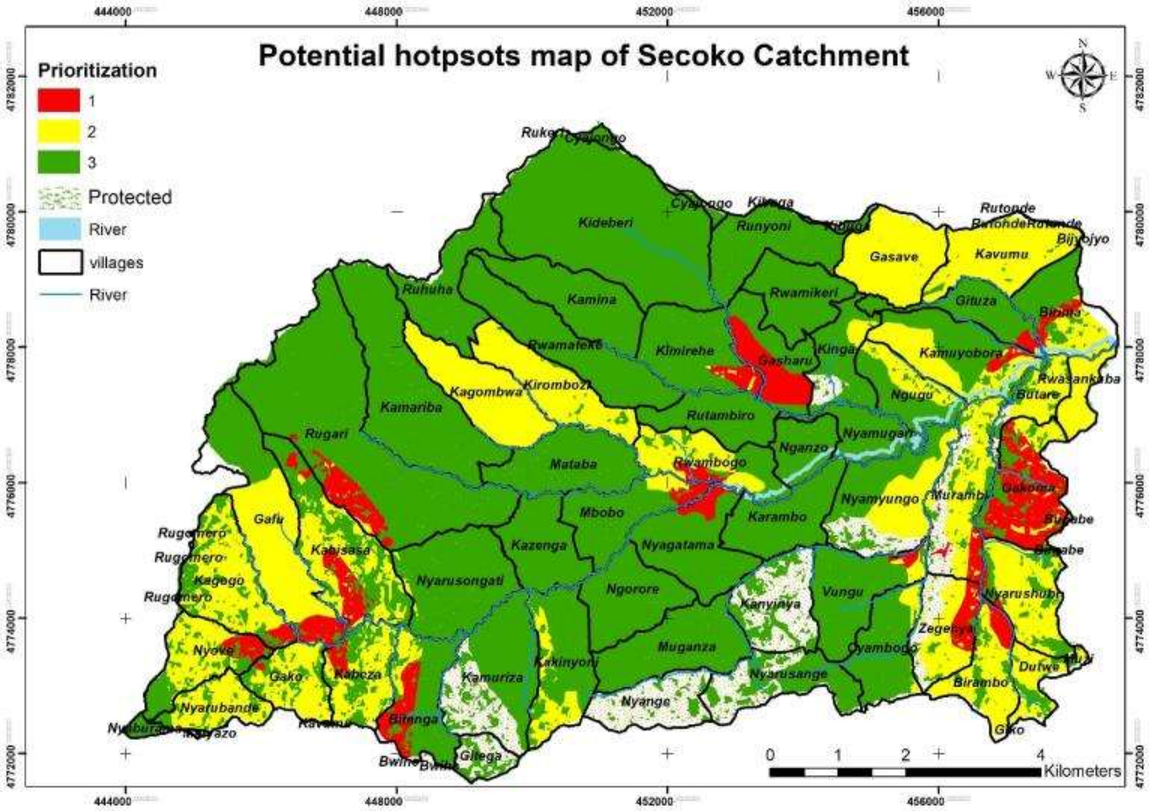

Figure 60: Potential hotspot map of Secoko Catchment.

The main degraded part (in priority 1 and 2) of the Secoko catchment is devastated by mining activities and another great part of it, is covered by landslide and agriculture of the seasonal corps. These activities expose the total land to erosion living behind a weak thin soil on steep slopes. The latter increased the vulnerability of the Secoko ecosystem to soil land corrosion and degradation reducing its recovery rate over time.

Mining activities followed by landslide heavily produce sediments with localized accentuation during particular rainfall events on the sites of Ho formation. The contribution of open agriculture was also observed to be important as it was related to the fact that large areas contribute sediments. The latter combined with specific localized rainfall events and unplanned settlements could accentuate the sediment contribution.

In general, in areas where forests are removed by deforestation, mining, landslide or agriculture, the sub-catchments remain prone to soil erosion. Unfortunately, the thin soils and steep slopes pose challenges to the rate of recovery of forest cover and productive soils. Plantation forestry, while being a useful socioeconomic activity still does not possess a dense multi-layered canopy to break the impact of rainfall upon the soil. The prevalence of agriculture in Secoko requires continuation of existing soil and water conservation efforts such as terracing as well as its maintenance, mulching and contour trenching, etc. Given the logistical challenges of undertaking these activities at the large spatial scale, the sediment fingerprinting process indicated the potential hotspots of erosion and priority of restoration and thereby could help to orient efforts efficiently for catchment rehabilitation in Secoko catchment area.

4.3. Sediment rating curve at the outlet of Secoko Sub-catchment

4.3.1. Results for river discharge

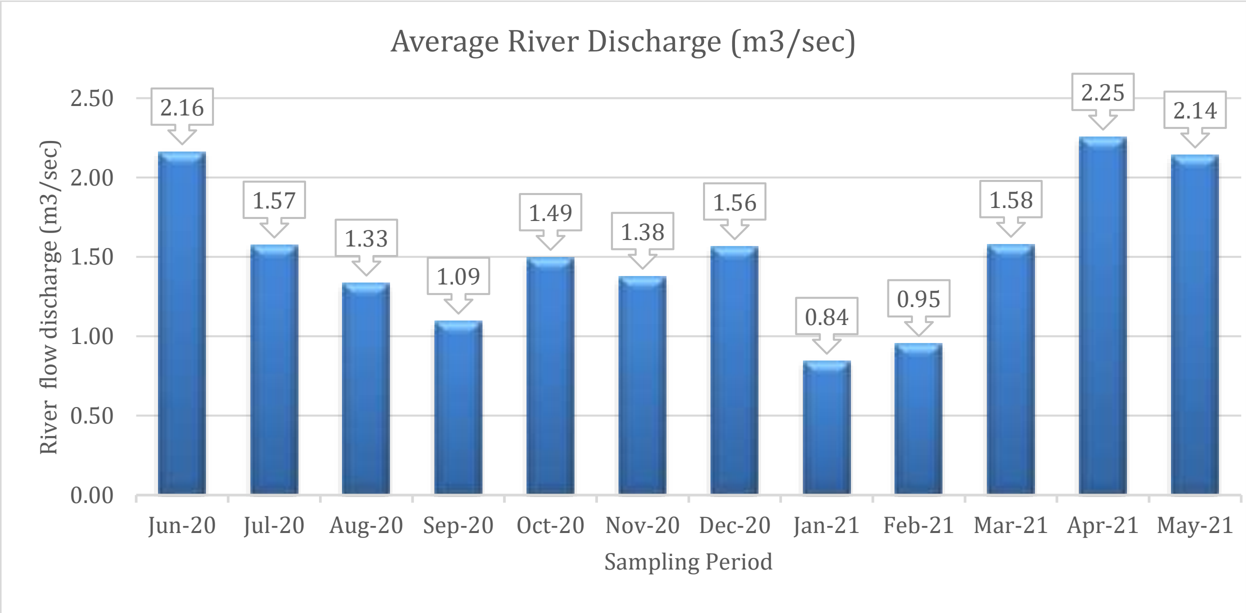

Figure 61: Average river discharge at the outlet of Secoko sub-catchment.

4.3.2. Results for Total Suspended Solids

The hourly variation in the concentration of TSS at outlet of Secoko sub catchment is provided in Figure.

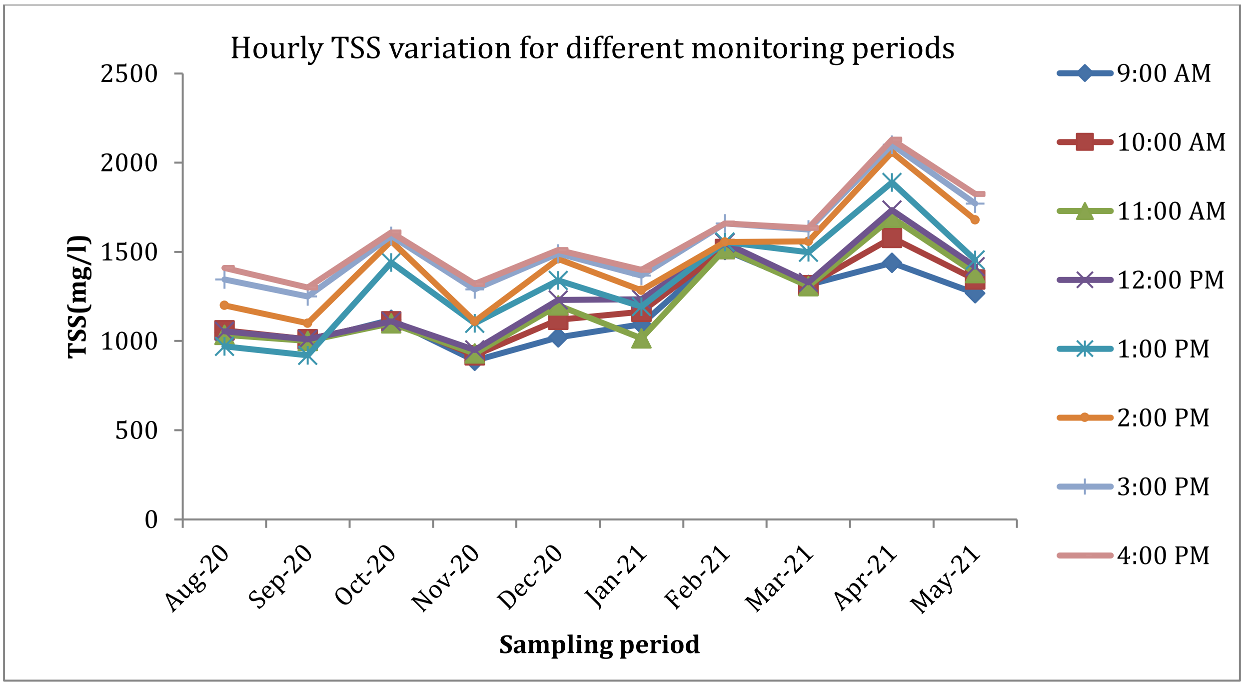

Figure 62: Hourly TSS variation at the outlet of Secoko River.

As indicated in Figure 63, the concentration of TSS is high in Secoko River. This is also confirmed by RWFA, 2019, in its report on research conducted in two periods (05-22 November 2018 and 04-22 February 2019) where it was found that the high sediment load and turbidity of Secoko river is mainly due to the combination of agricultural activities on hill side and intensive mining activities which contribute to the suspended solids accumulation in rivers of upper Nyabarongo catchment. The hourly variation of TSS during the day shows TSS concentrations increase from morning to late hours. This hourly variation status is justified mainly by daily mining activities taking place on hillside of Secoko River; where wastes (topsoil overburden, waste rock and tailings) are discharged into its tributaries as washing activities become intense during the the day and late working hours.

The monthly variation in the concentration of TSS at outlet of Secoko sub catchment is provided in Figure.

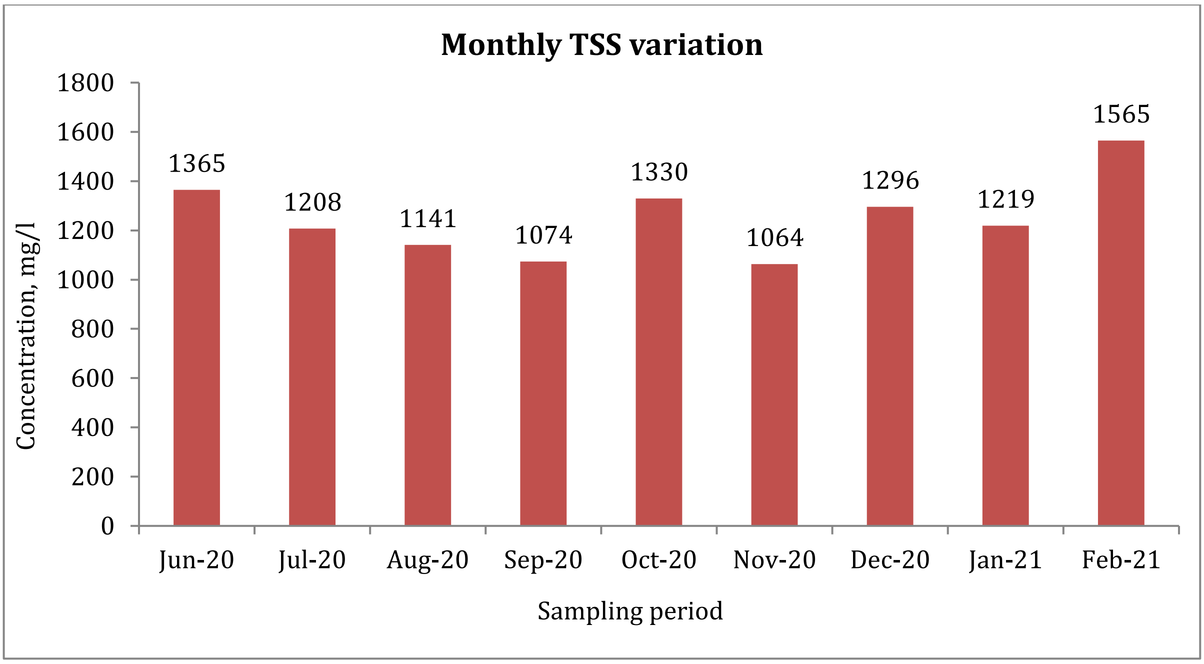

Figure 63: Monthly TSS variation at the outlet of Secoko River.

As indicate in Figure 64, the TSS concentration in Secoko River was higher in February 2020 and lower in November 2020. As it was discovered by RWFA in 2019, the TSS concentration is high during short rainy season and becomes low during dry short season. The reason is that during the dry short season there is no soil erosion and surface runoff which are in general the main factors influencing high TSS observed in surface water during the rainy season. However, the results (from June 2020 to February 2021) from this study contrast with the former discoveries; and the reason may be attributed to the variability of hydro-climatic conditions within the catchment and frequencies of mining activities.

4.3.3. Sediment Rating Curve at Secoko outlet

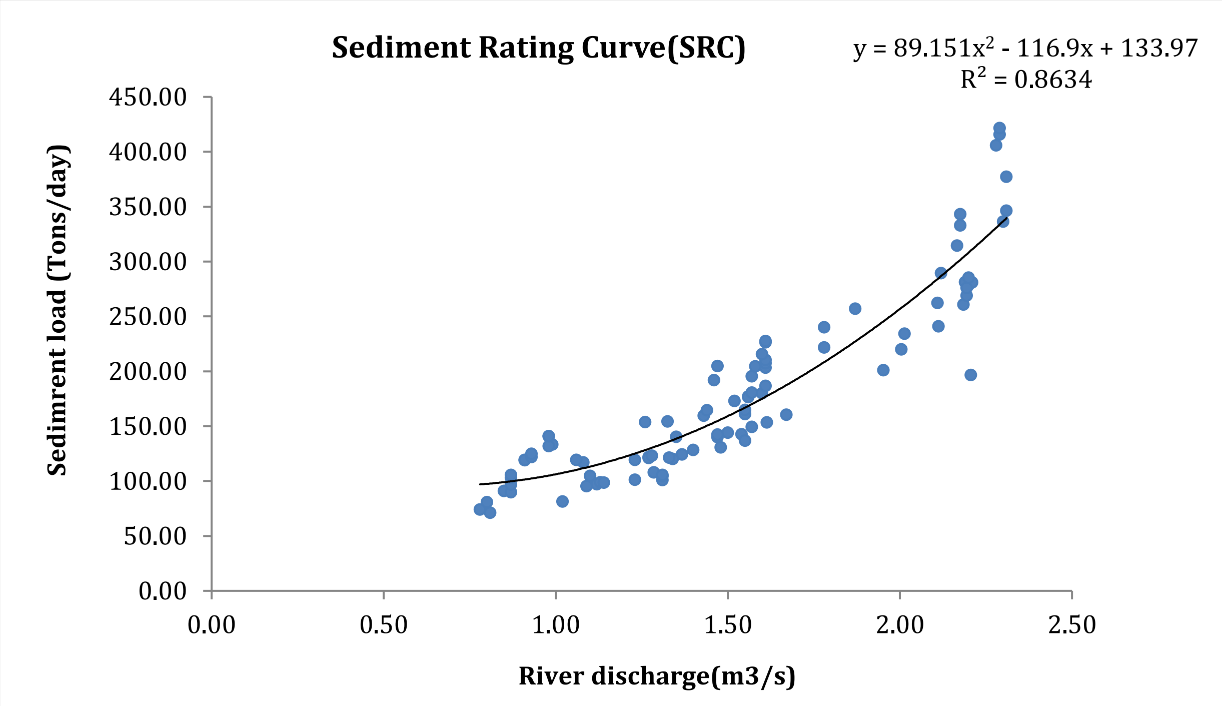

Figure 64: River discharge- TSS concentration at Secoko outlet.

The Sediment Rating curve shows a positive relationship between the river discharge and TSS. The high concentration of TSS at the outlet of Secoko sub-catchment is directly linked to the factors such as soil erosion influenced by rainfall, Soil type, Topography, land use land cover and management practice on the soil, as it is justified by satellite images of the area for different years (refer to fig. a-g).

Secoko outlet in March 2011: the valley was green with relatively less sediment

	
In July 2014: Secoko stream very turbide compared to Nyabarongo River	
	
January 2017: The reservoir of Nyabarongo hydropower was filled with water relatively clear compared to secoko stream	
July208: Secoko Stream very turbide in dry season	

December 2020: huge quantity of sediment deposited in NyabarongoI hydropower

Figure 65: Secoko river outlet changes over time.

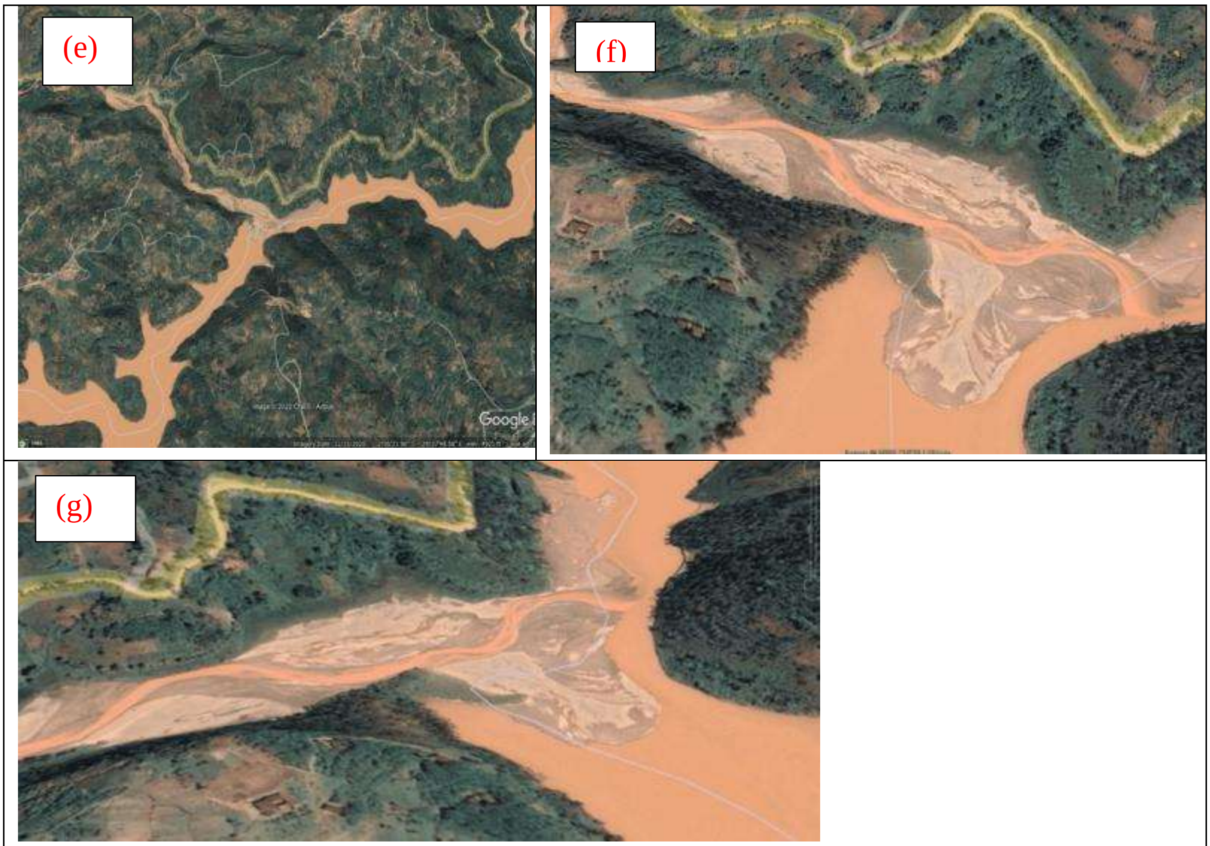

Figure 66: Illustration of secoko outlet at Nyabarongo I reservoir.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study assessed the contribution of mining activities to sediment loads in the Upper Nyabarongo Catchment, and specifically focused on Secoko sub-catchment. It consisted of assessing the spatial and temporal variability of water quality across the sub-catchments; assessing contribution of mining to sediment load by using the fingerprinting methodology and developing the sediment rating curve at the outlet of Secoko sub-catchment. 14 sampling points were selected across the sub-catchment. Through 8 campaigns, 112 water samples were collected to assess the variability of water quality. 20 Soil samples, and 112 suspended sediment samples were collected across the study area for fingerprinting analysis to identify different levels of erosion hotspots and sedimentation in 14 streams.

Water quality was analysed through its physico-chemical parameters (pH, Electrical conductivity, Total dissolved solids, Turbidity, Sulfate, Chloride and Fluoride) and metallic (Heavy and trace) elements (Calcium, Magnesium, Potassium, Iron, Manganese, Copper, Tin, Tungsten, Cobalt, Zinc, Lead, Arsenic, Aluminum, Cadmium and Antimony). Most of physico-chemical parameters were found to be acceptable range compared to RSB standards for surface water. However, the turbidity was found to be above acceptable range with values between 9.01 and 13660 NTU at Kagera and Rubanda streams respectively while the acceptable range is 25 NTU. On the metallic elements analysis, the results showed that some elements such Calcium, Aluminium, Zinc and as are in acceptable range for surface water quality compared to RSB standards. On other hand, the results showed that Iron, Manganese, Magnesium, Copper, Arsenic, Antimony, Tin, Cadmium, Cobalt, Tantalum and Lead, exceeded the acceptable values for surface water quality compared to RSB standards. The high values observed of metallic elements could be attributed to anthropogenic sources (land use activities) with low inputs from mine activities at the project site.

The findings showed that the degraded part of Secoko sub-catchment is devastated by mining activities and another part is covered by landslide and seasonal cropping. Consequently, these activities expose the total land to erosion leaving behind a weak thin soil on steep slopes. The latter increased the vulnerability of the Secoko ecosystem to soil erosion and degradation reducing its recovery rate over time. It was discovered also that mining activities followed by landslide heavily produce sediments with localized accentuation during particular rainfall events on the sites of Ho formation. The contribution of open agriculture was also observed to be important as it was related to the fact that large areas contribute sediments. The latter combined with specific localized rainfall events and unplanned settlements could accentuate the sediment contribution.

In general, in areas where forests are removed by deforestation, mining, landslide or agriculture, the sub-catchments remain prone to soil erosion. Plantation forestry, while being a useful socioeconomic activity still does not possess a dense multi-layered canopy to break the impact of rainfall upon the soil.

The development of sediment rating curve at the outlet of Secoko sub-catchment showed that the the concentration of Total Suspended Solids (TSS) is high in Secoko River. The hourly variation of TSS during the day shows increasing trend from morning to late hours due to daily mining activities taking place on hillside of Secoko River. This is due to wastes (topsoil overburden, waste rock and tailings) discharged into its tributaries as washing activities become intense during the day and late working hours. The TSS concentration is high during short rainy season and becomes low during dry short season. It was found also that the increase in river discharge imposes high concentration of total suspended solids. The high concentration of TSS at the outlet of Secoko sub-catchment is directly linked to the factors such as soil erosion influenced by rainfall, soil type, topography , and land use and management practice.

5.2. Recommendations

The findings from this research are helpful to guide on interventions needed for Upper Nyabarongo catchment management with focus on Secoko Sub-catchment. Based on the findings, some recommendations are highlighted:

- Continuation of existing soil and water conservation efforts (terracing, contour trenching, mulching) are required for strengthening land cover to reduce erosion risk.
- The potential hotspots of erosion can be used to prioritize restoration efforts and thereby helping undertake efficient catchment rehabilitation to achieve land degradation neutrality in Secoko catchment.
- The improvement in monitoring of mining activities is needed to reduce mining wastes thrown in rivers without pre-treatment.
- It is advised to build a check-dam nearby Secoko sub-catchment outlet in order to reduce the sedimentation of reservoir for efficient power production at Nyabarongo hydropower plant I.

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