Environ Monit Assess (2020) 192:806
https://doi.org/10.1007/s10661-020-08774-5

Using sediment fingerprinting to identify erosion hotspots in a sub-catchment of Lake Kivu, Rwanda

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Received: 16 August 2019 / Accepted: 22 November 2020

Abstract Sedimentation of water bodies affects water quality and biotic communities of aquatic ecosystems. Understanding the causes and origin of sediments is crucial for planning watershed management activities and safeguarding aquatic biodiversity and critical ecosystem services. Rwanda, as a hilly country, experiences increased sedimentation due to unsustainable land use practices in upstream catchment areas which negatively affects irrigation, fishing and hydropower generation. We used a sediment fingerprinting technique to determine sources of sedimentation and identifying hotspots of soil erosion in Sebeya River Catchment (area of 357 km^2), a sub-catchment of Lake Kivu located in Northwest Rwanda. Five soil samples were collected from each of the six geological classes, and 34 suspended sediment samples were taken within key locations of the hydrological network in the catchment. X-Ray Spectrometry was used to determine the geochemical composition of suspended sediments and soil. A multi-step statistical procedure with a Bayesian mixing model was used to determine the contribution of each geologic group and sub-catchment to the suspended sediments in the river. Erosion hotspots were classified based on the underlying land use and their contribution to the suspended sediments. The resulting erosion hotspot map shows that about 70.9% of the Sebeya Catchment area contributes at least 50% of sediment load in the river and currently experiences unsustainable land use and land cover. The erosion hotspots identified and culpable factors should be used to guide best land use practices, prioritizing the areas with high contribution to the river sedimentation in Sebeya Catchment.

Keywords Sebeya River · Erosion hotspots · Sediment fingerprinting · Rwanda

Introduction

Sedimentation is a challenge facing freshwater systems, with undesirable implications for aquatic ecosystem and

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human health. Sedimentation reduces water quality through enrichment with excessive nutrients and siltation, with negative impacts on key parameters such as transparency, turbidity and dissolved solids (Tundu et al. 2018). The compromise to water quality also affects biodiversity and ecosystem services supported by the water resources (Scholes et al. 2018). Sediments can be sources of other substances such as heavy metals that are contaminants of aquatic life and humans (Iwasaki et al. 2009; Omar et al. 2013). These challenges underscore the importance of controlling sedimentation.

Sediments in water bodies are derived from catchments mainly through erosion of topsoil (Slattery and Burt 1997). The rate of erosion, and therefore the rate of sedimentation depends on rainfall intensity (Mohamadi and Kavian 2015; Riebe et al. 2015; Haifang et al. 2015) and human activities such as uncontrolled agriculture and destruction of land cover (Kiragu 2009; Li et al. 2012). These conditions are common over much of the African Great Lakes region. The total annual rainfall in the East African region is predicted to increase by 15–20% by the end of the twenty-first century, resulting into a 50% increase in runoff for some areas by 2060 (Seimon et al. 2012). Land conversion in the region is also predicted to increase (Borrelli et al. 2017; Scholes et al. 2018), indicating that sedimentation, if not controlled, will increasingly threaten water resources. Some areas in East Africa will be more affected than others.

Rwanda, referred to as ‘the land of a thousand hills’, is among areas that are exposed to higher risk of erosion. Erosion in the country is worsened by unsustainable land use practices and absence of vegetation cover on the steep slopes (Ministry of Disaster Management and Refugee Affairs [MIDIMAR] 2013; Rwanda Environment Management Authority [REMA] 2015). Approximately 34 to 47% of the country experiences soil loss ranging from 50 to 100 t/ha/year, due to erosion (Ministry of Agriculture and Animal Resources [MINAGRI] 2012). On steep slopes with high annual rainfall and little vegetation cover, most of this soil lost from agriculture is transported into rivers where the high sediment load increases concerns of water pollution (Rwanda Natural Resources Authority [RNRA] 2015).

Because sediment in water bodies originates from their catchments, effective response interventions should target major sediment sources (hotspots) in the catchment. Using a ‘sediment fingerprinting technique’, we determined the origin of suspended sediments in Sebeya Catchment in Rwanda, a sub-catchment of Lake Kivu which is one of the African Great Lakes shared by Rwanda and the Democratic Republic of Congo (DRC). The technique links suspended sediments in a water body to their origin within the catchment to identify erosion hotspots to be prioritized for conservation (Dutton et al. 2013; Collins et al. 2017). Such an approach has been widely used to guide interventions for preventing excess sediment discharge in reservoirs (Nosrati et al. 2018) and rivers (Dutton et al. 2019). In the current study, sediment fingerprinting is applied to determine the potential erosion hotspots in the Sebeya River Catchment of North Western Rwanda, East Africa. The results constitute a continuous monitoring of water quality in Rwanda (RNRA 2015) and provide baseline data for planning catchment restoration, considering priority areas and existing initiatives on land rehabilitation and climate change adaptation and, can be applied on other African Great Lakes.

Materials and methods

Study area

Sebeya Catchment is located in North Western Rwanda and is shared between four districts (Fig. 1). The catchment has an area of approximately 357.3 km^2 and is part of the larger catchment of Lake Kivu. The main river in the catchment is Sebeya which empties into Lake Kivu, at the border between Rwanda and the Democratic Republic of Congo (DRC).

Geological formation and soil types in the Sebeya River Catchment are fragile, making it susceptible to heavy erosion (Ministry of Environment [MoE] 2018). Elevation in the catchment is high, ranging from 1462 to 2902 m above sea level. The soils are weathered lava soils from volcanic material with high infiltration rates. The dominant geological units in the Sebeya Catchment are the Butare complex (Bu) and volcanic rocks of Virunga Mountains (B) formations (see Online Resource 1). The latter comprise a complex network of caves and a thin layer of soil susceptible to runoff if not properly managed. The soil classes are predominantly Nitosol, Acricol, Alisol and Lixisol, which are pockets of Ferralsols, Cambisol and Andosols (RNRA 2015; Online Resource 1). In addition to the above susceptibility factors, poor land use within the catchment and the increasing human population accelerate erosion. The

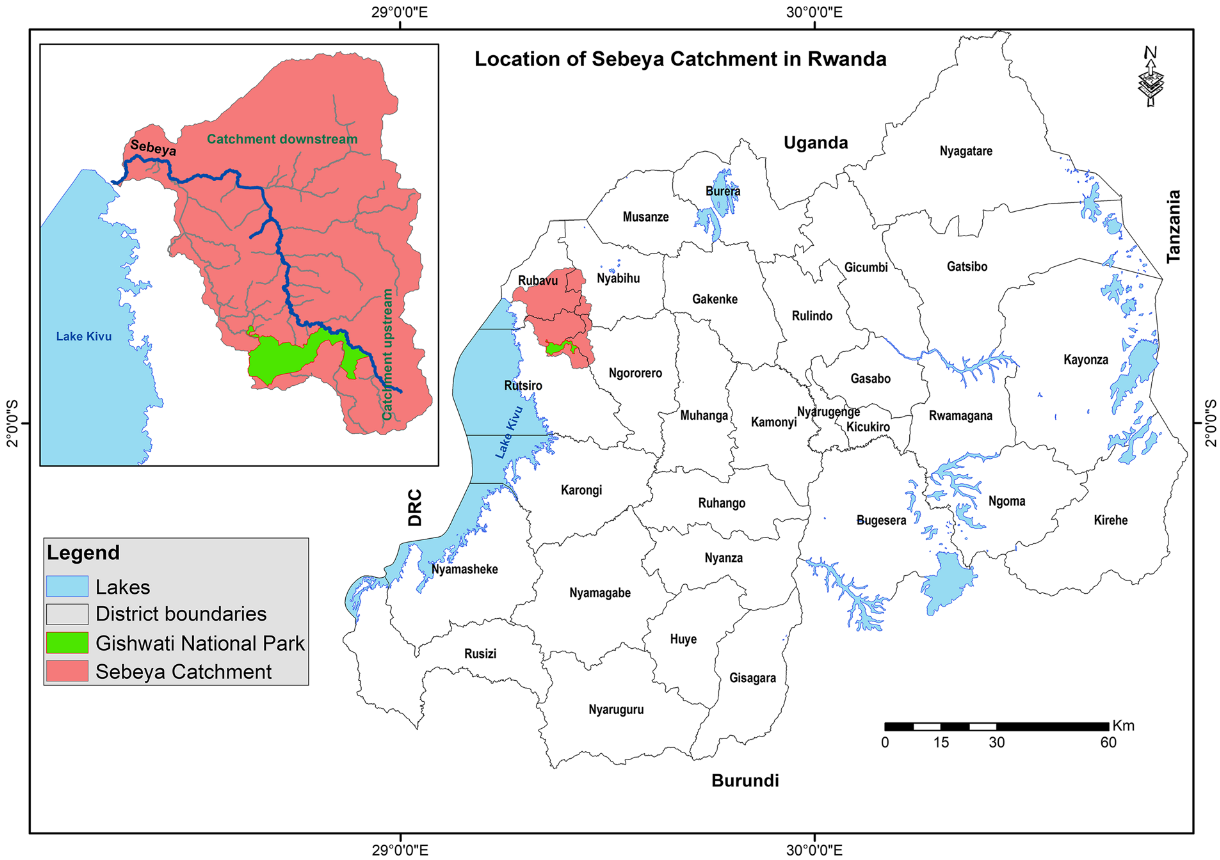


Fig. 1 Location of Sebeya Catchment within the larger catchment of Lake Kivu in North Western Rwanda

population density is high in the urban areas and along the shores of Lake Kivu (> 1000 inhabitants/km^2) and low in the rural and rugged terrain of the catchment (260–600 inhabitants/km^2) (Water For Growth Rwanda [W4GR] 2018). Land use is dominated by farmland (87.1%) with the rest being forest (10.7%) and built-up area (1.8%) (W4GR 2018). The erosion rates are much higher during rainy seasons (MIDIMAR 2013). Sedimentation within the river is of concern as it contaminates water for domestic use, interrupts hydropower generation and irrigation and deteriorates water quality with consequences for aquatic biodiversity (W4GR 2018).

Sediment and soil data collection

Soil and suspended sediment samples were collected at selected points, representing the hydrological network as well as the corresponding geological units in the catchment (described on Online Resource 2). Such an approach constitutes the 'sediment fingerprinting' technique that involves a statistical comparison of the chemical composition of suspended sediments in rivers with the composition of elements of soils that form various geological types in a given catchment (Collins et al. 2017; Pulley and Collins 2018). This technique pinpoints erosion hotspots through linking the river's suspended sediments to their source within the catchment. As a result, 14 sub-catchments and one corridor (Sebeya outlet) were monitored, and sediment data were collected in every sub-catchment in downstream and upstream areas (Table 1). Using a water bottle, water was collected at 4–5 m from the confluence of the main river and its tributary. The water was then measured with a graduated cylinder and 200 ml was filtered through a filter membrane (nylon polyamide, pore size = 0.45 μm and diameter 0.47 mm). The filter membrane containing the sediments was stored in a sterile 47-mm petri-dish. Suspended sediment samples were also taken at the outlet of Sebeya River.

In each geological unit, five composite soil samples were collected based on different land uses. At each location, a small amount of a soil sample was collected

Table 1 The total number of sub-catchments in Sebeya River Catchment

Sampling sub-catchment	Downstream sub-catchment	Upstream sub-catchment
1. Nyangirimbiri	Pfunda	N/A
2. Nyaburaro	Pfunda	N/A
3. Rwankuba	Pfunda	N/A
4. Yungwe	Karambo	N/A
5. Nyanzo	Bihongoro	N/A
6. Pfunda	Sebeya corridor	Rwankuba Nyaburaro Nyangirimbiri
7. Karambo	Sebeya corridor	Yungwe
8. Bihongoro	Sebeya corridor	Nyanzo
9. Kagera	Sebeya corridor	N/A
10. Kadobogo*	Sebeya corridor	N/A
11. Mubuga	Sebeya corridor	N/A
12. Bitenga	Sebeya corridor	N/A
13. Gatare	Sebeya corridor	N/A
14. Bikeneko	Sebeya corridor	N/A
15. Sebeya corridor	Catchment outlet	All other sampling sub-catchments

*The sub-catchment was not included in the mixing model, because only one sediment sampling was conducted there

A total of 14 sub-catchments correspond to the affluent of Sebeya River where sediment samples were collected, and a corridor constitutes the outlet. The sampling sub-catchments comprise of rivers that feed into others in the downstream sub-catchment and the upstream sub-catchment. The sub-catchments also contain rivers that are affluent in the downstream sub-catchment or Sebeya corridor (e.g. Rwankuba, Nyaburaro and Nyangirimbiri Rivers are affluent of Pfunda River)

at a depth of 20 cm, and all the five points (north, south, east, west and centre) were placed around a circle of a 10-m radius. A non-metal object was used for digging and collecting the sample to avoid risks of sample contamination and interference with metals. The subsamples at each location were then mixed to form a composite sample. Soil samples were stored in Ziploc plastic bags. In total, 30 soil and 34 sediment samples were collected during three different periods:October 16–November 3, 2017; January 15–26, 2018; and February 12–22, 2018 (Fig. 2). The soil was collected only once at each selected point to characterize the underlying geochemical composition of each geologic type. Suspended sediment samples were collected at each site during the three sampling periods.

Laboratory analysis of soil and sediment samples

The soil and sediment samples were analysed using the X-Ray Fluorescence Spectrometry (XRF) to generate the chemical composition of each sample. The analysis was done at the Rwanda Standards Board following their standard procedures outlined in NQTLD/MTLU/NDT/SOP-1 (see a sample test report shared on Online Resource 3). The XRF test method analysed different metal elements, from Sodium (Na) to Uranium (U). In this analysis, a portable XRF NITON XL3t spectrometer was used. Each soil and sediment sample was first dehumidified by oven drying (at 105° C) for approximately 2 hours until it keeps constant mass. Samples were then crushed and milled to very small particle size (less than 0.1 mm) in order to homogenize the sample. A subsample was then taken and hydraulically pressed into a compact flat cylinder pellet and subjected to X-Ray Spectrometry (Rwanda Standards Board [RSB] 2020). The test result of the analysed element was expressed in percentage or in ppm with the average of at least three repeated measurements.

Model development and statistical analyses

A multi-step statistical technique and a Bayesian mixing model were used to determine the major sources of suspended sediments. Soils were used to characterize all the potential sources, and suspended sediment samples were utilized as the mixed sample to be unmixed by the mixing model. The Sebeya Catchment was initially conceptualized into 14 sub-catchments and one corridor in development of the model (Fig. 2). This allowed the use of the suspended sediment samples as potential sources to determine the contribution of each sub-catchment to the downstream suspended sediments. One sub-catchment 'Kadobogo' was later removed from the analysis because sediments were collected there only once. All statistical analyses were done in R software (R Core Team 2016). Most of the modelling procedures are described in Stock et al. (2018), with our specific methodology described below. Models were run independently for each possible combination of geologic sources. Models were also run for each combination of sub-catchments present that could be used as potential sources.

Kruskal-Wallis H test was first used to identify tracers that showed significant differences between

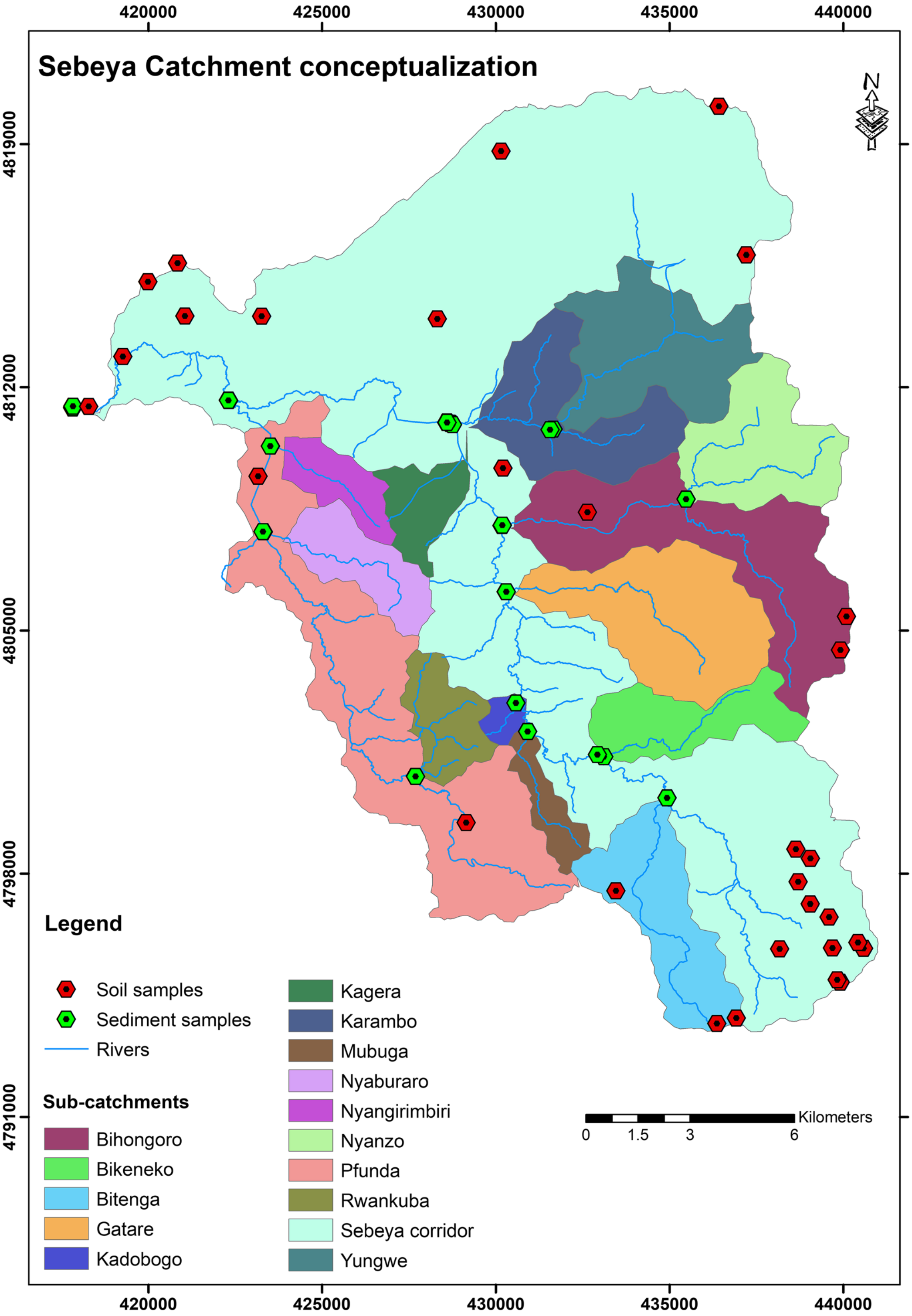


Fig. 2 The conceptualization of Sebeya River Catchment into sub-catchments. The catchment was initially subdivided into one corridor and 14 sub-catchments, but because of only one sediment sampling conducted for the 'Kadobogo sub-catchment', it could not be included in the mixing model. These sub-catchments show the hydrological connectivity, which is of prime importance for sediment fingerprinting analysis. This connection guides the distribution and amount of sediment load in the river, depending on the upstream contribution

source types (kruskal.test function) (Kruskal and 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. Therefore, the *p* value was adjusted up to 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 were ultimately reflected in the greater 95% confidence interval output by the Bayesian mixing model. A stepwise discriminant function analysis based on the minimization of Wilks' lambda was then used to determine which tracers were capable of discriminating between source types (greedy.wilks function in the kla R package and the lda function in the MASS package). A jack-knifed 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 jack-knifed 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 (Bordcard et al. 2011). Parameters identified as useful by the Kruskal-Wallis H test and verified with the discriminant function analysis were then examined to ensure that the tracer values exhibited by the downstream samples were within the range of values presented by the upstream samples.

A mixing model with Bayesian inference (MixSIAR) 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). 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. The MCMC routine was run through a user specified number of iterations and attempts 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. It is advisable to discard the first set of values determined in the MCMC as these may not represent a true convergence of the posterior distribution. This is referred to as 'burn-in'. The model was run for 500,000 iterations with the first 50,000 iterations discarded (burn-in). A uninformative prior distribution was specified in the models. The mixing model assumes that the contribution of the sources adds up to 100%. The means of all potential sources within the model may however 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 over 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. We have not used any correction factor because of the difficulty of applying a general correction factor across several different samples and elements (Pulley et al. 2015).

Understanding the model results

The interpretation of the statistical results was based on the catchment conceptualization in order to track sedimentation from upstream to downstream with control of source location. Sources of sediment usually vary with time due to several reasons; therefore, the analysis was done at sub-catchment level on each individual set of samples as well as over the pool of samples across the three sampling periods. The results yielded the proportion of sediment arising from each geological type within each sub-catchment and are presented in graphical formats.

Box plots were utilized to show the modelling results for each individual suspended sediment sample and composite sample for the all the sampling periods. The box plots indicate the likely geological sources of sediments over the sampling period. These plots provide suspended sediment sources in the river at the time when the sample was taken. The range of each sample in the box plot represents the 95% confidence intervals, and the dot for each source represents the most likely value for that source (mean). The variation in the source of sediment per sample indicates changes in sediment sources over time in a sub-catchment, due to differences in rainfall or human activities. In addition, there is another plotted box plot which indicates the composite result. Note that the composite is not the average of all the sampling periods; it is obtained by pooling together the analytical results of all the samples across the sampling events.

Erosion hotspot map

Building on the results from the mixing model, and sample locations, we produced an erosion hotspot map which shows priority areas to consider for land restoration interventions. The prioritization process starts from upstream sub-catchments to downstream, allowing the identification of sediment sources right at the very beginning of the river drainage. The initial prioritization was as follows: level 1, geological types that contributed 40% or more sediment; level 2, 20–40%; and level 3, 10–20%. Geological types contributing less than 10% were considered having a negligible contribution and were assignedlevel 0. 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 in slow flowing zones, such as river bends, wetlands or flow obstructions, while new sediment comes in. Hence, the sediment composition changes in space and time downstream. 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 downstream, a further prioritization strategy was taken as follows:

a) 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
b) Level 2: geological types that were level 1 in an upstream catchment but decrease in contribution level downstream
c) Level 3: geological types that were level 2 in an upstream catchment and decrease to level 3 or less
d) Level 0: was assigned to geological classes with negligible contribution to the river sedimentation

This process was repeated for results from each downstream sampling point, until the requisite region was covered. It is important to note that areas other than identified as levels 1–3 also may contribute to sedimentation, because of the reduction of vegetation cover. However, areas categorized in levels 1–3 contribute anywhere between 50% and above of the total sediment. In this paper, level 1 is referred to as high contribution, level 2 as medium, level 3 as low and level 0 as very low contribution to the sedimentation of Sebeya River.

Results

Geological contribution to sediment loading in the catchment

The mixing model of the geological types within the entire Sebeya Catchment found that the Ho geological type contributes most of the suspended sediments (Fig. 3). The second highest amount of sediments were coming from either the Bu, B, granites indifférenciés or Nw geological types. The model found with high certainty that the Uw/Cr geological class does not contribute much to suspended sediments at the catchment outlet.

Sub-catchment contribution to sediment loading in the catchment

The mixing model using all the potential sub-catchments had more difficulty in identifying the major sources of suspended sediments. However, the Nyangirimbiri and Karambo appeared to be the larger sources of suspended sediments. Bitenga, Nyaburaro, Bikeneko, Gatare and Bihongoro sub-catchments come in second place in contributing to sediment discharge in Sebeya Catchment. The model showed less contribution from Yungwe, Nyanzo and Rwankuba sub-catchments (Fig. 4).

Erosion hotspots

An erosion hotspot map showing priority areas (levels 1–3) contributing to erosion was generated for Sebeya Catchment (Fig. 5). At this stage, the areas with negligible contribution (level 0) were assigned their land use categories (e.g. forest, agriculture). Figure 5 delineates the small administrative boundaries (cells) covering each erosion priority site. Field verification of the land uses within each level of priority site indicated that generally, level 1 included mining sites and agricultural lands without erosion control measures while level 0 comprised natural forest (e.g. Gishwati National Park) and planted forest (e.g. large plots with *Alnus* spp.). After the ground-truthing of the erosion hotspots (Fig. 5), the areas with negligible contribution were assigned level 0, and a new map was produced showing four levels of erosion hotspots (Fig. 6). Levels 1–3 constitute 'priority sites' for land restoration and cover 70.9% of the total catchment area (Table 2). Level 1 is referred to

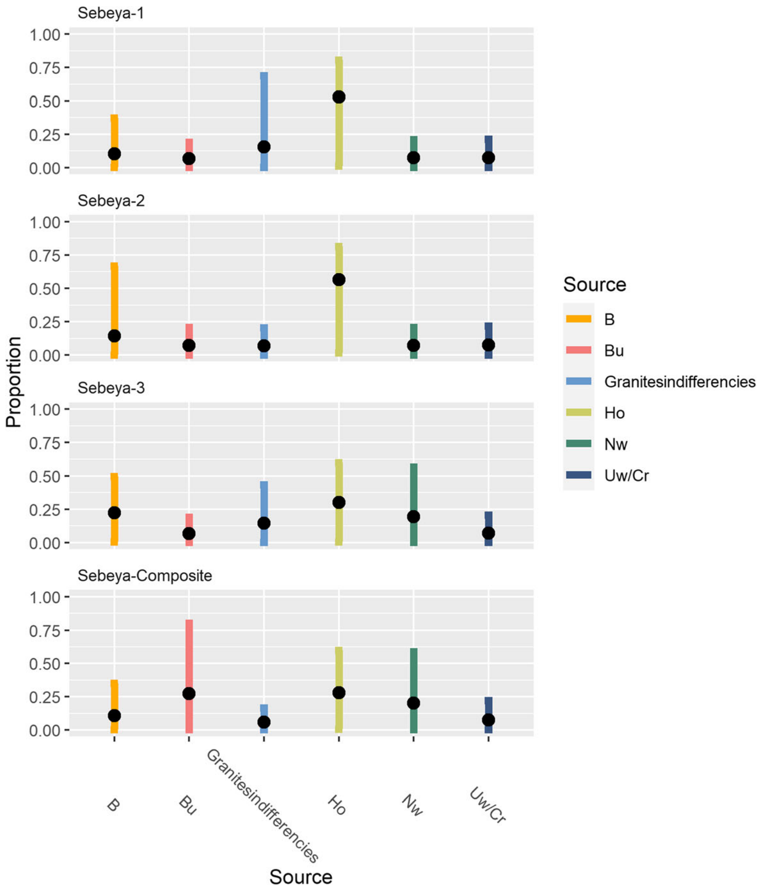


Fig. 3 Mixing model source proportions for all geologic types in the Sebeya Catchment. Dots represent the mean. Coloured boxes represent the 95% confidence intervals. Sebeya 1, 2 and 3 indicates the first, second and third sampling period (campaign)

as 'high contribution', level 2 'medium contribution', level 3 'low contribution' and level 0 'very low contribution' to sediment load in the catchment.

The area covered by different erosion hotspots per district in the Sebeya Catchment is presented in Table 2. The districts of Rutsiro and Ngororero are likely to have the highest to medium contribution to the sedimentation of Sebeya River, while Nyabihu and Rubavu take the low to very low contribution. This ranking considers the district area in the catchment. The districts with high contribution are generally characterized by high average elevation range (see the map on Online Resource 4). For instance, Rubavu district with average low elevation falls under sites with low to very low contribution to sedimentation, while Rutsiro district with the high average elevation comes on the first rank with high to medium contribution. Comparisons of the areas covered by erosion hotspot categories and land use/land cover type showed that 48.6% and 20.9% of agriculture and open land respectively are found in levels 1–3 of erosion hotspots, and hence they form major contributing land uses to the sediment load in Sebeya Catchment (Table 3). However, forest, irrigation and built-up areas have low contribution to sedimentation, with less than 2% area in the priority sites (levels 1–3). The farming land consists of rain fed agriculture; the open land includes the former Gishwati forest area that was converted to grazing (dense grasslands) but there are some remnant forest patches.

Discussion

Geological and sub-catchment contribution to sedimentation levels

Five geological classes (Ho, Bu, Nw, B and granites indifférenciés) had a higher contribution to erosion in Sebeya Catchment than Uw/Cr geology. The geological units represent the parent material which determines soil erodibility and sediment transport in river basins (Feiznia and Nosrati 2007). Previous applications of parent material as an indicator of erosion risk in Rwanda showed that schists had high erosion risk while the quartzite have no erosion risk (MoE 2018). Due to limited available information linking geology to erosion and runoff in catchments of Rwanda, our discussion focuses on the roles of sub-catchments, land use/land cover and topography. Geology is indirectly considered as it determines land use and topography for any landscape (Brion et al. 2011; Riebe et al. 2015).

The Bu geology covers a large area in the catchment, with most farming activities taking place there, while the Ho geology is mostly open land (see Online Resource 5). Each of the five top contributing geologies hosts several mining sites (see Online Resource 6). Where farming and mining are practiced without controlling the movement of soil, land degradation and river sedimentation are enhanced (Maloney and Weller 2011). By the 2050s, the rainfall is predicted to increase up to 20% (Republic of Rwanda [RoR] 2011), and this will affect the soil loss due to erosion, causing further degradation to river catchments in Rwanda (RNRA 2015).

Fig. 5 Map showing the potential erosion hotspots in Sebeya ▶ Catchment. The hotspots contribute at different levels to the sedimentation of the river. At this stage, level 0 areas were attributed their land use and land cover categories. The existing data (locations) of mining sites are overlaid, since these are reputed to contribute to land degradation in the Sebeya landscapes. The administrative boundaries corresponding to each of the erosion hotspots are also shown, allowing a smooth collaboration with local government when on-the-ground interventions for land protection are planned

The mixing model results showed differences in sediment sources per sub-catchment but with great uncertainty. Since the effect of particle size was considered during sediment data collection and laboratory analysis (Smith and Blake 2014), possible reasons for this uncertainty include the small number of sampling periods (three) conducted (Cerdà 2002; Dutton et al. 2013) or the lack of discrimination power between the elements tested within the different geologic types. The model results could have been improved by conducting at least five sampling periods for sediment data and analysing samples for more elements,

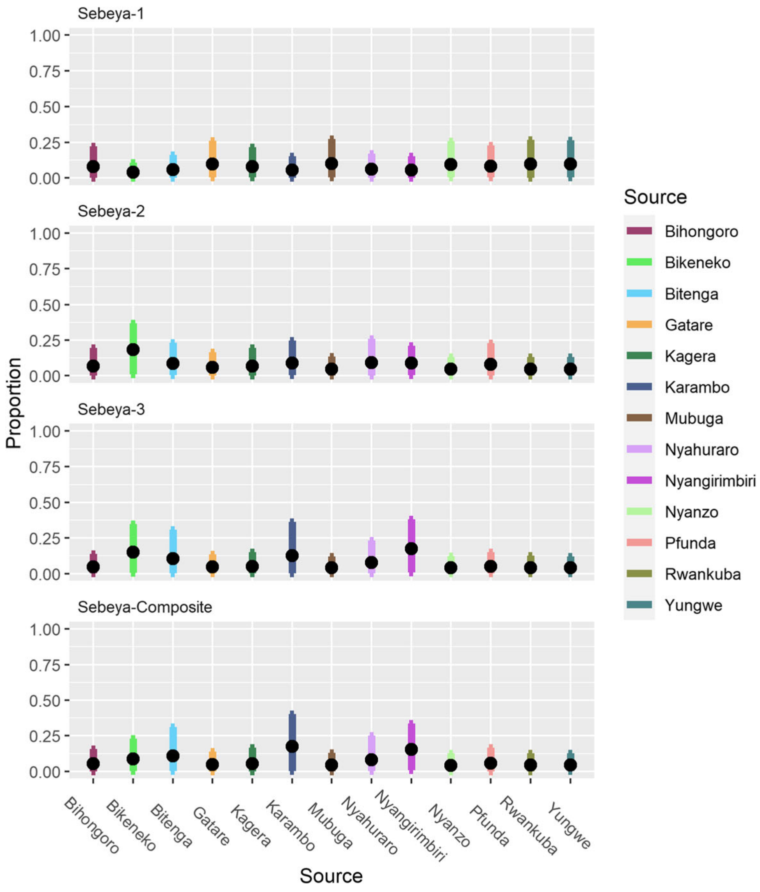
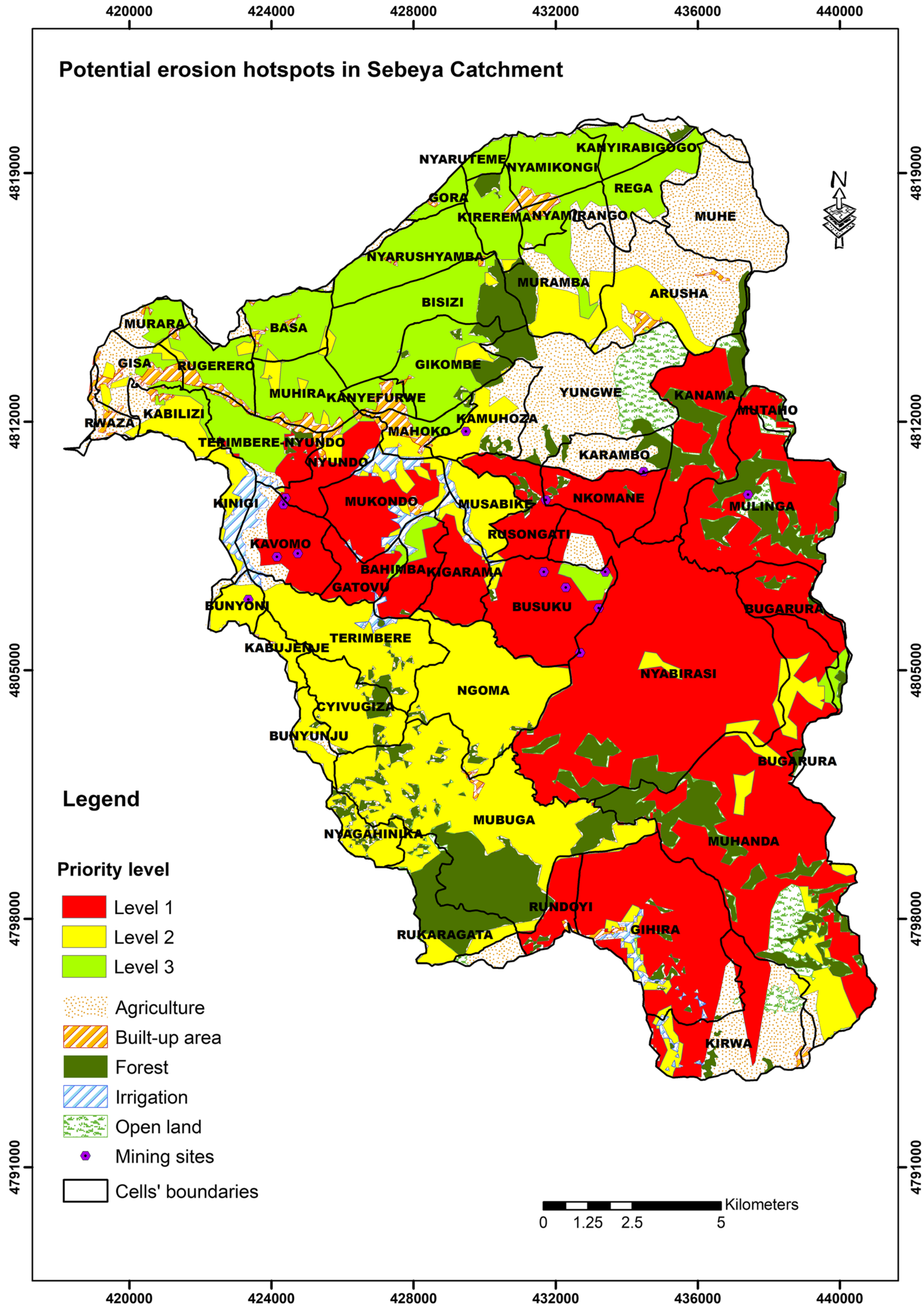


Fig. 4 Mixing model source proportions for all sub-catchments in the Sebeya Catchment. Dots represent the mean. Here, only 13 sub-catchments were considered, excluding Kadobogo sub-catchment where only one sampling was conducted. Coloured boxes represent the 95% confidence intervals. Sebeya 1, 2 and 3 indicates the first, second and third sampling period (campaign). The sub-catchment "Nyaburaro" was misspelt in the used database here, the name is not "Nyahuraro"


Potential erosion hotspots in Sebeya Catchment
420000
424000
428000
432000
436000
440000
4819000
4812000
4805000
4798000
4791000
N
NYARUTEME
KANYIRABIGOGO
NYAMIKONGI
REGA
GORA
KIREREMA
NYAMIRANGO
MUHE
NYARUSHYAMBA
BISIZI
MURAMBA
ARUSHA
MURARA
BASA
GISA
RUGERERO
GIKOMBE
YUNGWE
KANAMA
MUHIRA
KANYEFURWE
MUTAHO
KABILIZI
RWAZA
KAMUHOZA
MAHOKO
TERIMBERE-NYUNDO
NYUNDO
KARAMBO
KINIGI
MUKONDO
MUSABIKE
NKOMANE
MULINGA
RUSONGATI
KAVOMO
BAHIMBA
KIGARAMA
GATOVU
BUSUKU
BUNYONI
BUGARURA
TERIMBERE
KABUJENJE
NYABIRASI
NGOMA
CYIVUGIZA
BUNYUNJU
BUGARURA
Legend
MUBUGA
NYAGAHINIKA
MUHANDA
Priority level
🟥 Level 1
🟨 Level 2
🟩 Level 3
Agriculture
Built-up area
Forest
Irrigation
Open land
● Mining sites
☐ Cells' boundaries
RUNDOYI
RUKARAGATA
GIHIRA
KIRWA
Kilometers
0
1.25
2.5
5

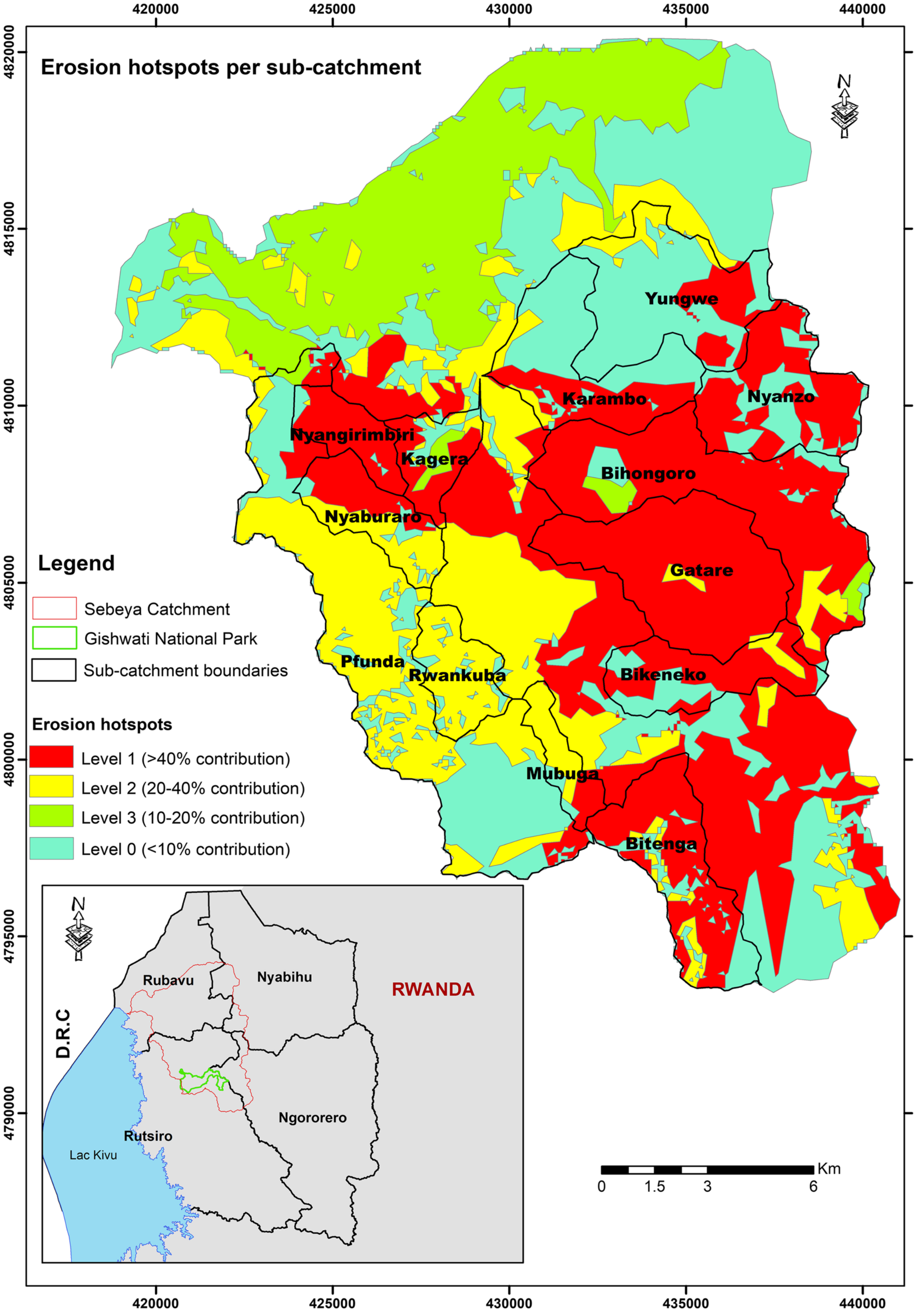


Fig. 6 Erosion hotspots per sub-catchment in Sebeya Catchment. Areas not delineated into sub-catchments are part of the Sebeya corridor. Note that level 0 was created based on the previous map (Fig. 5) where these areas with 'negligible contribution' were assigned their respective land use and land cover types. Level 0 is not a 'priority site' for land rehabilitation, but it still consists of landscapes with minimal contribution to erosion; hence, they constitute an 'erosion hotspot' as well

Table 2 The area in square kilometre (km^2) covered by different erosion hotspots per district composing Sebeya Catchment

District	Area in Sebeya Catchment (km^2)	Area level 1 (km^2)	Area level 2 (km^2)	Area level 3 (km^2)	Area level 0 (km^2)
Ngororero	37.083	22.943	4.625	0.621	8.866
Rutsiro	135.812	59.435	48.339	0.898	27.057
Rubavu	146.247	34.374	15.768	49.959	45.669
Nyabihu	38.108	10.117	3.241	3.144	21.571
Total	357.25	126.869	71.973	54.622	103.163

Level 1–3 sites cover an area of 253.4 km^2 , and they constitute priority sites for land rehabilitation

including minor and trace elements that may be more characteristic of different geologic types within the catchment. The sub-catchments of Nyangirimbiri, Karambo, Bitenga, Nyaburaro, Bikeneko, Gatare and Bihongoro contributed more to the sediment load compared to other sub-catchments (e.g. Pfunda, Nyanzo and Yungwe) in the larger Sebeya River system. Pfunda is the largest sub-catchment of Sebeya with water crossing agricultural lands and some forests, including the Gishwati natural forest. Tea plantations that generally retain sediments and protect the soil from erosion form a considerable part of agricultural land in Pfunda (Ministry of Land, Environment, Forests, Water and Mines [MINITERE] 2007).

More than half of Nyangirimbiri, Karambo, Bitenga, Nyaburaro and Kagera sub-catchments is agricultural land, while more than half of Bihongoro, Gatare and Bikeneko sub-catchment area is open land (see Online Resource 7). Agricultural and open lands are likely to promote higher rates of soil losses and river sedimentation than natural forests (Maloney and Weller 2011). Furthermore, the high slope and the presence of unregulated mining activities also contribute to the higher rates of water runoff and sedimentation during heavy rainfall seasons (Riebe et al. 2015).

Erosion hotspots in Sebeya catchment

The erosion hotspots within levels 1–3 corresponded to geological types contributing more than 50% of the total sediment load in the Sebeya River Catchment. Level 0 was attributed to the landscapes with negligible contribution to the rates of sedimentation, with existing land protection measures and natural or planted forest. Levels 1–3 constitute priority areas for land rehabilitation to reduce the amount of soil loss. Within the priority levels 1–3, additional focus should be given to mining sites and agricultural lands on steep slopes that do not utilize any erosion control techniques. There are current ongoing interventions by governmental and non-governmental organizations for land protection in Sebeya Catchment, but additional support is warranted. Good land stewardship practices should also be promoted with the local communities.

Many of the erosion hotspots are within the steep slopes of North Western Rwanda which are prone to landslides and flooding (MIDIMAR 2015). On these slopes, soil material is washed into the rivers, causing sedimentation. The soil loss on these slopes is likely to be enhanced by slope steepness, rainfall intensity and little to no vegetation cover (REMA 2015). Major areas of intervention to reduce erosion and sedimentation

Table 3 Area covered by erosion hotspots in each category of land use/land cover (LULC). The agriculture, irrigation and open land are considered 'farmlands'

LULC	Total area (km^2)	Area level 1 (km^2)	Area level 2 (km^2)	Area level 3 (km^2)	Area level 0 (km^2)
Agriculture	223.249	58.211	62.275	53.292	48.455
Irrigation	5.532	0.246	0.459	0.025	4.799
Built-up	6.495	0.064	0.231	0.473	5.695
Forest	38.517	1.658	1.214	0.247	35.176
Open land	83.458	66.574	7.727	0.556	8.418

could include increasing vegetation cover on land and the conservation of riparian zones. For example, herbaceous buffer strips have been efficient in reducing the sediment discharge and river siltation in Ethiopia (Alemu et al. 2017), while riparian zones play a key role in water purification (González et al. 2017). These interventions should be preceded with environmental education to encourage behavioural change of local communities and the formulation or enforcement of supportive policies.

The mining sector in Rwanda contributes to the national economy and job creation. However, this sector is dominated by small-scale miners with no capacity for managing mining waste and sites. This results in environmental degradation and river pollution through the washing of sediments directly into the river (Cole and Hogarth 2011). It is important to consider the effect of mining on river pollution as it increases the risk of contamination through leaching of heavy metals such as Copper, Zinc, Aluminium, Manganese, Arsenic, Iron, Nickel, Mercury and Lead, among others (Copaja et al. 2012). Unfortunately, like other developing countries, it has been a challenge to resolve issues surrounding unregulated mining in Rwanda due to the large financial costs needed to enact change, including advanced engineering techniques and change of community behaviour. Cole and Hogarth (2011) proposed several potential interventions including (1) investing in water treatment facilities at mining and processing sites, (2) creating water pollution control dams, (3) reusing contaminated water and (4) putting in place strategies for implementing best practices for water resource protection in mining.

Conclusion

Using a sediment fingerprinting technique, we identified erosion hotspots in Sebeya Catchment that is part of the Lake Kivu Catchment in North Western Rwanda. The procedure is important for finding out which land use practices play a major role in polluting the river and propose actions to improve the river quality. In addition, the culpable sub-catchments, elevation ranges and geologies were deduced, forming a basis for taking measures to mitigate erosion. The areas with active mining, the farming without soil erosion control were found to contribute much, while the forested and protected slopes contributed less to the river sedimentation. It is also important to note that generally, landscapes that were part of high elevation ranges contributed more to river sedimentation compared to those that were part of the low elevation zones. There is a need to focus land management interventions at the root causes of erosion and sedimentation in the catchment and in most affected areas. Particularly, our study avails the erosion hotspots map for Sebeya Catchment (shared as a georeferenced raster map on Online Resource 8). Overall, our model results demonstrated the reality on the ground, but its accuracy could be improved with more sediment sampling and the use of additional minor and trace elements as source tracers. Further studies should explore the impacts of sediment loading in Lake Kivu at the outlet of Sebeya River Catchment and possibly consider focused sampling at the mining, farming and forest sites to enable a direct comparison of their contributions to suspended sediment loads in the catchment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10661-020-08774-5.

Acknowledgements The authors are thankful to the anonymous reviewer who provided constructive remarks and comments that improved the manuscript. We would like to express our deep gratitude to the Rwanda Water and Forestry Authority (RWFA) for sharing the GIS shapefiles on Sebeya Catchment and advising on the sampling design. We extend our special thanks to the local governments and communities in the targeted districts for their collaboration and permission to undertake the sampling campaign. Much thanks to the two field assistants Thaulin Dushimiyimana and Josine Tuyishime for being passionate about the tough fieldwork in rugged terrain. We appreciate the efforts by the Rwanda Standards Board (RSB) for the laboratory analysis of soil and sediment samples and delivering results on time and in the desired format.

Funding This work was supported by the Nature Conservancy (grant # F103871-BirdLife_010718) and the John D. and Catherine T. MacArthur Foundation through its fund to ‘Building climate change resilience for local communities in the Lake Kivu and Rusizi River Basins’ project (grant # G-1609-151208).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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