Pan African University
PAU Institute of Water and Energy Sciences

PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

WATER ENGINEERING

Presented by

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Assessment of the Impact of Land Use Changes and Conservation Practices on Soil Loss and Sediment Yield using GeoWEPP Model; A Case Study of Mwogo Sub-catchment, Rwanda

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DECLARATION

I declare that this thesis is my original work, and that it has not been wholly or in part presented for an award of any degree in any University known to me.

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DEDICATION

This thesis is dedicated in memory of my late father NIYONSENGA Cyprien for his blessing and unconditional love.

This work is also dedicated to my family, my supervisors and my friends for their unconditional continued support and encouragement.

ACKNOWLEDGEMENTS

First of all, I would like to thank the Almighty God, who has walked with me throughout this journey and before. Without the constant guidance and protection of the Lord, this master thesis would not be accomplished. I express my heartfelt gratitude to the African Union Commission, which offered me the opportunity of pursuing a Master of Science in Water Engineering and providing all the requirements in terms of financial support to accomplish my master's studies.

Special thanks to my supervisor, Prof. Dr.-Ing. Benedict M. Mutua for his assistance, guidance and contribution to the execution of this project. I value so much your time, priceless criticism which pushed me harder to produce good work. My co-supervisor, Dr. Caroline W. Maina for her guidance, assistance and putting so much time in having me to produce good work.

I extend my gratitude to Algerian Government, to all PAUWES staff members, to PAUWES Stakeholders, to Tlemcen people and all Algerians in general; for their support, assistance and provision of enabling learning environment during my stay in Algeria. To the whole PAUWES community particularly my fellow fifth cohort colleagues. I am thankful for two years well spent together. You have been supportive in so many different ways, thank you for your material and moral support.

My deep appreciation goes to the staff of Rwanda Water Resources Board. Your support was extremely valuable to me during my research internship till the end of research. I would like to express my gratitude to all the institutions that provided the data to make this study a success. Last but not least, I send many thanks to my family for their invaluable care, encouragement and support throughout my studies. This work would not have been possible without the love and support of my entire family and friends who have always encouraged and believed in what I can do.

ABSTRACT

Surface water bodies are essential resources that provide water for different activities. However, Soil erosion and runoff generated as a result of human activities contribute to considerable amount of sediment yield that is deposited in receiving water bodies. Sediment deposited in surface water bodies threatens the reservoir capacities which impacts negatively on their useful lifespan. Nyabarongo reservoir catchment in Rwanda has continued to experience increased mining and intensive agricultural activities that are carried out on the steep slopes of the mountainous areas. This study therefore assessed the impact of land use changes and conservation practices on soil loss and sediment yield using GeoWEPP model in Mwogo sub-catchment of Nyabarongo reservoir catchment. Sensitivity analysis, calibration and validation of the model was undertaken. The coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) were used to evaluate the GeoWEPP model performance. The calibrated and validated model was used to simulate runoff depth, soil loss and sediment yield over a period of 20 years. To assess effectiveness of conservation practices and land use changes in reducing soil loss and sediment yield, no tillage management, grassland and forestland Scenarios were adopted for all agricultural land use as well as on 25% and 50% of most critical hillslopes. It was observed that runoff was sensitive to effective hydraulic conductivity only while sediment yield was sensitive to critical shear, effective hydraulic conductivity, rill and interrill erodibility. The model evaluation showed a satisfactory performance with R^2 of 0.75, NSE of 0.65 and PBIAS of 3.75 during calibration, and 0.88, 0.52 and 7.05 for validation respectively. The average annual runoff depth, soil loss and sediment yield were predicted as 418.4 mm, 194.6 ton/ha and 25.4 ton/ha, respectively under the Base Scenario. Compared to the Base Scenario, the simulated results under no tillage, grassland and forestland Scenarios showed a significant reduction in runoff depth, soil loss and sediment yield. Therefore, this study concluded that adopting a no tillage management and converting most critical hillslopes to grassland and forestland have an impact on reducing runoff depth, soil loss and sediment yield of Mwogo sub-catchment. This would further lead to reduction of sediment load into the reservoir. The results from this study are very useful to water resource managers in making informed decisions for sustainable catchment management.

Key words: GeoWEPP, Mwogo sub-catchment, Sediment yield, Soil loss, Land use, Conservation practices

RÉSUMÉ

Les surfaces d'eau sont des ressources essentielles qui fournissent de l'eau pour différentes activités. Cependant, l'érosion du sol et le ruissellement générés par les activités humaines contribuent à une quantité de sédiments déposés dans les plans d'eau récepteurs. Ces sédiments menacent les capacités des réservoirs, ce qui a un impact négatif sur leur durée de vie utile. Le bassin versant du réservoir de Nyabarongo au Rwanda a continué à connaître une augmentation des activités minières et agricoles intensives qui sont menées sur les pentes abruptes des zones montagneuses. Cette étude a évalué l'impact des changements d'utilisation des terres et des pratiques de conservation sur la perte du sol et le rendement en sédiments à l'aide du modèle GeoWEPP dans le sous-bassin Mwogo versant au réservoir de Nyabarongo. Une analyse de sensibilité, un étalonnage et une validation du modèle ont été entrepris. Le coefficient de détermination (R^2), l'efficacité de Nash-Sutcliffe (NSE) et le pourcentage de biais (PBIAS) ont été utilisés pour évaluer les performances du modèle. Ce modèle calibré et validé a été utilisé pour simuler la profondeur de ruissellement, la perte de sol et le rendement en sédiments sur une période de 20 ans. Pour évaluer l'efficacité des pratiques de conservation et des changements d'utilisation des terres pour réduire la perte du sol et le rendement des sédiments, aucune gestion du travail du sol, des scénarios de prairie et de forêt ont été adoptés pour toutes les utilisations des terres agricoles ainsi que sur 25% et 50% des pentes les plus critiques. Il a été observé que le ruissellement n'était sensible à la conductivité hydraulique effective, tandis que le rendement des sédiments était sensible au cisaillement critique, à la conductivité hydraulique effective, à l'érodabilité en rigoles et inter-forages. L'évaluation du modèle a montré une performance satisfaisante avec R^2 de 0,75 ; NSE de 0,65 et PBIAS de 3,75 lors de l'étalonnage, et 0,88 ; 0,52 et 7,05, pour la validation. Le ruissellement, la perte du sol et le rendement en sédiments annuelle étaient de 418,4 mm, 194,6 ton/ha et 25,4 ton/ha. Par rapport au scénario de Base, les résultats simulés dans les scénarios sans travail du sol, de prairie et de forêt ont montré une réduction significative de ruissellement, de la perte de sol et du rendement en sédiments. Cette étude a conclu que l'adoption d'une gestion sans labour et la conversion des pentes les plus critiques en prairies et forêts ont un impact sur la réduction de ruissellement, la perte du sol et le rendement en sédiments du sous-bassin de Mwogo. Cela entraînerait une réduction de sédiments dans le réservoir.

Mots clés: GeoWEPP, Sous-bassin de Mwogo, Rendement en sédiments, Perte de sol, Utilisation des terres, Pratiques de conservation

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LIST OF ABBREVIATIONS

AGNPS	Agricultural Non-Point Source Pollution Model
ASCII	American Standard Code for International Interchange
CSA	Critical Source Area
DEM	Digital Elevation Model
EPM	Erosion Potential Method
FAO	Food and Agriculture Organization
GEOWEPP	Geo-spatial interface for WEPP
GIS	Geographical Information System
HRU	Hydrological Response Unity
LULC	Land Use and Land Cover
MSCL	Minimum Source Channel Length
MUSLE	Modified Universal Soil Loss Equation
NSE	Nash-Sutcliffe Efficiency
PAUWES	Pan African University Institute for Water and Energy Science (incl. Climate Change)
PBIAS	Percentage Bias
PRISM	Parameter Elevation Regressions on Independent Slopes Model
REMA	Rwanda Environment Management Authority
RIWSP	Rwanda Integrated Water Security Program
RNRA	Rwanda Natural Resources Authority
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
SY	Sediment Yield
TOPAZ	Topographic Parameterization Tool
UN	United Nation
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WWAP	World Water Assessment Programme

DEFINITION OF TERMS

Albedo: Defined as the percent of the solar radiation which is reflected back to the atmosphere

Cation Exchange Capacity: Defined as quantity of cations adsorbed on soil particles per unit of mass of the soil under chemically neutral conditions

Critical Shear: Defined as a threshold value, under which rill detachment does not occur

Critical Source Area: Defined as the minimum drainage area

Effective hydraulic conductivity: Defines as the soil parameter used by the Green-Ampt model for estimation of infiltration and runoff, and it expresses the ease with which water moves in the soil

Interrill Erodibility: Defined as a measure of how well a soil can resist detachment by raindrop impact

Minimum Source Channel Length: Defined as the shortest channel length

Rill Erodibility: Represents a soil's resistance to detachment by concentrated rill flow

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CHAPTER ONE

INTRODUCTION

1.1 Background Information

Water resources support various aspects of human life around the world. For instance, surface water bodies are exploited to meet different demand such as domestic, industrial, agricultural, etc. However, these functions are threatened by climate change, erosion, sedimentation, pollution, deforestation, and landscape changes (UN-Water WWAP, 2006). Human activities have increased the sediment transported by global rivers through soil erosion by 2.3±0.6 billion metric tons per year (Karamage *et al.*, 2016). According to Walling (2009) soil erosion is a direct result of increased population pressure and overexploitation of surface vegetative resources. Soil erosion and runoff generate considerable amounts of sediment yield, leading to increased deposits of sediments in water bodies.

Sedimentation which is an indirect measure of soil erosion, is one of the most serious environmental problems affecting surface water bodies around the world (Walling, 2009). Sedimentation occurs when soil particles are eroded and transported by flowing water or other transporting media and deposited as layers of solid particles. The deposition of sediment can take place on land or in water bodies such as reservoirs and rivers. This process of sedimentation varies with catchment sediment yield, rate of transportation and mode of deposition (Ezugwu, 2013). Sediment deposition reduces the storage capacity and life span of reservoirs as well as river flows (Eroğlu *et al.*, 2010). Annually 0.5–1 % of global storage volume is estimated to be lost to sedimentation (Basson, 2009). Hence, sedimentation threatens the reservoir capacities normally used for hydropower, irrigation and water supply. Further, Puno (2014) reported that sedimentation threatens the sustainability of upland farming, as well as the quality and quantity of water resource.

According to Arekhi (2008), in developing countries, soil erosion is becoming a limiting factor on agricultural productivity. About 65% of Africa's agricultural land is degraded owing to soil erosion (Arekhi, 2008). Research work on river systems in the tropical regions of Africa indicated that there is continued uncontrolled environmental degradation (Munthali *et al.*, 2011). This has resulted to soil erosion, thereby leading to loss in soil fertility and sedimentation of rivers and reservoirs. Studies on some dams in Zimbabwe showed that reservoir capacities are being affected by sedimentation (Sawunyama *et al.*, 2006; Dalu *et al.*, 2013; Chitata *et al.*, 2014). According to the study conducted by Vanmaercke *et al*. (2014), the lowest sediment yields were observed in Western Africa, while Southern and Eastern Africa are generally characterized by higher sediment yield values. One such a country in Eastern Africa that is facing high land degradation, soil erosion and sedimentation is Rwanda.

Rwanda is characterized by rapidly growing population with limited economic and agricultural options, a fragile soil, steep slopes and intense rainfall (Fabien, 2006). In 2005, about 77% of Rwanda's total surface area was threatened by soil erosion (Bizoza, 2014; Nahayo *et al.*, 2016). In1990, 44 percent of Rwanda's territory were covered by forest, while 28 percent were occupied by cropland. In 2015, due to increase in food demand, more than 56 % of Rwanda's land had been converted to croplands, and this led to massive deforestation (Karamage *et al.*, 2016). The land conversion from natural forests to agricultural land use are associated with increase in soil erosion, which results in sedimentation of water bodies.

Rwanda is facing a challenge of sedimentation of rivers and lakes due to soil erosion originating from poor agriculture practices and mining activities (RIWSP, 2016). A study conducted in Keya hydropower plant located in western province of Rwanda found that sedimentation has reduced its capacity from 2.2 MW to 900 KW (Munyaneza *et al.*, 2015). Another hydropower reservoir in Rwanda that is highly threatened by sedimentation is Nyabarongo reservoir.

Nyabarongo hydropower reservoir is located in Nyabarongo reservoir catchment which is a mountainous area and has steep slopes around it. The increase of agriculture, settlement and use of firewood for cooking are putting high pressure to the natural forests within Nyabarongo reservoir catchment. The catchment is mainly facing significant problems, such as soil erosion including riverbank erosion by agriculture and cattle. In addition, mining exploitation increases siltation to rivers and streams feeding Nyabarongo reservoir. Another problem within the catchment is deforestation that reduces the soil cover, and poor agricultural practices (Bulder, 2018). Thus, there was need to conduct this study for assessing the impact of land use changes and conservation practices on soil erosion and sedimentation within the catchment.

1.2 Statement of the Problem

Nyabarongo reservoir catchment has an increase in human activities such as mining and intensive agriculture that is carried out on a mountainous area with steep slopes. Additionally, the high population density in the catchment, combined with increased use of fuel wood for cooking has put pressure on natural resources such as clearance of natural forest within the catchment. The catchment also experiences overexploitation of agricultural land and lack of adequate conservation practices. As a result, fertile soil is lost within the catchment thus impacting on agricultural productivity. On the other hand, the eroded soils contribute to high sediment loads in Nyabarongo river thereby resulting in reservoir sedimentation. Nyabarongo reservoir catchment has limited data available on soil erosion and no data on sediment. Also, the impacts of land use changes and conservation practices on sedimentation of Nyabarongo reservoir catchment are currently not understood. Hence there was a need to assess the impacts of land use changes and conservation practices on soil loss and sediment yield of Mwogo sub-catchment within Nyabarongo reservoir catchment.

1.3 Main Objective

The main objective of this study was to assess the impact of conservation practices and land use changes on soil loss and sediment yield in Mwogo sub-catchment using GeoWEPP model.

1.3.1 Specific Objectives

The specific objectives were to:

i. Calibrate and validate the GeoWEPP model for Mwogo sub-catchment within Nyabarongo reservoir catchment;
ii. Estimate annual runoff depth, soil loss and sediment yield of Mwogo sub-catchment using GeoWEPP model Based on current land use/land cover; and
iii. Assess the impact of conservation practices and land use changes in reducing soil loss and sediment yield of Mwogo sub-catchment using GeoWEPP model.

1.4 Research Questions

i. What are the various parameters for calibration and validation of GeoWEPP model for Mwogo sub-catchment?
ii. What is the amount of runoff depth, soil loss and sediment yield within Mwogo sub-catchment Based on current land use/ land cover?
iii. How effective are conservation practices and land use changes in reducing the magnitude of soil loss and sediment yield within Mwogo sub-catchment?

1.5 Justification

Climate change and increase in anthropogenic land use activities such as conversion of forest land use to agricultural, residential, mining, and industrial land use result in more erosion and sedimentation of water bodies (Kumar *et al.*, 2017). Sediment deposition reduces storage capacity and lifespan of water resources infrastructure such as reservoirs (Ara and Zakwan, 2018). It is important to maintain the storage capacity of the reservoir by taking appropriate measures that could reduce the rate of siltation. This would be possible if the amount of soil loss and sediment yield in the catchment is known. Thus, assessment and analysis of soil erosion and sediment yield in the catchment of the reservoir is essential. This study was carried out to investigate the impact of land use changes and conservation practices on soil erosion and sediment yield by using the GeoWEPP model. Models are the tools that help in understanding soil erosion and sediment yield where little data exist (Pandey *et al.*, 2016). In addition, models can be used to simulate the spatial and temporal dynamics of hydrological and erosive processes (Didoné *et al.*, 2017). Also, Physically Based soil erosion and sediment yield models help to evaluate the impacts of conservation practices on soil erosion and sediment yield (Pandey *et al.*, 2016).

1.6 Scope and Limitation of this Study

This study focused on assessing the impact of land use changes and conservation practices on soil loss and sediment yield in Mwogo sub-catchment within Nyabarongo reservoir catchment. Although there is a likelihood of the contribution of the impact of climate change on soil erosion and sedimentation, the study was not assessing the effect of climate change. This study focused on estimating sediment yield delivered into the reservoir from Mwogo river as one of the tributaries of Nyabarongo river. Also, the study assessed the effectiveness of land use changes and conservation practices in reducing soil loss and sediment yield within Mwogo sub-catchment. The study focused only on Mwogo sub-catchment because of availability of data for calibrating and validating the model. This study faced a limitation on data about the characterization and sediment yield of Mwogo sub-catchment. Therefore, the GeoWEPP model used in this study was only calibrated and validated by using observed runoff data.

CHAPTER TWO
LITERATURE REVIEW

2.1 Soil Erosion

Worldwide, soil erosion is among the main factors of environmental degradation. Global rates of soil erosion have been 10 to 20 times higher than those of new soil formation on almost every continent in the world in recent decades (FAO, 2015). Soil erosion is the removal of topsoil faster than soil-forming processes that can replace it. Soil erosion, whether due to water or wind, involves three actions such as; detachment, movement, and deposition of the soil. Soil erosion and its degradation affect the water quality of rivers, estuaries, and lakes as well as the productivity of land (Hajigholizadeh *et al*., 2018).

Soil erosion is the primary reason for land degradation in Sub-Saharan Africa (SSA) with serious effects on agricultural productivity (Tamene and Le, 2015). Rwanda as one of the countries of sub-Saharan Africa has been ranked among 22 countries facing land degradation problems, whereby 40 % of its land has a very excessive erosion risk (REMA, 2009). In Rwanda, the soil erosion caused by water was predicted to be 595 million tons per year (Karamage *et al.*, 2016). The increase in soil erosion is a direct consequence of growing human activities in catchments. Few studies have been conducted about the assessment of soil erosion in Rwanda. However, no study has been done in Nyabarongo reservoir catchment as well as in Mwogo sub-catchment to estimate soil loss and sediment yield. In addition, no research has been conducted for assessing the impact of land use changes and conservation practices on soil loss and sediment yield within the study area.

2.1.1 Types of Soil Erosion

Soil erosion due to surface water is one of the most essential land degradation issues and a vital environmental hazard worldwide (Jain and Das, 2010). Soil erosion by water is a natural process that takes place when the impact of water detaches and gets rid of soil particles. Both falling raindrops and water flowing over the land surface are among the driving mechanisms of soil detachment, transport, and deposition within a watershed (Ramsankaran *et al.*, 2013). Water erosion occurs in different forms such as; splash erosion, sheet erosion, rill erosion, gully erosion, and riverbanks erosion.

Splash erosion is recognized as the first stage of water erosion and it takes place when the soil is at once exposed to raindrop impact (Fernández *et al.*, 2017). Sheet erosion occurs when the rainfall intensity becomes higher than the infiltration rate of the soil, and it is induced through shallow sheets of water flowing over the soil surface (Zhao *et al.*, 2019). When the speed and turbulence of water increase, the flowing water concentrates deeper into soil surfaces, then the surface of the soil is cut to small channels or rills resulting in rill erosion. Gully erosion is the superior stage of rill erosion that entails the elimination of soil materials by water with the aid of developing big channels in contrast to rills. Apart from those types of erosion, bank erosion is the washing away of the banks of a river or a stream (Balasubramanian, 2017).

2.1.2 Factors Influencing Erosion

The main causes of soil erosion globally have been attributed to inappropriate agricultural practices, deforestation, overgrazing, land abandonment, forest fires, and construction activities (Balasubramanian, 2017). Among the listed causes of soil erosion, agricultural land uses is classified as the first to have the highest erosion rate (Nunes *et al.*, 2011). The increased rates of soil erosion are associated with the excessive conversion of natural vegetation to agricultural land coupled with poor conservation practices (Zhao *et al.*, 2019). The other key factors affecting erosion include climate, topography, characteristics of the soil, and vegetative cover (Ochoa *et al.*, 2016).

The structure and texture of the soil also influence soil erosion. Soils with low infiltration rates are most easily eroded. The more soil structure is improved, the less the soil is vulnerable to erosion. Soils that have silt, very fine sand and clay texture tend to be more vulnerable to soil erosion than sand, sandy loam, and loam textured soils. Erosion is also severe depending on the nature of the topography; naturally, the steeper the slope of the land surface is, the more the amount of the soil is eroded. Moreover, the length of the slope also affects the erosion process, if short lengths are put together can increase the amount of soil loss due to the accumulation of runoff (Pimentel and

Burgess, 2013).

The climatic factors that influence erosion are the intensity, frequency, and duration of rainfall. The higher the intensity and duration of rainfall, the greater the erosion risk if the raindrops hit the soil surface (Balasubramanian, 2017). Another factor that has an impact on erosion is vegetation cover as it decreases the erodibility of the land surface and reduces the risk of soil erosion (Sun *et al.*, 2014). The surface of the land that is occupied by vegetation and plant biomass is more resisted to runoff and soil erosion because the raindrops are dissipated by layers of biomass (Pimentel and Burgess, 2013). Vegetation reduces soil erosion by the use of its roots and the canopy. The growth pattern, structure, and composition of the plant community affect soil erosion as it determines the type of protective cover it renders to the soil (Sun *et al*., 2014).

2.2 Sediment Yield

Sediment yield is the total amount of sediment that is delivered to the outlet of a watershed (Dutta, 2016). Usually, characteristics of a river basin affect sediment yield because sediment yield is a function of precipitation, surface runoff, vegetation, lithology, soil type, watershed, and land use (Zhang, 2010). More vegetation decreases sediment yield by reducing runoff volume, while easily erodible rocks increase sediment yield, and steeper slope also increases sediment yield (Zhao *et al.*, 2019). In a catchment, the sediment delivery ratio depends on the sediment yield and it is represented by Equation 2.1 (Dutta, 2016).

$$SDR = \left(\frac{SY}{A}\right) \times 100 \tag{2.1}$$

Where:

SDR =Sediment delivery ratio(%)

SY = Sediment yield(t/ha)

A = Soil loss per unit of area (t/ha)

In short, the Sediment Delivery Ratio relates erosion to sediment yield. In this relationship, sediment yield depends on soil erosion.

2.3 Reservoir Sedimentation

Reservoirs and rivers become a natural means for the storage of transported sediment or eroded soil (George *et al.*, 2016). Globally, sedimentation has caused the reduction of reservoir storage capacity thereby decreasing the life span of dams (Ara and Zakwan, 2018). As time passes, reservoirs that are constructed across the rivers or streams fail to retain their capacity progressively due to the quantity of sediments accumulated in those reservoirs. Sediments affect the operating capacity of the reservoir as the water intake capacity may get affected (Ara and Zakwan, 2018). Furthermore, sediments that are deposited in reservoirs may damage hydro equipment, slow down the performance of outlet structures, and also affects water quality.

It is reported that almost all reservoirs are exposed to sedimentation and the issues of sedimentation cannot be eliminated (Warrick *et al.*, 2015). However, sedimentation can be controlled by various activities that take place in the upstream of the reservoir catchment. Therefore, there is a need to know the behavior of the upstream catchment towards sediment yield along with reservoir sedimentation (Foteh *et al.*, 2018). According to Merina *et al.* (2016), most of the reservoirs constructed on natural rivers are assigned to some level of sediment deposition. Approximately 40,000 large reservoirs across the world are facing sedimentation challenges (Haregeweyn *et al.*, 2006). Periodical capacity surveys of the water bodies are needed for evaluating the amount of sediments and checking the reduction in storage capacity, so that appropriate conservation strategy can be implemented (Jeyakanthan and Sanjeevi, 2013).

2.4 Land Use and Land Cover Changes

The terms land use and land cover are often used interchangeably, though they have different meanings. Land use is the purpose for which land is used, whereas land cover refers to the physical features that are covering the ground surface. Land-use change is the conversion of the activities that are carried on the earth's surface due to human interventions. Land use reflects human activities such as agriculture, infrastructure, mining and settlements (Bello *et al.*, 2019).

Generally, land use and land cover changes may be classified into two broad categories as conversion and modification. Conversion refers to changes from one cover or use type to another, meanwhile, modification may involve maintenance of the broad cover or use type in the face of changes in its attributes (Bello *et al*., 2019). According to the data from different sources, the Global Forest Resources Assessment revealed that the natural forests have undergone an average annual decrease of 16.1 million hectares during the 1990s (Balasubramanian, 2017). In Rwanda, the forest land use has decreased by approximately 28% from 1990 to 2015. This can be attributed to high population growth that resulted in the conversion of forest land use to the agricultural land to meet the food requirement (Karamage *et al.*, 2016).

2.4.1 Impact of Land use/cover changes on Soil Erosion

Land use/ land cover changes cause significant impacts on soil erosion, which is a global environmental problem. In recent years, various studies have been conducted to assess the impact of land use/ land cover changes on soil erosion (Fullen *et al.*, 2006; Li *et al*., 2013; Gashaw *et al.*, 2019; Tsegaye, 2019). According to Fullen *et al.* (2006) and Souchère *et al.* (2003), the conversion of forest land use/land cover to the agricultural and residential land use/ land cover have positive and negative impacts on soil erosion depending on various conditions. Land use/land cover changes are one of the variables that influence the rate of soil loss due to erosion. Generally, land use/land cover changes on cultivated land accelerate the issues of soil erosion unless appropriate conservation measures are adopted.

Globally, the majority of land use/land cover changes are in the form of clearing the forest and shrub terrain to agricultural land. Removal of vegetation cover exposes the land to soil erosion by decreasing the soil protection cover (Kapute *et al.*, 2019). This process accelerates the removal of soil particles, which increases sheet, rill, and gully erosions (Tsegaye, 2019). A study conducted by Li *et al*. (2013) revealed that forest and vegetation conversions induce soil erosion, while conversion from open land to forest decelerates soil erosion. This implies that the changes in vegetation cover significantly influence soil erosion. Land use and land cover changes induce soil erosion in cases of severe deforestation, overgrazing, and over-tilling of the land (Tang *et al.*, 2011). Due to the change in land use and land cover, a huge amount of sediments can be easily transported downstream.

2.4.2 Impact of Land use/cover Changes on Sediment Yield

The increase in soil erosion to a large extent results in the increase in sediment yield in a catchment that is not adequately managed. Several studies have demonstrated that changes in land use have a great effect on sediment yield than runoff intensity (Bakker *et al.*, 2008; Zuo *et al.*, 2016). Zuo *et al*. (2016) reported that land use/land cover changes reduced runoff by 25.3% and the sediment yield was decreased by 40.6%. The study conducted by Gebremicael *et al*. (2013) showed that land use/land cover changes from vegetative cover to agriculture in the upper Blue Nile basin have resulted in the increase of sediments from 91×10^6 ton/year to 147×10^6 ton/year. For instance, a study conducted in the upper Tapi river sub-basin (India) revealed that the increase in forest area decreases sediment yield and surface runoff, while the increase of agricultural land increases the sediment yield and surface runoff in the catchment (Munoth and Goyal, 2019).

The LULC changes have a significant impact not only on sediment load but also on surface runoff (Munoth and Goyal, 2019). The worldwide annual river discharge has increased significantly since 1900, and research suggests that LULC change may be directly responsible for more than 50% of this increase (Kumar *et al*., 2017). Sediment yield from LULC change may lead to excessive sedimentation in lakes and reservoirs, thereby threatening aquatic life and hydroelectric power generation (Yuan *et al.*, 2015). Variations in sediment yield to a large extent could be attributed to differences in parameters such as type and condition of plant cover, soil type, and slope. Thus, there is a need to model the effects of these attributes on soil erosion and sediment yield.

2.5 Soil Erosion and Sediment Yield Modeling

Models are mostly utilized to predict and understand different processes that take place within the catchment (Abdulkareem *et al.*, 2018). Models consist of various parameters that define their characteristics. However, models differ significantly in terms of their functionality, complexity and applicability, input data, the illustration of processes, spatial and temporal variability, and types of the findings they give (Zhao and Li, 2015). The majority of the designed soil erosion and sediment yield models can predict soil dislodgment and sediment yield phenomena at the hillslope level (Pandey *et al.*, 2016). There are several models (empirical, conceptual, and physically Based) developed to estimate soil loss and sediment yield and to assess the impact of management practices on soil erosion.

2.5.1 Empirical Models

Empirical models are Based on statistical observation and experiments, and they depend on the regression equation for simulating natural processes (Hajigholizadeh *et al.*, 2018). One advantage of using empirical models is their simple structure. Furthermore, the empirical models are easy to apply because they are Based on coefficients calculated from measured data or observations. However, empirical models cannot simulate or describe the erosion process Based on physical phenomena (Dutal *et al.*, 2017). This type of model also cannot be accurately applied outside the geographical area where their relationships were extracted. Sometimes empirical models use the unrealistic assumptions of the physical characteristics of the catchment, by ignoring the heterogeneity of important parameters such as soil types and precipitation (Hajigholizadeh *et al.*, 2018).

One of the commonly used empirical models is the Universal Soil Loss Equation (USLE). It is used to estimate annual soil erosion from an area simply as the product of empirical coefficients, which must therefore be accurately evaluated. The USLE was revised to RUSLE, and it is used to estimate the annual soil loss per unit area by use of an empirical equation, considering various erosion factors such as climate, soil type, topography, and land type (Dutal *et al.*, 2017) . Universal Soil Loss Equation is represented by Equation 2.2.

$$A = R \times K \times LS \times C \times P \qquad (2.2)$$

Where:

A = Average annual soil loss per unit area

R = Rainfall-runoff erosivity factor

K = Soil erodibility factor

LS = Slope length (L) and the slope steepness (S) factor

C = Cover and management factor

P = Support and conservation practice factor

2.5.2 Conceptual Models

Conceptual models are a mixture of empirical and physically based models. The models in this group were constructed based on the sediment continuity equation and require a lot of climate and hydrological data (Zhao *et al.*, 2019). They focus on predicting sediment yield by using the theory of unit hydrograph. In conceptual models, the catchment is represented by its internal storage system and it integrates different processes that produce runoff and sediment yield (Hajigholizadeh *et al.*, 2018). The conceptual models combine generalized representations of catchment processes regardless of the processes of interactions that require comprehensive information about the catchment. The conceptual models are used to evaluate the effects of land use/land cover changes that take place in the catchment, without accounting on the information from the spatial and temporal variations (Hajigholizadeh *et al.*, 2018). The disadvantage of using the conceptual model is that calibration is site-specific and the model does not consider directly the characteristics of rainfall and the soil properties (Cuomo *et al.,* 2015).

2.5.3 Physically Based Models

Physically Based models are numerically idealized representations of the existing phenomenon (Fatichi, 2016). These are also referred to as mechanistic models that incorporate the principles of physical processes and they consider spatial and temporal variabilities (Devia *et al.*, 2015). Physically Based models represent hydrological processes based on different fundamental equations such as conservation of mass, momentum, and energy equations (Hajigholizadeh *et al.*, 2018). Physically-Based models designed for modeling soil erosion and sediment yield are not 100 % physically developed because their processes are designed based on empirical or conceptual concepts (Pandey *et al.*, 2016).

Physically-Based models use state variables that are measurable and are functions of both time and space. The models belonging in this category can overcome many defects of the other two models because of the use of parameters having physical interpretation. The physically-based models can provide a large amount of information even outside the boundary and can be applied in a wide range of situations (Devia *et al.*, 2015). Water Erosion Prediction Project (WEPP) model is an example of a Physically-Based model used for soil erosion and sediment yield modeling.

2.6 Commonly Used Soil Erosion and Sediment Yield Models

2.6.1 Universal Soil Loss Equation and Revised Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is an empirical model that was developed to predict soil erosion at the field scale (Benavidez *et al.*, 2018). The USLE model is Based on five factors such as soil erodibility, rainfall pattern, cover management, conservation practices, and slope steepness and slope length (Ghosal and Bhattacharya, 2020). The USLE is used to estimate the amount of soil loss from sheet and rill erosion and it does not predict the soil loss from gully erosion (Ozcan *et al.*, 2008). One of the disadvantages of USLE is that the model does not predict soil erosion Based on events and also, the preparation of input data is time-consuming (Dutta, 2016). The Universal Soil Loss Equation (USLE) is the widely used empirical model for modeling erosion rates (Parveen and Kumar, 2012; Prasannakumar e*t al*., 2012; Ganasri and Ramesh, 2016).

The new version of the USLE model, known as the Revised Universal Soil Loss Equation (RUSLE), was created by enhancing the capability of the USLE to greater precisely estimate numerous factors of soil loss equation (Benavidez *et al.*, 2018). The RUSLE model cannot be directly used to predict the quantity of sediment reaching downstream zones because it does not account for the deposition of sediment within the different parts of the catchment (Arekhi *et al.*, 2012). The assessment of each input parameter of USLE or RUSLE is complicated because of a lot of combinations and time spent with data collection and analysis. The advantage of modeling soil loss by USLE or RUSLE model is that the overestimations and underestimations can compensate each other when the model is simulated over a long period and large catchment, resulting in a good overall assessment of total soil loss (Dutta, 2016).

2.6.2 Agricultural Non-Point Source Pollution Model (AGNPS)

Agricultural Non-Point Source Pollution Model (AGNPS) is used to evaluate soil erosion and sediment. The model is mostly used for assessing the effect of management practices on soil erosion and sediment yield within the catchment (Finn *et al.*, 2006). AGNPS model uses Universal Soil Loss Equation and steady-state continuity equation for modeling soil erosion and sediment yield (Pandey *et al.*, 2008, 2016). The main input parameters required by the AGNPS model include soil properties, land use, topography, and climate data. The AGNPS model is capable of predicting non-point source pollution (Pandey *et al.*, 2016). The AGNPS application in modeling runoff, sediment yield, peak runoff rate, and nutrient loss has been tested in different catchments around the world (Chowdary *et al.*, 2004; Cho *et al*., 2008; Jianchang *et al*., 2008).

2.6.3 Soil and Water Assessment Tool (SWAT) Model

The soil and water assessment tool was developed by the United States Department of Agricultural Research Service (Douglas *et al.*, 2010). The SWAT model is a physically Based spatially distributed watershed model. The model is capable of hydrological modeling at the river basin scale (Tibebe and Bewket, 2011). The input parameters used by SWAT are topography, land use, soil type, and climatic data (Ghaffari *et al.*, 2010). The SWAT model uses climate data that consist of rainfall, minimum and maximum temperature, relative humidity, wind speed, and solar radiation (Lee and Chung, 2007). The SWAT model breaks the entire watershed into sub-watersheds by using the Digital Elevation Model (DEM) (Tibebe and Bewket, 2011). Furthermore, the sub-watersheds are divided into numerous equivalent Hydrological Response Units (HRUs), whereby each HRU is composed of a particular combination of land use, soil type, and the mean slope (Dutta and Sen, 2017).

The surface runoff and sediment yield predicted by the SWAT model are first computed Based on the HRU level, then accumulated to the sub-watershed level and finally routed to get the total watershed output (Dutta and Sen, 2017). The SWAT model uses two methods to compute the surface runoff; Soil Conservation Service (SCS) curve number (CN) method and the Green and Ampt infiltration method. The SCS curve number method is mostly used because it requires fewer input data compared to the Green-Ampt method (Fontaine *et al*., 2002). The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) to estimate the sediment yield from each HRU (Jung *et al*., 2017). The SWAT model has been applied in modeling soil erosion and sediment yield in different catchments around the world (Shen *et al.*, 2009; Xu *et al*., 2009; Tesfahunegn *et* *al.*, 2012;Yesuf *et al.*, 2015; Dutta and Sen, 2017; Melaku *et al.*, 2018). Equation 2.3 is used by SWAT model for water balance within the catchment.

$$SW_t = SW_o - \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \tag{2.3}$$

Where:

SW_t = final soil water content (mm)

SW_o = initial soil water content on the day i (mm)

t = time (days)

R_{day} = amount of precipitation on day i (mm)

Q_{surf} = amount of surface runoff on day i (mm)

E_a = amount of evapotranspiration on day i (mm)

W_{seep} = amount of water entering the vadose zone from the soil profile on day i (mm)

Q_{gw} = amount of return flow on day i (mm)

2.6.4 Water Erosion Prediction Project (WEPP) Model

The WEPP model is a physically distributed continuous simulation model that was developed to predict soil erosion and sediment yield by using soil type, land use, climatic and topographic conditions. The climatic input data include rainfall, minimum and maximum temperature, relative humidity, solar radiation, and wind speed (Mohammad *et al.*, 2016). The WEPP model is capable of calculating spatial and temporal patterns of soil loss and sediment yield and also it can locate the possible depositions within the catchment (Amini *et al.*, 2014).

The WEPP model separates the catchment into at least one overland flow elements that have uniform soil characteristics, management practices, and slope (Pieri *et al.*, 2007.). Within the WEPP model, the catchment comprises of multiple hillslopes, channels, and impoundments. The WEPP model computes runoff, soil loss, and sediment yield starting from each hillslope, then the model aggregates the estimated results obtained from each hillslope to conduct the whole catchment predictions (Shen *et al.*, 2009). The WEPP model was designed to be used on the small catchment of not larger than 260 ha, however, the WEPP model has been applied on catchment greater than 260 ha (Baigorria and Romero, 2007; Pandey *et al.*, 2008; Al-Mukhtar *et al.*, 2014; Amini *et al.*, 2014).

The WEPP model was applied to predict runoff and sediment yield in a small agricultural catchment. The results of calibration and validation showed a good satisfactory model performance (Pandey *et al*., 2008). A study conducted in the Duhok reservoir watershed in Iraq by using WEPP and SWAT models, it has revealed that the prediction of both models for annual runoff and sediment gave reasonable results with measured data (Mohammad *et al*., 2016). Also, Amini *et al*. (2014) conducted a study in Southern Iran by comparing WEPP and EPM models for estimating soil erosion in Marmeh Watershed. The results showed that sediment yield simulated by the WEPP model was in good agreement with observed data compared to sediment yield simulated by the EPM model, so WEPP results were better than those predicted by EPM. The performance of the WEPP model was compared with the SWAT model, they found that the WEPP model performed better than the SWAT model in simulating different management Scenario for reduction of sediment yield (Shen *et al*., 2009).

2.6.5 Geo-spatial interface for WEPP (GeoWEPP Model)

Recently, advances in Geographic Information Systems (GIS) technology made it possible to integrate GIS and soil estimation models for assessing soil loss and predicting sediment yield. The GeoWEPP model used in this study is a geospatial interface for the WEPP model, and it is a Physically-Based, continuous simulation computer program. The model predicts soil loss and sediment transport and deposition from the overland flow on hill slopes, soil loss and sediment deposition from concentrated flow in small channels, and sediment deposition in impoundments (Alvarenga *et al*., 2017).

The GeoWEPP model is the connection of two free programming software which contains the WEPP Model and ArcGIS. The GeoWEPP model incorporates two components that extend its practicability. These components are; the Topographic Parameterization tool (TOPAZ) and Top-WEPP programming software. The TOPAZ tool is used to create hillslope profiles by using the Digital Elevation Model (DEM) (Maalim *et al*., 2013). The GeoWEPP model predicts the sediment yield using one intrinsic simulation method called the watershed simulation method or offsite method which uses one soil and one management for each hillslope losing the spatial variability of the study area for these parameters. The values reported represent the quantity of sediments that leave each hillslope and being reported at the outlet. Unlike the watershed method, the values reported in the Flow-path method (second method of simulation) refer to the amount of erosion or deposition occurring in each raster cell of the catchment. This method retains the diversity and spatial distribution of the soil and land-use layers which makes it more reliable in terms of soil loss estimation. The advantage of using the GeoWEPP model over the WEPP model is that the input data are generated in a digital format while for the WEPP model, the input parameters are generated manually (Yüksel *et al.*, 2008).

The GeoWEPP model was applied in different catchments around the world not only for modeling soil erosion and sediment yield but also for assessing the impact of land use/land cover changes and effective management practices on runoff and sediment yield (Yüksel *et al.*, 2008; Meghdadi, 2013; Puno, 2014; Narimani *et al.*, 2017; Puno *et al.*, 2020). Puno (2014) conducted a study on modeling runoff and sediment yield of Mapawa watershed by using GeoWEPP where the model performed satisfactorily by simulating runoff and sediment yield values that were close to the observed data. A study conducted by Narimani *et al*. (2017) evaluated the impact of management Scenarios and land-use changes on annual surface runoff and sediment yield using the GeoWEPP. Calibration and validation results showed a satisfactory model performance. Furthermore, In Meghdadi (2013), runoff and sediment data measured at the outlet of the watershed during one year (2000) were used to successfully calibrate the model where a close correlation between the values of observed and simulated sediment yield was demonstrated for the calibration period Based on the performance evaluation indicators calculated NSE=0.82 and RMSE=0.01549. The calibrated GeoWEPP model was then used to predict sediment yield, identify the most susceptible sub-watersheds to erosion, and evaluate the impact of effective management practices on daily sediment yield.

No studies have been conducted on the application of the GeoWEPP model in the current study area or any other watershed in Rwanda. Thus, this study was one of the first to utilize the GeoWEPP to estimate soil loss, sediment yield, and surface runoff for the Mwogo sub-catchment within the Nyabarongo reservoir Catchment. The GeoWEPP model was chosen for this study because of its ability to estimate the amount of erosion occurring in each raster cell of the catchment. Furthermore, the model can determine where the sediment yield and runoff occur and locates possible deposition sites.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

This study was conducted in Mwogo sub-catchment located in Nyabarongo reservoir catchment. The catchment has a hydropower dam that is constructed on Nyabarongo river and is located at 29°37′59.3″E longitude and 01°59′19.4″S latitude. Nyabarongo reservoir catchment is found in south-western part of Rwanda. Nyabarongo reservoir catchment extends over an area of 2647 km^2 and it has many sub-catchments namely Mwogo, Rukararara, Mbirurume, Kiryango, Secoko sub-catchments (RIWSP, 2016).This study focused only on Mwogo sub-catchment, which is served by Mwogo river, a tributary of Nyabarongo river. Mwogo sub-catchment is located between longitude 29°30′ to 29°45′ E and latitude 2°15′ to 2°30′S, and occupies 24 % of the total catchment area (Figure 3.1).

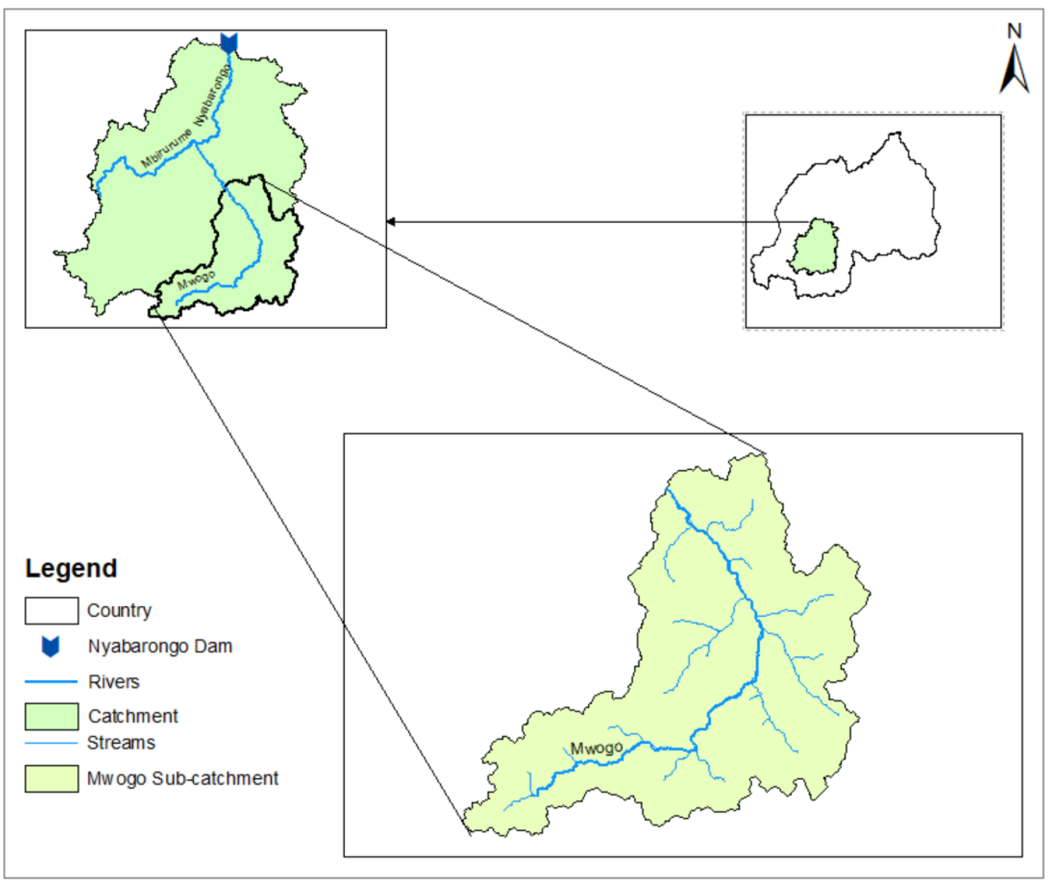

Figure 3. 1: Mwogo Sub-catchment within Nyabarongo Reservoir Catchment in Rwanda

The topography of the Nyabarongo reservoir catchment ranges from 1250 to 3000 m above sea level (Bulder, 2018).The catchment is characterized by a tropical temperate climate with an average temperature of 20°C. The maximum and minimum daily temperature of 23.6°C and 14.0°C, respectively (Bulder, 2018). According to RNRA (2015), the average annual rainfall of the catchment is approximately 1365 mm.

Agriculture is the most dominant land use in the catchment, covering 85% of the total catchment area which is divided into; seasonal and perennial agriculture as well as open areas. Forest occupies 10%, while settlements and buildings, water, and wetlands occupy very small areas of the catchment (Bulder, 2018). The catchment is characterized by eight soil textures such as Clay, Clay Loam, Loam, Loamy Sand, Sand Clay, Sand Clay Loam, Sandy Loam, and Silt Loam. Thus, the dominant soil textures are Clay Loam, Sandy Clay Loam, and Sand Clay respectively (Bulder, 2018). The geological formation of the catchment is sub-divided into the granite basement aquifer, with a low water storage capacity, sandstone, quartzophylite, phyllite, and the quartzite and shale/schist aquifer in the central part with intermediate water storage and recharge conditions (RIWSP, 2016).

3.2 Calibration and Validation of GeoWEPP Model for Mwogo Sub-catchment

3.2.1 Catchment Characterization

The catchment was delineated using ArcGIS 10.4.1 where dam coordinate of Nyabarongo hydropower reservoir were used as the pour point. The slope map of the study area was extracted from a 30 m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The DEM was downloaded from (http://opendata.rcmrd.org/datasets/rwanda-srtm-dem-30-meters). The streamflow data from 2009 to 2013, and classified land use and land cover map of 2018 for the whole country was sourced from Rwanda Water Resources Board. From country's land use map, Mwogo sub-catchment's land use map was extracted.

The soil data were obtained from the website of SOTER-Based soil parameter estimates (SOTWIS) for Central Africa (https://files.isric.org/public/sotwis/SOTWIS_CAF). Soil parameters used in this study included soil type, percentage of organic matter content, cation exchange capacity, percentage of sand and clay. Other soil properties of the catchment such as soil albedo, inter-rill erodibility, rill erodibility, critical shear and effective hydraulic conductivity were calculated using equations described in WEPP manual (Flanagan and Nearing, 1995).

Climate data used in this study included; daily precipitation, maximum and minimum temperature, wind speed, relative humidity and solar radiation for 20 years' period (1997 to 2016). The climate data were collected from Rwanda Meteorology Agency as well as Global weather data for SWAT (https://globalweather.tamu.edu). Since the climate data was not generated in the format of CLIGEN model used by WEPP, the Rock Clime application in the Forest Service WEPP was used to prepare the climate data into WEPP format. The Rock Clime can access the Parameter Elevation Regressions on Independent Slopes Model (PRISM) dataBase which estimates the precipitation and temperature Based on orographic effects. A similar procedure had been followed by Meghdadi (2013) in a study conducted in Kasilian watershed on the identification of best effective management practices in reducing sediment yield. Also, Yüksel *et al*. (2008) followed the same procedure in a study conducted in the Orcan Creek Watershed.

3.2.2 GeoWEPP Model Setup

The GeoWEPP model used in this study had two independent softwares; WEPP Model Version 2012 and ArcGIS 10.4.1. According to Zhang *et al*. (2015), ArcView project, Topographic Parameterization tool (TOPAZ) and Topwepp software are the main components of GeoWEPP model. The DEM, land use and soil maps of the study area were prepared into American Standard Code for International Interchange (ASCII) format. To initiate GeoWEPP model, the following input data for Mwogo sub-catchment were used; the DEM.asc, land use map.asc, corresponding land use description with their dataBase files, soil map.asc as well as their corresponding soil description and dataBase files. The description and dataBase files of soil (soilmap.txt, soildb.txt) and land use (landcov.txt, landusedb.txt) were prepared following the procedures described in Minkowski and Renschler (2008).

The channel network was adjusted by changing the values of mean source channel length (MSCL) and critical source area (CSA). The MSCL is defined as the shortest channel length, while CSA is the minimum drainage area (Yüksel *et al*., 2008). After defining the channel network, the watershed was delineated Based on selected outlet point and TOPAZ was used to generate the sub-watersheds (hillslopes). Each grid cell within the created hillslope was assigned a specific land cover and soil type. The model simulations considering watershed method were executed using climate file described in section 3.2.1. Further, Topwepp program was used in executing model runs and generating the output results. A similar procedure of setting up GeoWEPP model had been followed by Puno (2014) in a study conducted in Mapawa catchment for modeling runoff and sediment yield. Also, Alhasaan *et al*. (2018) followed a similar procedure in a study conducted in Tono reservoir watershed.

3.2.3 Sensitivity Analysis of GeoWEPP Model

Sensitivity analysis was carried out following the procedures given by Al-Mukhtar *et al.* (2014), Meghdadi (2013), Pandey *et al*. (2008) and Ramsankaran *et al*. (2009). According to Fashi and Ejlali (2015), sensitivity analysis is used to identify the input parameters that have high effect on the results of the model. It was performed to assess the variations in the model output with change in input parameter. In assessing GeoWEPP model for sensitivity, the initial calculated values of effective hydraulic conductivity, rill erodibility, inter-rill erodibility and critical shear were increased and decreased by 10%, 20% and 25%. The parameter of interest was varied while keeping other parameters constant. Considering the output and input of parameter, Equation 3.1 adopted from Ramsankaran *et al.* (2009) was used to calculate the sensitivity ratio.

$$S = \frac{(O_2 - O_1)/\bar{O}}{(I_2 - I_1)/\bar{I}} \qquad (3.1)$$

Where:

S = Sensitivity ratio

O_2 = Maximum value of output parameter

O_1 = Minimum value of output parameter

$\bar{O}$ = Mean value of output parameters

I_2 = Maximum value of input parameter

I_1 = Minimum value of input parameter

$\bar{I}$ = Mean value of input parameters

3.2.4 Model Calibration and Validation

In this study, calibration and validation of GeoWEPP model were performed by splitting the available streamflow data into two. Streamflow data from 2009 to 2011 was used for model calibration, while streamflow data from 2012 to 2013 was used for validation. The observed streamflow data was converted into daily runoff depth (mm) using the drainage area of the sub-catchment. Calibration was done manually by using trial and error method where the focus was on soil parameters that had been identified to be sensitive to runoff. A similar procedure was followed by Al-Mukhtar *et al*. (2014) in a study conducted in Bautzen dam catchment. After calibration, validation was undertaken where the model was run without adjustment on calibrated parameters. To assess the performance of the model during calibration and validation statistical analysis was undertaken.

3.2.5 Model Performance

The Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2) and Percent bias (PBIAS) statistical criteria were used to check the goodness fit of the model. Equations 3.2 to 3.4 were used to determine how well the model simulation matched the observed data.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(O - \bar{O}\right)^2} \tag{3.2}$$

Where:

n= Number of observations or samples

O_i = Observed values

P_i = Predicted values

$\bar{O}$ = Mean of observed values

$i =$ Counter for individual observed and predicted values

The NSE ranges from $-\infty$ to one, with a value of one representing a perfect fit between predicted and measured data (Nash and Sutcliffe, 1970). Moriasi *et al*. (2015) suggested that NSE values greater than 0.5 indicate satisfactory model performance.

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(O_i - \bar{O} \right) \left(P_i - \bar{P} \right)}{\sqrt{\sum_{i=1}^{n} \left(O_i - \bar{O} \right)^2} \sqrt{\sum_{i=1}^{n} \left(P_i - \bar{P} \right)^2}} \right]^2 \tag{3.3}$$

Where:

$\bar{P} =$ Mean of predicted values

R^2 ranges from 0 to 1, where one means that the predicted value is equal to the observed value and zero means that there is no correlation between the predicted and observed values (Krause *et al*., 2005). According to Santhi *et al*. (2001) and Van Liew *et al*. (2003) values greater than 0.5 are considered acceptable.

$$PBIAS = \left[\frac{\sum_{i=1}^{n} \left(O_i - P_i \right) \times 100}{\sum_{i=1}^{n} \left(O_i \right)} \right] \tag{3.4}$$

PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts, with optimal value of 0.0 indicating accurate model simulation (Moriasi *et al*., 2007).

3.3 Estimation of Runoff Depth, Soil Loss and Sediment Yield within Mwogo Sub-catchment

The calibrated and validated model was applied to simulate runoff, soil loss and sediment yield from Mwogo sub-catchment by using the current land use and climate data for the past 20 years. In WEPP model, the runoff is estimated by using kinematic wave equations and an approximation to the kinematic wave solutions. On the other hand, infiltration was computed by using Green–Ampt Mein Larson (GAML) model (Equation 3.5) for unsteady intermittent rainfall (Shen *et al.*, 2009).

$$f_{\inf,t} = K_e\left(1+\frac{\psi_{wf}\,\Delta\theta_V}{F_{\inf,t}}\right) \tag{3.5}$$

Where:

$f_{\inf,t} =$ Infiltration rate at time t (mm/h)

$K_e =$ Effective hydraulic conductivity (mm/h)

$\psi_{wf} =$ Wetting front matric potential (mm)

$\Delta\theta_V =$ Change in volumetric moisture content across the wetting front

$F_{\inf,t} =$ Cumulative infiltration at time t (mm)

In WEPP Model, Evapotranspiration is computed by using Priestly-Taylor method (Equation 3.6) when only solar radiation and temperature data are available (Flanagan and Nearing, 1995).

$$E_u = 0.00128\,\frac{R_n l}{58.3}\,\frac{\delta}{\delta+\gamma} \tag{3.6}$$

Where:

$E_u =$ Daily potential evapotranspiration (MJ. m^{-2}. d^{-1})

$R_n l =$ Daily net solar radiation (ly)

$\delta =$ Slope of the saturated vapor pressure curve at mean air temperature

$\gamma =$ Psychrometric constant

In predicting sediment yield, the steady state sediment continuity (Equation 3.7) was used. The WEPP model calculates sediment yield from both hillslopes and channels considering detachment, transport and deposition of sediment. Movement of suspended sediment on rill, inter-rill and channel flow areas is Based on the steady state erosion model that solves a sediment continuity equation at peak run off rate (Akbari *et al*., 2015).

$$\frac{dG}{dx} = D_f + D_i \tag{3.7}$$

Where:

$G =$ Sediment load (kg s^{-1} m^{-1})

$x =$ Distance downslope (m)

$D_f =$ rill erosion rate (kg s^{-1} m^{-2})

$D_i =$ inter-rill sediment delivery to the rill (kg s^{-1} m^{-2})

The D_i is considered as independent of x, and it is always greater than zero. D_f is >0 for detachment and for deposition. For model computations, both D_f and D_i are calculated on a per rill area basis, thus G is solved on a per unit rill width basis. After computations, sediment yield is expressed as sediment yield per unit land area (Shen *et al*., 2009). A similar procedure had been followed by Maalim *et al*. (2013) in a study conducted in Le Sueur watershed by using GeoWEPP. Also, Akbari *et al*. (2015) applied the same procedure in a study conducted in the Latyan dam watershed. According to Melaku *et al.* (2018) and Puno *et al.* (2020), the tolerable soil loss value for the tropical region, where Rwanda is located, varies between 10 and 12 ton/ha/year. To identify the areas with the highest sediment yield within Mwogo sub-catchment, tolerable soil loss limit of 10 ton/ha/year was used.

3.4 Assessing Impacts of Conservation Practices and Land Use Changes on Soil Loss and Sediment Yield

The effectiveness of conservation practices and land use changes in reducing soil loss and sediment yield within Mwogo sub-catchment was assessed using the calibrated and validated GeoWEPP model. GeoWEPP model provides the opportunity to change the hillslope soil or land use type and rerunning the model to observe the induced change in terms of soil loss and sediment yield (Flanagan *et al.*, 2013). To assess the effect of management practices, no tillage management was adopted for all agricultural land use/land cover (no tillage Scenario 1). Also, no tillage Scenario was simulated on 25 % of most critical hillslopes (no tillage Scenario 2) as well as on 50 % of most critical hillslopes (no tillage Scenario 3). On the other hand, to evaluate impact of land use changes, all agricultural land use was converted to grassland (grassland Scenario 1) and forestland (forestland Scenario 1). Also, 25 % and 50% of hillslopes that have been identified as having highest soil loss and sediment yield were converted to grass land use/land cover (grassland Scenarios 2 and 3), and also to forest land use/land cover (forestland Scenarios 2 and 3). Those proposed Scenarios were used for checking their impacts in reducing the surface runoff, soil loss and sediment yield. The process of simulation was repeated for each management Scenario, and the model was run for 20 years by use of watershed method. A similar procedure was applied by, Alhasaan *et al*. (2018), Maalim *et al*. (2013) and Meghdadi (2013) in studies conducted in Tono reservoir watershed, Le Sueur watershed and Kasilian watershed, respectively.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Mwogo Sub-Catchment Characterization

4.1.1 Topography

It was found out that topography of Mwogo sub-catchment ranges from 1529 and 2382 m above mean sea level as shown in Figure 4.1.

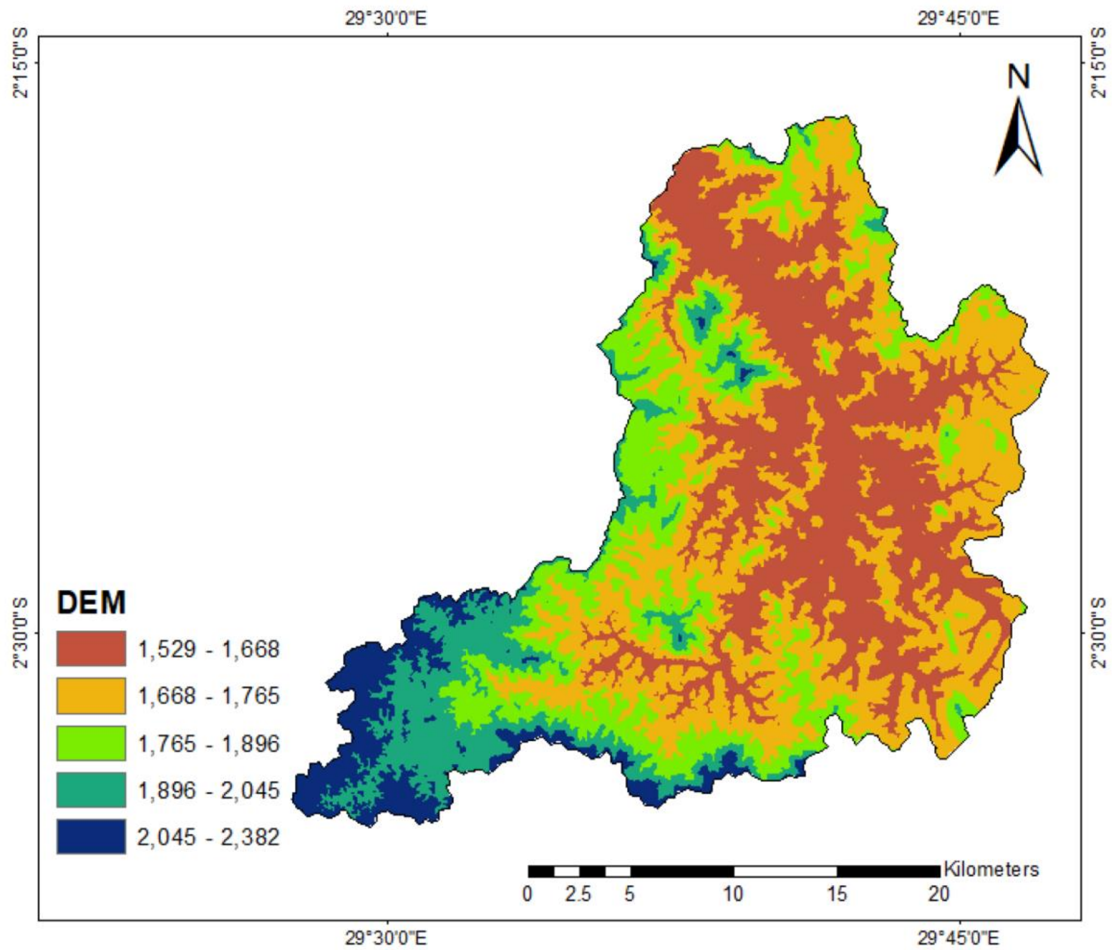

Figure 4. 1: Topographical Map of Mwogo Sub-Catchment

Bulder (2018) reported that the topography in Nyabarongo reservoir catchment ranges from 1250 to 3000 m, this implies that Mwogo sub-catchment is located towards the higher elevation side. It was also observed that the slope of the sub-catchment varies from 0 to 61 % with a mean slope of 30.5 %. 80.5 % of the sub-catchment area is characterized by the slope that fluctuating between 7% and 61%. The steeper the slope of the ground is, the more the amount of the soil is lost by water erosion. Karamage *et al*. (2016) revealed that the catchment with steep slope angle greater than 30% contributed to 73.5% of the total soil loss within Nyabarongo river catchment.

4.1.2 Land Use and Land Cover

It was found that Mwogo sub-catchment is highly dominated with agricultural land activities that are divided into perennial and seasonal agriculture. Other land use/ land cover types found in the sub-catchment include forests, water, open areas or grass, settlements and buildings (Figure 4.2).

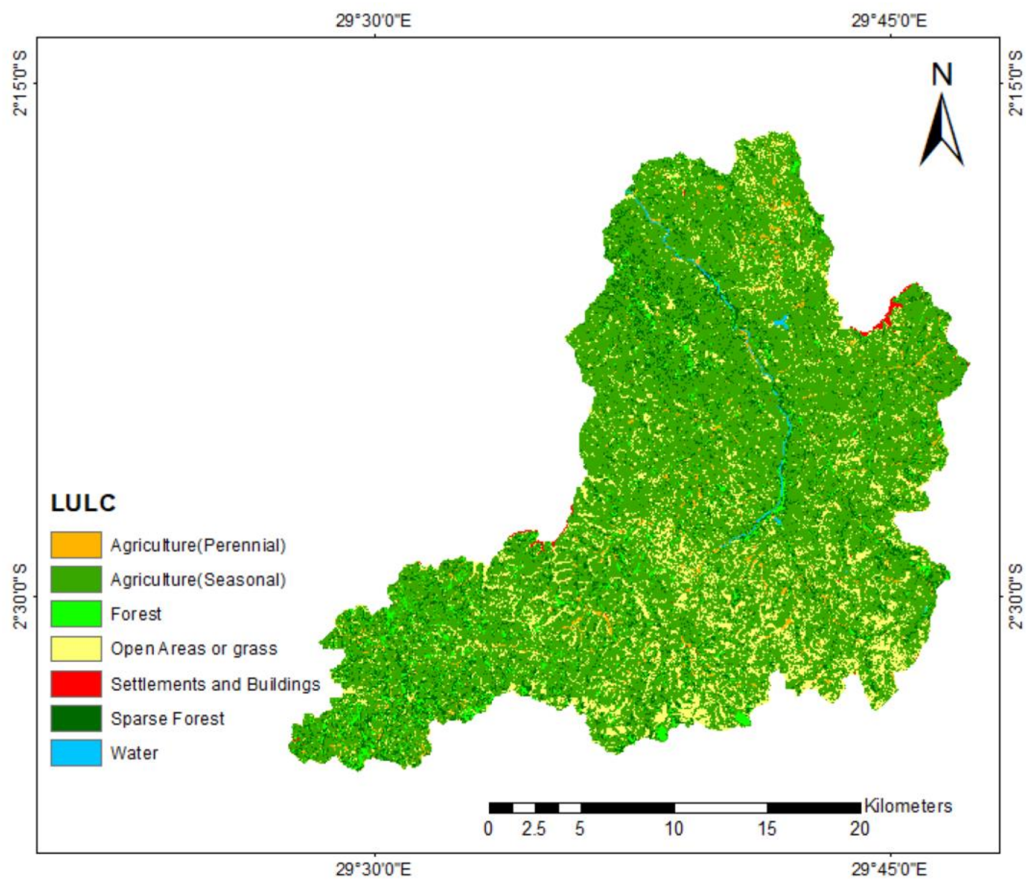

Figure 4. 2: Land Use/ Land Cover Map of Mwogo Sub-Catchment

Form the results given in Table 4.1, it was observed that agricultural land occupies 75.05 %, open areas or grass (12.62 %), forest (11.73 %), water (0.32 %) while settlements and buildings cover 0.27 % of the total sub-catchment area.

Table 4. 1: Land Use/ Land Cover Distribution in Mwogo Sub-Catchment

Land Use/Land Cover Classes	Area (km^2)	Percentage (%)
Agriculture (Perennial)	12.34	1.96
Agriculture (Seasonal)	461.20	73.09
Forest	24.54	3.89
Open Areas or grass	79.65	12.62
Settlements and Buildings	1.73	0.27
Sparse Forest	49.50	7.84
Water	2.04	0.32

A high percentage of agricultural land coupled with unsustainable conservation practices within the catchment may lead to the high soil loss and sediment yield. Kidane *et al*. (2019) conducted a study about the impact of land use and land cover dynamics on soil erosion and sediment yield in Ethiopia, the results of the study indicated that the cultivated land associated with poor farming practices was highly erodible compared to other land use/land cover classes. Similarly, Kapute *et al*. (2019) reported that the expansion of agricultural land from forestland could be the cause for increased soil erosion and sediment yield within the middle Shire river catchment. In addition, Fu *et al*. (2006) revealed that the agricultural land which was the most dominant in the Pataha Creek Watershed was the major source of soil erosion, contributing about 92.4% of the total soil loss in the watershed.

4.1.3 Types of Soil

There are four soil types identified in the Mwogo sub-catchment (Figure 4.3).

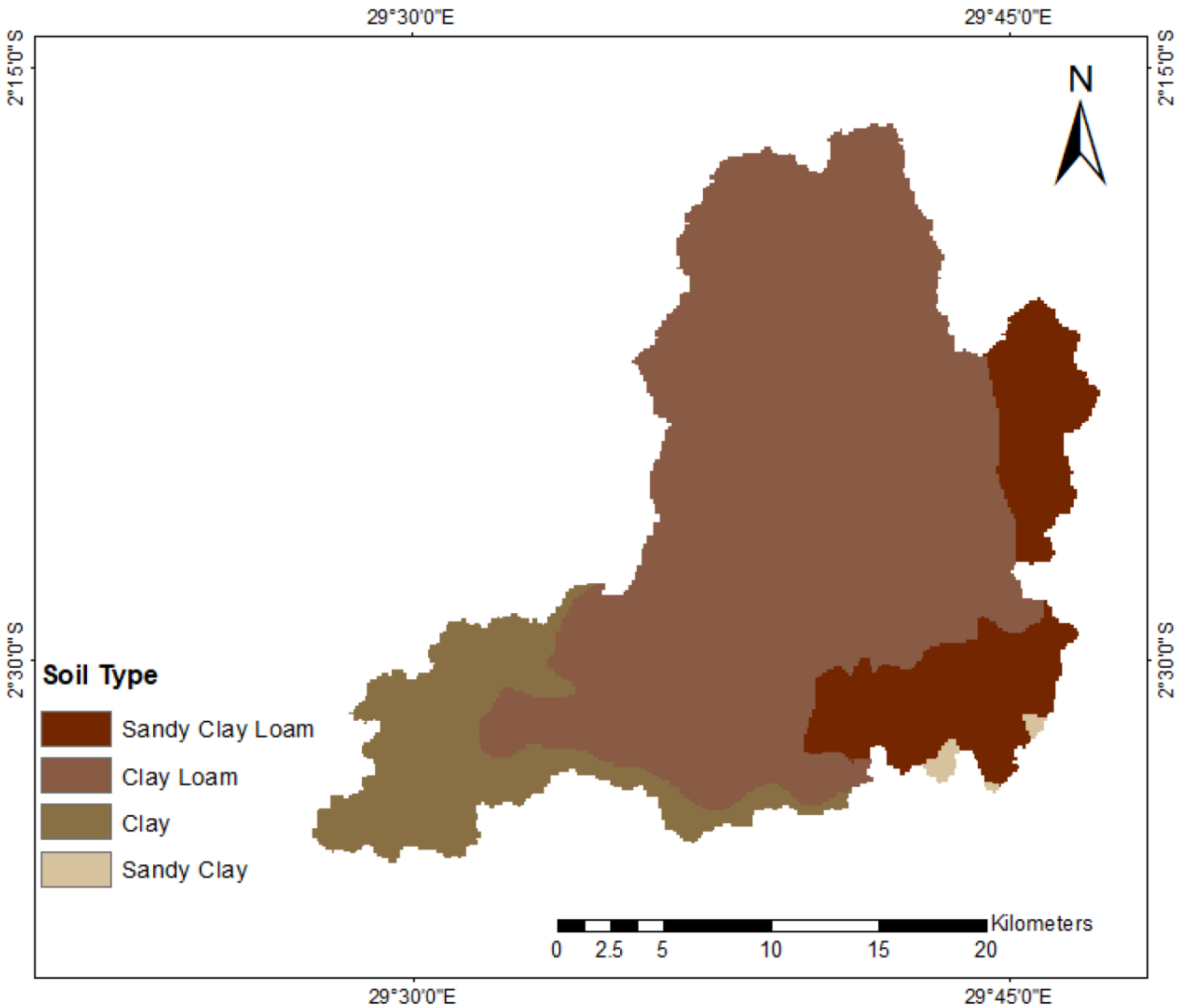

Figure 4. 3: Soil Type Map of Mwogo Sub-Catchment

Form Table 4.2, it is observed that the most dominant soil type in the sub-catchment is clay loam which occupies 69.72 %, followed by sandy clay loam (15.35 %), clay (14.46 %) while sandy clay covers 0.47% of the total surface area of Mwogo sub-catchment.

Table 4. 2: Soil Type Distribution in Mwogo Sub-Catchment

Soil Type	Area (km^2)	Percentage (%)
Sandy Clay Loam	96.83	15.35
Clay Loam	439.94	69.72
Clay	91.25	14.46
Sandy Clay	2.98	0.47

Clay loam is a fine textured soil characterized by slow infiltration rate and high runoff volume. Clay soil type has the slowest infiltration rate and high runoff compared to sandy clay loam and sandy clay. Among the soil type identified in the Mwogo sub-catchment, clay loam and clay are more susceptible to soil erosion (Ross *et al*., 2018).

4.2 Calibration and Validation of GeoWEPP Model

4.2.1 Sensitivity Analysis

Sensitivity analysis results showed that the runoff was only sensitive to effective hydraulic conductivity, whereas sediment yield predicted using the GeoWEPP model was highly sensitive to critical shear, rill erodibility, inter-rill erodibility and effective hydraulic conductivity. Sensitivity analysis results of this study are presented in Tables 4.3 and 4.4.

Table 4. 3: Sensitivity Ratio by Increasing and Decreasing Input Parameters by 10%

SOIL TYPE	Run Off				Sediment Yield			
	Effective Hydraulic Conductivity	Interill Erodibility	Critical Shear	Rill Erodibility	Effective Hydraulic Conductivity	Interill Erodibility	Critical Shear	Rill Erodibility
Clay Loam	-0.2258	0	0	0	-9.8640	0.0019	-0.9208	5.7792
Clay	-0.0481	0	0	0	-7.4471	2.3854	-9.6132	3.8883
Sandy Clay Loam	-0.0525	0	0	0	-0.2521	0.0005	-0.0039	0.0032
Sandy Clay	-0.0019	0	0	0	-0.0064	3.71E-05	-0.0011	3.71E-05

Table 4. 4: Sensitivity Ratio by Increasing and Decreasing Input Parameters by 20%

SOIL TYPE	Run Off				Sediment Yield			
	Effective Hydraulic Conductivity	Interill Erodibility	Critical Shear	Rill Erodibility	Effective Hydraulic Conductivity	Interill Erodibility	Critical Shear	Rill Erodibility
Clay Loam	-0.2293	0	0	0	-4.1776	0.0022	-0.1422	1.9029
Clay	-0.0486	0	0	0	-4.7744	1.1922	-1.0696	0.8742
Sandy Clay Loam	-0.0526	0	0	0	-3.4103	0.0002	-0.0035	0.0515
Sandy Clay	-0.0021	0	0	0	-0.0257	3.41E-05	-0.0015	4.95E-05

The sensitivity analysis of GeoWEPP model showed that the increase of rill and interill erodibility resulted in the increase of sediment yield, while the decrease in effective hydraulic conductivity increases runoff and sediment yield. When the critical shear increases, the sediment yield decreases. From results presented in Tables 4.3 and 4.4, negative values indicate a decrease in output results with increase in input parameters, whereas positive values indicate the increase in output results with increase in input parameters. High sensitivity of the model to rill erodibilty compared to inter-rill erodibility indicate that rill erosion is more dominant in Mwogo sub-catchment. This was attributed to more concentrated overland flow caused by low infiltration rate that took place on agricultural land with tillage management on steep slopes. The findings of sensitivity ratio for the decrease and increase of 25% were not considered because the computed input parameters were found to be out of the recommended parameter range by Flanagan and Nearing (1995). Pandey *et al.* (2008), Ramsankaran *et al.* (2009), Al-Mukhtar *et al.* (2014) and Narimani *et al.* (2017), and also found out that simulated runoff and sediment yield from WEPP model were sensitive to effective hydraulic conductivity, critical shear, rill erodibility and inter-rill erodibility.

4.2.2 Calibration and Validation

The results of this study showed that the simulated annual runoff was 296.61 mm while the annual observed runoff was 308.17 mm for calibration period. Further, the GeoWEPP model predicted the annual runoff of 358.39 mm while the measured annual runoff was 385.56 mm for validation period. In assessing the GeoWEPP model performance on monthly runoff, a coefficient of determination of 0.75 and 0.88 was achieved for calibration and validation period as presented in Figures 4.4 and 4.5.

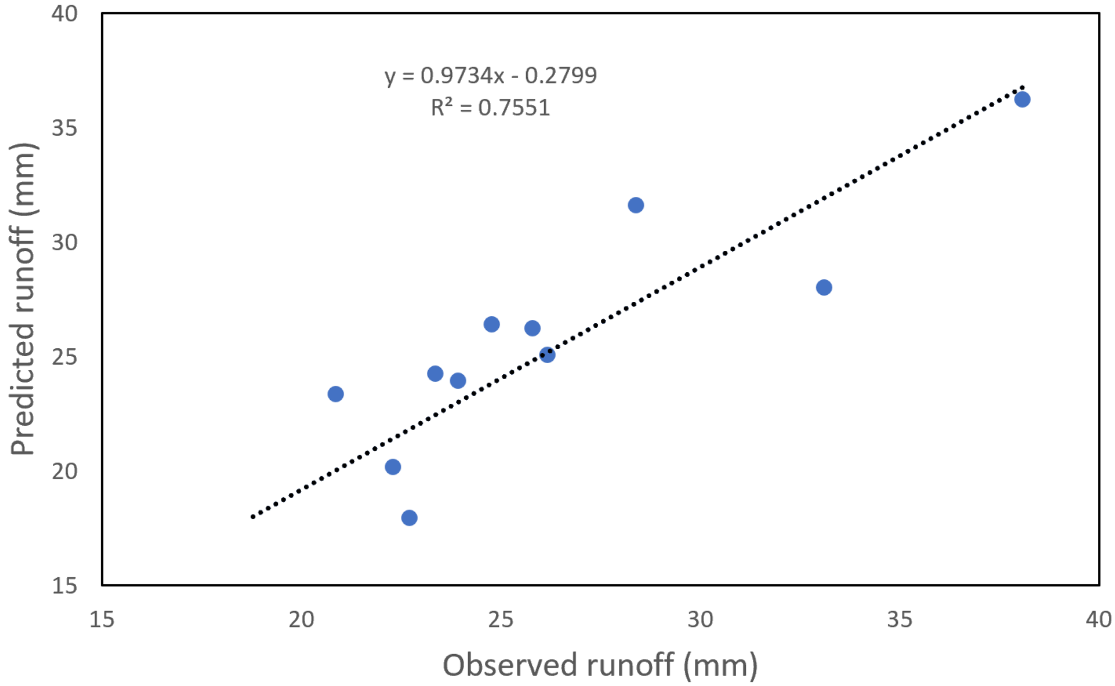

Figure 4. 4: Comparison between Observed and Simulated Monthly Runoff during Calibration Period

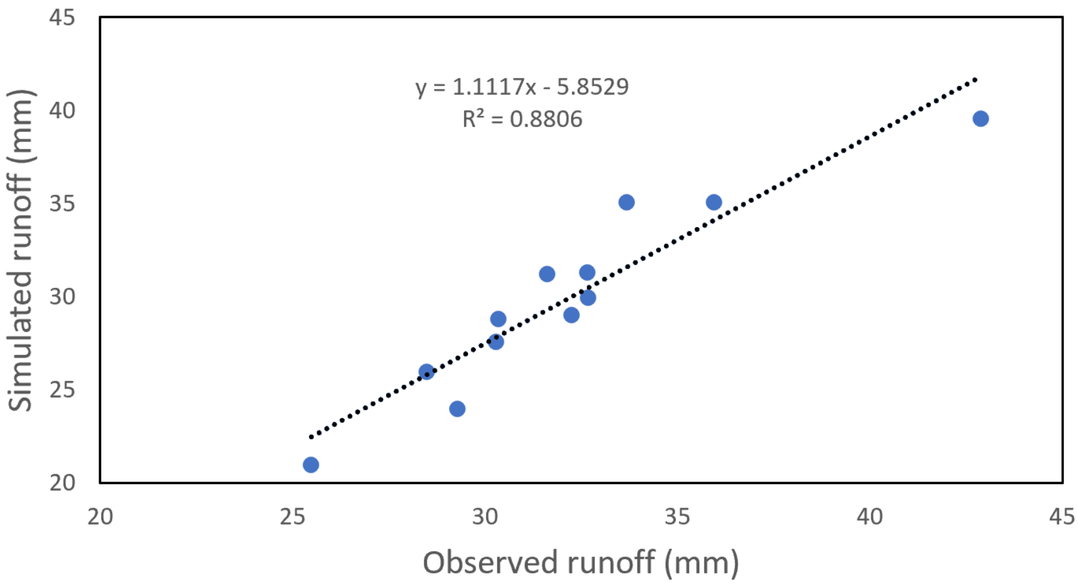

Figure 4. 5: Comparison between Observed and Simulated Monthly Runoff during Validation Period

The results on monthly runoff showed a PBIAS of 3.74 and 7.05 during calibration and validation period, respectively. According to Moriasi *et al*. (2015), the model performance was classified as satisfactory considering the coefficient of determination and PBIAS. In addition, considering the Nash–Sutcliffe model efficiency the GeoWEPP model was classified as satisfactory since values of 0.65 and 0.52 were achieved for the calibration and validation period, respectively. From the results, it can be observed that the model predicted well the monthly runoff for both periods although some results of runoff was underestimated or overestimated (Figures 4.6 and 4.7). The findings of this study on model performance using the selected statistical criteria closely agreed with those reported by (Al-Mukhtar *et al.*, 2014; Narimani *et al.*, 2017). Narimani *et al.* (2017) applied GeoWEPP model in Lighvanchai watershed and found coefficients of determination of 0.86 and 0.89 during calibration and validation period respectively. On the other hand, Al-Mukhtar *et al*. (2014) found a Nash–Sutcliffe model efficiency of 0.57 and 0.63 during calibration and validation respectively for a study conducted in the Bautzen dam catchment.

In the current study, it was observed that the GeoWEPP model captured the various seasonal flows (low and high) existing in Mwogo sub-catchment. Figures 4.6 and 4.7 show monthly observed and simulated runoff during calibration and validation period.

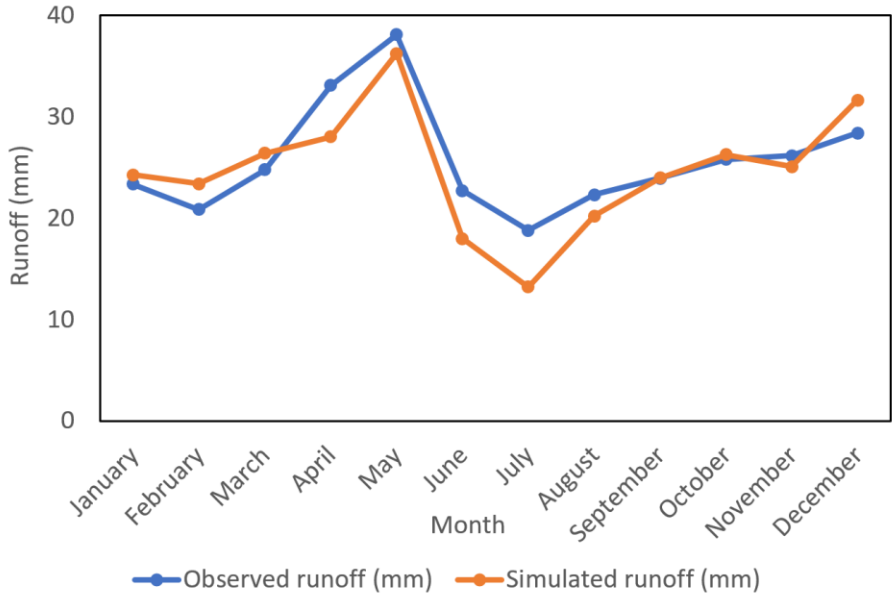

Figure 4. 6: Time Series of Observed and Simulated Monthly Runoff during Calibration Period

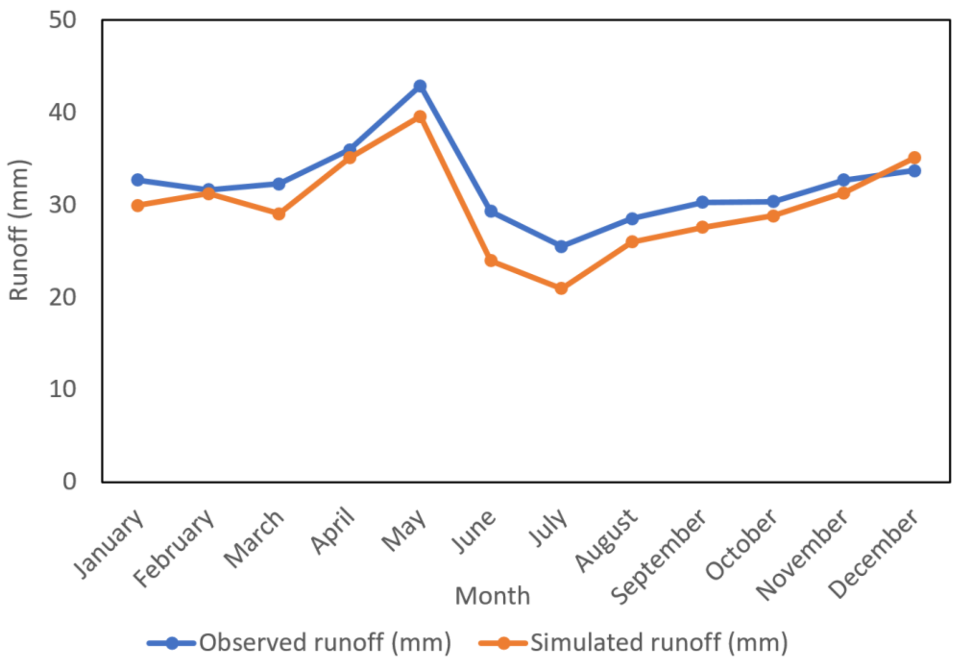

Figure 4. 7: Time Series of Observed and Simulated Monthly Runoff during Validation Period

The model performance results were found satisfactory and, thus the GeoWEPP model was used in estimating the runoff depth, soil loss and sediment yield for Mwogo sub-catchment over the 20 years' period.

4.3 Mwogo Sub-Catchment Runoff Depth, Soil Loss and Sediment Yield over a Period of 20 Years

The GeoWEPP model simulation predicted the average annual runoff depth and soil loss of 418.4 mm and 194.6 ton/ha, respectively. The predicted average annual runoff depth of Mwogo sub-catchment (418.4mm) was slightly higher than that of Nyabarongo reservoir catchment (385 mm) reported in RNRA (2015). In addition, sediment yield within Mwogo sub-catchment was found to be 25.4 ton/ha/year as presented in Table 4.5.

Table 4. 5: GeoWEPP Model Simulation Results under Current Land use/Land Cover

Parameter	Predicted	Unit
Average annual runoff depth	418.4	mm/year
Average annual total hillslope soil loss	9958773.7	ton/year
Average annual soil loss per unit area	194.6	ton/ha/year
Average annual sediment discharge from outlet	1298507.6	ton/year
Average annual Sediment delivery per unit area	25.4	ton/ha/year

Further, the spatial distribution of sediment yield within Mwogo sub-catchment is presented in Figure 4.8.

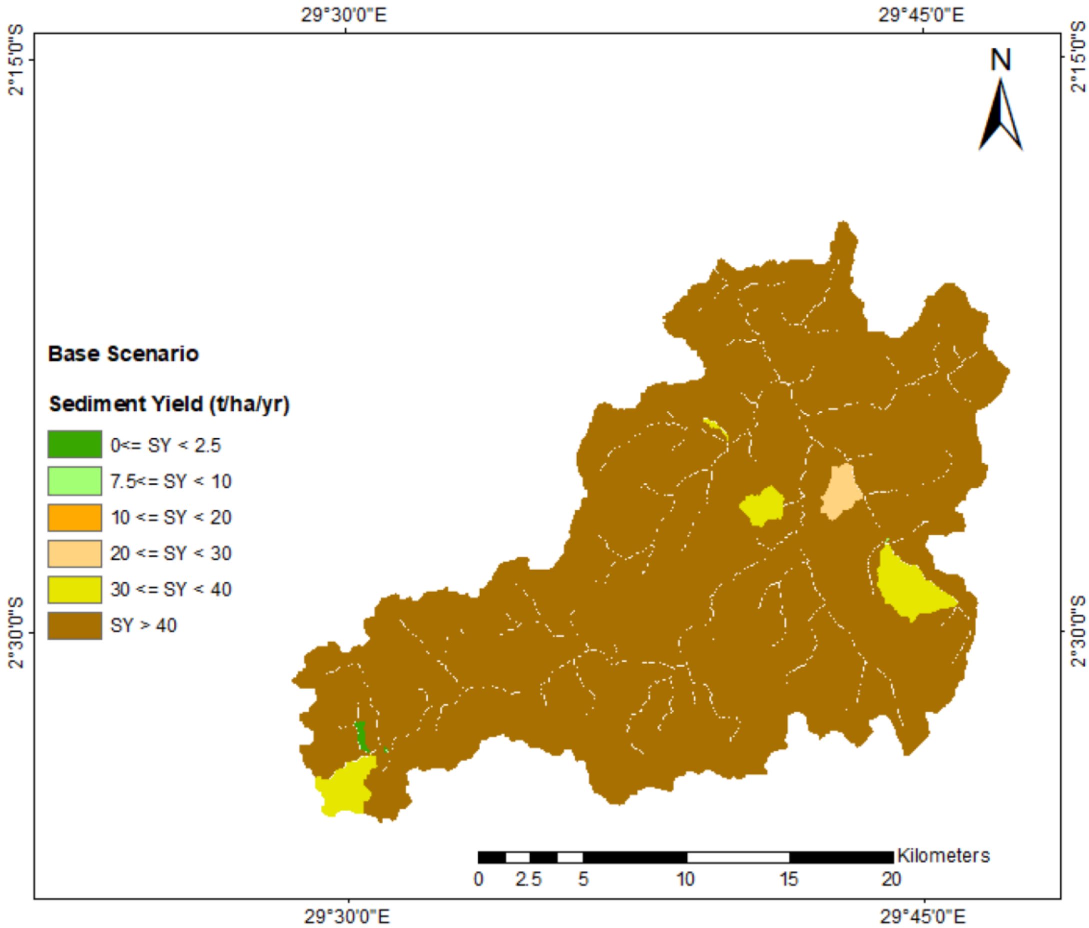

Figure 4. 8: Sediment Yield Map of Mwogo Sub-Catchment

Table 4. 6: Distribution of Sediment Yield within Mwogo Sub-catchment

Sediment Yield (ton/ha/year)	Area (ha)	Percentage (%)
0 <=SY< 2.5	56.25	0.110
7.5 <=SY< 10	2.52	0.005
10 <=SY< 20	0.09	0.000
20 <=SY< 30	336.15	0.658
30 <=SY< 40	1533.78	3.000
SY> 40	49192.47	96.227

The model predictions showed that 96.2% of the total sub-catchment area has sediment yield greater than 40 ton/ha/year (Table 4.6). The predicted soil loss of 194.6 ton/ha/year is very high compared to the tolerable soil loss limit of 10 ton/h/year. The high soil loss and sediment yield within Mwogo sub-catchment was attributed to inappropriate conservation practices and deforestation. The steep slopes and high rainfall intensity are also the drivers to increase the soil loss and sediment yield in the sub-catchment.

The soil erosion rate predicted by GeoWEPP model was found to be lower than the findings obtained by Karamege *et al*. (2016) in a study conducted in Nyabarongo river catchment by using USLE (490 ton/ha/year). This was attributed to the different soil types and land use/land cover, as well as different types of models used. Another study that was previously conducted on the extent of cropland and related soil erosion risk in Rwanda by Karamage *et al*. (2016) revealed that the mean soil erosion rate was higher than 10 ton/ha/year. The results of this study on high erosion are in agreement with the findings from other studies which showed that tilling associated with high slopes results in accelerating soil erosion (Narimani *et al.*, 2017; Puno *et al.*, 2020).

The highest soil erosion rate was found in agricultural land use/land cover. This is in agreement with the results reported by Karamage *et al*. (2016) in Nyabarongo river catchment, and elsewhere such as Gashaw *et al.* (2019) in Andassa watershed and Fu *et al*. (2006) in Pataha Creek watershed. The highest contribution of agricultural land use/ land cover to the soil erosion was attributed to the facts that agriculture is occupying the high percentage of the total surface area of the sub-catchment. Also, this type of land use / land cover is susceptible to high erosion rate.

4.4 Impacts of Conservation Practices and Land Use Changes in Reducing Soil Loss and Sediment Yield

4.4.1 Effect no Tillage Practice on Runoff Depth, Soil Loss and Sediment Yield

The results predicted by GeoWEPP model under no tillage Scenarios adopted for all agricultural land use (no tillage Scenario 1), and 25% of most critical hillslopes (no tillage Scenario 2) are shown in Table 4.7. Also, the findings simulated by the model for converting 50 % of most critical hillslopes to no tillage management (no tillage Scenario 3) are presented in Table 4.7.

Table 4. 7: Variations of Runoff Depth, Soil Loss and Sediment Yield under Base and no Tillage Scenarios 1, 2 and 3

Parameter	**Scenarios**			
	Base Scenario	**No Tillage Scenario 1**	**No Tillage Scenario 2**	**No Tillage Scenario 3**
Average annual runoff depth (mm)	418.4	315.1	356.9	332.7
Runoff depth reduction compared to BS (%)	0.0	24.7	14.6	20.5
Average Annual soil loss (ton)	9958773.7	967874.9	7110332.1	4774642.8
Average annual soil loss rate (ton/ha)	194.6	18.9	138.8	93.3
Soil loss rate reduction compared to BS (%)	0.0	90.3	28.6	52.1
Average annual sediment yield (ton)	1298507.6	37812	643821	309228.4
Average annual Sediment yield rate (ton/ ha)	25.4	0.7	12.6	6.0
Sediment yield reduction compared to BS (%)	0.0	97.2	50.4	76.1

Base Scenario (BS): Current land use/land cover with agricultural land use under tillage management

No Tillage Scenario 1: No tillage management practice adopted for all agricultural land use

No Tillage Scenario 2: No tillage management practice adopted for 25% of most critical hillslopes

No Tillage Scenario 3: No tillage management practice adopted for 50% of most critical hillslopes

The results of average annual runoff depth, soil loss and sediment yield predicted by GeoWEPP model within Mwogo sub-catchment under no tillage Scenario 1 was found to be 315.1 mm, 18.9 ton/ha and 0.7 ton/ha, respectively. Further, it was observed that the model simulated the average annual runoff depth of 356.9 mm, soil loss of 138.8 ton/ha, and sediment yield of 12.6 ton/ha under no tillage Scenario 2. In addition, the average annual runoff, soil and sediment yield were found to be 332.7 mm, 93.3 ton/ha and 6.0 ton/ha, respectively under no tillage Scenario 3.

The spatial patterns of sediment yield within Mwogo sub-catchment under no tillage Scenario 1 are shown in Figure 4.9.

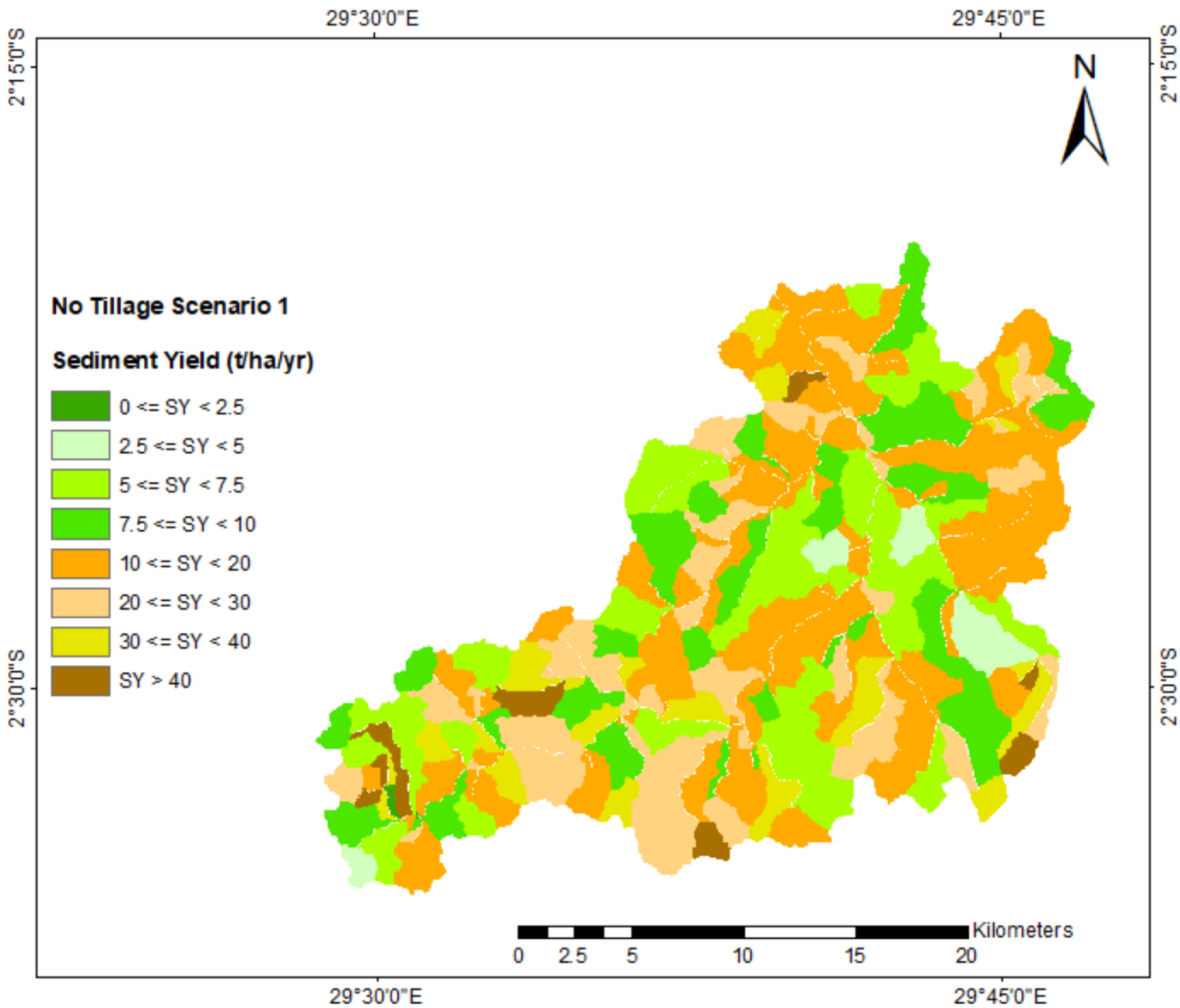

Figure 4. 9: Sediment Yield under no Tillage Scenario 1 in Mwogo Sub-catchment

It is observed that some hillslopes that were classified as having sediment yield greater than 40 ton/ha/year under the Base Scenario shifted to sediment yield classified between 5-7.5 ton/ha/year (20.2%), 7.5-10 ton/ha/year (16.6%) and 10-20 ton/ha/year (33.6%) under no tillage Scenario 1 as presented in Figure 4.9.

The results showed that Converting all agricultural land use to no tillage management reduced the average annual runoff depth, soil loss and sediment yield by 24.7%, 90.3% and 97.2%, respectively. On the other hand, adopting no tillage management to 25% of most critical hillslopes reduced runoff depth by 14.6%, soil loss by 28.6% and sediment yield by 50.4%. While the runoff depth, soil loss and sediment yield reduced to 20.5%, 52.1%, and 76.1%, respectively when no tillage was simulated on 50% of most critical hillslopes.

As shown in Table 4.7, the runoff depth predicted using the GeoWEPP model under no tillage Scenarios was found out to be less than the one predicted under Base Scenario. This reduction in runoff depth is due to the presence of crop residue resulting from no tillage management that would allow enough time for rainfall to infiltrate into the soil. The soil loss predicted under no tillage Scenarios 1, 2 and 3 show a reduction of 90.3%, 28.6% and 52.1%, respectively from the soil loss predicted under Base Scenario. This reduction of soil loss is influenced by minimal surface soil disturbance associated with no tillage management practice (Maalim *et al*., 2013). Tillage practices reduce crop residue which results in accelerating surface runoff and soil erosion, while no till practice reduce surface runoff, soil erosion and sediment yield by preventing rill generation (Fu *et al*., 2006; Luetzenburg et *al*., 2019).

The results of this study are in agreement with the findings of previous studies that showed that no till management practice reduces runoff depth, soil loss and sediment yield (Maalim *et al*., 2013; Alhassan *et al*., 2018). For instance, in the study carried out on modeling the impact of land use changes on runoff and sediment yield in Le Sueur watershed using the GeoWEPP model showed that no tillage management practice reduced surface runoff by 14%, soil loss by 79% and sediment yield by 78.5% (Maalim *et al*., 2013). In addition, another study conducted in Tono reservoir watershed for assessing the impact of land use changes on soil erosion and sedimentation using the GeoWEPP model revealed that runoff depth, soil loss and sediment yield reduced by 20.1%, 87.78% and 94.1%, respectively, and this is due to the change of management practices from fallow tilled to no till management practice (Alhassan *et al.*, 2018).

4.4.2 Effect of Land Use/Land Cover on Runoff Depth, Soil Loss and Sediment Yield

The findings predicted by the model when all agricultural land use was converted to grass land use (grassland Scenario 1) are presented in Table 4.9. Also, the results of converting 25% and 50% of most critical hillslopes to grass land use (grassland Scenarios 2 and 3) are shown in Table 4.8.

Table 4. 8: Simulation Results under Grassland Scenarios 1, 2 and 3

Parameter	Scenarios			
	Base Scenario	**Grassland Scenario 1**	**Grassland Scenario 2**	**Grassland Scenario 3**
Average annual runoff depth (mm)	418.4	230.2	328.5	293.1
Runoff depth reduction compared to BS (%)	0.0	44.9	21.4	30.0
Average Annual soil loss (ton)	9958773.7	420899.7	6068413.9	4293311.3
Average annual soil loss rate (ton/ha)	194.6	8.2	118.6	83.9
Soil loss rate reduction compared to BS (%)	0.0	95.7	39.1	56.8
Average annual sediment yield (ton)	1298507.6	353520.8	767684.7	470085.5
Average annual Sediment yield rate (ton/ ha)	25.4	6.9	15.0	9.1
Sediment yield reduction compared to BS (%)	0.0	72.8	40.9	64.2

Base Scenario (BS): Current land use/land cover with agricultural land use under tillage management

Grassland Scenario 1: Conversion of all agricultural land use to grassland

Grassland Scenario 2: Conversion of 25% of most critical hillslopes to grassland

Grassland Scenario 3: Conversion of 50% of most critical hillslopes to grassland

It was observed that the average annual runoff depth, soil loss and sediment yield predicted by the model were 230.2 mm, 8.2 ton/ha and 6.9 ton/ha, respectively under grassland Scenario 1. For grassland Scenario 2, the simulated results were found to be 328.5 mm, 118.6 ton/ha and 15.0 ton/ha, respectively. For grassland Scenario 3, the model output was predicted to be 293.1 mm, 83.9 ton/ha and 9.1 ton/ha, respectively (Table 4.8).

The spatial distribution of sediment yield within Mwogo sub-catchment under grassland Scenario 3 are shown in Figure 4.10.

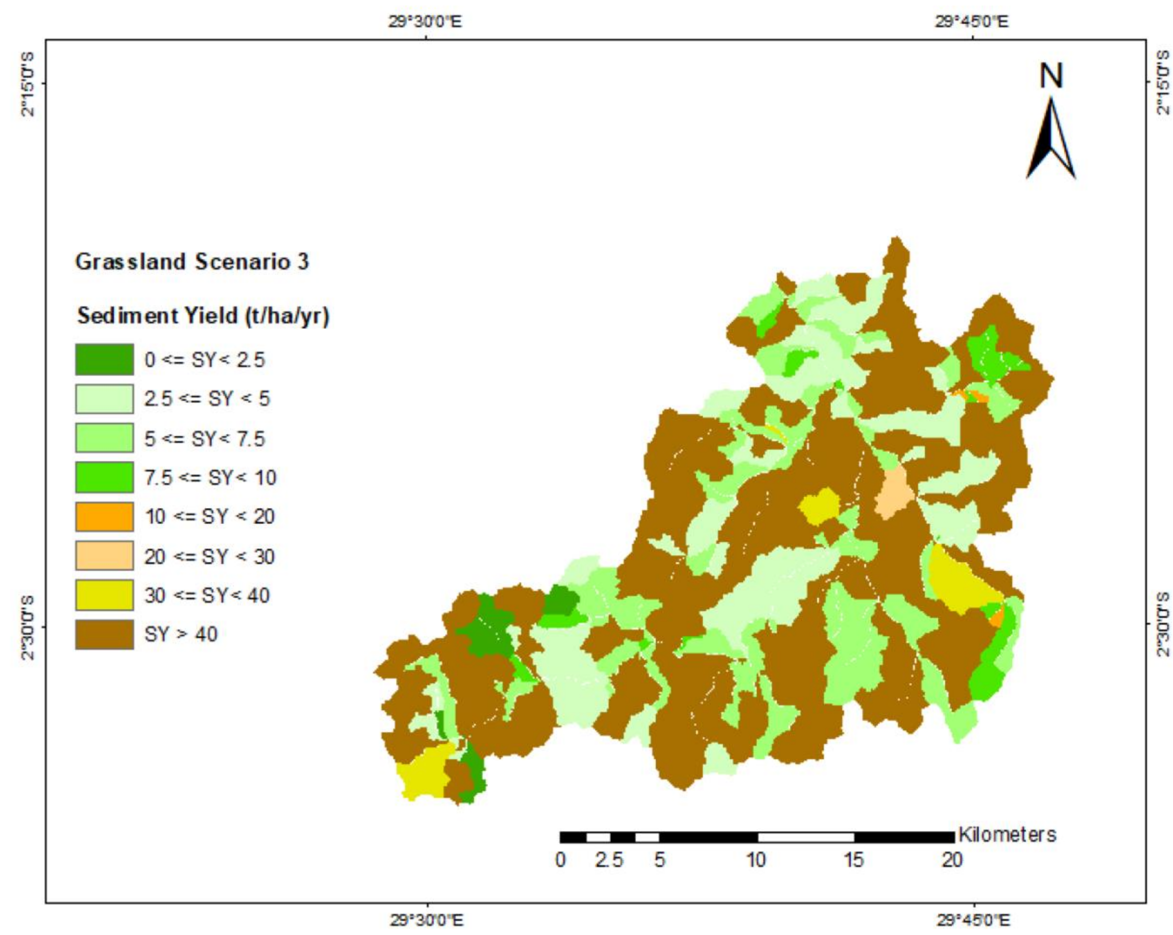

Figure 4. 10: Sediment Yield for Grassland Scenario 3 in Mwogo Sub-catchment

It is observed that some hillslopes that were classified as having sediment yield greater than 40 ton/ha/year under Base Scenario shifted to sediment yield classified between 2.5-5 ton/ha/year (17.1%), 5-7.5 ton/ha/year (16.0%) and 7.5-10 ton/ha/year (3.1%) under grassland Scenario 3 (Figure 4.10).

The findings of this study showed that by converting all agricultural land use to grassland reduced the average annual runoff depth, soil loss and sediment yield by 44.9%, 95.7% and 72.8%, respectively. On the other hand, converting 25% of most critical hillslopes from agricultural land use to grassland reduced runoff depth by 21.4%, soil loss by 39.1% and sediment yield by 40.9%. It was also observed that the runoff depth, soil loss and sediment yield reduced to 30.0%, 56.8%, and 64.2%, respectively when the grassland was simulated on 50% of most critical hillslopes.

As shown in Table 4.8, grassland Scenarios have led to significant reduction in soil loss, runoff and sediment yield in Mwogo sub-catchment. This is due to the increase of vegetation cover that reduces runoff through rainfall interception, infiltration and resistance to flow. The effectiveness of grassland in reducing soil loss and sediment yield have been reported in other studies (Hu *et al.*, 2017; Narimani *et al.*, 2017). Narimani *et al*. (2017) showed that grassland development decreased the surface runoff and sediment yield by 67% and 94%, respectively. Another study conducted by Hu *et al*. (2017) in the Loess Plateau of China revealed that grassland reduced the annual surface runoff by 50.60%.

Table 4.9 shows the results predicted by the model when all agricultural land use was converted to forest land use (forestland Scenario 1). Also, the findings of converting 25% and 50% of most critical hillslopes to forestland (forestland Scenarios 2 and 3) are presented in Table 4.9.

Table 4. 9: Simulation Results under Forestland Scenarios 1, 2 and 3

Parameter	Scenarios			
	Base Scenario	Forestland Scenario 1	Forestland Scenario 2	Forestland Scenario 3
Average annual runoff depth (mm)	418.4	283.2	340.5	313.4
Runoff depth reduction compared to BS (%)	0.0	32.3	18.6	25.1
Average Annual soil loss (ton)	9958773.7	479455.4	6469621.3	5131345.6
Average annual soil loss rate (ton/ha)	194.6	9.4	126.4	100.3
Soil loss rate reduction compared to BS (%)	0.0	95.2	35.0	48.5
Average annual sediment yield (ton)	1298507.6	393520.8	971677	571817.9
Average annual Sediment yield rate (ton/ ha)	25.4	7.7	18.9	11.2
Sediment yield reduction compared to BS (%)	0.0	69.7	25.6	55.9

Base Scenario (BS): Current land use/land cover with agricultural land use under tillage management

Forestland Scenario 1: Conversion of all agricultural land use to forestland

Forestland Scenario 2: Conversion of 25% of most critical hillslopes to forestland

Forestland Scenario 3: Conversion of 50% of most critical hillslopes to forestland

The spatial distribution of sediment yield within Mwogo sub-catchment under forestland Scenario 3 are shown in Figure 4.11.

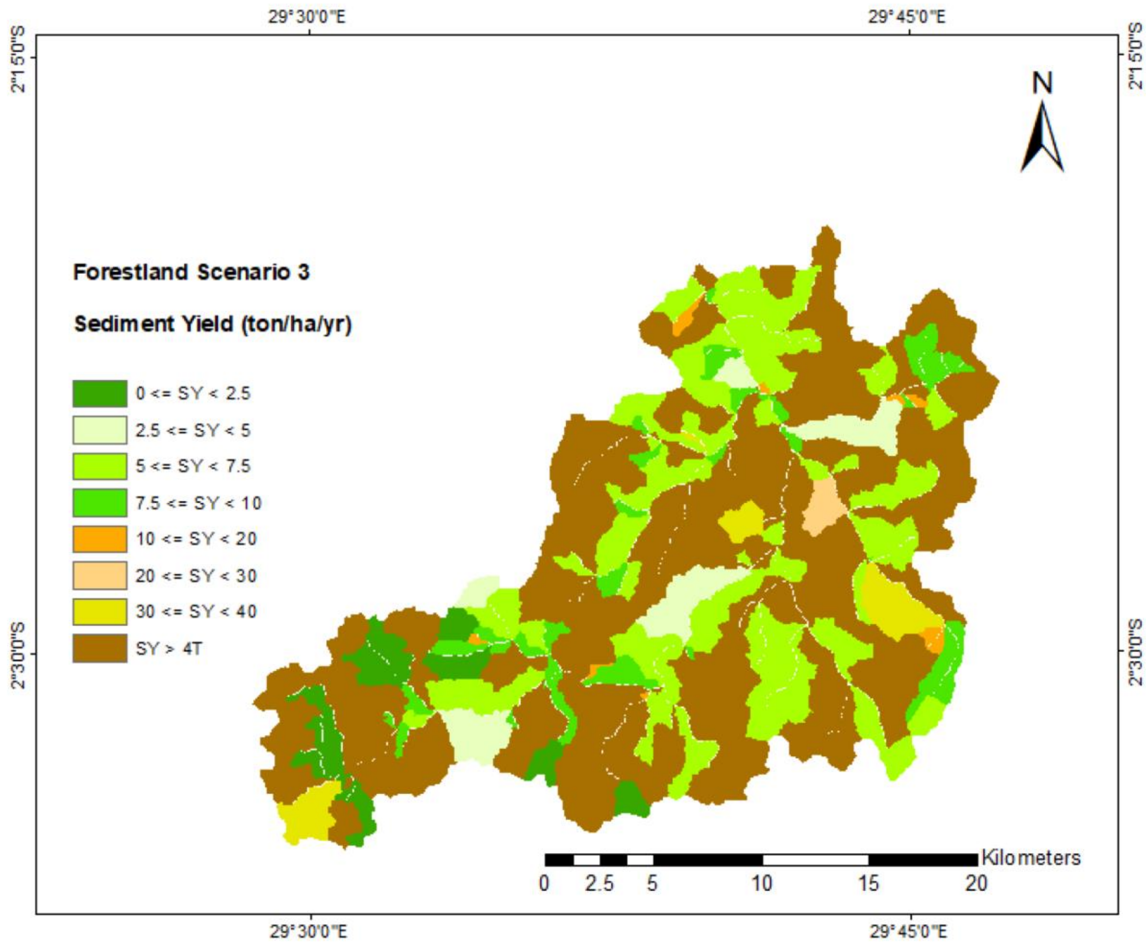

Figure 4. 11: Sediment Yield for Forestland Scenario 3 in Mwogo Sub-catchment

From Figure 4.11, it is observed that some hillslopes that were classified as having sediment yield greater than 40 ton/ha/year under the Base Scenario shifted to sediment yield classified between 0-2.5 ton/ha/year (4.6%), 2.5-5 ton/ha/year (4.7%), 5-7.5 ton/ha/year (22.6%) and 7.5-10 ton/ha/year (5.5%) under forestland Scenario 3.

Compared to the Base Scenario, converting all agricultural land use to forestland resulted to a reduction of 32.3%, 95.2% and 69.7% for runoff depth, soil loss and sediment yield, respectively. While the reduction of 18.6 %, 35% and 25.6% was observed when 25% of most critical hillslopes were converted to forest land use. On the other hand, the runoff depth, soil loss and sediment yield reduced to 25.1%, 48.5%, and 55.9%, respectively when forestland was simulated on 50% of most critical hillslopes. This reduction rate is influenced by the forest that reduces the kinetic energy of raindrops and the hydrodynamic power of flowing water. Also, the forest increases interception, protects the ground surface from the impact of raindrops and it increases the rate of infiltration by reducing the surface runoff and soil erosion (Xinxiao *et al*., 2013).

The study conducted by Mingjun *et al*. (2019) on impacts of forest restoration on soil erosion in the three Gorges Reservoir area, China revealed that the conversion of cropland to forestland resulted into a decrease of mean annual soil erosion rate by 1.28%. Similarly, Zuo *et al*. (2016) showed that the increase of forestland in the Huangfuchuan catchment reduced the surface runoff and sediment yield by 25.3% and 40.6%, respectively. In addition, Zhang *et al*. (2015) reported that forestland decreased the runoff by 44.7% and sediment yield by 43.7% in a study conducted in the hilly Watershed of Southern China.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study assessed the impact of land use changes and conservation practices on soil loss and sediment yield in Mwogo sub-catchment using GeoWEPP model. From the results obtained in this study, it was concluded that:

i. The simulated runoff is sensitive to effective hydraulic conductivity only, while sediment yield is sensitive to critical shear, effective hydraulic conductivity, rill and interrill erodibility. The GeoWEPP model evaluation showed a satisfactory model performance with coefficient of determination, Nash-Sutcliffe Efficiency, and Percent Bias of 0.75, 0.65 and 3.75, respectively for calibration and 0.88, 0.52 and 7.05, respectively for validation;
ii. The average annual runoff depth, soil loss and sediment yield in Mwogo sub-catchment were predicted to be 418.4 mm, 194.6 ton/ha and 25.4 ton/ha, respectively. Therefore, soil loss and sediment yield within Mwogo sub-catchment are severe and above the annual tolerable soil loss limit of 10 -12 ton/ha; and
iii. The no tillage management practice, grassland and forestland Scenarios adopted for all agricultural land use as well as on 25%, and 50% of most critical hillslopes can be used to reduce runoff depth, soil loss and sediment yield of Mwogo sub-catchment. Reduction in runoff depth, soil loss and sediment yield were found to range between 14.6-44.9%, 28.6-95.7% and 25.6-97.2%, respectively.

5.2 Recommendations

In order to get better results to help the water resource managers make informed decisions for sustainable management of sediment yield within the Mwogo sub-catchment of Nyabarongo reservoir catchment, there is need to establish a comprehensive hydro-meteorological database for the catchment. This study therefore recommends the following:

i. Establishment of more hydrological gauging stations for streamflow and sediment measurements that will provide long term and continuous datasets;

ii. Further studies that cover the entire Nyabarongo reservoir catchment be carried out since the present study focused on Mwogo sub-catchment. This will help to quantify soil loss and sediment yield originating from other sub-catchments; and

iii. Further research work to be carried out using other soil erosion and sediment yield models for comparison of their performance and hence help in selecting the appropriate sediment yield prediction model(s).

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