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ESTIMATION OF SOIL EROSION RISK, ITS VALUATION AND ECONOMIC IMPLICATIONS FOR AGRICULTURAL PRODUCTION IN WESTERN PART OF RWANDA

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ABSTRACT

Multifunctional soil conservation strategies have the capacity to control soil erosion as well as increase its quality, thus leading to sustained yields as long as planners have knowledge on the severity of soil loss. A comprehensive methodology that integrates Revised Universal Soil Loss Equation (RUSLE) model and Geographic Information System (GIS) techniques was adopted to determine the soil erosion vulnerability within Katabuvuga, Nyamyumba and Mukamira watersheds in western part of Rwanda, with the aim of supporting planning of land and water management interventions. The dominant slop class in all watershed was 16-40% covering 50% in Katabuvuga watershed, 43% in Mukamira watershed and 70.6% in Nyamyumba watershed. High erosion risk was recorded in Mukamira (72 %) and it was followed by Nyamyumba (46 %). The average soil loss in selected watersheds was 32t/ha/year. Among the various studied watershed, highest average loss was reported in Nyamyumba watershed (37t/ha/year) while the lowest average was in Mukamira watershed (28t/ha/year). Soil loss was higher in cropland and lower in settlement. The average loss of nutrients was 1705 kg/ha/year of carbon, 155 kg/ha/year of nitrogen, 3 kg/ha/year of phosphorus and 111 kg/ha/year of potassium, the highest nutrient loss occurred in cropland. Based on the cost of NPK the average value of N lost per ha per year is 167507 Rwandan Francs (Rwf) while the value of P and K loss per ha per year is 3309 Rwf and 120189 Rwf respectively.

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The study shows that soil loss in studied watershed is high therefore compelling the appropriate soil conservation measures in order to make agricultural productivity sustainable. The spatial erosion risk maps generated with RUSLE method and GIS can serve as effective inputs for land use planning and management in the environmentally sensitive mountainous areas such as West Rwanda.

1 Introduction

Land degradation especially by water accelerated soil erosion is a serious problem on agricultural land in several regions of developing countries (Anderson & Thampapillai, 1990; Dregne, 1990; Lal, 1993). Soil erosion, an irregular rainfall pattern, poor soils and eroded steep slopes have further aggravated the low productivity levels. Because of its adverse agronomic, environmental, social and economic effects, it has attracted considerable attention from scientists and development agencies around the world (Amsalu, 2006). Soil erosion is often associated with deterioration or loss of water resources and may well be the most serious and least reversible form of land degradation in tropical environments (El-Swaify et al., 1985). Soil erosion is a risk associated with agriculture in tropical areas and is important for its long-term effects on soil productivity and sustainable agriculture. Erosion also leads to environmental damage through sedimentation, pollution and increased flooding. The costs associated with the movement and deposition of sediment in the landscape frequently outweighs those arising from the long-term loss of soil in eroding fields (Morgan & Duzant, 2008).

In Rwanda, many parts of the country are mountainous with steep slopes, which allow soil run-off and, hence, contribute to soil erosion. Further, land degradation in Rwanda negatively affects the agriculture sector and consequently, the latter is failing to meet the demands of a rapidly growing population. According to the Stockholm Environment Institute (2009), soil erosion in Rwanda results in a loss of 1.4 million tons of soil per year, equivalent to an economic loss of US \$ 34,320,000, or almost 2% of GDP. In fact, land degradation has provided the challenge of achieving economic and sustainable use of natural resource under the pressure of high population density and consequently raising food insecurity for Rwanda (Bidogeza et al., 2015).

Indeed, Agriculture sector contributes approximately 31% of the national GDP of Rwanda and more than 80% of the Rwandan population depends on agriculture sector (NISR, 2015). Recently, agriculture sector grew by 4 percent and contributed to 1.3 percentage points to the overall GDP growth (NISR, 2015). Subsistence farming is the dominant agricultural activity where

the average farm size is not exceeding than 0.6 ha, on which farmers cultivate only food crops for self-consumption. At the same time, the per capita size of agricultural fields in Rwanda has diminished dramatically in the last 3 decades (Bidogeza et al., 2009). This is one of the densely populated countries in Africa with over 11 million inhabitants at area of 26,338 km² and its population is projected to rise around 16 million by 2020. This is likely contributing to an intense pressure on degradation of natural resources especially land and water. Productivity decline resulting from excessive soil loss occurs everywhere (Roose & Ndayizigiye, 1997) and it is particularly more acute in the highlands of Rwanda (Roose & Ndayizigiye, 1997; Steiner & Drechsel, 1998; Kagabo et al., 2013; Nzeyimana et al., 2017).

Mitigating these effects and improving soil productivity is required by adopting the erosion control techniques. This is one of the crosscutting factors that are subjected to support productive high value and market oriented agriculture toward national priority in Rwanda's Vision 2020. Experts have addressed the erosion question by arguing for the implementation of soil and water conservation strategies that range from 'biological' or 'vegetative' methods to 'physical' or mechanical methods, such as terraces (De Graaff, 1996; Hurni et al., 2008).

However, estimation of the erosion costs is essential since it can be used to prioritize implementation of soil and water conservation, and economic analysis of alternative conservation technologies can be used to identify courses of action that efficiently employ available resources (Clark, 1996). What would it cost to prevent, reduce or mitigate the on- and offsite effects of soil erosion? There are hardly publications available, especially for Rwanda that give a precise answer to this question or an estimate or indication or allow a calculation of the costs involved in preventive action, such as the application of soil erosion control measures by individual farmers.

This study aims to estimate and mapping the potential soil erosion risk using RUSLE model for the three erosion hot-spot watersheds of the Western Part of Rwanda and provide valuable, effective and efficient soil and water conservation strategies to mitigate the problems of land degradation.

particular field with a specific crop and management system to "tolerable soil loss" rates. Alternative management and crop systems may also be evaluated to determine the adequacy of conservation measures in farm planning. Five major factors are used to calculate the soil loss for a given site. Each factor is the numerical estimate of a specific condition that affects the severity of soil erosion at a particular location. The erosion values reflected by these factors can

vary considerably due to varying weather conditions. Therefore, the values obtained from the USLE more accurately represent long-term averages. This equation calculates the average annual soil loss of a point on the earth's surface by combining the effects of rainfall-runoff, soil erodibility, the topography, cover-management factor (Figure 2), and the practice factor. The RUSLE equation is defined as follows:

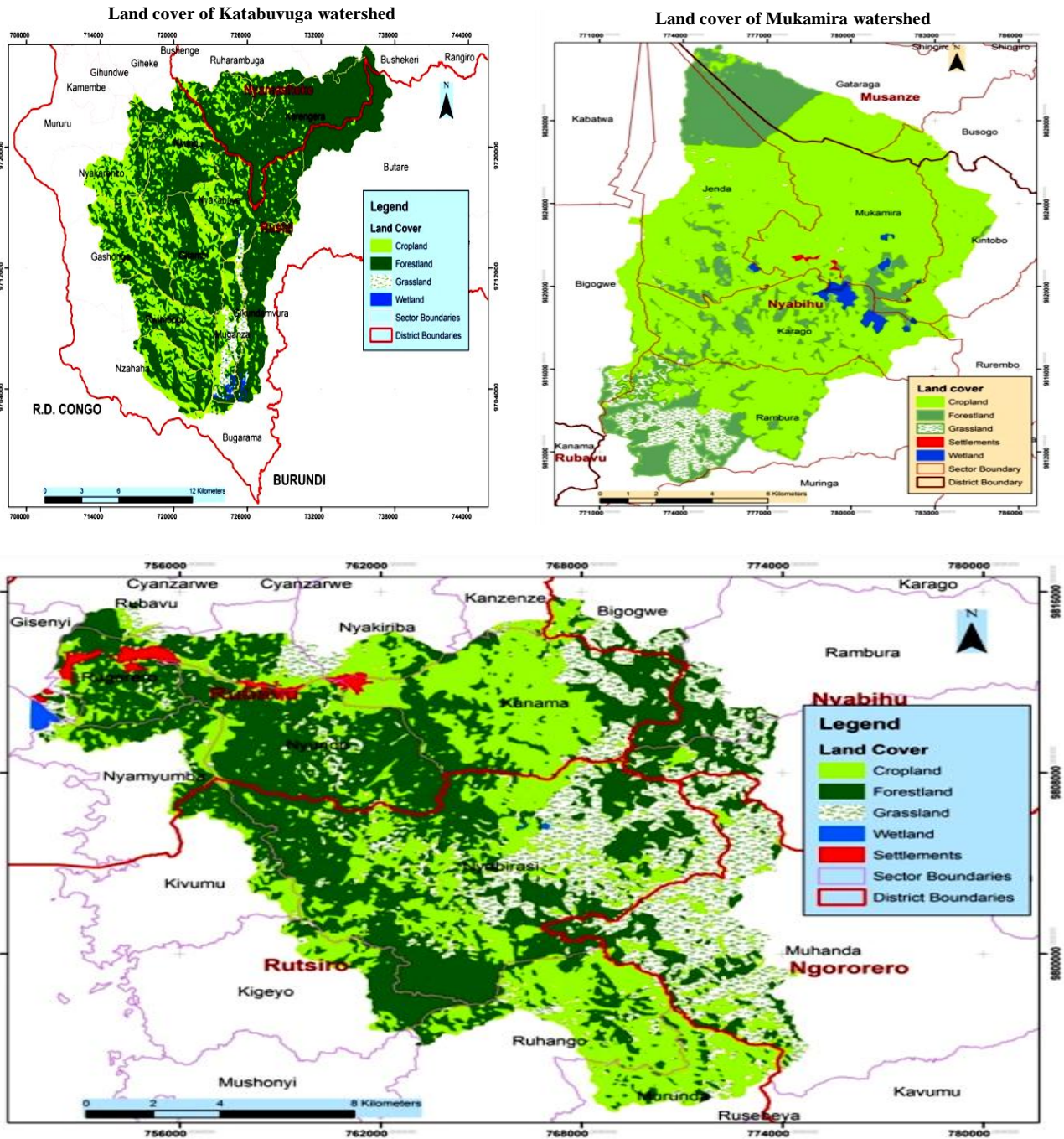


Figure 2 Land cover maps for selected watersheds

$$A = R K (LS) C P$$

Where: A is the average annual soil loss in tn/ha/yr, R is the rainfall-runoff factor ($\text{MJ mm ha}^{-1}\text{hr}^{-1}\text{yr}^{-1}$), K is the soil erodibility factor ($\text{tn} \cdot \text{ha} \cdot \text{hr} \cdot \text{ha}^{-1} \cdot \text{MJ}^{-1} \cdot \text{mm}^{-1}$), LS is the topographic factor, C is the cover-management factor and P is the support practice factor.

2.3.1 R factor

R factor was calculated using the following formula:

$$R = 47.5 + 0.38 * P$$

Where,

R=rain erosivity (joules m^{-2}); P=annual rainfall (mm year^{-1}).

2.3.2 The topographic factor

The L and S factors represent the effects of slope length (L) and slope steepness (S) on the erosion of a slope. The combination of the two factors is commonly called the "topographic factor." The L factor is the ratio of the actual horizontal slope length to the experimentally measured slope length of 22.1m. The S factor is the ratio of the actual slope to an experimental slope of 9%. The L and S factors are designed such that they are one when the actual slope length is 22.1 and the actual slope is 9%. Accurately calculating the LS factor turns out to be something of an art. It requires that the user pay close attention to gathering good empirical data about the landscape and choosing an appropriate method of calculating LS (of which there are many). Readers might be interested in reading which provides a very high level overview of the common problem of miscalculating the topographic factor from DEMs in GIS software. The topographic factor was calculated using the following formula

$$LS = (\text{Flow accumulation} \times \text{Cell size}/22.13)^{0.4} \times (\sin \text{slope}/0.0896)^{1.3}$$

2.3.3 K factor

K is the soil erodibility factor and it is the average soil loss in tons/hectare (tons/acre) for a particular soil in cultivated, continuous fallow with an arbitrarily selected slope length of 22.13 m (72.6 ft) and slope steepness of 9%. K is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. Texture is the principal factor affecting K, but structure, organic matter and permeability also contribute. **K factor** was calculated using the following formula:

$$K = \left(0.2 + 0.3e^{(-0.0256SAN(1 - \frac{SIL}{100}))} \right) \times \left(\frac{SIL}{CLA + SIL} \right)^{0.3} \times \left[1 - \frac{0.25C'}{C' + e^{(3.72 - 2.95C')}} \right] \times \left[1 - \frac{0.7SN_1}{SN_1 + e^{(22.9SN_1 - 5.51)}} \right]$$

Where SAN is the sand content %, SIL is the silt content %, CLA is the clay content %, C' is the soil organic carbon content % and

$$SN_1 = 1 - SAN/100.$$

2.3.4 C factor

C is the crop/vegetation and management factor. It is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss. The C factor is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land. The main land use types and respective C values considered in this study are: Cropland (0.5), forestland (0.01), grassland (0.1) and settlement (0.001).

2.3.5 P factor

P is the support practice factor. It reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. The P factor represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. The most commonly used supporting cropland practices are cross-slope cultivation, contour farming

and strip cropping. **P values** was estimated at 0.6 considering that in the area at least farmer practice contour cropping system. Slope classes considered were i) Low (0-2t/ha/year), ii) Moderate (2-9t/ha/year) and High (>9t/ha/year).

2.4 Soil erosion valuation

The method used to value the effect of erosion was replacement cost as it is described in Clark (1996). This is based on the cost of replacing lost soil nutrients with synthetic fertilizers; it may also include the cost of physically returning eroded sediment to the land. Soil loss valuation was based on the cost of replenishment of soil nutrients washed away according to the N, P and K content in the soil. Rwanda soil map database was used to identify soil profiles and their respective nutrients content which were characterized in the watershed. The average N, P and K content was used to estimate the amount which will be washed away in accordance to the amount of soil loss in the watershed. The summary of nutrients content is in table 1, Nyamyumba watershed has higher nutrients content compared to other watershed while Mukamira has lower nutrients contents.

Table 1 Average nutrients content in respective watersheds

Watershed	C (%)	N (%)	P (Ppm)	K (cmol/kg)
Katabuvuga	5.784	0.586	16.011	1.258
Mukamira	1.880	0.172	7.630	0.220
Nyamyumba	7.556	0.652	7.000	1.163

Source: Rwanda soil map database developed between 1981 and 1994 through the cooperation of the Rwandan Ministry of Agriculture, Livestock and Forestry and the Belgian government in order to develop a national soil map of Rwanda.

3 Results

3.1 Slopes classes

The dominant slop class reported in all watersheds is between 16-40%, covering 50% in Katabuvuga watershed, 43% in Mukamira

watershed and 70.6% in Nyamyumba watershed. In Katabuvuga watershed slop classes of 0-6%, 6-16%, 40-60%, and above 60% cover 6.2%, 16.9%, 19.3%, and 8.1%, respectively. In Mukamira and Nyamyumba watersheds, slope class of 40-60% covers 20% and 26% respectively. Spatial distribution of slopes in each watershed is summarized in figure 3.

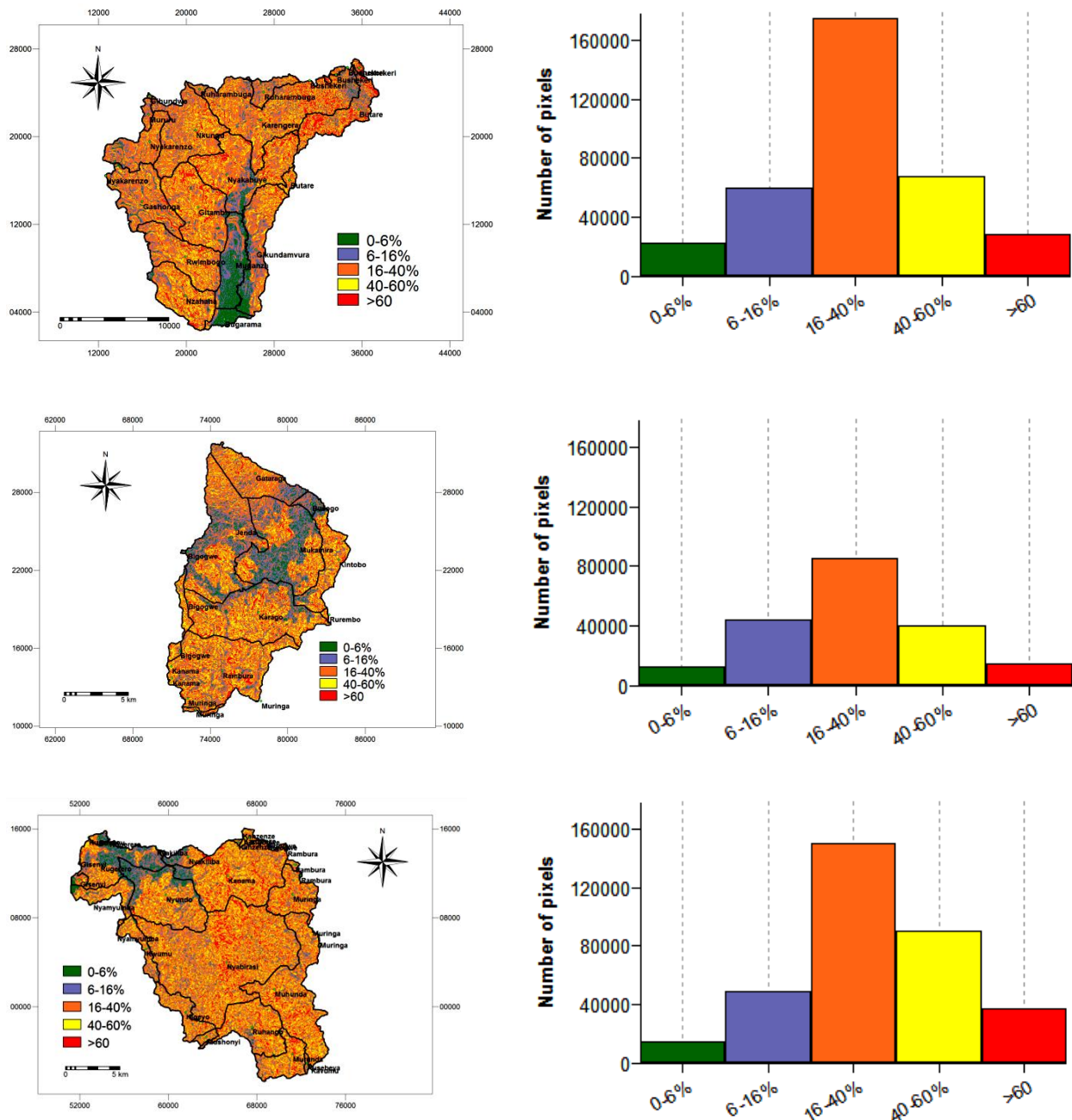


Figure 3 Slope Classes and corresponding histogram of Katabuvuga (A), Mukamira (B) and Nyamyumba (C) watersheds

3.2 Soil loss

The figure 4 shows maps of soil loss by watershed in absolute values. Nyamyumba watershed had more pixels experiencing loss

of 200t/ha/year or more than this while Katabuvuga watershed had relatively less number of pixels experiencing loss of 200t/ha/year or more.

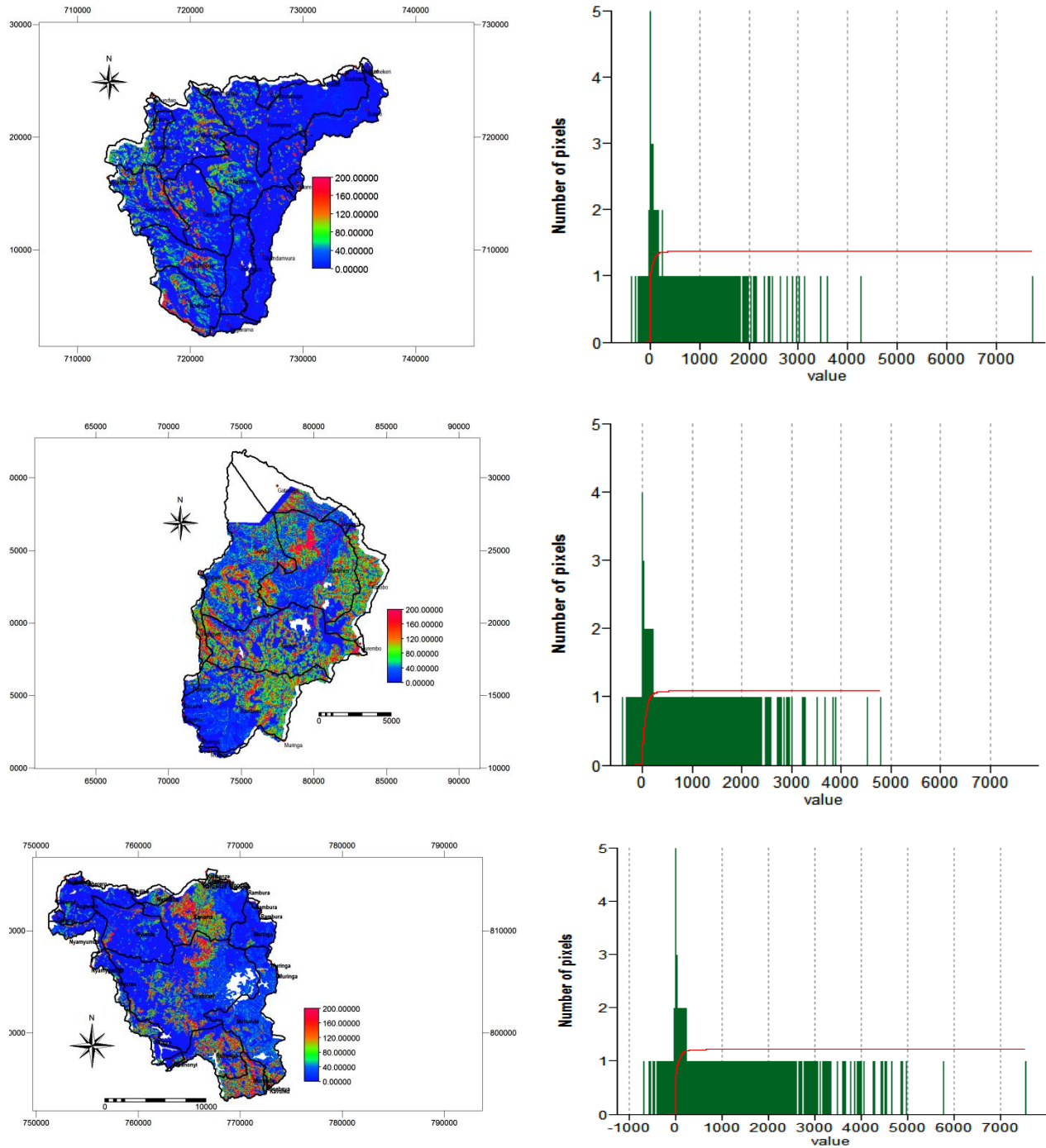


Figure 4 Soil loss in respective watersheds in absolute values Katabuvuga (A), Mukamira (B) and Nyamyumba (C) watersheds

3.3 Erosion risk maps

The erosion risk map (Figure 5) of Katabuvuga demonstrated that the largest part of it lies in low erosion risk and almost equal portion of Moderate and High. Majority of the land at Mukamira

is at the high erosion risk level (72%) and it was followed by moderate risk (16%). The majority Nyamyumba watershed has high erosion risk (46%), highlighting the urgency of the erosion issue in the area.

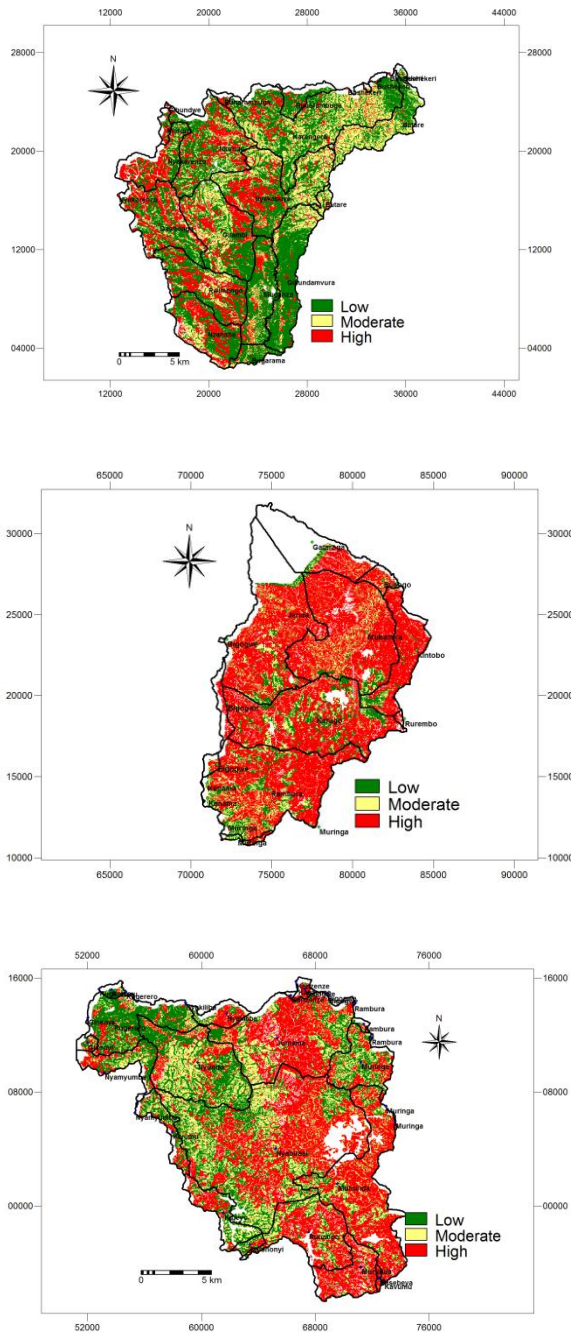


Figure 5 Erosion Risk Maps and corresponding histogram of Katabuvuga (A), Mukamira (B) and Nyamyumba (C) watersheds

3.4 Soil loss by land use and corresponding nutrients losses

The average soil loss (Table 2) in selected watersheds is 32t/ha/year the highest average loss occurring in Nyamyumba watershed (37t/ha/year) and the lowest average being in Mukamira watershed (28t/ha/year). Soil loss is higher in cropland and lower in settlement but the loss in forestland is also minimized. The average loss of nutrients is 1705C kg/ha/year, 155N kg/ha/year, 3P kg/ha/year and 111K kg/ha/year the highest

nutrient loss occurring in cropland.

3.5 Value in Rwandan francs of lost N, P and K nutrients (1\$=750 Rwf)

Considering that the NPK 17:17:17 cost 555Rwf/kg, the average value of N lost per ha per year (Table 3) is 167507Rwf while the value of P and K loss per ha per year is 3309Rwf and 120189Rwf respectively.

Table 2 Soil loss by land use and corresponding nutrients losses

Watershed	Land use	Soil loss (t/ha/y)	C_Loss (kg/ha/y)	N_Loss (kg/ha/y)	P_loss (kg/ha/y)	K_Loss (kg/ha/y)
Katabuvuga	Cropland	84.10 ^c	4864.62	493.13	13.47	412.62
	Forestland	2.50 ^f	144.51	14.65	0.40	12.26
	Grassland	4.67 ^f	269.84	27.35	0.75	22.89
Mukamira	Cropland	92.45 ^b	1738.00	159.01	7.05	79.32
	Forestland	2.17 ^f	40.74	3.73	0.17	1.86
	Grassland	18.54 ^{de}	348.46	31.88	1.41	15.90
	Settlement	0.08 ^f	1.42	0.13	0.01	0.06
Nyamyumba	Cropland	124.72 ^a	9423.42	813.19	8.73	565.86
	Forestland	2.48 ^f	187.20	16.15	0.17	11.24
	Grassland	22.78 ^d	1721.37	148.54	1.59	103.37
	Settlement	0.23	17.34	1.50	0.02	1.04
Average		32	1705	155	3	111

Mean value followed by the different letter in same vertical column are significantly different

Table 3 Value in Rwandan francs of lost N, P and K nutrients

Watershed	Land use	N_Value (Rwf/ha/y)	P_Value (Rwf/ha/y)	K_Value (Rwf/ha/y)
Katabuvuga	Cropland	531595	14516	444805
	Forestland	15792	431	13213
	Grassland	29488	805	24673
Mukamira	Cropland	171411	7604	85506
	Forestland	4018	178	2004
	Grassland	34367	1525	17144
	Settlement	140	6	70
Nyamyumba	Cropland	876615	9412	610000
	Forestland	17414	187	12118
	Grassland	160131	1719	111428
	Settlement	1613	17	1122
Average		167507	3309	120189

4 Discussion

Bibliographic studies show that, in Rwanda, an extraordinary effort has been dedicated for erosion control from 1937 though infrastructures were abandoned and some destroyed later in 1962. The Government of Rwanda initiated several national programs of soil erosion control since 1966 however erosion threats are still observed in the farmers' fields, which may be an evidence of low adoption or/and their capacity to maintain soil erosion control infrastructures.

The average of soil loss obtained in this study is 32t/ha/year which is closer to the results of Kagabo et al. (2013) who observed soil loss of 41.5 t/ha/year in his study of soil erosion, soil fertility and crop yield on slow-forming terraces in the highlands of Buberuka in Rwanda. Results of study are also in agreement with Tamene & Le (2015) findings on soil erosion in sub-Saharan Africa, these researchers reported that soil loss ranged from 25-75t/ha/year. However the results are far less than the results obtained by Karamage et al. (2016) who observed the average soil loss of 250 t/ha/year in his study on extent of cropland and related soil erosion risk in Rwanda and 490 t/ha/year in his study of usle-based assessment of soil erosion by water in the Nyabarongo River Catchment, Rwanda. Comparing findings of Karamage et al. (2016), with finding of this study and other soil loss estimation studies in Rwanda and in the region make his results suspected to be overestimated.

Soil loss occurred more in cropland in all watershed and less in other form of land use though in Mukamira and Nyamyumba erosion loss in grassland was also high compared to Katabuvuga watershed. Soils of Mukamira and Nyamyumba are volcanic thus fragile in structure and most of the time subjected to landslides reason why in grassland soil loss was higher compared to Katabuvuga watershed. The research conducted by Sun et al. (2014) highlighted that soil loss is correlated to land cover because of provision of canopy cover where forestlands provide 30% canopy cover while grasslands provide 50% thus less vulnerable to soil erosion caused by water. It has been discussed that economic development coupled with increasing population drive land use changes mostly land use conversion into cropland (Wasige et al., 2013). This will increase soil loss as with the results of this study soil loss is higher in cropland than in any other land use settings. Furthermore with the population increase people began settling in marginal areas such as on steep hill slopes, poor soils, high altitude regions and pasture areas making the land more vulnerable to water erosion.

The results of this study show that soil erosion is seriously taking place in Rwanda. Although a widespread problem in east and central Africa, soil erosion reaches an extreme in Rwanda due to its steep topography, natural soil susceptibility to

erosion and leaching and climatic conditions. This poses a threat to the farm for the future initiatives aiming at promoting the environmental, economic, and social well-being of farms for sustainable food system. The study highlights that the implications of soil erosion extend beyond the removal of topsoil. Like it has been discussed in several studies the impacts of land degradation and the depletion of soil resources have reflective economic implications especially in developing countries. In addition to this, heavily degraded soils are unable to support a large plant biomass because of depleted soil nutrients and soil organic matter the important element for maintaining soil structure and maximizing nutrient retention.

The government of Rwanda through ministry of agriculture has launched a crop intensification program (CIP) in September 2007 as a flagship that aims to increase agricultural productivity in high potential food crops and ensure food security and self-sufficiency. The program strategies to boost agricultural productivity include the improvement of productive inputs use, irrigation and rainwater use efficiency and soil quality. With the results of this study the considerable amount of nutrients are washed away by erosion hence challenging the program to achieve the expected potential increase in yield. This study suggests the consideration of soil erosion control measures for all government plans to increase agricultural productivity through intensification and commercialization.

There is tendency to give attention to soil erosion only when a visible portion of land is detached or landslides. However even when a smallest particle of soil is washed away it carries the value in it. As it has been discussed by Telles et al. (2013) the impacts of soil erosion can be evaluated either in crop production reduction cost or the soil change in its physical, chemical and biological characteristics which will further results in gradual drop in its potential productivity. From this respect there will be a cost for replenishing soil fertility by application of mineral synthetic fertilizers however the biological point of view will not be taken care off.

Major investment is, therefore, needed to improve land management and promote an integrated conservation sustainable agriculture approach to ensure household food security and achieve pro-poor, environmentally support effective poverty reduction and therefore contribute to national sustainable development. Results of Nzeyimana et al. (2017) suggest the use of mulch as one of method to control soil erosion which is a triple win approach. First it increase soil stability through increased resistance to soil detachment as a result of humic acid accumulation from organic matter mineralization, secondly it protect soil from direct raindrops which causes soil detachment and thirdly the improvement of soil fertility through residues decomposition by soil micro organisms. However the effect of

mulch on soil properties is site specific depending mainly on temperature and rainfall or soil moisture regimes which are major factors in organic matter decomposition.

Conclusion and recommendations

The study has revealed that erosion is seriously taking place in respective study watersheds of western Rwanda. Nyamyumba watershed had more pixels experiencing loss of soil while Katabuvuga watershed had relatively less. The steep topography and climatic conditions coupled with continuous cultivation magnify soil erosion in Rwanda especially in western part. The average soil loss in selected watersheds is 32t/ha/year the highest average loss occurring in Nyamyumba watershed (37t/ha/year) and the lowest average being in Mukamira watershed (28t/ha/year). The average value of N lost per ha per year is 167507Rwf while the value of P and K loss per ha per year is 3309Rwf and 120189Rwf respectively. This study suggests the consideration of soil erosion control measures for all government plans to increase agricultural productivity through intensification and commercialization.

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