

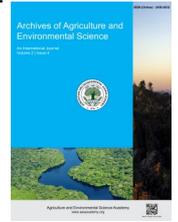


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ORIGINAL RESEARCH ARTICLE



Soil loss estimation and mapping of water erosion management strategies in the Northern region of Rwanda

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ABSTRACT

This study was conducted in Gakenke, Musanze and Rulindo districts in northern province of Rwanda from December 2019 to October 2021 to determine Soil and Water Conservation (SWC) status, mapping soil erosion areas, annual estimation of soil loss and spatial distribution in northern Rwanda. The study used Revised Universal Soil Loss Equation (RUSLE) model based on erosivity index, erodibility of soil, slope steepness, slope distance, vegetation covers and conservation practice parameters generated through arc GIS. The utilized data included the Digital Elevation Model (DEM) for production of slope steepness. Landsat 8 have been processed in ERDAS Imagine 2014 for land use and land cover. Field data for conservation practice factor and rainfall data for soil erosivity in Google Earth Pro and ArcGIS respectively have been produced. The results indicated that the forest was identified as the largest area covering of 84.08% followed by built up areas with 10.43%, radical terraces account for 4.45 %, bare soil (3.23%), agroforestry (0.77%), waterbodies (0.727%), riverbanks (0.38%), and wetland (0.35%). The average rate of water erosion was discovered as 72 t. ha⁻¹. y⁻¹ and observed that soil erosion is more severe in steep areas than in other places. Inadequate erosion control management results as the cause of spatial distribution of erosion. Thus, it is advisable to prioritize soil and water management practices in steep and mid-elevation unprotected areas before applying them to lower elevations.

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INTRODUCTION

Rwanda is one of smallest but highest population density in Africa where 70 % of Rwandan population lives in rural area and mostly depend on rained Agriculture and exerting pressure on natural resources and population are expected to be doubled in 2052 (SIDA, 2024). Soils and water are the peak valuable natural resources and are both susceptible to erosion brought on by both natural and human activities (Majoro *et al.*, 2020). Soil erosion rate lies between 50 to 100 tons per hectares per annum. Gakenke indicated 33 tones/ha/year of soil loss and

represented as highest erosion risk area at 71 % followed by Rulindo at 68 % and least area is Burera at 56 % followed by Musanze at 37 % as highest soil loss (RWB & IUCN, 2022). There is a growing concern over the rapid degradation of soil and water resources This is mainly due to the lack of adequate identification and evaluation of degradation processes and the relationships between causes and effects (Sentis, 2010). Data on soil erosion rates are key to develop sustainable soil conservation and management plans and to assess environmental implications and research has indicated that degradation of soil and land is main cause counter to agricultural sustainability

(Arega et al., 2024). Land degradation is one of the main challenges for Rwandan agricultural development and has recently caught the attention of many researchers (Bizoza, 2011; Bizimana, 2018; Murindangabo et al., 2021). A combination of topographic features, poor farming practices on these slopes and recent change in weather patterns and climate, have been reported as major causes of poor soil fertility and land productivity as a whole (Nambajimana et al., 2020). As Rwanda experienced an acceleration in soil erosion, Estimation of annual soil losses are necessary to take mitigation measures. Revised Universal Soil Loss Equation (RUSLE) model using Geographical Information System (GIS) and remote sensing (RS) can be used to estimate soil loss (Luvai et al., 2022). This model was used by Byizigiro et al. (2020) to estimate soil loss in satinsyi catchment area in Ngororero District and model was also used for soil loss estimation in western province (Niyo, 2023). This study was achieved by mapping soil and water resources conservation techniques in the field of research and evaluating the annual soil loss as a result of water erosion. Recognizing and mapping the present physical soil and water conservation (SWC) technologies is key to decide the specific conservation measures and their effectiveness against land degradation and soil erosion (Amera, 2017). This study can help farmers improve working methods for soil and water resources conservation and agricultural production. Moreover, it can also serve as a guide for relevant institutions to make appropriate decisions during watershed protection. The main objective of this study were to map and quantify erosion rates caused by rainfall and evaluate implemented soil and water conservation measures to mitigate erosion hazard in Rulindo, Gakenke and Musanze districts of northern province Rwanda.

MATERIALS AND METHODS

Study area is located in Northern Province, district of Rulindo, Gakenke, and Musanze of Rwanda (Figure 1). These districts are characterized with high precipitation, steep slope and generally having similar environmental conditions. The rainfall stations are also shown in Figure 2. The utilized data contains the Digital Elevation Model (DEM) obtained from the website of the Regional Center for Mapping Resources for Development (RCMRD); satellite image downloaded from the United States Geological Survey (USGS) website; soil data provided by the Ministry of Agriculture in Rwanda (MINAGRI) as well as the FAO Digital Soil Map of the World (DSMW) and rainfall data collected from the Rwanda Meteorology Center (Table 1). During data processing, Erdas Imagine 2014, ArcGIS 2015, Google Earth Pro as well as Microsoft office have been used. Using Supervised Classification, LANDSAT 8 image was processed and analyzed for Soil and water conservation techniques mapping in ERDAS Imagine software (Table 2). Revised universal soil loss equation erosion model has been used for soil loss calculation and is globally accepted with five influences (Suhara et al., 2023). Again RUSLE is the methodology mostly used for assessing sheet and rill erosion as part of various field land management practices (Benavidez et al., 2018). An empirical and used multi-

ple-regression equation that includes the factors influencing erosion is expressed as follows:

$$A = R * K * L * S * C * P \quad (1)$$

The RUSLE model computes soil erosion (A) centered on different factors. R symbolizes the effect of rainfall intensity, K means the soil's susceptibility to erosion, LS combines the effects of slope length and steepness, C stands for vegetation or land cover and P reflects in place conservation measures. Together, these components represent how both natural conditions and land management impact soil erosion. Erosion occurs when rainfall erosivity surpasses soil erodibility (Shiferaw, 2011). Erosivity (R) factor was determined by the rainfall's ability to displace soil particles (erosivity) and the soil's resistance to raindrop impact (erodibility). Empirical equation to calculate R factor of each station before being extrapolated at the whole landscape was used in the ArcGIS tools and saved in a raster format (Kabirigi et al., 2017). Erodibility (K) factor is the ability of the soil to resist particle detachment and transport by erosive forces. K factor was calculated using Williams (1995) equation and FAO soil using the following equation:

$$KUSLE = Kw * Fcsand * Fcl-si * Forge * Fhisand \quad (2)$$

In the of erodibility framework, Fcsand normally states to the coarser sand fraction in the composition of soil.

The soil erosion coefficient (K) is adjusted based on FCSAND, FCL-SI, FORGC and FHSAND factor soil characteristics. FCSAND reduces K in the soil with high sand content, and the FCL-SI reduces the K of the soil with high clay and compression ratios. Forge decreases the soil erodibility factor (K) in soils that are rich in organic carbon, and similarly, K is also reduced in soils with high sand content.

These above mentioned soil erodibility factors were calculated using a following equation (3-6):

$$Fcsand = (0.2 + 0.3 \cdot \exp(-0.256 \cdot ms \cdot (1 - \frac{msilt}{100}))) \quad (3)$$

$$Fcl-si = \left(\frac{msilt}{mc + msilt} \right)^{0.3} \quad (4)$$

$$Forge = \left(1 - \frac{0.25 \cdot orgC}{orgC + \exp(3.72 - 2.95 \cdot orgC)} \right) \quad (5)$$

$$Fhisand = \left(1 - \frac{0.7 \cdot (1 - \frac{ms}{100})}{\left(1 - \frac{ms}{100} \right) + \exp(-5.51 + 22.9 \cdot (1 - (1 - \frac{ms}{100})))} \right) \quad (6)$$

In the equations mentioned, ms represents the percentage of sand (0.05-2.00 mm), msilt is the percentage of silt (0.002-0.05 mm), mc refers to the clay content (less than 0.002 mm), and orgC indicates the organic carbon content. Based on these variables, equation (7) is used to determine the soil erodibility factor, KUSLE.

$$KUSLE = \left(0.2 + 0.3 \cdot \exp(-0.256 \cdot ms \cdot (1 - \frac{msilt}{100})) \right) \cdot \left(\frac{msilt}{mc + msilt} \right)^{0.3} \cdot \left(1 - \frac{0.25 \cdot orgC}{orgC + \exp(3.72 - 2.95 \cdot orgC)} \right) \cdot \left(\frac{0.7 \cdot (1 - \frac{ms}{100})}{\left(1 - \frac{ms}{100} \right) + \exp(-5.51 + 22.9 \cdot (1 - (1 - \frac{ms}{100})))} \right) \quad (7)$$

Soil cover management factor

It is important because it reflects land cover and management practices and is the most controlled factor to reduce soil erosion. Once the crop management factor (C) (McCool et al., 1995) is $C \approx 0$ indicates that is highly effective soil protection like dense forest but once crop management factor (C) $C \approx 1$ designates bare soil with no protection, prone to extreme erosion risk. In arc GIS during data processing, C factor values were determined following the findings of Wischmeier & Smith (1978).

Slope length and steepness (LS) factor

The LS factor indicates the impact of slope length and steepness on soil loss. As it has been used, a 9% slope results in a slope length of 22 meters. The Slope steepness impacts runoff speed, whereas the slope length shows the distance of inter-rill erosion, as defined by Wischmeier & Smith (1978). Calculation of the LS factor was performed using watershed slope data obtained through ARC GIS and flow accumulation produced by Arc Hydro tool. The greater the slope's length and steepness, the stronger the force that led to soil erosion. The LS has been produced in ArcGIS by the Raster Calculator, applying the map algebra expression as given in the following equation where FAC stand for flow accumulation. The Digital Elevation Model was used as the input layer to compute the LS factor in ArcGIS.

$$LS = \text{power}((FAC) * (\frac{\text{cell size}}{22.1})^{0.4}) * \text{power}(\frac{\sin((\text{slope}) * 0.01745)}{0.09, 1.4}) \quad (8)$$

Land management factor (P) designates the influence of soil and water resources management strategies such as terraces, strip farming and ridging. These interventions help decrease the water erosion consequence, thereby reducing soil erosion. Estimations of P values range beginning from 0 to 1. A value drawing nearer to 1 represent lands without erosion control practices while an estimation of about 0.1 indicate low-sloping lands (FAO, 1996).

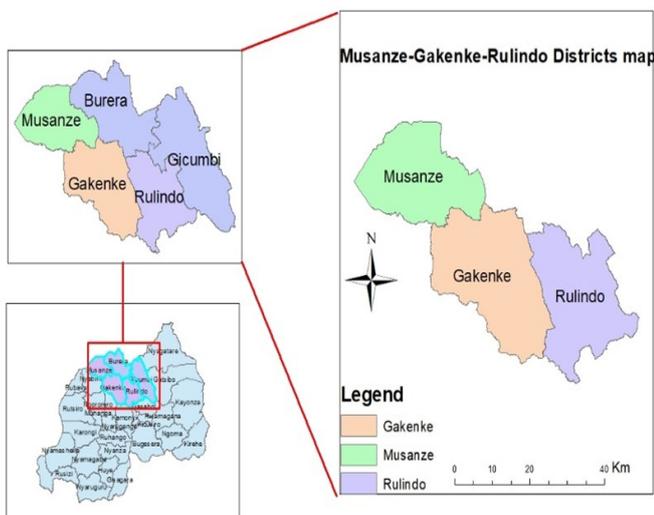


Figure 1. Map showing the study area in three districts of Rwanda.

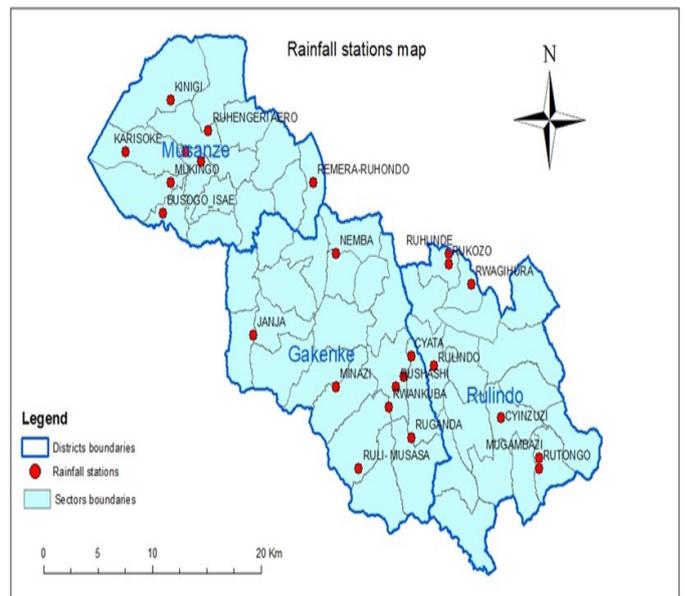


Figure 2. Map showing the rainfall stations in three districts of Rwanda.

Table 1. Data type, its source and description used for the study.

Data type	Source	Description
DEM	Regional center for mapping resources for development (RCMRD) website	Digital Elevation models
Satellite image	US Geological Survey (USGS) website	Satellite Landsat 8 Image
Soil data	MINAGRI & FAO DSMW	Soil map, categories of soil based on soil texture
Rainfall data	Rwanda meteorology center	Rainfall data for a period of 2015 within 21 rain gauge station

Table 2. Details of software's used for data analysis.

Software name	Function
ERDAS IMAGINE 2014	The ERDAS IMAGINE software has capabilities to process the image
ArcGIS 2015	ArcGIS provides a visual representation of data and visually in a mapped format
Google Earth Pro	Google Earth Pro supports visualization of everyplace on Earth to observe satellite imagery, maps, 3D structures, landscape, from galaxies in outer space. Google Earth Pro. can discover geographical content, map and save explored space and share with others.
Other software	Microsoft office environment (Excel, PowerPoint) was used to build database and analyze them; as well as to plot figures and tables

RESULTS AND DISCUSSION

The outcomes of processed and analyzed data from field sources and remotely sensed data brought detailed information on estimation of soil loss rate and mapping soil and water conservation techniques and soil loss status evaluation in Gakenke, Musanze, and Rulindo districts of Northern province of Rwanda are shown in Figures 3-7. In this study, forest was covered the largest area by 84.08% followed by built up areas with 10.43%, radical terraces account for 4.45 %, bare soil (3.23%), agroforestry (0.77%), waterbodies (0.727%), riverbanks (0.38%), and wetland (0.35%) (Figures 3 and 4). Nambajimana et al. (2020) also reported the land use change due to water erosion.

Estimation of soil loss rates

During the study, the level of erosion depends on the soil's vulnerability to raindrop impact (erodibility), rainfall capacity to detach soil particles (erosivity) and the threshold where rainfall erosivity exceeds soil erodibility. Figure 5 shows the degree of change in soil erosion potential and the level of soil loss (tons/ha/Year) in various regions of high-steep slope areas. The average rate of water erosion was discovered as $72 \text{ t. ha}^{-1} \cdot \text{y}^{-1}$ and observed that soil erosion is more severe in steep areas than in other places (Figure 5). The obtained average soil loss in this study is closer to the findings of Kagabo et al. (2013) who studied soil erosion, soil fertility and crop productivity on progressive terraces in highland of Buberuka in Rwanda and found soil loss of 41.5 t/ha/year . Once more Tamene & Le (2015) found that the soil lost was $25\text{-}75 \text{ t/ha/year}$ in sub-Sahara Africa. The outcomes are far not exactly the results acquired by Karamage et al. (2016) who observed the average soil loss of 250 t/ha/year in his investigation 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. The main factors affecting the possibility of soil erosion at certain places for erosive rainfall intensity are land use, land management methods, soil erodibility, steep slopes, and slope length (Allotey & Reidpath, 2000).

Status and mapping of soil and water conservation techniques

During the study, the forest has been identified as the largest in the study area covering of 84.08 % followed by built up areas with 10.43%, bare soil (3.23%), agroforestry (0.77%), waterbodies (0.727%), riverbanks (0.38%), and wetland (0.35%) (Figures 6 and 7). Woodlots Forest and agroforestry trees more integrated and scattered throughout cropping areas of the study sites and less in other type of land uses. Fruits trees like Mangoes and avocados are most agroforestry trees in Musanze, Gakenke and Rulindo districts. Such agroforestry practice is the land management technique accompanied with the fruit trees production for human consumption and livestock feeding. Bigger agroforestry and river banks observed in Musanze and Gakenke than Rulindo. The river banks are mostly distributed along shores of the lakes, rivers and stream. This improved soil fertility in Musanze and Gakenke more than Rulindo. Regarding

to the finding of the Mutuyimana (2015) indicated that least utilized soil and water conservation techniques, tree planting is the most adopted at 23.3%, followed by agroforestry at 19.63%. Grass strips and rainwater harvesting are less commonly used, with adoption rates of 8.52% and 0.74%, respectively. Based on the study findings after mapping, satellite image use and ground truthing the found area covered with terraces was 7146.19 Ha (Figures 6 and 7). The result indicate that terraces are also not highly adopted in the study site as it requires more expert guidance by comparing with different currents science and indigenous knowledge. When compared to adequate soil erosion and runoff control, this research found that radical terraces require a substantial amount of work, regardless of whether they are the being not highly adopted in the study area zone. Radical terraces are highly effective at minimizing steep slopes to reduce excessive runoff and soil erosion while simultaneously improving agricultural yield. Terraces are recognized as essential methods for soil and water resources conservation for human survival. Furthermore, families are still uniting themselves for those possible soil and water conservation techniques but radical terraces need a lot of effort and resources so families cannot create radical terraces on their own without government intervention. Additionally, low appropriation of radical terraces can be attributed to the fact that the innovation is still relatively new in the research area and has not been adopted by many farmers.

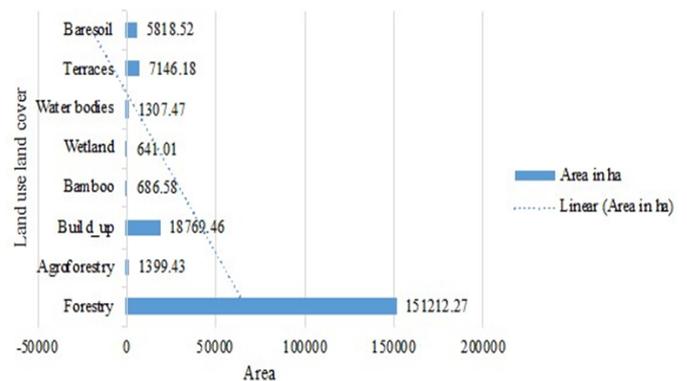


Figure 3. Land use and land cover of the study area.

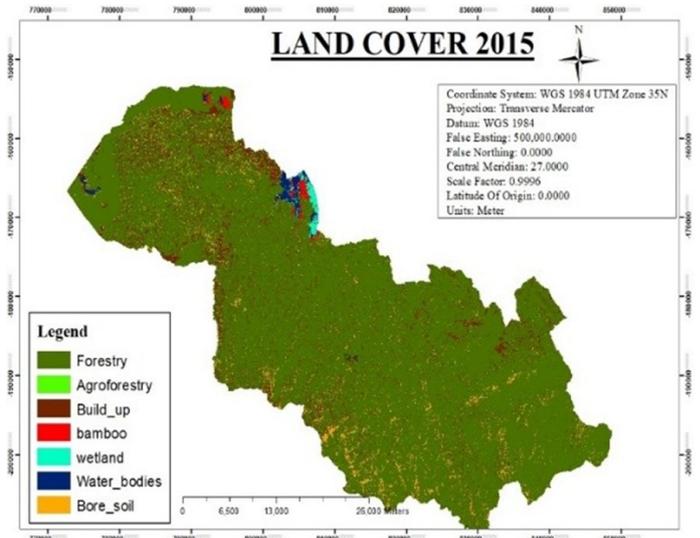


Figure 4. Land use and land cover pattern of the study area.

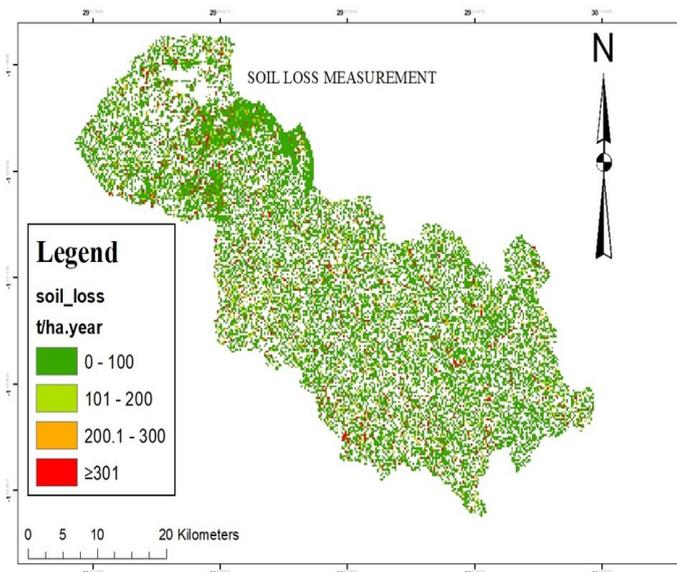


Figure 5. Soil loss measurement in the study area.

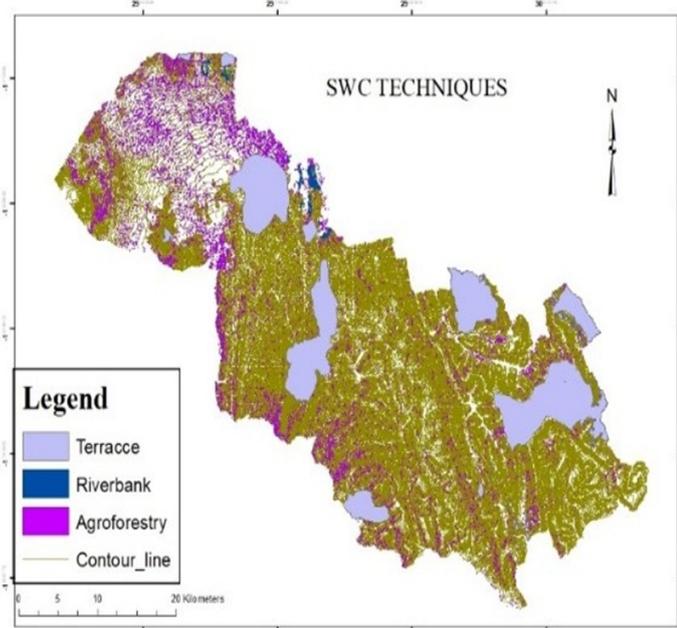


Figure 6. Major SWC techniques applied during the study.

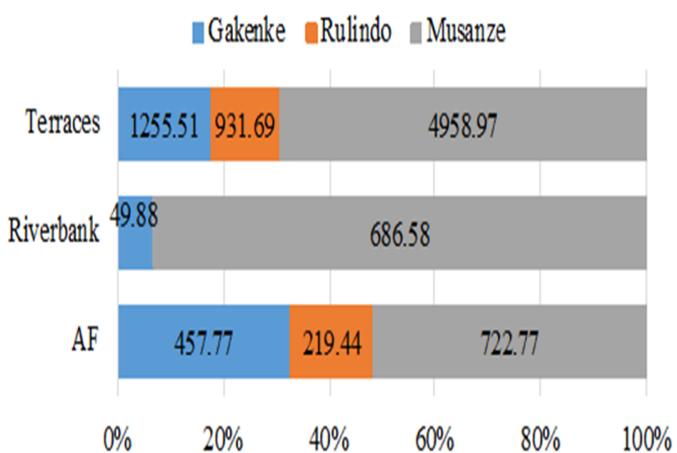


Figure 7. Soil and water conservation strategies (Riverbanks, terraces and agroforestry) used in the study area.

Conclusion

According to the soil erosion map and map of soil and water conservation strategies derived from field data, remotely sensed data, water erosion management techniques have demonstrated to reduce water erosion. Major finding related to soil and water management strategies such as forests dominated the study area, making up 84.08 % followed by terraces, agroforestry and riverbanks resulted 4.45%, 0.77%, 0.38%, respectively. Also, average rate of soil loss was 72.5 tons/ha/year. Forests and radical terraces particularly have helped to decrease water velocity and reduce soil erosion. Variability in soil types, slope gradient and landscapes (Upper, middle and bottom slopes) affect also the efficiency of different water erosion control measure. Therefore, it is advisable to increase the agroforest tree and forest especially on steep-slop that will help to prevent soil erosion and improve soil fertility with climate change mitigation. Sustainable management of existing forest plantation should be taken into consideration. Due to higher soil loss rate proven in non-protected steep land of the study site, future water erosion control techniques should be applied first in the high altitude where we recorded high soil loss rate.

DECLARATIONS

Author contribution statement

Conceptualization: M.N., B.B and F.X.N., Methodology: M.N. and B.B.; Software and validation: M.N., B.B, F.X.N.; Formal analysis and investigation: M.N.; Resources: M.N.; Data curation: M.N and BB; Writing-original draft preparation: M.N.; Writing review and editing: M.N., M.C.M.; Visualization: M.N., M.C.M. Supervision: B.B and F.X.N. All authors have read and agreed to the published version of the manuscript.

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