



UNIVERSITY of
RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY
SCHOOL OF ENGINEERING

DEPARTMENT OF CIVIL, ENVIRONMENTAL AND GEOMATIC ENGINEERING

ACCEPTED PHD THESIS

PhD thesis title: **SOIL EROSION POTENTIAL AND ITS CONTROL IN THE
SEBEYA CATCHMENT, RWANDA**



This thesis was submitted in partial fulfillment of academic requirements for the award of the degree of DOCTOR OF PHILOSOPHY in Water Resources Engineering

By: Félicien MAJORO

Supervised by:

Professor Umaru Garba WALI (Main supervisor, UR-CST)


Professor Omar MUNYANEZA (Co-supervisor, UR-CST)

Professor Francois-Xavier NARAMABUYE (Co-supervisor, UR-CAVM)

April 2021

DECLARATION

I, **Félicien MAJORO**, do hereby declare that this research project, being submitted to the University of Rwanda for the degree of **DOCTOR OF PHILOSOPHY in Water Resources Engineering**, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the University of Rwanda, and has not been submitted before to any institution by myself or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Félicien MAJORO 
University of Rwanda
Student number: 218014110
Date: 21st April 2023

EXTERNAL EXAMINERS:

Prof. Roberto VALENTINO

University of Parma

Faculty of Engineering

Department of Civil, Environmental, Territory Engineering and Architecture.

Telephone: 0521906112

Email: roberto.valentino@unipr.it

and

Prof. (Eng.) Sibilike Khamala MAKHANU

Masinde Muliro University of Science and Technology

Department of Civil and Structural Engineering

School of Engineering and Built Environment (MMUST)

Telephone: +254733798997


Email: smakhanu@mmust.ac.ke

Félicien MAJORO (Reg. No: 218014110) has successfully defended his PhD thesis entitled *“SOIL EROSION POTENTIAL AND ITS CONTROL IN THE SEBEYA CATCHMENT, RWANDA”* on 21st April 2023 after fulfilling all other requirements specified in the Academic Regulations for PhD by research at the University of Rwanda.

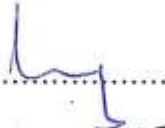
PHD THESIS SUPERVISORS:

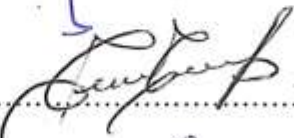
Prof. Umaru Garba WALI, Main Supervisor:  15th May 2015

Prof. Omar MUNYANEZA, Co-Supervisor:  15th May 2023

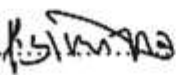
Prof. Francois-Xavier NARAMABUYE, Co-Supervisor:  15th May 2023

PHD THESIS VIVA VOCE DEFENSE MEMBERS:

Prof. Telesphore KABERA (Chairman):  15.05.2023

Prof. Emmanuel TWARABAMENYE:  15.05.2023

Prof. Leopold MBEREREYAHU:  15/05/2023

Dr. Hussein BIZIMANA:  15th May 2023

Date of submission: 06th February 2023

Date of defense: 21st April 2023

To my wife

FOREWORD

My teaching experience at University of Rwanda (UR) started at the former Kigali Institute of Science and Technology (KIST) on 01 Mar 2001 as Assistant Lecturer in the Department of Civil and Environmental Technology where I got my 1st promotion on 05 January 2005 as Lecturer in the same department. At that time, the idea of doing a PhD research was not yet in my mind because there was no possibility of doing PhD locally in Rwanda.

The naissance of University of Rwanda in 2013 was characterized with diversified PhD studies which incited me to think about the possibility of doing a PhD per research locally at UR. Simply, a local PhD was found to be more economically feasible at UR.

Through our discussions during the tea-break at Nobleza Workshop on 05 May 2015, Professor Umaru Garba WALI (Dean of SoE at UR-CST) and Professor M. SANKARANARAYANAN (Dean at UR-CAVM) told me: *“You are able to publish a PhD thesis with your 15 years experience of teaching in a higher learning institution”*. These encouragements stimulated me to start my PhD.

The contribution to a better understanding of soil erosion processes and control of it for a sustainable environmental management in the Sebeya catchment was agreed when the idea of doing my PhD research was grown sufficiently to be put in action in 2016. This was the time when I approached Professor Omar MUNYANEZA with a proposal of 3 topics formulated. Professor Omar MUNYANEZA encouraged me to develop more on the actual formulated PhD research topic and approved my proposal to be supervised by Professor Umaru Garba WALI, the current Dean of the School of Engineering at UR. At that time, Professor Umaru Garba WALI accepted to be the main supervisor and Professor Omar MUNYANEZA the co-supervisor.

I submitted my application for PhD per research at UR on 18 Mar 2016 and I got my admission for PhD program at UR-CST on 09 Jan 2017. My registration in year one of PhD studies at UR dated on 15 June 2017.

When I submitted my application to UR for tuition fee waiver on 29 August 2017, the Vice-Chancellor reacted saying that my PhD topic was a multidisciplinary topic and he recommended to include a soil science specialist from CAVM. That’s why the main supervisor has proposed Professor Francois-Xavier NARAMABUYE to be a 2nd co-supervisor for this PhD research on 10

May 2018. On 26 June 2018, I got approval of my PhD Tuition Waiver request by The UR Vice Chancellor.

Parallel to the application for tuition fee waiver, I was firstly busy with the writing of a review paper. But the main challenge was about to find a supporting fund to help in data collection. On 15 February 2017, I submitted my application for UR-Sweden PhD grant and by chance on 29 May 2018 I won a UR-Sweden PhD research grant of 9,000,000 Rwf to help me in field data collection.

In Rwanda, 80% of economy is mostly based on agriculture (Munyaneza et al., 2016). This research held to know the situation of soil erosion by investigating its causes and factors affecting it and by analysing the current status of its control for an ultimate objective of sustainable environmental management in the Sebeya catchment located in Western Province of Rwanda. Site visits, questionnaire and interviews, simulations and predictions of soil loss and crop yields were used to carry out this work.

Economic constraints were found to be the main limitative factors against the implementation of soil erosion control measures in the Sebeya catchment. Also, the majority of farmers suggest trainings and mobilization of a specialized technical team to assist them in implementing soil conservation measures and to generalize the application of fertilizers in the whole catchment.

This study provided a clear knowledge to farmers on various Best Management Practices (BMPs): benefits of cultivation of suitable cover crops, implementation of soft BMPs (mulching, crop rotation, no tillage, strip ploughing, use of vegetation for slope stabilization, etc.) and adoption of hard soil erosion control measures like radical terraces and anti-erosive ditches which will minimize soil erosion in the Sebeya catchment agricultural fields.

This PhD research allowed me to monitor on-site and off-site effects of soil erosion particularly its impacts on socio-economic development projects in the Sebeya catchment. The uniqueness of this research is that it has designed a Soil Loss and Crop Yield (SOLCY) model to focus on the parcel soil loss and to predict crop yield for sustainable land management decisions in the Sebeya catchment. Farmers, District agriculture planners and technicians in the Sebeya catchment can use SOLCY model.

Along this PhD study, my capacity building has increased as a result of compiling different research and teaching-methodologies from various authors. I learned a lot about various soil

erosion processes and diversified best management practices to be applied in a catchment for its control. During this multidisciplinary research, I also gained large experience in sampling and testing protocols for bed load analysis and water sampling for suspended load, turbidity and NPK nutrients fluctuations in rivers of level-2 like the Sebeya river. In addition, the challenges encountered and way forward during the planning and monitoring of the field experiments in soil erosion plots and in conducting the farmers interviews constituted a strong pillar to my future research in experiments design and analysis. My 2 published papers in the Sustainability Journal, which is a SCI journal, opened my eyes on how to publish in peer-review journals. PhD, MSc and BSc students in Water and Environmental Management and Engineering, Applied Sciences and Agriculture Programmes in Rwanda will benefit from my experience. This study is limited to the Sebeya catchment but worldwide researchers will find through this PhD by research an appropriate methodology and procedures allowing to duplicate the designed Soil Loss and Crop Yield (SOLCY) model to other catchments.

Félicien MAJORO
University of Rwanda
April 2023

ACKNOWLEDGEMENTS

Glory goes to God for blessing our life and protecting us.

Many thanks to the University of Rwanda for having given me admission, tuition fees waiver and integration in these doctoral studies.

I would like to express my profound gratitude to my main supervisor Professor Umaru Garba WALI and co-supervisors Professor Omar MUNYANEZA and Professor Francois-Xavier NARAMABUYE who accepted to supervise and mentor this PhD research and for their limitless guidance and persistent help.

Also, I wish to express my thanks to Dr. Gershome ABAHO (Head of Department of Civil, Environmental and Geomatics Engineering) for his support and cooperation received during the progress of this PhD research. My deepest thanks to laboratory technicians in UR-CST Environmental Engineering and soil mechanics laboratories for providing their technical advice, information and support on different aspects of my PhD research.

This research project could not be started without the help of the UR-Sweden Programme for the financial support as a UR-Sweden PhD Grant won for one year to conduct field works from 01 July 2018 to 30 June 2019 for this PhD research.

I would like to extend my thanks to Mr Laurent TUYISINGIZE for accepting to assist me in field monitoring and sampling during all field activities. I am also thankful to the guidance, technical support, friendless and care received from all assistant researchers (Eng. Theogene HABUMUREMYI⁺, Eng. Theogene INGABIRE, Mr Adrien MUGABUSHAKA, Mr Athanase TWAGIRIMNA, Mr Jean de Dieu NSABIMANA) and colleagues.

I would also like to particularly thank Prof. Leopold MBEREYAHU, Eng. Jean Bosco NDAYISENGA, Dr Abias UWIMANA, Eng. Salathiel MUNDELI and Dr Derrick Eric BUGENIMANA for accepting to make proofreading and their constructive comments for this PhD thesis. My special gratitude is also addressed to Prof. Telesphore KABERA, Dr Philibert NSENGIYUMVA, Eng. Romuald BAGARAGAZA, and Mrs Concilie MUKAMWAMBALI for their support and motivation along my PhD studies.

Finally, I would like to express my deepest appreciation to all people, directly or indirectly, who helped me in addressing my PhD research works at various stages.

SUMMARY

Soil erosion is one of the major causes of land degradation because it results into soil denudation with main consequences of low agriculture productivity and food insecurity. Located in the Western Province of Rwanda, the Sebeya catchment is characterized by high altitude varying between 1,462 m to 2,979 m a.s.l. (meters above sea level). The Sebeya catchment is also characterised by steep slopes and abundant rainfall (1,200 mm to 1,700 mm per year). The combination of the geological formation and soil data characterizes the Sebeya catchment as a fragile ecosystem susceptible to heavy erosion. The transported sediments lead to scour on bridge, increase pollutants in water bodies and reduce the performance of hydropower plants constructed along the Sebeya river. Soil erosion is an environmental issue which can be avoided by maintaining a protective cover on the soil to prevent the impact of rain drops or to reduce the runoff and the infiltration of rain water. A similar result can also be achieved by modifying the landscape to control runoff amounts and rates.

The main objective of this study is the assessment of the spatial-temporal distribution of soil erosion and future-based remedial measures to control soil erosion on agricultural land of the Sebeya catchment to contribute to sustainable agriculture and environment protection. This research has specifically focused on the following specific objectives: (1) Assessment of soil erosion process and LULC changes in the Sebeya catchment; (2) Development of runoff coefficients and soil erodibility factors in the Sebeya catchment; (3) Assessment of Sebeya river sediment transport and its impacts in relation to rainfall events; (4) Proposal of future-based remedial measures on agricultural land against soil erosion; (5) Development of an erosion control model for farming systems and soil loss in the Sebeya catchment.

During the study period, different site visits were frequently conducted to get primary data through informal and structural interviews on main cultivated crops and agriculture practices, main features of the Sebeya river, site topography, hydrographic network, soil characteristics and about the existing soil erosion control measures in the Sebeya catchment. Literature review was used to know about the status of soil erosion and its control measures throughout the world and particularly in the Sebeya catchment. DEM data have been collected from the Center of Geographical Information System (CGIS Rwanda) for delineation of the Sebeya catchment. ArcGIS software was used to delineate the catchment and its sub-catchments and for mapping all USLE factors. The

input data including Digital Elevation Model (DEM), soil data, rainfall data, land use / land cover data were collected from the Center of Geographical Information System of University of Rwanda (CGIS UR). To assess the impacts of the Sebeya river sediment load on Gihira water treatment plant, 3 hydropower plants (Keya, Gihira and Gisenyi) and Lake Kivu, water samples were hand-collected from five different sampling points along the Sebeya river during rainy and dry seasons. Laboratory analysis for turbidity, total suspended solids, sieve analysis for bed load materials and NPK content of water and bed load samples were conducted. Agro-climatological data were required for planning crops cultivation and field experiments in soil erosion plots. The proposed methodology was much concerned with the performance assessment and suitability of various best management practices of soil erosion control for the Sebeya catchment.

In an effort to achieve the objectives of this PhD research, the 1st activity has gathered worldwide literature views on various causes, effects and remedial measures of soil erosion. From 75 farmers interviewed during this PhD research, it was clear that the main natural causes of soil erosion in the Sebeya catchment are heavy rainfall (69.33%) and the slope steepness (28%) (Section 4.A.1). This study also assessed the various preventive measures against the soil surface crusting and the development of runoff coefficients in order to minimize the soil loss in the Sebeya catchment agricultural fields. The results from the field experiments showed that the mulched plot had high moisture content with low runoff and soil loss compared to 2 other plots (Section 4.A.2). This research revealed also that the average turbidity and suspended solids concentrations in the the Sebeya river were found to be high during rainy season compared to dry season. At all 5 sampling sites and during rainy season compared to dry season, the average mass flowrates of bed load materials were 7.84 and 2.96 kg/hr respectively. Sieve analysis results showed that all bed load sediments were mainly composed of high proportions of fine sand from which more than 70% adversely cause damages on hydropower turbines. In addition, the effect of high soil erosion rates on Gihira water treatment plant was indicated by high turbidity of raw water and excessive costs of reagents. At the Sebeya river outlet, nutrients load and high turbidity reduce significantly the aesthetic quality of Lake Kivu, having a harmful impact on recreation and tourism, aquatic life and affect the livelihoods of people living in the vicinity (Section 4.A.3). Farmers in the Sebeya catchment have not yet implemented sufficient soil erosion control measures in such a way that the estimated average soil loss from the whole catchment area was 130.724 t/ha/yr in 2012 and 100 t/ha/yr in 2018, which is extremely high. The same farmers interview has revealed that among

the 22 existing soil erosion control measures, about 4.57% of farmers confirmed their existence while 95.43% expressed the need of their implementation in the Sebeya catchment (Section 4.A.4). Simulating a combination of 0, 1, 2 and 3 soil erosion control measures on each of the 259,673 parcels, the average of the simulated annual soil loss from the Sebeya catchment was 849.94; 143.27; 88.64 and 28.59 t/ha/yr respectively. Soil Loss and Crop Yield (SOLCY) model has been developed to predict soil loss and crop yields on each of the 13 main cultivated crops in the Sebeya catchment. A combination of 3 soil erosion control measures such as (bench terrace + mulching + drainage channels) has been found to be the most effective in reducing soil erosion on each parcel with a slope range of (16-60) % (Section 4.A.5).

Assessing the sediment load fluctuations in the Sebeya river is useful for water managers and planners to adjust operations accordingly at the water treatment and hydropower plants. Finally, soil erosion control measures including agro-forestry, terraces, mulching, tree planting, contour bunds, vegetative measures for slopes and buffer zones, check dams, riverbanks stabilization are proposed and recommended to be implemented in the Sebeya catchment. Public and private land conservation agencies should be more involved in soil management centred on farmer's awareness and capacity building. The majority of farmers suggested trainings and mobilization of a specialized technical team to assist them in implementing soil conservation measures and make sure that the fertilizers application is properly done in the whole catchment. Farmers and agriculture technicians can use SOLCY model to focus on the parcel soil loss and predicted crop yields for sustainable land management decision makings. Worldwide researchers should develop similar models on other catchments based on SOLCY model design concept.

Various factors influencing farmers' perceptions of soil erosion causes, effects, and willingness to adopt soil erosion control measures were analyzed using descriptive statistics and SPSS (Version 20), including t-tests, chi-square tests, and a binary logistic regression model. Chi-square test results indicate that gender, farmer age, land ownership, farmland size, social media access, and credit access were strongly associated ($p < 0.05$) with the adoption of SEC measures, while marital status and education were not. A binary logistic regression model showed that among farmers' socioeconomic characteristics, farming experience ($B = 0.749$; $p = 0.020$) and access to socio media ($B = 2.107$; $p = 0.027$) were positively correlated, while age ($B = -0.642$; $p = 0.035$) and gender ($B = -2.034$; $p = 0.032$) were negatively correlated ($p < 0.05$) with the adoption of SEC measures (Section 4.B.1).

Simulating the existing and the site-based recommended soil erosion control measures, soil loss was reduced significantly from 73 t/ha/yr to 29 t/ha/yr. To highlight the implication of the site-based recommended SEC measures in improving agricultural productivity, this study suggests field investigations in soil erosion plots and prediction of crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya catchment. For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya catchment, the present research recommends implementing the site-based recommended soil erosion control measures with mulching and drainage channels on the same farmland (Section 4.B.2).

Keywords: Sebeya catchment, erosion effects, erosion control measures, erosion modelling, crop yield, Rwanda

TABLE OF CONTENTS

DECLARATION	i
FOREWORD	iv
ACKNOWLEDGEMENTS	vii
SUMMARY	viii
LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS	xviii
LIST OF TABLES	xxi
LIST OF FIGURES	xxiii
CHAPTER 1. GENERAL INTRODUCTION	1
1.1 BACKGROUND.....	1
1.2 PROBLEM STATEMENT	2
1.3 OBJECTIVES	4
1.3.1 Main objective	4
1.3.2 Specific objectives	4
1.4 RESEARCH QUESTIONS.....	5
1.5 SIGNIFICANCE OF THE STUDY	5
1.5.1 Farmers benefits	5
1.5.2 Government benefits.....	5
1.5.3 Scientific significance.....	5
1.5.4 Personal benefits.....	6
1.6 SCOPE OF THE STUDY	6
1.7 LIMITATIONS OF THE STUDY	6
1.8 THESIS OUTLINE.....	6
CHAPTER 2. LITERATURE REVIEW	8
2.1 INTRODUCTION.....	8
2.2 SOIL EROSION MEASUREMENT: APPLICATION OF SOIL EROSION MODELS	9
2.2.1 Soil erosion measurement.....	9

2.2.2 Models inventory and classification	10
2.2.3 Historical aspects and evolution of USLE-type modelling	12
2.3 SEDIMENT TRANSPORT AND ITS IMPACTS ON SOCIO-ECONOMIC DEVELOPMENT PROJECTS	13
2.4 BMPS OF SOIL EROSION CONTROL	15
2.4.1 Soft BMPs.....	16
2.4.2 Hard BMPs	18
2.4.3 Limitative factors on the implementation of soil erosion control measures.....	22
2.5 RESEARCH GAPS.....	22
CHAPTER 3. MATERIALS AND METHODS.....	24
3.1 STUDY AREA.....	24
3.1.1 Site localization	24
3.1.2 Population density	25
3.1.3 Soil characteristics	25
3.1.4 Site topography.....	26
3.1.5 Climate.....	26
3.1.6 Land use / Land cover	26
3.1.7 Hydrography of the Sebeya catchment.....	27
3.2 DATA COLLECTION.....	28
3.2.1 Secondary data collection.....	28
3.2.2 Primary data collection.....	29
3.3 DATA ANALYSIS	37
CHAPTER 4. RESULTS AND DISCUSSIONS	39
PART A. PRELIMINARY INVESTIGATIONS	39
4.A.1 FARMERS PERCEPTIONS ON SOIL EROSION IN THE SEBEYA CATCHMENT	39
A.1.1 Introduction.....	39
A.1.2 Methodology	40
A.1.3 Research outcomes.....	40
A.1.3.1 Identification of respondents	40
A.1.3.2 Socio-economic issues of farmers	40

A.1.3.3 Farmers knowledge about soil erosion and types of soil erosion in catchment	40
A.1.3.4 Spatial distribution of soil erosion in the Sebeya catchment.....	42
A.1.3.5 Causes of erosion in the Sebeya catchment.....	44
A.1.3.6 Effects of soil erosion in the Sebeya catchment.....	46
A.1.4 Concluding remarks	47
4.A.2 ASSESSMENT AND PREVENTION STRATEGIES OF SOIL SURFACE CRUSTING CAUSED BY RAINFALL EVENTS IN THE SEBEYA CATCHMENT AGRICULTURAL LAND	48
A.2.1 Introduction.....	48
A.2.2 Methodology	48
A.2.3 Research outcomes.....	48
A.2.3.1 Soil characteristics in the Sebeya catchment.....	48
A.2.3.2 Soil tests and soil classification.....	49
A.2.3.3 Effects of rainfall on various scenarios of land cover	50
A.2.3.4 Effect of land cover on soil loss and runoff coefficient	50
A.2.3.5 Development of rills and interrills in the experimental field	52
A.2.3.6 Effect of rainfall intensity on soil erodibility	53
A.2.3.7 Effect of rainfall on soil crusting.....	54
A.2.3.8 Benefits from investigations in erosion plots to the farmers in the Sebeya catchment	56
A.2.4 Concluding remarks	56
4.A.3 ASSESSMENT OF THE SEBEYA RIVER SEDIMENT TRANSPORT AND ITS IMPACTS IN RELATION TO RAINFALL EVENTS	57
A.3.1 Introduction.....	57
A.3.2 Methodology	57
A.3.3 Research outcomes.....	58
A.3.3.1 The Sebeya river water quality fluctuations.....	58
A.3.3.2 Monitoring discharge, bed load rates and water quality of the Sebeya river	58
A.3.3.3 Impacts of the Sebeya river sediments on Keya, Gihira and Gisenyi hydropower plants	61
A.3.3.4 Impacts of soil erosion on Gihira water treatment plant	62
A.3.3.5 Estimation of Nutrients (NPK) in the Sebeya river.....	64
A.3.3.6 Effects of sediment load on the performance of Gihira WTP	65

A.3.3.7 Environmental mitigation measures of the Sebeya river sediment load impacts	69
A.3.4 Concluding remarks	69
4.A.4 PROPOSAL OF FUTURE-BASED REMEDIAL MEASURES ON AGRICULTURAL LAND AGAINST SOIL EROSION IN THE SEBEYA CATCHMENT	71
A.4.1 Introduction	71
A.4.2 Methodology	71
A.4.3 Research outcomes	72
A.4.3.1 Existing soil erosion control measures in the Sebeya catchment	72
A.4.3.2 Improvement needed for implementing soil erosion control measures in the Sebeya catchment	72
A.4.3.3 Performance assessment of various erosion control measures	74
A.4.3.4 Suitability and proposal of BMPs for soil erosion control in the Sebeya catchment	74
A.4.3.5 Constraints for implementation of soil erosion measures in the Sebeya catchment	78
A.4.4 Concluding remarks	82
4.A.5 DEVELOPMENT OF AN EROSION CONTROL MODEL FOR FARMING SYSTEMS AND SOIL LOSS IN THE SEBEYA CATCHMENT	83
A.5.1 Introduction	83
A.5.2 Data and methods	83
A.5.3 Research outcomes	89
A.5.3.1 Actual status of soil erosion in the Sebeya catchment	89
A.5.3.2 Values of USLE parameters for each parcel in the Sebeya catchment	89
A.5.3.3 SOLCY Model assembly in Excel sheet	95
A.5.3.4 SOLCY Model validation	100
A.5.4 Concluding remarks	104
PART B. PUBLISHED PAPERS	105
Paper 4.B.1 ANALYZING VARIOUS FACTORS AFFECTING FARMERS' WILLINGNESS TO ADOPT SOIL EROSION CONTROL MEASURES IN THE SEBEYA CATCHMENT	105
B.1.1 Introduction	106
B.1.2 Methodology	107

B.1.2.1 Study Area	107
B.1.2.2 Determining the Sample Size and Sampling Procedures	108
B.1.2.3 Data Collection	108
B.1.2.4 Data Analysis.....	109
B.1.3 Results	110
B.1.3.1 Estimating Soil Loss from the Sebeya Catchment	110
B.1.3.2 Farmers’ Socioeconomic Characteristics	111
B.1.3.3 Farmers’ Perceptions of Causes and Effects of Soil Erosion	113
B.1.3.4 Needs for the Implementation of SEC Measures in the Sebeya Catchment ...	115
B.1.4 Discussion.....	117
B.1.4.1 Actual Status of Soil Erosion and its Control in the Sebeya Catchment	117
B.1.4.2 Adoptability of SEC Measures in the Sebeya Catchment	117
B.1.4.3 SWOT Analysis.....	122
B.1.4.4 Future Work.....	123
B.1.5 Conclusion and Recommendations	124
Paper 4.B.2 SUSTAINABILITY ANALYSIS OF SOIL EROSION CONTROL IN RWANDA: CASE STUDY OF THE SEBEYA CATCHMENT	125
B.2.1 Introduction	126
B.2.2 Methodology	127
B.2.2.2 Data collection.....	130
B.2.2.3 Data Analysis.....	135
B.2.3 Results	136
B.2.3.1 Hydrological Processes in the Sebeya catchment.....	136
B.2.3.2 Impact of LULC on Water Erosion in the Sebeya catchment	136
B.2.3.3 Estimating the Actual Soil Erosion Rates in the Sebeya catchment.....	142
B.2.3.4 Soil Nutrients Depletion Due to Water Erosion in the Sebeya catchment	143
B.2.3.5 Sediments and Nutrients Dynamics in the Sebeya catchment.....	144
B.2.3.6 Site-Based Recommended Soil Erosion Control Measures and Associated Soil Loss Rates in the Sebeya catchment	144
B.2.3.7 Implications of Soil Erosion Control Measures on Crop Productivity in the Sebeya catchment.....	146
B.2.4 Discussion	147
B.2.4.1 Erosion Process and Its Damages in the Sebeya catchment	147

B.2.4.2 Implications of LULC Changes on Water Erosion within the Sebeya catchment	148
B.2.4.3 Future Work.....	148
B.2.5 Conclusion and recommendations	149
PART C. GENERAL DISCUSSION.....	150
4.C.1 Variability of soil erosion in the Sebeya catchment	150
4.C.3 Modelling soil erosion in the Sebeya catchment	150
4.C.3 Future Work.....	151
CHAPTER 5. CONCLUSION AND RECOMMENDATIONS	151
REFERENCES.....	155
PUBLICATIONS BY THE AUTHOR	172
TRAININGS, WORKSHOPS, SEMINARS AND CONFERENCES.....	172
ABOUT THE AUTHOR	174
MAJORO’S PhD QUESTIONNAIRE FOR FARMERS INTERVIEW IN THE SEBEYA CATCHMENT (Part A: English version)	175
MAJORO’S PhD QUESTIONNAIRE FOR FARMERS INTERVIEW IN THE SEBEYA CATCHMENT (Part B: Kinyarwanda version).....	188

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

A	Average annually soil loss (t/ha/yr)
ai	Area covered by each SEC measure or LULC type
A_i	Soil loss induced by the i th SEC measure of LULC type
A_{max}	Maximum soil loss from a parcel
A_{min}	Minimum soil loss from a parcel
ANOVA	Analysis of Variance
BMPs	Best Management Practices
BS	Bare Soil
C	Crop management factor or C-factor (dimensionless)
CAVM	College of Agriculture and Animal Veterinary Medicine
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems
CST	College of Science and Technology
DEM	Digital Elevation Model
DS	Dry Season
EUROSEM	European Soil Erosion Model
FAO	Food and Agriculture Organization
F_{crit}	Critical value of F-distribution
GH	Intake of Gihira water treatment plant
GIS	Geographical Information System
GSH	Intake of Gisenyi hydropower plant
GUEST	Griffith University Erosion System Template
HPP	Hydropower Plant
H₀	Null Hypothesis
H₁	Alternative Hypothesis
i	Rainfall intensity (cm/hr)
IN	Improvement Needed
INN	Improvement Not Needed
IWRM	Integrated Water Resources Management
K	Soil erodibility factor or K-factor (tons*ha*hr/ha*MJ*mm)

KY	Intake of Keya hydropower plant
L	Slope length (m)
LS	Slope length factor or LS-factor (dimensionless)
LULC	Land use / land cover
MF	Maize-Fertilizer
MFM	Maize-Fertilizer-Mulching
MIDMAR	Ministry of Disaster Management and Refugees
MINAGRI	Ministry of Agriculture and Animal Resources
MoE	Ministry of Environment
MUSLE	Modified Universal Soil Loss Equation
NG	Needed Gap
NGOs	Non-Governmental Organizations
NISR	National Institute of Statistics of Rwanda
NPK	Nitrogen Phosphorous and Potassium
NYB	Nyamugari bridge
p	Parcel perimeter (m)
P	Erosion control practice factor or P-factor (dimensionless)
\bar{P}	Average precipitation on a parcel (mm)
P_{max}	Maximum precipitation on a parcel (mm)
P_{mix}	Minimum precipitation on a parcel (mm)
PhD	Doctorate of Philosophy
Q	Total discharge (m^3/s)
Q_p	Peak discharge (m^3/s)
R	Rainfall erosivity factor or R-factor ($MJ*mm/ha*hr*yr$)
Rc	Runoff coefficient (fraction)
RNRA	Rwanda Natural Resources Authority
RS	Rainy season
RSB	Rwanda Standards Board
RUSLE	Revised Universal Soil Loss Equation
Rwf	Rwandan francs
RWB	Rwanda Water Resources Board

S	Slope gradient (%)
SEC	Soil Erosion Control
SECM	Soil Erosion Control Measures
SLEMSA	Soil Loss Estimation Model for Southern Africa
SO	Outlet of the Sebeya river
STREAM	Sealing, Transfer, Runoff, Erosion, Agricultural Modification model
SoE	School of Engineering
SOLCY	Soil Loss and Crop Yield model
SWAT	Soil and Water Assessment Tool
SWC	Soil and Water Conservation
SWIM	Soil and Water Integrated Model
TOPMODEL	Topography based hydrological MODEL
TSS	Total Suspended Solids
UPI	Unique Parcel Identification code
UR	University of Rwanda
UR-CGIS	Center of Geographical Information System of University of Rwanda
USLE	Universal Soil Loss Equation
WTP	Water Treatment Plant
WHO	World Health Organisation
WTP	Water Treatment Plant
x₁	Maximum soil loss from the Sebeya catchment (t/ha/yr)
x₂	Minimum soil loss or soil loss tolerance limit (t/ha/yr)
X	Parcel soil loss (t/ha/yr)
X_n	Percentage of farmers declaring needs to improve erosion control measures
X_p	Percentage of farmers confirming existence of erosion control measures
Y	Parcel crop yield (kg/ha)
y₁	Maximum crop yield from the Sebeya catchment (MINAGRI, 2009)
y₂	Minimum crop yield from all Rwandan districts (MINAGRI, 2009)
α	Significance level in a statistical test (%)

LIST OF TABLES

Table 2.1 Spatial scale sizes for erosion modeling (Raza et al., 2021).....	10
Table 2.2 Types and classification of soil erosion models (Hajigholizadeh et al.,2018; Alewell et al., 2019)	11
Table 2.3 Various SEC measures mostly applied on agricultural lands	15
Table 3.1 Overlap between Districts and the Sebeya catchment (RNRA, 2012)	30
Table 3.2 Selection of sectors for farmers interview in the Sebeya catchment	30
Table 4.1 Various signs of soil erosion in the Sebeya catchment.....	41
Table 4.2 Types of soil erosion in the Sebeya catchment.....	42
Table 4.4 Natural causes of soil erosion	44
Table 4.5 Negative impact of farming practices in the Sebeya catchment	45
Table 4.6 Strategies to make farming more environmentally friendly in the Sebeya catchment .	46
Table 4.7 Effects of soil erosion in the Sebeya catchment	46
Table 4.8 Effect of rainfall on soil loss and runoff coefficient	50
Table 4.9 Monitoring of the Sebeya river discharge.....	59
Table 4.10a Sediments loading rates and water quality in the Sebeya river.....	60
Table 4.10b Sediments loading rates and water quality in the Sebeya river	60
Table 4.11 Sieve analysis results of bed load sediment during rainy and dry season	62
Table 4.12 Monthly volume of water with its turbidity and sud floc consumed (WASAC, 2018)	66
Table 4.13 Sediment concentrations and risk to fish (Chang et al., 2013)	67
Table 4.14 Improvement needed in the implementation of BMPs in the Sebeya catchment	73
Table 4.15 Calculation of average slope of the Sebeya catchment.....	75
Table 4.16 Crops grown in the Sebeya catchment.....	76
Table 4.17 Proposed BMPs for soil erosion control in the Sebeya catchment.....	78
[adapted from (IWRM, 2016)].....	78
Table 4.18 Social constraints against the implementation of BMPs in the Sebeya catchment.....	79
Table 4.19 Economic factors against the implementation of BMPs in the Sebeya catchment.....	80
Table 4.20 Institutional factors against BMPs in the Sebeya catchment	81
Table 4.21 Government responsibility in improving farming system in the Sebeya catchment ..	82
Table 4.22 Soil texture and corresponding soil erodibility values.....	91
Table 4.23 C-factors for 13 main crops cultivated in the Sebeya catchment	93
Table 4.24 Various soil erosion control measures and their corresponding P-factors.....	94
Table 4.25 Proposed combinations of soil erosion control measures in SOLCY model (Adapted from IWRM, 2016).	94
Table 4.26 Sowing dates and simulated crop rotation in SOLCY model (NISR, 2017).	96
Table 4.27 Range of soil loss rates in the Sebeya catchment for various C-factors	97
Table 4.28 Ranges of crop yields in the Sebeya catchment (MINAGRI, 2009; NISR, 2009).	97

Table 4.29 SOLCY printout for UPI = 30305034908	99
Table 4.30 Comparison of USLE with GIS applications and SOLCY model results	101
Table 4.31 F-test results for the 2 samples of the Table 4.30	102
Table 4.32 Typical K values for different soil texture for field plot.....	102
Table 4.33 Estimating soil loss from field plots.	103
Table 4.34 Research design.	109
Table 4.35 Qualitative results of different farmers’ socioeconomic characteristics as analyzed using SPSS in the Sebeya catchment ($n = 75$).	111
Table 4.36. Quantitative results on different farmers’ socioeconomic characteristics as analyzed using SPSS in the Sebeya catchment ($n = 75$).	112
Table 4.37 Proposed combinations of SEC measures in the Sebeya catchment	115
Table 4.38. Significance of variables (adoption factors) for the four selected SEC measures...	117
Table 4.39 Compiled results from the binary logistic regression model (*).	118
Table 4.40 SWOT analysis of the performance and adoption of SEC measures in the Sebeya catchment.	123
Table 4.41 Classification of erosion risks in Rwanda (MoE, 2020).	132
Table 4.42 Crop management factor (C) and erosion control factor (P) for different land use/land cover types.	133
Table 4.43 Crop management factor (C) and erosion control factor (P) for different soil erosion control measures	134
Table 4.44 Possible ranges of crop yields in the Sebeya catchment (NISR, 2009).	135
Table 4.45 Area covered by each land use/land cover type in the Sebeya catchment (2008 and 2015).	138
Table 4.46 Area covered by each land use/land cover type in the Sebeya catchment (2018 and 2022).	139
Table 4.47 Effect of land use/land cover on water erosion within the Sebeya catchment in 2008, 2015, 2018 and 2022.	139
Table 4.48 Existing soil erosion control measures and their induced soil loss rates in the Sebeya catchment (RWB, 2018).	143
Table 4.49 Quantifying various nutrients available in a soil (Niaz et al., 2022; Suchithra and Pai, 2020).	144
Table 4.50. Availability of soil nutrients within the Sebeya catchment (ppm).	144
Table 4.51 Erosion rates induced by the site-based recommended soil erosion control measures in the Sebeya catchment.	146

LIST OF FIGURES

Fig. 3.1 Location of the Sebeya catchment on Rwanda map.....	25
Fig. 3.2 The Sebeya catchment hydrographic map.....	27
Fig. 3.3 Taking point velocities for discharge measurement using a currentmeter	31
Fig. 3.4 Sampling points	32
Fig. 3.5 The Sebeya river water sampling	33
Fig. 3.6 Bed load sampler	34
Fig. 3.7 Field plots at initial and middle stages of growing maize	36
Fig. 4.2 Various sub-catchments of the Sebeya catchment	43
Fig. 4.3 Grading curve for soil sample from the experimental field.....	49
Fig. 4.4 Variation of Soil moisture content.....	50
Fig. 4.5 Effect of land cover on soil loss	51
Fig. 4.6 Effect of land cover on runoff coefficient	52
Fig. 4.7 Development of interrills and rills in BS plot.....	52
Fig. 4.8 Rainfall fluctuations and variability of soil loss from MFM Plot	53
Fig. 4.9 Rainfall fluctuations and variability of soil loss from MF Plot.....	54
Fig. 4.10 Rainfall fluctuations and variability of soil loss from BS Plot.....	54
Fig. 4.11 Rainfall fluctuations and variability of runoff coefficients for MFM Plot.....	55
Fig. 4.12 Rainfall fluctuations and variability of runoff coefficients for MF Plot	56
Fig. 4.13 Rainfall fluctuations and variability of runoff coefficients for BS Plot	56
Fig. 4.14 Variation of bed load mass flow rates	61
Fig. 4.15 Variation of Suspended Solids	63
Fig. 4.16 Variation of Turbidity.....	64
Fig. 4.17 NPK variation in the Sebeya river water samples	65
Fig. 4.18 NPK variation in the Sebeya river bed load samples	68
Fig. 4.19 The Sebeya catchment slope map.....	75
Fig. 4.20 The Sebeya catchment soil depth map	77
Fig. 4.21 Extract of a region from the parcels map	85
Fig. 4.22 SOLCY model flow diagram.....	86
Fig. 4.23 Rainfall map of the Sebeya catchment	87
Fig. 4.24 Soil texture map of the Sebeya catchment.....	88
Fig. 4.25 LULC map of the Sebeya catchment.....	89
Fig. 4.26 Rwanda map showing the Sebeya catchment.....	107
Fig. 4.27 Assessment of farmers’ perceptions of soil erosion in the Sebeya catchment based on indicators, causes, and effects.....	114
Fig. 4.28 The Sebeya catchment localization.	128
Fig. 4.29 The Sebeya catchment topographic map.....	129
Fig. 4.30 Rainfall map of the Sebeya catchment	130

Fig. 4.31 The Sebeya catchment slope length factor map.	133
Fig. 4.32 Typical monthly precipitations at Gisenyi airport station (IWRM, 2016).	136
Fig.4.33 Land use/land cover detection for 2008, 2015, 2018 and 2022 in the Sebeya catchment.	138
Fig.4.34 Historical variation of soil erosion rates induced by the land use/land cover in the Sebeya catchment.....	142
Fig. 4.35 Existing soil erosion control measures and soil loss ranges in the Sebeya catchment (RWB, 2018).....	143
Fig. 4.36 Recommended soil erosion control measures in the Sebeya catchment (RWB, 2018).	145

CHAPTER 1. GENERAL INTRODUCTION

1.1 BACKGROUND

Soil erosion is one of the most serious environmental problems in the world because it threatens agriculture and also the natural environment. Soil erosion has become one of the global environmental hazards that limits today's human survival and restricts global socio-economic sustainable development (Igwe et al., 2017)

Land degradation due to accelerated erosion is a serious global issue because soil resources of the world are finite, nonrenewable at the human-time scale and sensitive to land misuse and soil mismanagement, especially in ecologically sensitive regions (Ahmad & Pandey, 2018). On the basis of area coverage by water erosion at the continental scale, land degradation is of the order of Asia>Africa>South America>Europe> Oceania>North America>Central America. It is estimated that one sixth of the surface land is affected by accelerated water erosion (Borrelli et al., 2013). Soil erosion takes away the top soil removing fertile land from agricultural use. Controlling erosion is therefore essential for minimizing loss of productivity, sedimentation and water quality degradation.

Soil erosion reduces the agricultural value of lands via physico-chemical degradations and this lead to soil nutrient loss through runoff and sediment; it is a major driver for soil fertility decline. The eroded sediments or soil are highly concentrated with crop nutrients, which are washed away from farmlands. Erosion-based constraints coupled with unfavorable climatic conditions reduce significantly the productivity of farming systems. Soil erosion leads to extreme losses of economic and environmental resources which negatively impact the economies of affected regions (Bashagaluke et al., 2018). Soil erosion is one of the major causes of land degradation and is a serious threat to food security and agricultural sustainability (Kalambukattu and Kumar, 2017).

It has proven that the effect of LULC change lead to soil erosion. Land use land cover change associated with climatic and geomorphologic conditions of the area have an accelerating impact on the land degradation. Natural as well as human-induced land use land cover change has significant impacts on regional soil degradation, including soil erosion, soil acidification, nutrient leaching and organic matter depletion. Since the last century, soil erosion accelerated by human activities has become a serious environmental problem. It has a manifold environmental impact by

negatively affecting water supply, reservoir storage capacity, agricultural productivity and freshwater ecology of the region (Sharma et al., 2011). Soil erosion is a serious obstacle to agricultural development in many african nations. Yet in almost all cases, data bases are too weak to assess accurately the real extent and magnitude of erosion problem (Bhandari et al., 2021).

In Rwanda, soil erosion is predominantly the relocation of soil to lower lying areas or slopes within catchments. Eroded soil becomes disaggregated into sand, which is deposited on lower slopes and wetlands, and into soluble organic material and clay (containing nutrients) which is washed out into rivers. Eroded sand covers fertile soils rendering them unsuitable for crop production. The Universal Soil Loss Equation (USLE) was applied to all the 9 level-1 catchments in Rwanda between 1990 and 2015. The trends in soil loss (t/ha/yr) are respectively indicated as follows (NISR, 2019): Mukungwa catchment (60 to 130) ; Upper Nyabarongo (60 to 90); Lower Nyabarongo (60 to 90); Kivu (30 to 70); Rusizi (50 to 60); Muvumba (45 to 60); Akanyaru (43 to 50); Upper Akagera (15 to 30) and Lower Akagera (15 to 20). Being a level-2 catchment, the Sebeya catchment is an integral part of Kivu level-1 catchment. Generally, the increase in soil erosion from 1990 to 2015 is due to: the increase of population responsible to the deforestation for fire wood and shelter; the urbanization which increases impervious areas leading to high runoff; the intense rainfall (climate change) on highly elevated mountainous areas; the intensive seasonal cropping (unsustainable land use practices namely over cultivation) and the insufficiency of modern erosion control measures.

This research will provide a set of alternative solutions to counter the erosion problems downhill, taking into account activities done on the hillside by the population and also thinking about the aesthetical aspect of the hillside. This study will also quantify soil nutrient loss and will develop an erosion control model for the improvement of farming systems under specific crop and soil management practices in the Sebeya catchment.

1.2 PROBLEM STATEMENT

Soil erosion is characterized by the detachment, transport and deposition of soil particles caused by one or more natural or anthropogenic erosive forces (rain, runoff, wind, gravity, tillage and other type of land disturbance) (Sun et al., 2021). With considerable damages, the soil erosion reduces the soil fertility, the water-storage capacity and leads to an increase in the concentration

of sediment in the runoff which further increases the risk of flood disasters (Xungui and Xia, 2014; Park, 2013).

Located in the Western Province of Rwanda, the Sebeya catchment is facing erosion causing problems to the population living downhill, especially in rainy season. The major flood events were recorded in Rutsiro and Rubavu between 2010 and 2014 causing serious destructions to the peoples living in these Districts. In 2011, 10 people have been killed, 354 houses destroyed and 3,000 ha of farmland damaged forcing farmers to seek refuge on higher ground (MIDMAR, 2012). On the 12th April 2012, a flood encountered in Rubavu District precisely in Mahoko center has destroyed infrastructure and agricultural activities. Another flood occurred in April 2013, has affected three sectors (Kanama, Nyakiriba, and Nyundo) in Rubavu District and damaged crops followed by property destruction (Ndagijimana and Shukuru, 2015). The Sebeya river is causing insecurity in Rubavu District during natural disasters of floods and soil erosion where about 150 families were relocated (Mugisha, 2012).

The Sebeya catchment is encountered with serious problems of landscape degradation and the Sebeya river bank attacks due to high rated soil erosion motivated by high hillside steepness. Moreover, the efforts made to protect the river banks from erosion by growing new trees are handicapped by residents who let their cattle graze near the river banks, and by farmers who grow crops too close to the river. The effect of upstream forest clearance resulted in a rapid erosion depositing silt into the Sebeya river causing the river to flood over its banks onto fields and roads during the rainy seasons (Munyaneza et al., 2015).

Landslide occurrence is to increase worldwide while its consequences can include loss of life, loss of livestock, damaging or destroying residential and industrial developments, villages or even entire towns, destroying agricultural and forest land and negatively influencing the quality of water in rivers and streams (Perera et al., 2018). The Sebeya catchment has hillsides with very steep slopes where soil erosion and water loss are arduous for the whole catchment. Consequently, there are serious damages caused by water erosion. This erosion is accelerated by large population with relatively land prone areas to erosion in the mountainous region (Munyaneza et al., 2015).

The practices of burning trees for fuel wood are still done. These practices are greatly aggravating hill slope erosion during the rainy season. Surface horizons which are rich in crop nutrients are eroded and taken away to the river flow, and the remaining lands remain unproductive. Anthropogenic erosion includes various forms of soil erosion and water loss, caused

by human activities such as mining, road building, steep slope reclamation etc. Soil erosion and water loss have not only caused runoff and soil erosion problems but also caused severe damages of soil fertility (Munyaneza et al., 2015).

Although soil degradation is recognized as a very widespread problem, its geographical distribution and total area affected are only very roughly known (Ndomba, 2010). Sediments are fragments of rocks and minerals, loosened from the surface of the earth due to weathering processes and the impact of rain, blowing winds and flowing water. Sebeya river is taking its origin in high elevated mountains of Gishwati forest in the South of Rubavu District, Western Province of Rwanda. A typical important challenge developed on this river is the difficulty of operation and maintenance of the Keya Hydro-Electric Power plant due to large quantity of sediment inflow with hard and abrasive minerals (Munyaneza et al., 2015).

In this research, various causes and effects were analyzed and the best management practices were assessed and proposed as remedial measures to reduce on-site and offsite soil erosion effects to tolerable rates in the Sebeya catchment. The ultimate objective of this study was to finally develop an erosion control model which can help the Sebeya catchment farmers to control soil erosion to tolerable soil loss rates under a specific crop and efficient soil management practices in their farming systems.

1.3 OBJECTIVES

1.3.1 Main objective

The main objective of this study is the assessment of the spatial-temporal distribution of soil erosion and future-based remedial measures to control soil erosion on agricultural land of the Sebeya catchment to contribute to sustainable agriculture and environment protection.

1.3.2 Specific objectives

In an effort to achieve the aforementioned main objective, this research has specifically focused on the following specific objectives:

- (1) Assessment of soil erosion process and land use /land cover changes in the Sebeya catchment;
- (2) Development of runoff coefficients and soil erodibility factors in the Sebeya catchment;
- (3) Assessment of the Sebeya river sediment transport and its impacts in relation to rainfall events;

- (4) Development of an erosion control model for farming systems and soil loss in the Sebeya catchment;
- (5) Proposal of future-based remedial measures on agricultural land against soil erosion.

1.4 RESEARCH QUESTIONS

In order to address the main issues raised in section 1.3, the following research questions were formulated based on the specific objectives mentioned above. The overall question is: How do changes in land use and land cover alter soil fertility and soil erosion dynamics? This question leads to the following specific questions in addressing the key elements of this study:

- (1) What are the current types of land use/ land cover in the Sebeya catchment?"
- (2) What is the simulated change in run-off coefficients and soil erodibility per year?
- (3) What is the simulated change in sediment dynamics per year?
- (4) What is the effect of soil erosion on nutrient balance of the different farming systems?
- (5) What are the implications of soil erosion control for the sustainable land management?

1.5 SIGNIFICANCE OF THE STUDY

The Thesis was presented logically from introduction, literature review, methodology, results, conclusions and recommendations.

1.5.1 Farmers benefits

Soil erosion control integrates the indigeneous knowledge, increases the soil productivity, leads to improvements in food security, improves health status of local people and consumers, and finally, increase farmers prosperity.

1.5.2 Government benefits

Soil erosion control impacts indirectly on the reduction of rivers sedimentation, and the reduction of flash floods.

1.5.3 Scientific significance

By availing specialised references, PhD, MSc and BSc students in Water and Environmental Engineering, and Agriculture Programmes will benefit from this study. This study is limited to the Sebeya catchment but worldwide researchers will find through this PhD by research an appropriate

methodology and procedures allowing to duplicate the designed Soil Loss and Crop Yield (SOLCY) model to other catchments.

1.5.4 Personal benefits

The challenges encountered and way forward during the planning and monitoring of the field experiments in soil erosion plots, in sampling and testing protocols, and in conducting the farmers interviews constituted a strong pillar to my future research in experiments design and analysis. My 2 published papers in the Sustainability Journal, which is a SCI journal, opened my eyes on how to publish in peer-review journals.

1.6 SCOPE OF THE STUDY

Referring to its main objective, the scope of this PhD by research can be summarized into the following 4 steps:

- (1) To assess the spatial-temporal distribution of soil erosion in the Sebeya catchment;
- (2) To propose suitable BMPs and predict their performance using USLE type models and simulations;
- (3) To develop a Soil Erosion Control Model which can help to lower down the high soil loss rates below the maximum soil loss tolerance rate of 11.5 t/ha/y throughout the entire catchment;
- (4) To develop strategies required to sensitize farmers and stakeholders to adopt, implement, and maintain SEC measures in their farmlands.

1.7 LIMITATIONS OF THE STUDY

A grant fund should come to help for implementation of this research project according to the findings from the PhD investigations.

1.8 THESIS OUTLINE

This thesis is composed of 5 chapters. The Chapter 1 introduces the topic where it briefly presents the background, the problem statement and defines the objectives of this study.

In Chapter 2, the general purpose of this literature review is to make an overview of soil erosion throughout the world in order to highlight required studies on which to be based when proposing appropriate erosion control measures for agricultural fields. Different scientific

documents including journal articles, internet materials, conference papers and books were used as research materials to achieve the objectives of the present work.

In Chapter 3, the materials and methods which were used in the study are presented. The study area, the data characteristics, the details on sampling, the test procedures used and the assumptions made for achieving the research objectives are described.

The Chapter 4 presents and discusses the research results of this PhD thesis (Part A: Preliminary investigations, Part B: Published papers and Part C: General discussion): Causes and effects of soil erosion in the Sebeya catchment, the catchment soil loss rates, sediment transport and its impacts, erosion remediation measures, the development of the Soil Loss and Crop Yield (SOLCY) model to focus on the parcel soil loss and predict crop yields for sustainable land management decisions, an in-deep assessment of various factors affecting farmers' willingness to adopt soil erosion control measures in the Sebeya catchment and an in-deep assessment of the agricultural and environmental sustainability of soil erosion control in the Sebeya catchment.

This thesis ends with the conclusions and recommendations in Chapter 5, where all findings are summarized and some recommendations are given for future research.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

All over the world, wherever human being started the agricultural operations, there exists the problem of soil erosion in some extent. Soil erosion leads to the reduction of water infiltration rate and enhances runoff and soil degradation. Naturally, rainfall erosion is characterized by a series of many phenomena: compaction, disintegration, detachment, transport and deposition (Sun et al., 2021).

Although soil erosion is a slow process in natural ecosystem, substantial serious effects, like loss of top soil and effects on soil and water quality, have been observed. Globally, eroded soil in flat land with grass cover and mountainous regions with normal vegetation cover amounts from 0.001 to 1 t/ha/yr and from 1 to 5 t/ha/yr respectively (Pimentel and Michael, 2013). Soil erosion has resulted in a huge deposition of soils with large deltas associated to Nile, Ganges and Mississippi Rivers (DeVere, 2010).

Soil erosion is one of the most serious environmental problems in the world because it threatens agriculture and also the natural environment. About 99.7% of human food is produced from land while less than 0.3% comes from aquatic ecosystems and this indicates the importance of soil for huge food supplies for future generations (Pimentel and Michael, 2013). Again, the total earth surface area is 510.1 Million km² and the earth surface area covered by land is about 29.2% while 70.8% is covered by water. Approximately 50% of the earth's land is devoted to agriculture (Zermeño-Hernández et al 2016) while 75 billion tons per year of fertile soil is lost from agricultural land due to erosion (DeVere, 2010). The limited land resource has to be managed very carefully by adopting various conservation measures.

Agricultural land of developing countries is prone to erosion effects because of poor farming techniques and lack of financial means for their farming systems to replace lost soils and nutrients (Pimentel and Michael, 2013). Farming and other economic activities in these areas have become environmentally unsustainable causing on-site and off-site effects (Pimentel and Michael, 2013)

Rainfall is the major cause of soil erosion which is responsible to remove soil to a new place of deposition through runoff process (Sakinatu and Muhammad, 2017). On the basis of causes of soil erosion, it can be classified as erosion by gravity, water splash, interrill, rill, gully

and streambank erosion due to the action of flowing water (Shi et al 2022). The two main types of soil erosion are geological and accelerated soil erosion. Compared to soil formation, the geological soil erosion occurs at the same rate while the accelerated soil erosion has a very high rate (Jeong et al 2021). Known as a natural geomorphologic process, soil erosion is strongly linked to water and land interactions but highly influenced by different human activities to be an environmental hazard (Farayi, 2011).

The main on-site effect of soil erosion is the reduction of soil quality (nutrient loss and decrease in water holding capacity) which significantly leads to the reduced soil productivity (Issaka & Ashraf, 2017). Sediment in rivers is composed mainly by eroded soil and associated pollutants from agriculture and its impact on socio-economic development projects along the river course constitutes the main off-site effect of soil erosion. Soil erosion control is one option to increase crops productivity while controlling river and lake sedimentation (Huffman et al., 2011).

2.2 SOIL EROSION MEASUREMENT: APPLICATION OF SOIL EROSION MODELS

2.2.1 Soil erosion measurement

Data on soil erosion and its controlling factors can be collected in the field or from the simulated conditions in the laboratory. Field measurements provide more realistic data on soil loss because many factors are controlled in laboratory experiments. The following three methods are commonly used to estimate or to predict the soil erosion.

The simplest way of measuring changes in ground level over time is to use what is technically known as an erosion pin. In reality an erosion pin is a 250–300 mm long nail, 5-12 mm in diameter, driven into the soil (Ghimire et al., 2013). The head of the nail should be some 20–30mm above the soil surface and the base of the nail sufficiently far into the ground not to be disturbed by changes in soil volume due to wetting-and-drying. Periodic measurements of the gap between the head of the nail and the ground level indicate the extent to which the surface has been lowered. This method is used to estimate the soil losses and the deposition that occur along the hill slopes of a catchment.

A widely used method of quantifying surface erosion is to measure the amount of soil that washes from bounded plots. In installing these plots, collecting tanks are sunk along the width of the bottom of the plots and walls of plastic or sheet metal or concrete are inserted into the soil surface to form the boundaries of the plot (Brooks et al., 2013). The collecting tanks collect both the entrained soil particles with surface runoff are collected.

Lastly, the 3rd method uses empirically-based equations to predict soil loss and sediment yields from a catchment.

2.2.2 Models inventory and classification

Several models have been developed to simulate soil erosion and sedimentation over the last decades, differing in their representation of processes involved in soil erosion, the complexity of these processes, input and output data and their temporal and spatial scale limitations (Raza et al., 2021). In general, the model selection depends on the intended application and characteristics of the landscape. Therefore, many factors must be considered before the model selection such as: objective, data requirements, data availability, accuracy, validity and spatial scale size.

Sedimentological and hydrological processes involved in the modeling of soil erosion by water are explained mainly by considering the principle that every soil erosion model operates at different spatial scales (Table 2.1).

Table 2.1 Spatial scale sizes for erosion modeling (Raza et al., 2021)

Category	Spatial scale	Size
Large scale	Basin	>500 km ²
	Catchment	50-500 km ²
	Catchment	1-50 km ²
Small scale	Field/ hillslope	<1 km ²
	Plot	0.6-23 m ²

Based on the complexity and the level of dynamic physical processes that are implemented, soil erosion models can be categorized into three different groups, namely empirical, conceptual, and physically-based models to estimate soil erosion at different spatial and temporal scales (Karydas e al., 2014).

Empirical models (Table 2.2) are simulations based primarily on the analysis of field experiments and seek to characterize the response from these erosion plots using a statistical inference. The computational and data requirements for such models are usually less than for conceptual and physically based models. The most critical limitation of empirical models for soil erosion is their inadequate level of accuracy in analyzing large data sets which would require processing and analysis using special complex mathematical approaches (Eisazadeh et al., 2012).

Conceptual models (Table 2.2) are based on the sediment and runoff continuity equations, and basically take a position between physically based and empirical models (Kabir et al.,2010) . The primary focus of conceptual models has been to estimate sediment yield based on the concept of unit hydrograph (Tesema and Leta, 2020). Most of the conceptual models use equations from empirical approaches. The empirical models USLE and MUSLE, for example, are implemented in conceptual models such as SWIM for estimating soil erosion. These conceptual models can predict the temporal and spatial distribution of soil detachment and sedimentation at a field scale depending on crop and soil management at daily time steps. Conceptual models are basically a combination of empirical and physically-based models and are more applicable to answering general questions (Mohammad et al., 2018). These models were developed on the basis of spatially-lumped forms of water and the sediment continuity equation (Hajigholizadeh et al.,2018). The main focus of a conceptual model is to predict sediment yield, basically using the concept of the unit hydrograph.

Physically-based models (Table 2.2) are generally based on the concept of the conservation of mass, momentum equations and energy as governing equations describing streamflow or overland flow, and conservation of mass equation for sediment (Tajbakhsh et al., 2018). Most of the developed physically-based soil erosion models that are being used worldwide to predict erosion and sediment yield are not 100% physically-based because mathematical expressions describing each individual process are developed based on the empirical /conceptual approaches and their assumptions and consideration (Ramsankaran et al., 2013).

Table 2.2 Types and classification of soil erosion models (Hajigholizadeh et al.,2018; Alewell et al., 2019)

SN	Model	Model Capabilities	Model Limitations
		Empirical Models	
1	USLE (Universal Soil Loss Equation)	Soil Erosion estimation	Does not quantify the events that are likely to result in large-scale erosion
2	MUSLE (Modified Universal Soil Loss Equation)	Erosion, prediction of sediment yield, simulation of individual storm events	Calibration is complex, shows significant difference with measured sediment yield in many catchments

3	RUSLE (Revised Universal Soil Loss Equation)	Erosion, process-based auxiliary components	Slope length factor may not be suitable for more than 25° and does not estimate gully
4	SLEMSA (Soil Loss Estimation Model for Southern Africa)	Soil erosion, decision on land management techniques	High sensitivity to the input factors
Conceptual Models			
1	SWAT (Soil and Water Assessment Tool)	Hydrological assessments, pollutant loss studies, water erosion, sediment yield	Weak in stream channel degradation and sediment deposition analysis, inadequate data availability for calibration and validation
2	SWIM (Soil and Water Integrated Model)	Simulation of runoff, soil erosion, sedimentation	relatively complex, no simulation of gully erosion
3	STREAM (Sealing, Transfer, Runoff, Erosion, Agricultural Modification model)	Simulates land use impacts, erosion, sedimentation	applicable to single rainfall events
4	TOPMODEL (Topography based hydrological MODEL)	Soil moisture deficit, rainfall runoff, simulation of surface/ subsurface hydrology; sediment yield and transport	Suitable only for shallow homogenous soil catchments
Physical-based Models			
1	CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems)	Erosion, sedimentation, runoff, from agricultural area	suitable only for field scale, low potential for GIS integration
2	GUEST (Griffith University Erosion System Template)	Simulation of runoff, sedimentation	Low potential for GIS integration, high data requirement
3	EUROSEM(European Soil Erosion Model)	Simulation of erosion, sediment yield, deposition and runoff	Lower accuracy for large catchments

2.2.3 Historical aspects and evolution of USLE-type modelling

Modelling and prediction of soil erosion has a long history with first studies published in international journals more than seven decades ago using north American data sets (Alewell et al., 2019)

At present, USLE and the Revised USLE (RUSLE) are the most widely applied soil erosion prediction models according to (Djoukba et al.,2018). As USLE-type models (USLE/RUSLE) were designed to predict long-term average annual soil loss, they have been successful to predict event soil losses reasonably well at some geographic locations (Alewell et al., 2019), but often fail to predict event erosion, which is highly influenced by the fact that the USLE and its revisions (RUSLE) do not consider runoff explicitly. RUSLE2 was developed to scientifically enhance the USLE/RUSLE equations and offer an improved tool to guide and assist erosion control planning (USDA, 2013). One of the main reasons why USLE type modelling is so widely used throughout the world is certainly its high degree of flexibility, data accessibility and extensive scientific literature allowing to adapt the model to nearly every kind of condition and region of the world (Alewell et al.,2019)

The Universal Soil Loss Equation (USLE) has been originally proposed in 1958 and actually modified to its present form in 1978 by Wischmeier and Smith. The empirical equation of this model is as follows:

$$A = K * R * (LS) * C * P \quad \text{Eq.(2.1)}$$

Where:

Average annual soil loss A (t/ha*year); Soil erodibility or K-factor (ton*ha*hr/ha*MJ*mm); Rainfall erosivity or R-factor (MJ*mm/ha*hr*yr); Slope length factor or LS-factor (dimensionless); Crop management factor or C-factor (dimensionless); Erosion-control practice factor or P-factor (dimensionless). Compared with other models, Universal Soil Loss Equation is a familiar model used to quantify soil erosion because of less data demand (Benavidez et al.,2018) but its applicability is limited to sheet and rill erosion without any consideration of gully erosion.

2.3 SEDIMENT TRANSPORT AND ITS IMPACTS ON SOCIO-ECONOMIC DEVELOPMENT PROJECTS

Globally, soil erosion increases the amount of sediment transported in rivers at a rate of 2.3 billion tons per year (Wohl, 2015). Storm water is a main leading cause of water pollution. It runs off surface solids and collects pollutants such as oil, pesticides, sediments, bacteria, and other chemicals, and then deposits them into waterways. A high eroded sediment load impacts on water treatment and hydropower plants taking the river as a source of water and impacts also on water reservoirs and lakes. Referring on the transport capacity of the flow, sediment is picked up

or deposited. Rills are widened and deepened to gullies, stream banks are undercut. Ditches and bridges are damaged (Claman and Way, 2021)

Bridges are structures constructed to carry smoothly road traffic for easy passing of physical obstacles like rivers, lakes, valley. Their piers are constructed mainly in the riverbed or alluvial sediments which is the main cause of scour through the movement of water with abrasive materials. Scour can be classified as contraction and degradation scour which occurs when water accelerates as it flows through an opening that is narrower than the channel upstream from the bridge. Over long periods of time, degradation scour either on upstream or downstream can result in lowering of the stream bed (Julien, 2011).

Most of aquatic habitats are destroyed by eroded soil from catchment (construction and mining sites, agricultural fields, etc.). The eroded soil flows in stream, rivers or into lake and water reservoirs with a lot of quantity of chemicals and heavy metals where it causes excess turbidity and water eutrophication that harms aquatic life and makes the water less useful for domestic use and recreation (Zhai, 2010; Bing et al., 2013).

Water pollution is caused mainly by run off as when it flows, it collects pollutants such as oil, pesticides, sediments, bacteria, and other chemicals, and then deposits them into waterways and may alter aquatic life and make waterways toxic to human life. Aquatic ecosystem nutrients create water treatment problems (Shortle et al., 2020). Soil erosion can create negative impact on water quality and aquatic ecosystems due to the high concentration of sediments and associated nutrients from land into water bodies. The effects of sediments load on the performance of a water treatment plant are: high turbidity, high cost of coagulants to be used in water treatment, low quantity of water to be supplied, damage of valves and taps, filters blockages and stoppages from working effectively, fills of tanks and pipes with mud and silt and it can also be causing the delay in water treatment process.

During rainy season, a large quantity of sediment related to soil erosion reduce the performance of hydropower plants by reducing the total energy production by 7% annually (Gasore et al., 2021) . Sediment can lead to significant damages of hydropower turbines and other mechanical equipment as a result of the breakdown of the oxide coating on the blades, and leading to the total cut-off of the plant with the needs of replacement of damaged materials (Munyaneza et al., 2015). Rwandan hydropower plants which draw their water from the Sebeya river face heavy impacts of sediment related to erosion. Keya and Gisenyi HPPs are runoff river projects facing

different issues of sedimentation. Sediment flows with hard and abrasive materials from the Sebeya river are the main leading cause to damages on hydropower turbines during heavy rainy season (Munyaneza et al., 2015). Erosion control within the catchment of a hydropower dam would mitigate the impacts of sedimentation by reducing the volume of sediment that is brought to the dam by the river (Adeogun et al., 2018). There are only two methods of reducing the amount of sediment that enters a reservoir: either to implement erosion control measures or trapping eroded sediment before it reaches the reservoir.

2.4 BMPS OF SOIL EROSION CONTROL

Erosion control is any action which prevents soil erosion to detach the soil surface particles, conserving then the soil with its fertility contents. Soil erosion is one of the most pressing environmental problems worldwide because it threatens agriculture. With high percentages of soil loss reduction if applied on agricultural lands, Table 2.3 lists 35 BMPs practices mostly applied to control soil erosion as classified into 6 groups according to their respective purposes.

Table 2.3 Various SEC measures mostly applied on agricultural lands

SN	Purposes	Typical SEC measures
1	BMPs for erosion control on farmlands	<i>terraces, contour bunds</i> , no-tillage, cover crops, <i>mulching</i> , <i>anti-erosive ditches</i> , strip cropping, crop rotation, agroforestry, <i>stabilizing grasses</i> on farm bunds (vetiver grass, reed, cetaria, tripsacum, paspalum)
2	BMPs for slope stabilization	stabilizing trees (<i>grevelia, bamboo</i>), stabilizing grasses (<i>vetiver grass, reed, cetaria, tripsacum, paspalum</i> , etc.), retaining walls (<i>use of gabions</i> or stones)
3	BMPs for river banks stabilization	stabilizing trees (<i>grevelia, bamboo</i>), <i>stabilizing grasses</i> (<i>vetiver grass, reed, cetaria, tripsacum, paspalum</i> , etc.), <i>stone revetment, use of riprap</i> , retaining wall (made of <i>gabions</i>); <i>use of sand bags</i> .
4	BMPs for sediments control	<i>Sand trap, sediment basins</i> , constructed wetlands, strip cropping along the river buffer zones; siltation ponds at the

		end of storm sewers; grassed waterways, protective sediment barriers.
5	BMPs to prevent large velocities of runoff	<i>Check dams, grassed waterways, stones blocks in a channel, stilling basins, storm sewer drains, roadside channels, ditches, and hillside water ponds.</i>
6	BMPs to prevent significant volume flow rates of runoff	<i>Hillside water ponds, roof runoff and cisterns.</i>

2.4.1 Soft BMPs

Surface cover or mulching and cover crops, contour ploughing, vegetative filter strip, no tillage method, trees planting, vegetative measures for slopes stabilization, protective grasses on river banks, buffer zones, and infiltration are considered as soft BMPs or agronomic measures. Many studies revealed that a large number of soft BMPs reduce runoff and soil loss (Moriaque et al., 2022).

(1) Mulching

Mulch is any layer of material applied to the surface of soil to protect the soil from the erosion and evaporative effects of wind and sun. Mulch can be organic, inorganic or plastic: Mulch can be plant material, like straw and wood chips or it can be gravel or non- living material like recycled glass, cinders, decorative rock, and recycled rubber. In addition to erosion reduction, mulch increases water holding capacity of soil by reducing compaction. It increases infiltration by slowing runoff and giving it more time to soak into the soil by reducing erosion from bare soil and supply nutrients and organic matter to the soils. Mulching helps in controlling moisture content of the soil and temperature fluctuations, improves soil properties such as the addition of the soil nutrients which result in an increase of the crop yield.

Mulching is one of the most efficient techniques of soil erosion control where it influences C factor in reducing soil erosion (IWRM, 2016). Mulching increases the crop yield by 50-60 per cent under rain fed situations and it is a best way of achieving food security sustainably (Patil et al., 2013). When mulching is applied using straw cover at slopes ranging from 15% to 25%, its performance varies from 90% to 60% in a period of six month (Prosdocimi et al., 2016)

(2) Cover crops and vegetation

Cover crops increases soil health, improves soil structure and reduces the need for costly inputs such as fertilizer and mechanical tillage. Cover crops protect water quality by slowing erosion and runoff and increase water infiltration and retention. If trees are removed, open land become erosion prone areas at high extent. Soil surface is protected by vegetation from raindrop impact which acts as a detachment agent of soil particles. (Franz et al., 2018) noted that vegetation is the most common natural element used to control the erosion as it aids in protecting the soil and preventing the erosion by absorbing water that the soil is unable to hold and also by hindering the wind that might blow off the topsoil. The vegetation can reduce the soil erosion rate by 90% (Franz et al., 2018). A series of laboratory flume simulation experiments have shown that vegetation could reduce the mean velocity by 31–65% (Mu et al., 2019a). Researchers also found that the average runoff and sediment reductions were 51.02% and 32.22% for soil with vegetation respectively (Bai et al., 2019).

In addition, trees and shrubs can act as soil stabilizer by ensuring the soil stability and the continuity of agricultural activities.

(3) No tillage method

In zero tillage, the land for crop cultivation is left undisturbed from harvest to planting or not ploughed at all while in the case of minimum tillage, just holes for planting are made and only at the places where the crop is going to be planted or grain sown. A combination of no-tillage with crop residue mulch is more effective in runoff and erosion control.

No tillage method is one of the best land management techniques used to manage soil structure, organic matter and to reduce soil erodibility and erosion. No tillage technique reduces soil loss by 26–52% (Barsher et al., 2016).

(4) Protective grasses on river banks

Bank erosion mostly occurs in rivers and depends on frequency and magnitude of water forces. Human activities (sand mining, infrastructure building, artificial cutoffs and land use alterations or removal of vegetation, change the river morphology and natural dynamics of rivers) influence the processes of erosion by sediment transport and deposition along the river corridor.

The major benefits of grasses in soil erosion control are: to intercept rain, bind soil particles, trap sediment, reduce energy of runoff and to enhance water infiltration. By their roots, grasses provided 80% to 85% of the force that resisted slope failure and reduced runoff at 90% (Li

& Pan, 2018). Protective grasses increase the resistance of stream banks to erosion and play an important role to fish and wildlife populations and contribute to an aesthetic view of the riverbanks. Grassed water ways have the ability to traps suspended sediments at rate greater than 90% (Fiener et al., 2017).

(5) Trees planting

Trees plantation is one of the best management practices used to control erosion. Canopy of trees intercepts rain drops, binds soil particles and reduces runoff by enhancing infiltration. In a region covered by canopy trees, erosion has been reduced at a rate of 95% (Li et al., 2019).

(6) Buffer zones

Buffer zones increase the capture of sediment and organic material. It is revealed that buffer zones increased the trapping of sediment and infiltration from 10 to 90% respectively (Carluer et al., 2017). Vegetated buffers decrease the runoff velocity of water. They are experienced to have a high sediment trapping efficiency (Ramesh et. al., 2021).

2.4.2 Hard BMPs

(1) Terraces

When the rain falls, a part of water infiltrates into the soil surface and the remaining flows as a runoff downhill until it reaches natural zones of deposition.

Terraces are mechanical structures such as an earthen ridge or a stone wall which reduces the slope steepness and divides the slope into short gently sloping sections. Terraces intercept runoff, reduce the runoff velocity and soil loss, increase the soil moisture content through improved infiltration, reduce evaporation and can be created to divert runoff to a prepared or safe area for minimizing the effects of erosion to a tolerable level (Fang, 2021)

Regular inspections of terraces especially after large storm events are recommended in order to increase their performance (Deng et al., 2021). Terraces are more favorable in agricultural land with steep slopes ranging from 16% to 40% with high erodibility factor and not in sandy and coarse soil (IWRM, 2016). It is shown that terracing reduces soil erosion up to 99% (Bai et al., 2019).

Terracing is one of the oldest methods of erosion control and nowadays it is used as best management practice for soil and water conservation all over the world but it is a more expensive soil conservation practice (IWRM, 2016).

(2) Contour Bunds

As progressive terraces, contour bunds are suited to flat areas of slopes less than 16% (IWRM, 2016). These are constructed along the contours, low rainfall areas (less than 600 mm/year), soil depth > 20 cm, slope < 7 %, good infiltration capacity, built in series to divide the length of the slope. In the areas of contours bunds applications, gullies were reduced at a very high rate of 72% (Birhanu et al., 2014). According to the workshop report compiled by (Savadogo et al., 2017), it is reported that the contour bunds can reduce the soil erosion and increase the soil water holding capacity in the intervention area. As an example, the yield for a maize farmland under contour bund management increased from 35% to 38% while for millet and sorghum, the yield increased from 30% to 60% (Savadogo et al., 2017).

(3) Contour tillage

This is the simplest soil erosion control measure on sloping land, which concurrently reduces runoff and increase water infiltration compared to that which occurs in cultivation parallel to slope. The performance of contour tillage in reducing soil erosion is ranged between 67-75% (Liu et al., 2010).

(4) Check Dam

Check dams are structures constructed across a channel or a river to lessen water velocity and to catch sediments (Shit et al., 2013). The major function of check dams is to lessen water velocity and to catch sediments in gullies with performance about 41.5% (Shit et al., 2013). The experiment conducted by (Pravat et al., 2013) has revealed that check dams performance may reach up to 50% sediment reduction when used properly.

(5) Anti-erosive ditches

An anti-erosive channel is a drainage channel constructed to prevent runoff water from upper hill to enter to a cropped land. In this channel, water may infiltrate or may be diverted. To increase the performance of anti-erosive ditches, protective grasses are planted on ridges along the channels and the collecting drain should not slope less than 1% lengthwise in order to reduce the scouring effect of high flow velocity. Like other erosion control structures, regular maintenance is required to keep the channeling capacity of the drainage ditches (Dollinge et., 2015)

(6) Grassed waterways

Grassed waterways are effective conservation practices used to prevent gullies formation along natural drainage ways. It has been found that grassed waterways combined with terraces reduced runoff by 86% and soil erosion by 95% (Gali et al., 2015).

Grassed waterways are more important in filtering by retaining runoff sediments, pollutants and other particulate matter within storm water and their performance will depend on soil permeability within the area. According to the study conducted by (Fiener et al., 2017) the runoff and sediments were reduced by 90% to 10% and by 97% to 77% respectively.

(7) Hillside water ponds

Rainwater harvesting is a system of collecting water through different techniques such as storage of rainwater on surface reservoirs and groundwater recharge for future use.

Hillside Rainwater Harvesting (RWH) Ponds are most efficient techniques which controls soil erosion by reducing run off velocity and sediment transport with efficiency varying between 99% to 76% (Barsher et al., 2016). The research conducted in Bugesera District of Rwanda showed that 88.89% of farmers adopted the use of hillside water ponds in agriculture fields, their life standard has been both economically and healthily improved (Munyaneza et al., 2016). In addition, the study conducted in China (2011) revealed that the use of ponds for retaining rainwater reduced soil erosion up to 15.9% (Peng et al., 2011).

(8) Riverbank stones revetment: use of riprap and gabions

The revetments are applied to protect riverbanks from erosion and piping collapses which would be caused by strong river current. The gabions are used in civil engineering for earth retention and erosion control. Gabions promote growth of vegetation and consequently reduce erosion (Morgan, 2005; Saleem et al., 2018). The shear strength of the soil behind the gabion revetments increase in 6 to 12 months after construction by 59.6% and 162.9%, while the shear strength of the soil under riprap increased by 115.6% and 239.1% respectively. The results also indicated that the gabion and riprap revetments could increase the river water purification costs and the ecological biodiversity in the region (Van et al., 2018).

(9) Retaining walls made of gabions for slope stabilization

Retaining walls are structures made of masonry, stone, brick, concrete or a combination of these. They are used to support soil laterally from a building or any other structure and they may be used

also as erosion control structure. They are mainly used where the toe of slope can collapse and the slope failure is likely to progress upward along the slope.

Based on the type of materials, gabions are rectangular metal cage fabricated from a hexagonal mesh of galvanized steel wire filled with natural stones. Comparatively to other retaining walls, the main advantage of gabions retaining walls, is to reduce the runoff velocity or to increase the stability of sloping surface area with seepage problems. Their implementation is easy, economically and flexible and they can be vegetated (Najeeb et al., 2019).

(10) Sediment basin or catch basin

A sediment trap or sediment basin is an earthen embankment constructed across a waterway with a spillway made of stones or aggregates to slow the evacuation of runoff by retaining it for a short period of time which allow the settlement of sediments. The main function of sediment basins is to prevent sediment transport and reduce sediment delivery. Sediments basins remove mainly silts but will not remove fine silts and clay. The efficiency of sediment basins to control soil erosion is 30% (Peng et al., 2011). These basins may also be used to control the volume and velocity of the runoff through a timely release by utilizing multiple spillways.

(11) Constructed wetland

Permeable soils are not suited for constructed storm water wetlands. Constructed wetlands improve water quality: Constructed wetlands showed a good performance on removal of the total suspended solid and ammonia with 70% and 76% respectively (Ayeni et al., 2017).

(12) Sediment fences

Sediment fence is a structure which acts as a barrier of sediment or constructed to retain the soil or sediment from disturbed land by settling until the activities disturbing the land are sufficiently completed to allow revegetation. Researches showed that sediment fences reduce effluent total suspended solids (TSS) and turbidity ranging from 88.2% to 98.4% and from 49.2% to 92.8% respectively (Troxel, 2013).

(13) Use of paved block as energy dissipaters

Paving blocks are used for reducing the runoff velocity depending on paving types. Each type of paving blocks has different performance in reducing the flow velocity. The surface runoff velocity reduction using paving blocks is generally above 40% (Laksni et al., 2017).

(14) Roof runoff and cisterns

Rainwater harvesting is more important as it reduces surface runoff which is the main cause of soil erosion, flooding and destruction of socio-economic infrastructures. It is reported that the use of roof runoff cisterns reduces soil erosion by 98% (Kiggundu et al., 2018).

2.4.3 Limitative factors on the implementation of soil erosion control measures

Most of SWC techniques (terraces, contour bunds, retaining walls, check dams, sediment basins, etc.) are costly to build. Many researchers reported that the limiting factors of the adoption of soil and water conservation techniques are related to poverty and limited knowledge (Bizoza and De Graaff, 2012; Debebe et al., 2013).

Worldwide, soil erosion is a major environmental problem. It is one of the environmental phenomena to which the adage “Prevention is better than cure” is most applicable. For the goals of best management practices to be achieved, all stakeholders can participate in setting out of policies, rules and regulations with their implementation to reduce and manage the soil degradation rate in their country. A lot of researchers should focus their attention on catchments management measures that can be easily applied by the indigenous knowledge to fight against the occurrence of soil erosion. Increasing vegetation cover of soils in this climatic change-driven 21st century characterized by increased incidences of rainfall is very expedient so as to reduce the power of rainfall to induce soil erosion. To this end, laws for afforestation and against deforestation should be erected by governments with provisions to punish offenders adequately. Prioritizing dry season farming becomes necessary to avoid more disturbance of soils during rainy period which would predispose them to the impact of raindrops and runoff that detach and transport soil particles in splash-sheet-rill-gully erosion processes. All affected people (landholders, farmers, etc.) should be empowered through grants from governments, donor agencies and non-governmental organizations (NGOs) to adopt and implement erosion control measures at an early stage. Trainings and sensitization in soil erosion management should eradicate all agricultural practices that uncover the soil and expose it to the erosive power of rainfall.

2.5 RESEARCH GAPS

The history of soil erosion is an integral part of the agriculture. All over the world, wherever human being started the agricultural operations, there exists the problem of soil erosion in some extent. Throughout the literature, all the publications consulted revealed that soil erosion rates are always greater than the maximum soil loss tolerance rate of 11.5 t/ha/y in the major parts of all catchments.

Practically, lowering the high soil loss rates below the maximum soil loss tolerance rate of 11.5 t/ha/y throughout the entire catchment should be the main target in implementing SEC measures (Sakinatu and Muhammad, 2017).

The information related to the current situation of soil erosion rates and its control in the Sebeya catchment were obtained from published journal articles and different reports of government bodies. This methodology enabled the researcher to record the following research gaps in soil erosion and its control in the Sebeya catchment. In fact no publication found on:

- (1) The impact of land use /land cover changes on soil erosion in the Sebeya catchment;
- (2) The soil crusting and soil erodibility in the Sebeya catchment;
- (3) The Sebeya river sediment loading rates and its impacts on various socio-economic development projects;
- (4) Farmers' willingness to adopt, implement and maintain SEM measures in the Sebeya catchment;
- (5) The sustainability analysis of soil erosion control in the Sebeya catchment.

CHAPTER 3. MATERIALS AND METHODS

3.1 STUDY AREA

3.1.1 Site localization

This study is entirely focused on the Sebeya level 2 catchment which is a part of the larger level 1 Lake Kivu catchment and located in the Western Province of Rwanda. As presented in Fig. 3.1, the Sebeya catchment is shared by four administrative units namely Rubavu and Nyabihu Districts in the North, and Rutsiro and Ngororero Districts in the South. The main river flowing in this catchment is Sebeya, which originates in the mountains of Rutsiro District. It flows past the mission of Nyundo established in 1901 on the banks of the river about 12 kilometres upstream from Lake Kivu.

Located on the Western flanks of the Congo-Nile divide, the Sebeya and Lake Kivu catchments are some of the most upstream parts of the Congo River Basin (that flows into the Atlantic Ocean). The Sebeya catchment is one of the small catchments that drain the Western slopes of the Nile Congo catchment of Rwanda between $01^{\circ}50'57.15''$ and $01^{\circ}42'21.99''$ degrees South (22.984 km) latitude and $29^{\circ}23'52.04''$ and $29^{\circ}25'06.14''$ degrees East (27.455 km) longitude (IWRM, 2018). The total surface area of the Sebeya catchment represents 1.38 % of the total surface area of Rwanda (26,338 km² including water bodies), which totalizes 363.1 km² (NISR, 2014; IWRM, 2017).

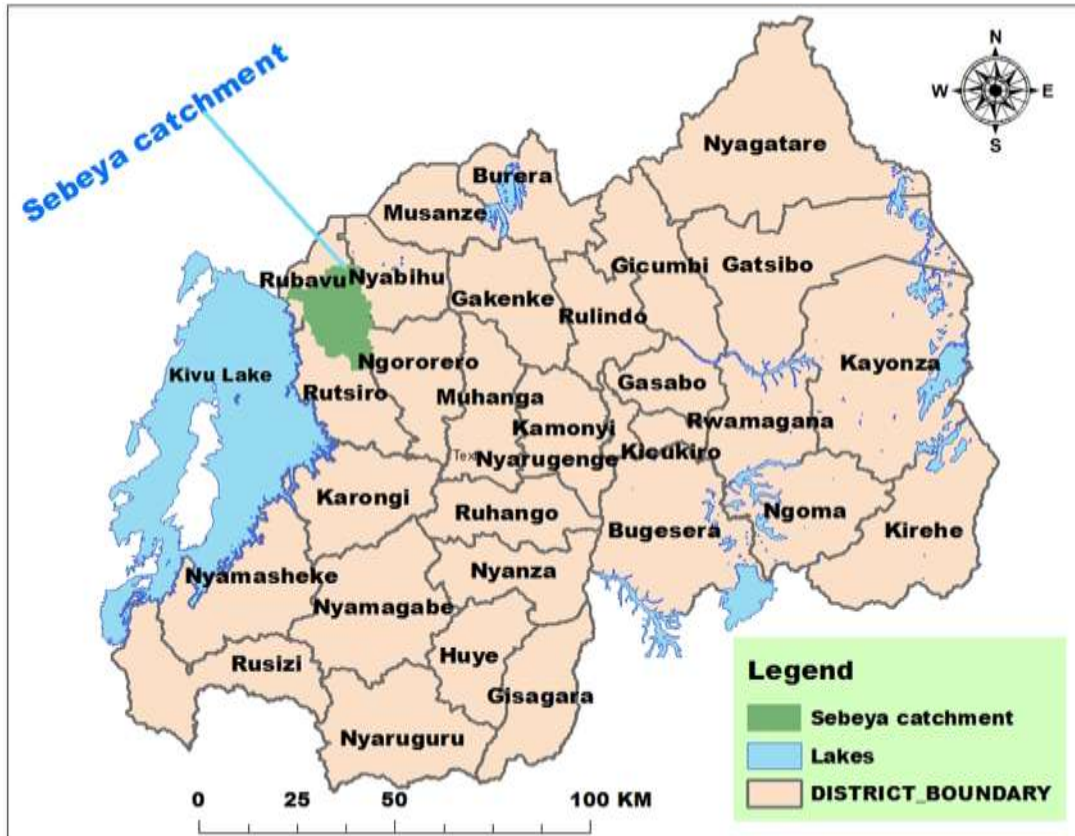


Fig. 3.1 Location of the Sebeya catchment on Rwanda map

3.1.2 Population density

The average density of the Sebeya catchment is estimated to be 644 hab/km² which is bigger than the average population density of Rwanda (415 habitants per km²) (NISR, 2015). This high demographic pressure is one of the indirect factors accelerating soil erosion in the Sebeya catchment (NISR, 2014).

3.1.3 Soil characteristics

Butare complex (Bu) and the volcanic rocks of Virunga Mountains (B) are two main geological formations in the Sebeya catchment and nitosol, acricol, alisol and lixisol are the main soil classes (IWRM, 2018). The soil in this catchment favors agriculture due to its high infiltration rates and its high minerals content. The combination of the geological formation and soil data characterize the Sebeya catchment as a fragile ecosystem susceptible to heavy erosion (MoE, 2018).

3.1.4 Site topography

The topography of the Sebeya catchment is among the mountainous chain of Congo-Nile river divide extending North-South from Nyungwe forest in South to Gishwati forest in North. This mountainous chain divides the country into two catchments. The Sebeya catchment is characterised by steep slopes and complex topography (abrupt changes of altitude on small distances) (IWRM, 2018).

3.1.5 Climate

Rwanda has a climate with an average temperature around 20°C and low monthly variation. The rainfall pattern of Rwanda is bi-modal i.e. it has two distinct rainy seasons. A heavy rains season (March, April, and May) and a light rains season (September, October, November and December). Rwanda has a dry climate in the East (lower elevation) and a wet climate in the West (high altitude of mountains) resulting in a large and varied pattern of agro-ecological zones. Located in the high elevation region of the country with altitude varying between 1,462 m to 2,979 m a.s.l. (meters above sea level), the Sebeya catchment is also characterised by steep slopes and abundant rainfall (1,200 mm to 1,700 mm per year) and a relatively short dry season in June – August where erratic showers continue in January – February, which is considered as the second dry season (IWRM, 2018).

3.1.6 Land use / Land cover

Land use and land cover are not identical terms. Land cover denotes the physical, chemical or biological categorization of the terrestrial surface (For example, a grassland, forest or any cover on the land surface such as roads and buildings or any water body), whereas land use refers to purposes associated with that cover such as raising cattle, recreation, housing (residential, commercial, industrial, etc.) or any other type of human activities. Land use is the arrangements of activities by people in a certain land cover type to produce or to change or to maintain it (Nedd et al., 2021).

Land-use and land-cover changes refer to quantitative changes in the aerial extent (increases or decreases) of a given type of land use or land cover, respectively. However, land-cover changes may result either from land conversion (a change from one cover type to another), or land modification (alterations of structure or function without a wholesale change from one type

to another), or even maintenance of land in its current condition against agents of change (Li et al., 2021).

The Sebeya catchment land cover classes include: forest plantation, rainfed herbaceous crops, herbaceous vegetation, shrubs, tea plantation, natural forests, build up areas, water bodies etc. Excessive trees and vegetation retards soil erosion in the catchment.

The major land use classes in the Sebeya catchment include: cattle grazing, agriculture and forest plantations. There are practices to support green agriculture and mining, but several cases of unsustainable mining and agriculture still cause terrible sedimentation of the Sebeya river during heavy rainfall (IWRM, 2018).

3.1.7 Hydrography of the Sebeya catchment

The Sebeya catchment contains two main rivers, Sebeya and Pfunda. These rivers are the source of water for Gihira Water Treatment Plant and for hydropower generation of Keya, Gihira and Gisenyi Hydropower Plants. It is also drained by a number of small rivers including Bihongoro, Gatara and Karambo upstream (RNRA, 2014).

The Sebeya river is running in the North–Westerly direction along 48 km from its source in the mountains of Congo-Nile divide at an altitude of 2660 m.a.s.l of Gishwati forest to its outfall at Lake Kivu at an altitude of 1470 m.a.s.l (IWRM, 2018). Its main tributaries are shown on the following hydrographic map (Fig. 3.2).

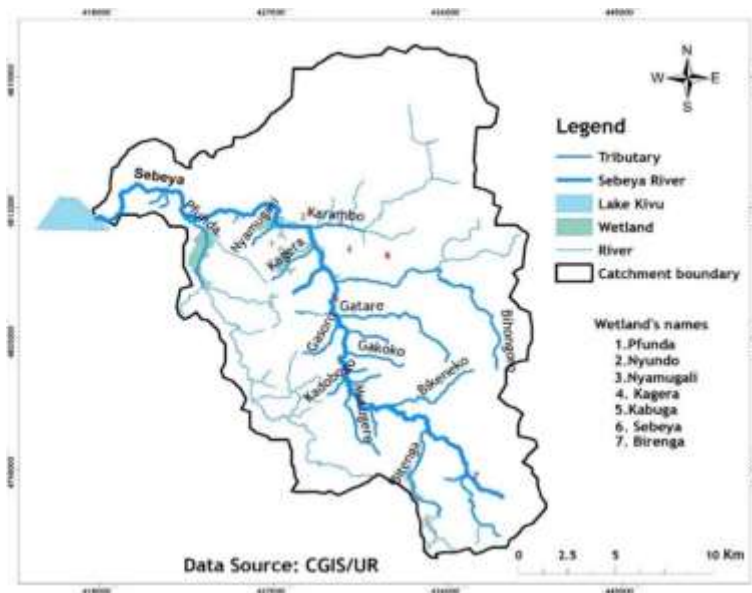


Fig. 3.2 The Sebeya catchment hydrographic map

3.2 DATA COLLECTION

3.2.1 Secondary data collection

(1) Worldwide researchers views on soil erosion and its control

The information related to the current situation of soil erosion rates and soil erosion control in the Sebeya catchment have been obtained from published journal articles and different reports of government bodies. This methodology enabled the researcher to make a synthesis of various researchers' views on this topic.

(2) Agro-climatological data

Agro-climatological data were required for planning crops cultivation and field experiments in soil erosion plots: Historical data for rainfall were collected from Center of Geographical Information System of University of Rwanda (UR-CGIS) to produce the rainfall erosivity map of the Sebeya catchment. The sowing dates and the simulated crop rotation in SOLCY model (Table 4.25) were fixed based on the the 3 recognized agricultural seasons in Rwanda which are: Season A (September-February); Season B (March-June) and Season C (July-September) (NISR, 2017).

(3) Natural disasters in the catchment

Historical information on natural disasters (erosion, floods, etc) was obtained from the Ministry in charge of Emergency Management, the former Ministry of Disaster Management and Refugees (MIDMAR).

(4) Hydrological data

Ten-year historical data like water stages of the river, river discharges were collected from the Rwanda Water Resources Board in its website “Rwanda Water Portal”.

(5) GIS data

In this study, Digital Elevation Model and different shapefiles were collected from the Center of GIS of University of Rwanda (UR-CGIS) to generate the topographic map and the soil texture and land use / land cover maps of the Sebeya catchment.

The Ministry of Environment (MoE) is using the “Catchment Restoration Opportunity Mapping” (CROM) model created by the Environmental Systems Research Institute (ESRI)

Rwanda Ltd. to classify soil erosion risks in Rwanda. Advantageously, this study took this opportunity to collect different shapefiles for the existing and site-based recommended SECM from the Rwanda Water Resources Board (RWB, 2018).

(6) Landsat images

This research used Landsat images acquired in September 2008, September 2015, August 2018, and September 2022 to assess the impact of the LULC change on water erosion in the Sebeya catchment.

3.2.2 Primary data collection

(1) Farmers views on soil erosion in the Sebeya catchment (from 06 to 09 Sept 2018)

In sampling analysis, the sample size (n) should be optimum i.e. it should neither be excessively large nor too small (Faber & Fonseca, 2014) observed that regardless of population size, a sample should not be less than 30 respondents in which a statistical data analysis is to be done. In this present study, the number of farmers interviewed was limited to 75 farmers. A questionnaire containing 37 questions was used to interview a total number of 75 farmers living and having their farm lands in 6 sectors of the Sebeya catchment which are Gisenyi, Rugerero, Nyundo, Nyakiriba, Kanama sectors of Rubavu District and Nyabirasi sector of Rutsiro District. Mahoko market site has been found to be appropriate point where face to face interviews have been conducted from 06 to 09 September 2018. The strategy to select the nearest site adjacent to Mahoko market is justified in finding sufficient representative farmers coming to the market from all Districts including the remote Nyabirasi Sector of Rutsiro District. Also after satisfying their needs from the market, farmers were free to respond to this PhD interview.

The Fig. 3.1 shows that the Sebeya catchment extends on many sectors of 4 Districts while the Table 3.1 below shows that the overlapped area between Rubavu and the Sebeya catchment is the largest and equal to 44.6%. The next largest overlapped area comes to be 41.3% between Rutsiro and the Sebeya catchment.

Table 3.1 Overlap between Districts and the Sebeya catchment (RNRA, 2012)

Catchment Name	Area km ²	Area of each District			Overlapping areas	
		District	Area km ²	Area km ²	% Catchment	% District
Sebeya catchment	363	Ngororero	679	37	11%	5%
		Rutsiro	1,157	139	41.3%	12%
		Nyabihu	532	38	11.3%	7%
		Rubavu	388	150	44.6%	39%
		Total		363		100%

Following to this fact, the sampled sectors for farmers' interview in the Sebeya catchment have been limited to these 2 Districts of large overlapped areas. The table 3.2 below shows the sampled sectors and the number of farmers interviewed in each sector.

Table 3.2 Selection of sectors for farmers interview in the Sebeya catchment

SN	District	Sector	Number of interviewees
1		Gisenyi	12
2		Rugerero	14
3	Rubavu	Nyundo	15
4		Nyakiriba	4
5		Kanama	15
6	Rutsiro	Nyabirasi	15
TOTAL			75

On the site, structured interviews were conducted to get constructive views from 75 farmers on the current status of soil erosion rates and the implementation of its control measures in the Sebeya catchment.

(2) The Sebeya river sediment dynamics and its impacts

➤ The Sebeya river flow

The Sebeya river discharges were measured using the area velocity method, commonly known as current meter method. The current meter was used to measure the point velocity at 60% depth of

each vertical of the river width at Nyamugari bridge (Fig. 3.3) where the width of the river is 8 m while 0.5 m between 2 successive verticals was adopted.



Fig. 3.3 Taking point velocities for discharge measurement using a currentmeter

A current meter uses a propeller component to measure the local velocity of flow (v) and water depth was measured using a tap measure. As described by (Le Coz et al., 2014), the mean-section method was used to calculate the total discharge (Q) by integration of the velocity (v) over the river cross section area (A).

➤ **Sampling sites for bed load and water samples for TSS, turbidity and NPK content**

Due to the fact that main socio-economic development projects (Gihira WTP and 3 hydropower plants namely Keya, Gihira and Gisenyi HPPs) are concentrated downstream within 12 km from Lake Kivu, water and bed load samples were seasonally hand-collected at the 5 five selected sites along the Sebeya river ((NYB, KY, GH, GSH and SO) as shown in Fig. 3.4. Bed load samples and water samples were taken respectively to soil mechanics and chemistry laboratories of University of Rwanda, College of Science and Technology where different parameters were analyzed including sieve analysis of bed load aggregates, total suspended solids, turbidity and NPK content.

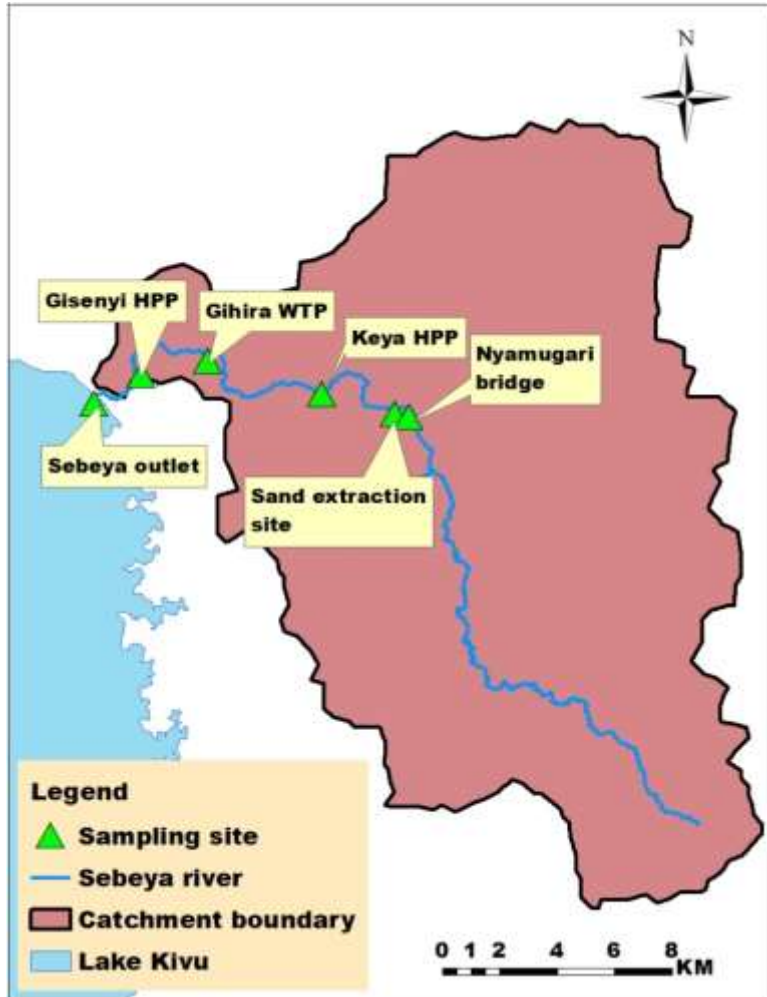


Fig. 3.4 Sampling points

➤ **Sampling and laboratory tests for Suspended Solids and Turbidity**

Sampling for testing of suspended solids and turbidity was needed in this research to assess the sediment loading rates in the Sebeya river. In order to compare the results of this study, sampling period was extended from rainy season (26/4/2019, 3/5/2019 and 18/5/2019) to dry season (26/7/2019, 2/8/2019 and 8/8/2019). The width of the river at Nyamugari bridge is 8 m and the depth of water was about 0.60 m at each sampling date and time. In the following Fig. 3.5, a field technician taking water samples in the Sebeya river for TSS and turbidity analysis. Successively at (2 m, 4 m and 6 m) along the Sebeya river width from the left river bank, a sampling bottle of 500 ml was inserted at 15 cm below the water surface for prevention of disturbance due to floating

debris (Musselman, 2012). From a well-mixed collection of the 3 water samples at each of the 5 river cross-sections, 500 ml water sample was taken, making a total of 5 samples for laboratory analysis.



Fig. 3.5 The Sebeya river water sampling

➤ **Suspended sediment determination procedures**

From each water sample of 500 ml taken from the respective sampling site, a small quantity of 100 ml was placed in an aluminium sheet plate which was then heated on a hot plate for about 30 minutes in order to vaporize water. The humid residues left on the aluminium sheet plate was then dried in the oven at 105°C for 24 hours and after that time the dried TSS was weighed and the concentration of TSS determined in mg/l.

➤ **Turbidity measurement**

Turbidity meter is a complex and delicate instrument which needs to be calibrated before its use. In this study, a 50 ml water sample was poured in a turbidity glass which was then placed in the turbidity meter to allow reading of the turbidity value in NTU.

➤ **The Sebeya river bed load sampling**

Sampling for testing of bed load sediments was needed to check the sediment loading rates, its composition at the river bed and its gradation. Samples were hand-collected in the Sebeya river at

five selected sampling points. The sampler used for this study (Fig. 3.6) was designed referring to the description given by (Kristin and Steven, 2003). The characteristics of the designed sampler are as follows: opening front size of 0.3 m * 0.2 m (large enough to allow sediments to enter), total length of 0.9 m and the mesh size of 3.9 mm (for capturing different sizes of sediments greater than 3.9 mm). For bed load sampling, 3 samplers were immersed at the bottom of the river at 3 equidistant points along the river cross-section (at 2 m, at 4 m and at 6 m from the river bank). Before starting the sampling process, the mass of each empty sampler was recorded and samplers placed in contact with the river bed against the flow, allowing the sediment transported as bed load to accumulate or be trapped inside the sampler for 1hr (Long duration for the collection of infrequently moving large particle sizes near the threshold of motion). After one hour, the samplers were raised up to the surface and the weight of the content of each sampler was recorded. The bed load from the 3 samplers were well mixed and 1kg taken from this mixture for further analysis in the laboratory.



Fig. 3.6 Bed load sampler

➤ **Sieve analysis for bed load aggregates**

Laboratory procedures were performed by sieve analysis as per IS: 2386 (Part I) – 1963 to determine the particle size distribution of the coarse and fine aggregates with the following sieve sizes: 20 mm, 10 mm, 8 mm, 6 mm, 4.75 mm, 3.35 mm, 2.36 mm, 1.18 mm, 600 μm , 300 μm , 150 μm and 75 μm . Because there was no artificial vibration or mixing to disturb the natural collection of the bed load samples, the presence of fine particles in the bed load samples was unavoidable. This study assessed their presence and gradation because fine sand particles were accused to cause abrasion on hydropower turbines (Munyaneza et. al., 2015). The bed load sediment composition was determined using MIT (Massachusetts Institute Technology) grain size classification standard.

(3) Development of runoff coefficients and soil erodibility under LULC

The field experimental setup constructed was comprised of three farm field plots namely MFM (Maize Fertilizer Mulching), MF (Maize Fertilizer) and BS (Bare Soil) (Fig. 3.7). Each plot was associated with its runoff collection tank that facilitated water sampling in order to estimate soil loss from each plot. Soil classification was also done. Due to the fact that the behavior of soil moisture content in the 3 plots should be assessed after the 1st rainfall event. However, this study has performed not more than 3 samplings for soil moisture evaluation after each rainfall event. By estimating the local rainfall using a fabricated low cost raingauge, runoff coefficients were also estimated after each rainfall event as a ratio of volume collected over precipitated volume.

➤ Rainfall measurement at the field location

Agro-climatological data are required for planning crops cultivation and forecasting agricultural productivity (Rogers, 2013). In this study, the site rainfall was measured in the field location using a prefabricated rain gauge. The idea of local rainfall measurement was to compare rainfall recorded at Gisenyi meteo station with real rainfall in the experimental field plots. In fact, the variation of a point-rainfall in time and space depends on topographic effects and wind direction (Ly et al., 2013).

➤ Field experimental design

The standard USLE Plot of 22.1m x 4m was proposed and tested on a slope of 9% (Lal, 1994). The present study has designed three experimental plots of (21m x 4m) each sloping at about 14%. Plots were sufficiently wide to minimize the border effects and long enough to allow the development of the combined downslope processes of rill and interrill erosion. As shown in Fig. 3.7, the proposed names for the 3 experimental field plots are: MFM (Maize-Fertilizer-Mulching), MF (Maize-Fertilizer) and Bare Soil (BS). All those plots were constructed in Rugerero sector of Rubavu District and the main characteristics for the 3 constructed plots are as follows:

- The ploughing, levelling and sloping conditions are the same;
- With compost and chemical fertilizer applications, the maize seeding was done in the first 2 plots (MFM and MF) only while the 3rd one (BS) was kept blank without any crop seeding and no fertilizer application;
- Differently to 2 other plots, the 1st plot (MFM) was additionally mulched. All the 3 field plots were under the same conditions except land cover.

- All the borders of each plot were banded with gabions socked into the ground and wrapped with plastic sheets so that only runoff from direct precipitation on the plot could be collected in the coupled runoff collecting tank;
- Each runoff collecting tank was large enough to store the total runoff after each rainfall event. After each rainfall event and after taking the water sample, each runoff collection tank was emptied through a drainage pipe at its bottom.

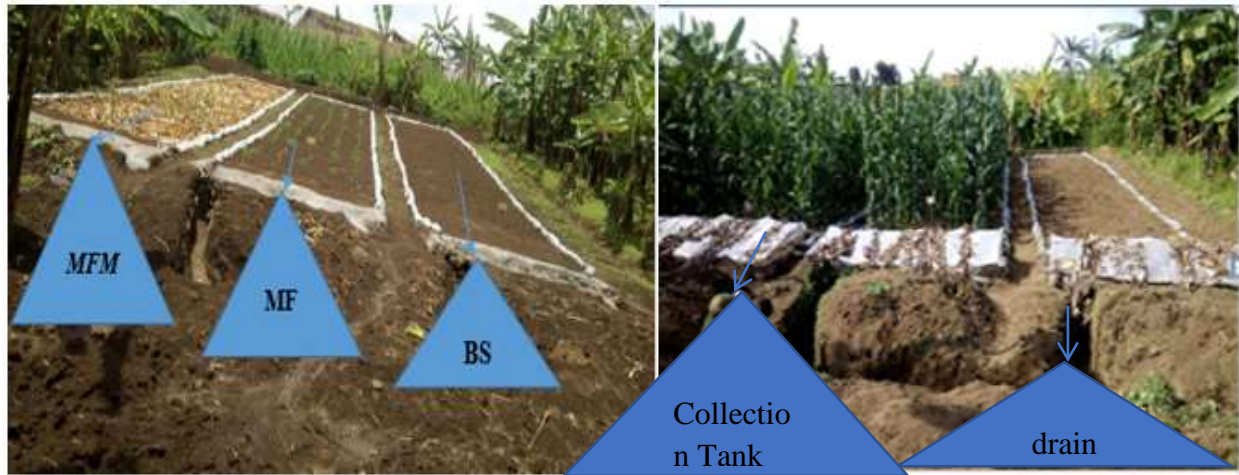


Fig. 3.7 Field plots at initial and middle stages of growing maize

➤ **Soil texture determination through sieve analysis**

Three soil samples were taken from the experimental field: about 1Kg at the top; 1Kg at the middle and about 1Kg at the bottom and well mixed. About 1Kg of soil sample from a well-mixed soil samples was taken to Soil Mechanics Laboratory of University of Rwanda, College of Science and Technology (UR-CST). The particle size distribution analysis was performed using the method proposed by Bureau of Indian Standards in 1963 known as IS: 2386 (Part I) – 1963. Different sieves with different sizes of 63mm, 50mm, 40mm, 25mm, 20mm, 16mm, 12.5mm, 10mm, 6.3mm, 4.75mm, 2.36mm, 1.18mm, 600 μ m, 150 μ m and 75 μ m were used. The Soil Classification was done using MIT (Massachusetts Institute of Technology) Soil Grain Classification Standard.

➤ **Sampling and testing of water from runoff collecting tanks**

A water sample of 500mL was collected from the runoff collecting tank installed at the bottom of each of the 3 plots. Before taking water samples, the volume of water collected in each tank was recorded and thoroughly mixed. After each rainfall event, the collected three water samples were taken to Soil Mechanics Laboratory of UR-CST to estimate the induced soil loss from each plot.

Finally, each runoff collecting tank was emptied through a drain pipe connected at each bottom level in order to be ready for next sampling experiment. About 100mL from the mixed water sample was boiled to vaporize all water on the vaporization dish. The remaining wet soil was then put in an oven-drier during 24 hours at about 105°C. After this time, soil loss per 100mL was estimated.

➤ **Determination procedures for soil moisture content**

Three samples of soil were taken at 3 different sampling points: at the top, at the center and at the bottom of each plot. A cleaned dried plastic cup of 500 mL was inserted vertically into the soil for taking the soil sample until the bottom of the cup reached the level of the soil surface. Then the cup was returned up without disturbing the state of the soil inside the cup and the weight of the cup with the wet soil was recorded. In order to obtain a well dried soil after 105°C, a reduced sample of 200g was taken from the 500 mL cup content and weighted with the plate before inserting the plate and its content in the drying oven. After drying the reduced sample with the plate in an oven at a temperature of 105°C for 24 hours, the weight of the reduced sample with the plate was recorded. The average moisture content for each plot was computed.

3.3 DATA ANALYSIS

Microsoft Excel was used to analyze data in terms of figures and tables. Throughout this PhD study, data have been analyzed using the following applications and procedures:

- (1) In the review paper, the researcher was able to make a synthesis of various researchers' views on this topic. Both on-site and off-site effects of soil erosion were analyzed and remedial measures highlighted.
- (2) During the farmers interview and after, qualitative and quantitative data were collected and analyzed.
- (3) In assessing the soil surface crusting caused by rainfall events in this research, samples of soil from field plots and water from runoff collecting tanks were tested for soil classification, moisture content analysis and soil loss estimation from each plot respectively and after each rainfall event.
- (4) Laboratory analysis for turbidity, total suspended solids, sieve analysis for bed load materials and NPK content of water and bed load samples were conducted.

- (5) Aiming to assess the performance of erosion remediation measures and to propose the Best Management Practices (BMPs) for erosion control in the Sebeya catchment, various erosion control measures were analyzed in terms of performance and suitability. Land slope and soil depth maps were generated using ArcGIS software and the interview results were analysed statistically.
- (6) Aiming to develop a USLE-type erosion model to be used in predicting soil loss and associated crop yields for sustainable environmental management in the Sebeya catchment:
- ArcGIS software was used to delineate the catchment and for mapping all USLE factors. The input data include Digital Elevation Model (DEM) for delineation and slope analysis of the Sebeya catchment, soil data shapefile to assess the soil depth within the catchment, rainfall data, land use / land cover data which were collected from the Center of Geographical Information System of University of Rwanda (UR-CGIS). The Universal Soil Loss Equation (USLE) model has been used to estimate soil loss from the Sebeya catchment.
 - The 5 USLE parameters were determined on each parcel in the Sebeya catchment by maps overlapping techniques as applied in Geographical Information System (GIS). Correlatively on each culturable parcel of the Sebeya catchment, the crop yield was predicted from the soil loss value using an established linear relationship.
 - Statistically, F-test was used for testing the difference between 2 mean values of 2 samples (GIS results and results obtained by applying the designed Soil Loss and Crop Yield (SOLCY) model).
- (7) The actual soil loss rates and the soil loss rates induced by the site-based recommended SEC measures in the Sebeya catchment were simulated and predicted using USLE model and various shapefiles obtained from RWB. In these simulations, typical values of the USLE factors were found from the existing worldwide literature.
- (8) Various factors affecting farmers' adoption of SEC measures were assessed using SPSS (Version 20), the t-test, the chi-square test, and the binary logistic regression model.

CHAPTER 4. RESULTS AND DISCUSSIONS

In an effort to achieve the objectives of this PhD research, the following three parts (Part A: Preliminary investigations, Part B: Published papers and Part C: General discussion of the PhD results) present, discuss and analyse the main research results and clarify how the above 5 listed specific objectives of this PhD research have been achieved.

PART A. PRELIMINARY INVESTIGATIONS

4.A.1 FARMERS PERCEPTIONS ON SOIL EROSION IN THE SEBEYA CATCHMENT

A.1.1 Introduction

Environmental deterioration associated to soil erosion is one of the most serious threats in developing countries (Pravat et al., 2015). Generally, the high vulnerability to soil erosion in Rwanda is due to various factors such as abundant rainfall, hilly and mountainous relief, demographic pressure and agricultural expansion on steep slope terrain (Karamage et al., 2016; IWRM, 2018; MoE, 2018).

A recent study by the Rwanda Ministry of Environment has shown a very high risk of erosion in the north western Rwanda, covering areas of the Sebeya catchment (MoE, 2018). Soil erosion increases the amount of sediments transported in the Sebeya river. The eroded sand materials cause abrasion in hydro turbines and lead to change in flow pattern, losses in efficiency, vibrations and even final breakdown of turbine components (Munyaneza et al., 2015, Thapa et al., 2017) while high sediments load imposes high turbidity and high cost of coagulants to Gihira water treatment plant. At the Sebeya river outlet, nutrients lost from agriculture and high turbidity reduce significantly the aesthetic quality of Lake Kivu, having a harmful impact on recreation and tourism.

Therefore, it is imperative to prevent soil loss from agricultural land and consequently reduce the amount of sediment load in the Sebeya river. This research held to explore the actual status of soil erosion in the Sebeya catchment by investigating its causes and factors affecting it and by assessing the existing soil erosion control measures for their improvement.

A.1.2 Methodology

During the study period, different site visits were frequently conducted to get primary data through informal and structural interviews on main cultivated crops and agriculture practices, main features of the Sebeya river, site topography, hydrographic network, soil characteristics and about the existing soil erosion control measures in the Sebeya catchment. The details and procedures for this interview are presented in chapter 3.

A.1.3 Research outcomes

A.1.3.1 Identification of respondents

Among the farmers surveyed, 54.67% were men while 45.33% were female with ages ranging from 18 to above 55 years old. However, some researchers agree with large numbers of women in farmers interviews (Senkoro, 2010). A large number of farmers were found in the age range of 31-40 years old because they are more stressed to fulfill their family needs such as food security and school fees for their children. Again, 81.33% of the interviewed farmers are married. Comparatively, the number of farmers in the range from 18 to 25 ages were very small because they are still at school and some of them are not interested in farming activities after completion of their secondary studies.

A.1.3.2 Socio-economic issues of farmers

This research found that the main cultivated crops in the Sebeya catchment are groundnuts, bananas, coffee and tea, beans, maize, cassava, potatoes, rice and vegetables like eggplant and cabbage (MINAGRI, 2010; NISR, 2015). The results from this interview showed that several farmers are engaged in farming for agriculture business (40%), lack of other jobs (37.33%) and food security (22.67%). The main challenge of farmers in the Sebeya catchment is to struggle in fulfilling their basic needs such as food, health care, school fees, clothes, domestic water, etc.

A.1.3.3 Farmers knowledge about soil erosion and types of soil erosion in catchment

Soil erosion is considered to be severe when visible signs such as rills and gullies appear on the field. Various soil erosion signs given in the Table 4.1 indicate that soil erosion in the Sebeya catchment is well known by about 80.67% of farmers. Similarly, the research conducted in central highlands of Ethiopia shows that 72% of the farmers reported high rated erosion requiring soil conservation measures to be erected (Mekuriaw et al., 2018)

Table 4.1 Various signs of soil erosion in the Sebeya catchment

SN	Erosion sign	Number of respondents	Percentage (%)
1	Damaging Flood with mud flow	5	6.67
2	Channels formation in the fields	14	18.67
3	Soil detachment by rain and runoff	24	32.00
4	Soil detachment, transport and deposition of soil materials	12	16.00
5	Landslides	15	20.00
6	Floods: High runoff which overtops channels and can damage agriculture crops, lives and properties	5	6.67
7	Wind erosion: Soil detachment, transport and deposition by wind	0	0.00
Total		75	100.00

The majority of farmers argued that soil erosion appears in the form of gully, rill, stream bank and sheet erosion as shown in the Table 4.2 below. The results are supported by Misebo in 2018 who reported that sheet and rill erosion are considered as the most common types on cultivated hillsides. Both sheet and rill erosion considerably damage the croplands and reduce the productivity while the break in vegetation cover provides gully erosion to start. For the Sebeya river, streambanks erosion is due to the erosive power of runoff from uplands areas.

Table 4.2 Types of soil erosion in the Sebeya catchment

SN	Type	Number	%
1	Sheet erosion (or interrill erosion)	14	18.7
2	Rill erosion	15	20.0
3	Gully erosion	32	42.7
4	Streambank erosion	14	18.7
Total		75	100.0

A.1.3.4 Spatial distribution of soil erosion in the Sebeya catchment

The majority of farmers knows the existence of excessive soil erosion with its causes and effects in the Sebeya catchment. In order to highlight the spatial distribution of erosion processes in the Sebeya catchment, ArcGIS software was used to delineate the catchment. By integrating all maps of USLE factors in GIS (Majoro et al., 2020) , the Fig 4.1 displays the soil erosion rates in the Sebeya catchment with a mean annual soil loss rate of 130.724 t/ha/yr. In the Sebeya catchment, the high risk of soil erosion results from improper management of land, heavy rainfall and human activities that disturb the soil (MoE, 2018).

In addition, this research has divided the Sebeya catchment into 8 sub-catchments which were delineated based on the flow accumulation at different pourpoints of the existing tributaries in this catchment (Fig.4.2).

By extracting each subcatchment from the soil loss map of the Sebeya catchment shown in Fig. 4.1, the Table 4.3 shows the associated readings of mean soil loss rates values. Kanzenze and Bikeneko sub-catchments exhibited the greatest and the lowest soil loss rates of 243.868 t/ha/yr and 2.362 t/ha/yr while Bikeneko doesn't alerte immediate intervention of soil erosion control in the Sebeya catchment. This study revealed that Bikeneko sub-catchment does not require immediate intervention because its soil loss falls below the maximum soil loss tolerance value of 11.5 t/ha/yer (Bagarello, 2015).

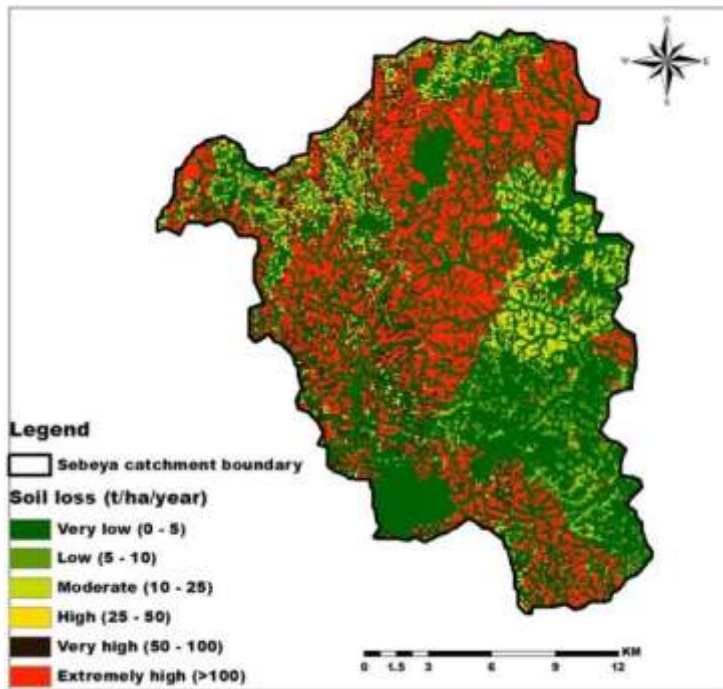


Fig. 4.1 Soil erosion potential in Sebeya catchment

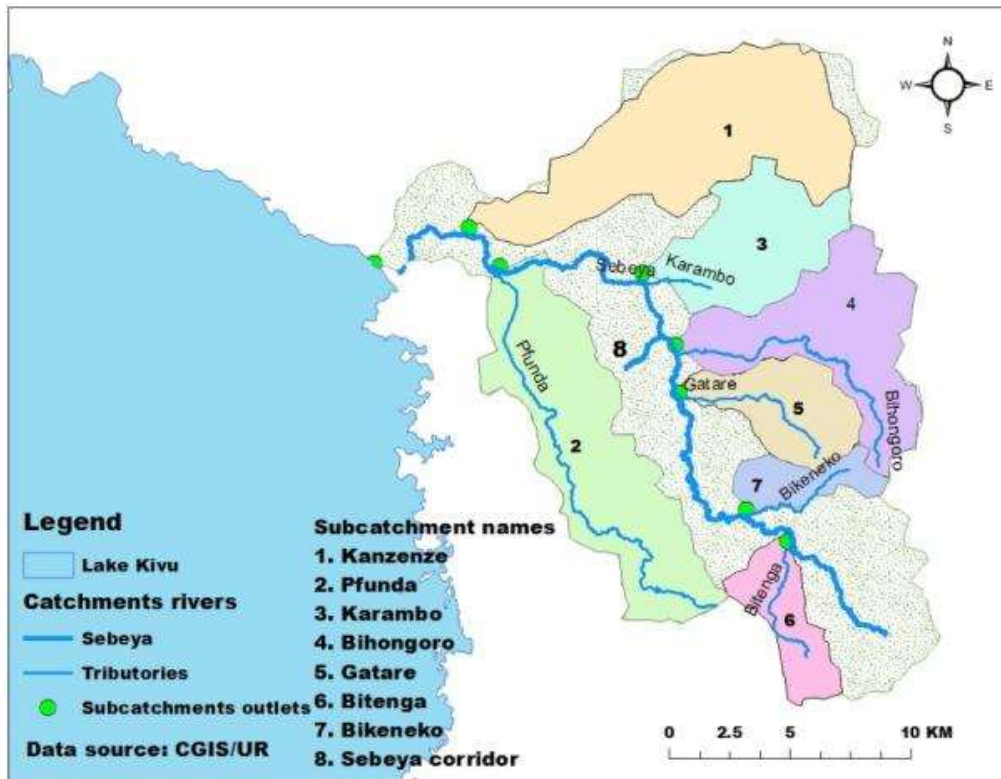


Fig. 4.2 Various sub-catchments of the Sebeya catchment

Table 4.3 Soil loss estimation in the Sebeya sub-catchments

SN	Sub-catchment	Covered area ai (ha)	Soil loss Ai (t/ha/yr)	Weighted (Ai*ai)
1	Kanzenze	6468.2	243.868	1577387
2	Pfunda	6030.4	87.102	525259.9
3	Karambo	3100.1	198.325	614827.3
4	Bihongoro	4163	127.192	529500.3
5	Gatare	2037.9	65.339	133154.3
6	Bitenga	1488.1	86.922	129348.6
7	Bikeneko	998.3	2.362	2357.985
8	Sebeya corridor	12045	102.74	1237503
TOTAL		36331		4749339
Average soil loss is 4749339/36331=130.724 t/ha/yr				

A.1.3.5 Causes of erosion in the Sebeya catchment

- **Natural causes of soil erosion**

The Table 4.4 shows that the main natural cause of soil erosion is heavy rainfall which generate high runoff. The results are not far from that reported by (Nambajimana et al., 2020) who stated that a combination of a hilly landscape, extensive land use, and intensive rainy seasons leads to high erosion risk in Rwanda. (Karamage, et al., 2016) confirmed that heavy rainfall is the cause of enhanced erosion on hillside lands.

Table 4.4 Natural causes of soil erosion

SN	Cause	Number	%
1	Slope of the terrain	21	28
2	Rainfall and runoff causing sometimes floods	36	48
3	Rainfall and runoff causing sometimes landslides	16	21.33
4	Earthquakes	1	1.33
5	High wind	1	1.33
Total		75	100

- **Anthropogenic activities causing soil disturbance**

The anthropogenic activities causing soil disturbance in the Sebeya catchment include mining, excavation for road and building construction, quarries for roads (lateritic soil and construction stones) and borrow pits for power transmission lines. For land use, soil erosion is caused mainly by agriculture, mining and roads construction sites.

- **Negative impact of farming practices in the Sebeya catchment**

The Table 4.5 is reporting negative impact of farming practices as mentioned by farmers in the Sebeya catchment with a very high percentage of deforestation for agriculture. IWRM in 2017, justified that the increase of deforestation in the Sebeya catchment is due to insufficient land for cultivation and settlement.

Table 4.5 Negative impact of farming practices in the Sebeya catchment

SN	Impact	Number of respondents	Percentage (%)
1	Deforestation for land agriculture	31	41.33
2	Soil disturbance by agriculture machinery	2	2.67
3	Soil disturbance by agriculture terracing	2	2.67
4	Soil disturbance by tea plantations channels	4	5.33
5	Remove of vegetative cover (overgrazing)	3	4.00
6	Land becomes harden due to pasture	3	4.00
7	Remove of soil due to soil erosion on agriculture land	14	18.67
8	Water pollution (turbidity) due to erosion from agriculture fields	10	13.33
9	Others	6	8.00
Total		75	100.00

- **Steps taken to make farming more environmentally friendly**

According to farmers in the Sebeya catchment, steps taken to make farming more environmentally friendly are shown in Table 4.6 below. For more environmentally friendly, most of farmers in the Sebeya catchment voted for cultivation of slope stabilization grasses to avoid soil erosion during the rainy season and they are cutting illegally trees due to lack of land for agriculture. Deforestation is primarily a concern for the developing countries of the tropics as it reduces the areas of tropical forest and exposing the land to soil hazards and loss of biodiversity (Chakravarty et al.,2012)

Table 4.6 Strategies to make farming more environmentally friendly in the Sebeya catchment

SN	Step	Number	Percentage (%)
1	Avoiding to cut trees illegal	8	10.67
2	Avoiding to burn grasses	5	6.67
3	Avoiding tillage cultivation	6	8.00
4	Use of recommended chemicals for soil fertilization	6	8.00
5	Cultivation of recommended crops	6	8.00
6	Cultivation of slope stabilization grasses	31	41.33
7	Cultivation on recommended area	8	10.67
8	Others	5	6.67
Total		75	100.00

A.1.3.6 Effects of soil erosion in the Sebeya catchment

Table 4.7 lists various effects of soil erosion in the Sebeya catchment. It is shown that during rainy season, floods and landslides may cause damages of buildings, loss of human lives and domestic animals. Soil erosion changes fertility status of the soil by removing top soils which is rich in nutrients and organic matter. Being the major cause of land degradation with large decrease of soil productivity (Nenadovic et al., 2013).

Table 4.7 Effects of soil erosion in the Sebeya catchment

SN	Damages	Number	Percentage (%)
1	Crops removed with landslides	13	17.33
2	Crops covered by soil erosion materials	7	9.33
3	Crops roots exposed up due to erosion	2	2.67
4	Soil loss due to landslides	6	8.00
5	Agriculture soil and nutrient losses	3	4.00
6	Loss of human lives	8	10.67
7	Loss of domestic animals	7	9.333

8	Buildings	14	18.67
9	High concentration of sediments at Keya and Gisenyi HEPPs	1	1.33
10	Silting up of waterways	1	1.33
11	Deposit of erosion materials in roads	2	2.67
12	Gullies formation on the side of a road	2	2.67
13	Cutoff road access due to progressive gullies	3	4.00
14	Abrasion of bridges piers by various types of sediment	6	8.00
Total		75	100

A.1.4 Concluding remarks

This research was conducted to collect sufficient information required to analyze the situation of soil erosion in the Sebeya catchment. Farmers reported high rated soil erosion with its negative impacts such as loss of buildings, loss of human lives and crop removed requiring implementation of soil erosion control measures. As remedial measures, farmers in the Sebeya catchment have not yet implemented soil conservation measures in their fields. However, these investigations revealed that there are some efforts made in terms of soil erosion control.

Intended to assess the level of satisfaction by assessing the socio-economic issues, the interview revealed that several farmers are engaged in farming for food security, agriculture business or due to lack of other jobs.

The Government and NGOs should motivate farmers who are applying well the BMPs in their farming system, facilitate the access of farmers to microfinance credits and generalize the application of fertilizers with priority on farmer's trainings and mobilization of a specialized technical team to assist in implementation of soil erosion control measures in the Sebeya catchment.

4.A.2 ASSESSMENT AND PREVENTION STRATEGIES OF SOIL SURFACE CRUSTING CAUSED BY RAINFALL EVENTS IN THE SEBEYA CATCHMENT AGRICULTURAL LAND

A.2.1 Introduction

All over the world, wherever human being started the agricultural operations, there exists the problem of soil erosion. Naturally, rainfall erosion is characterized by a series of many phenomena: compaction, disintegration, detachment, transport and deposition (Batista et al., 2019). These actions result in the formation of seal and subsequently the crust of soils. (Armenise et al., 2018) define a crust as a thin layer at the soil surface characterized by a greater density, higher shear strength and lower hydraulic conductivity than the underlying soil.

The occurrence of soil crusting is extended to over the whole range of climates: drier and humid regions. Soil seals and crusts can significantly reduce infiltration rate and largely blamed for initiating runoff and favoring interrill soil erosion and inhibiting seedling development (Chen et al., 2013). The extreme soil erosion in Rwanda is due to abundant rainfall and agricultural expansion on steep slopes terrain (Karamage et al., 2016).

The main objective of this research was to assess and draw preventive measures against soil surface crusting and development of runoff coefficients in order to propose suitable measures to minimize the soil loss in the Sebeya catchment agricultural fields in Rwanda. In a more detailed way, the specific objectives of this study were: (1) to assess the actual status of soil erosion in the Sebeya catchment; (2) to simulate rills and interrills by constructing field plots in the Sebeya catchment agricultural land; (3) to monitor erosion process and compare soil surface crusting, development of runoff coefficients and soil loss in 3 different scenarios of land cover.

A.2.2 Methodology

This study assessed the various preventive measures against the soil surface crusting and the development of runoff coefficients in order to minimize the soil loss in the Sebeya catchment agricultural fields. Three fields soil erosion plots were designed and installed in Rugerero Sector of Rubavu District (Fig. 3.7). The description and details on the designed field soil erosion plots, sampling and testing procedures are presented in chapter 3.

A.2.3 Research outcomes

A.2.3.1 Soil characteristics in the Sebeya catchment

The volcanic rocks of Virunga Mountains are the main geological formations in the Sebeya catchment where nitosol, acricol, alisol and lixisol are the main soil classes (IWRM, 2018). The

soil in this catchment favors agriculture due to its high infiltration rates and its high minerals content except for the case of clay soils on flat topography encountered in the catchment. The combination of the geological formation and soil data characterize the Sebeya catchment as a fragile ecosystem susceptible to heavy erosion (MoE, 2018).

A.2.3.2 Soil tests and soil classification

- *Sieve analysis*

The Fig. 4.3 represents the grading curve of soil from the experimental field where the sand portion is predominant (sand:56.27%; clay and silt: 3.24% and gravel: 40.49%).

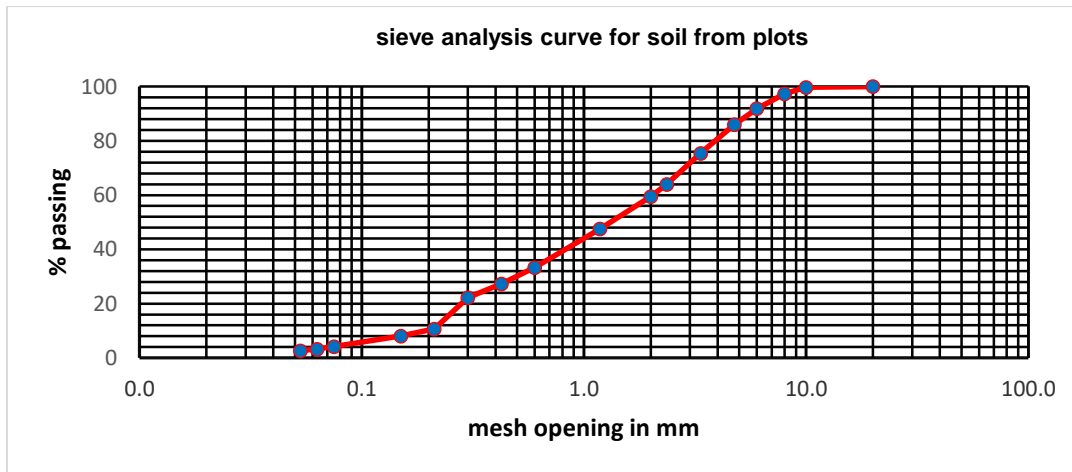


Fig. 4.3 Grading curve for soil sample from the experimental field

Soil particle size distribution, particularly clay, affects soil crusting. Soils with less than 20% clay are usually very susceptible to crusting (Laker and Noertjé, 2019).

- *Moisture content*

According to all sampling dates (Fig. 4.4), the soil moisture content results revealed that the plot which is fully covered (MFM) had high value of water content compared to the other plots. This implies that MFM possesses such high ability to resist to soil detachment. Mulching is one of the most efficient techniques of soil erosion control, where it influences C factor in reducing soil erosion. Covering the ground with mulch saves water by preventing surface evaporation and reduces soil erosion compared to bare agricultural soil. There is a wide variety of permeable mulching materials. Organic mulches conserve water more effectively and do not limit soil water infiltration and retention. Appropriate mulch can reduce the need for irrigation and in some landscapes can eliminate irrigation.

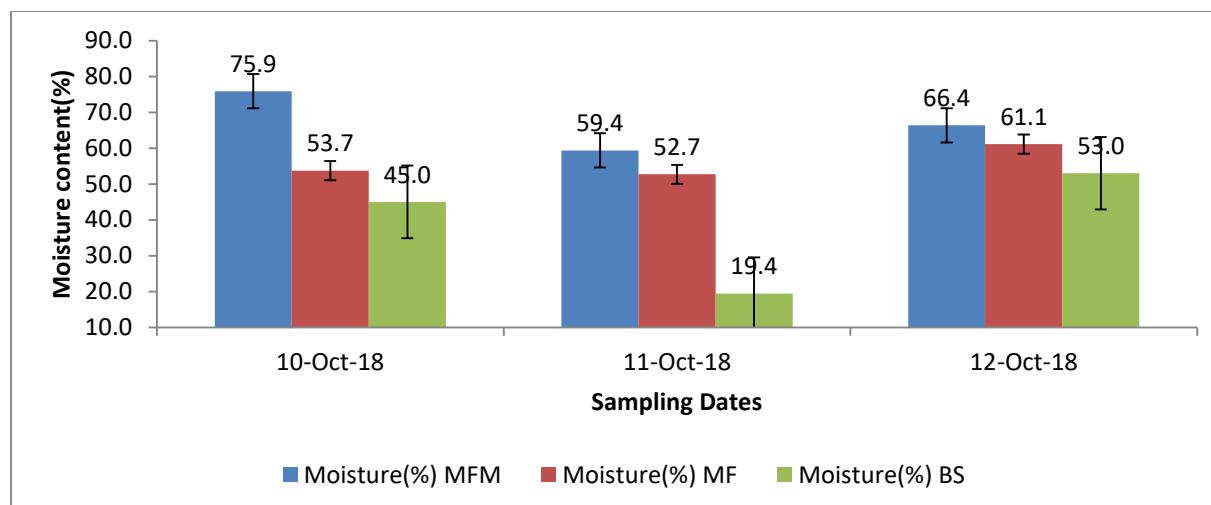


Fig. 4.4 Variation of Soil moisture content

A.2.3.3 Effects of rainfall on various scenarios of land cover

In order to compare the effects of rainfall on various scenarios of land cover, soil loss and runoff coefficients have been estimated when the 3 plots were exposed to the same rainfall events at different dates (Table 4.8). The rainfall intensity was deduced from the field precipitation measurements.

Table 4.8 Effect of rainfall on soil loss and runoff coefficient

Date	i (cm/hr)	MFM		MF		BS	
		Rc	A(g/m ² /hr)	Rc	A(g/m ² /hr)	Rc	A(g/m ² /hr)
08-10-2018	26.23	0.121	8.318	0.144	66.249	0.341	93.068
11-10-2018	14.57	0.131	5.729	0.154	20.261	0.411	68.220
13-10-2018	10.09	0.201	3.519	0.487	40.921	0.631	55.456
14-10-2018	11.21	0.091	3.892	0.120	8.314	0.191	25.888
19-10-2018	6.39	0.191	0.625	0.332	10.609	0.751	33.968
02-11-2018	16.01	0.021	4.500	0.106	25.009	0.121	30.539
11-11-2018	6.34	0.101	3.750	0.202	29.920	0.251	68.714

i = rainfall intensity; Rc = runoff coefficient; A = soil loss

A.2.3.4 Effect of land cover on soil loss and runoff coefficient

Among all the three plots (Fig. 4.5 and Fig. 4.6), there is a variation in soil loss as well as in runoff coefficients due to several responsible factors. The results of Table 4.7 show that the soil loss and runoff coefficient were very high as observed from BS plot followed by Plot MF and Plot MFM.

The reason for a such difference is that all plots are covered differently because the Plot MFM is fully covered, Plot MF medium covered and Plot BS is bare soil which is fully exposed to rainfall. Consequently, the fully exposed Plot BS caused the largest runoff coefficient (0.751) compared to the biggest runoff coefficients of 0.486 and 0.201 in MF and in MFM plots respectively. The largest runoff coefficient observed in BS plot was associated with largest soil loss of 93.067 gr/m²/hr compared to the observed largest soil loss of 66.249 gr/m²/hr and 8.318 gr/m²/hr from MF and MFM plots respectively.

Due to complete surface protection, water samples collected from MFM plot were fairly clean while the collected runoff from BS plot was very high turbid due to the excessive soil loss. Influenced by the rain drop impact, the runoff received in the collection tank was raised for the exposed soil surface in BS plot. The closely spaced maize coverings reduced the flow velocity and consequently the soil detachment and the amount of suspended sediments in the downstream runoff collection tank were also reduced. When exposed on the same rainfall intensity, the responses from the 3 plots showed similar variability in the following order:

$$R_{CMFM} < R_{CMF} < R_{CBS} \text{ and } A_{MFM} < A_{MF} < A_{BS}.$$

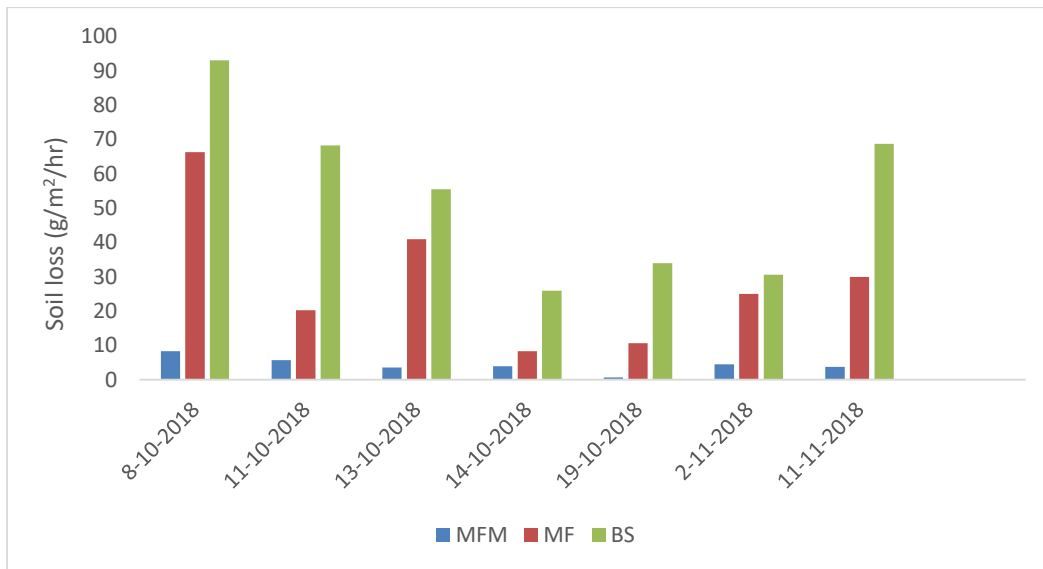


Fig. 4.5 Effect of land cover on soil loss

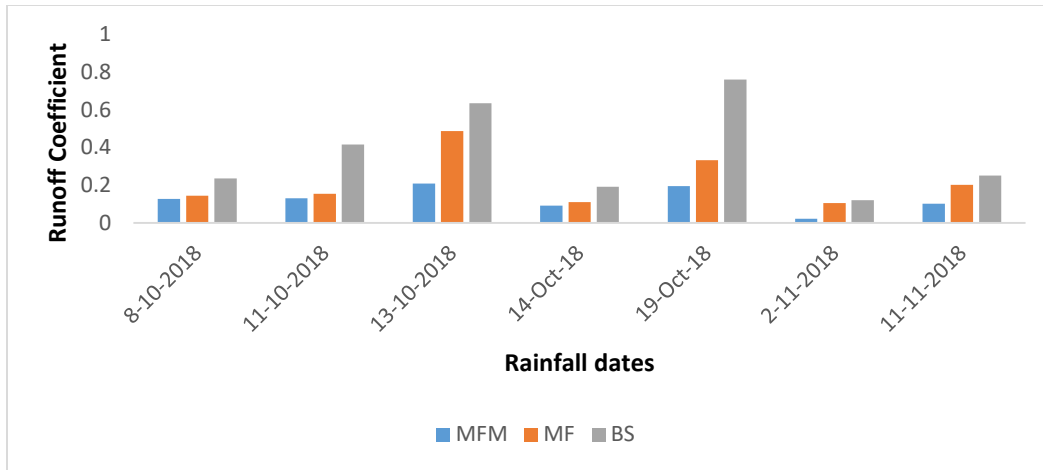


Fig. 4.6 Effect of land cover on runoff coefficient

A.2.3. 5 Development of rills and interrills in the experimental field

After each rainfall event, the routine observations revealed that rills were developed in the experimental plots. Firstly, interrills were formed as shown in Fig. 4.7. Generally, rills are frequently observed on sloped farmlands where rill erosion significantly contributes to sediment yields. Factors like rainfall, runoff, soil type, land topography, vegetation and tillage systems influence the development of rills. Rill erosion is usually identified as a series of little channels or rills up to 30 cm deep (Seutloali & Beckedahl, 2015). The loss of the topsoil and nutrients caused by rill erosion will reduce soil productivity while river sedimentation and water-quality deterioration are the main offsite effects of soil erosion. Concentrated flow in rills is one of the main sources of energy for soil detachment (Hajigholizadeh et al., 2015).



Fig. 4.7 Development of interrills and rills in BS plot

A.2.3.6 Effect of rainfall intensity on soil erodibility

Soil erodibility (K) is one of the factors in the Universal Soil Loss Equation (USLE) that refers to the resistance of soil to its detachment by rainfall impact and the force of surface flow. Soil erodibility factor (K) was found to strongly correlate with soil loss (Manyiwa and Dikinya, 2013). In this study, the effect of rainfall intensity on soil erodibility was highlighted by exhibiting the relationship between rainfall intensities and corresponding soil losses from different plots. For all 3 plots, the Fig. 4.8 , 4.9 and 4.10 revealed that the soil loss increase is not in linear relationship with the increase of rainfall intensity because weathering actions have changed the exposed soil type and the antecedent soil moisture conditions prior to the rainfall event. For the same conditions of soil type and rainfall events, high intensity storms increase soil erosion and sediment transport (Mohamadi and Kavian, 2015).

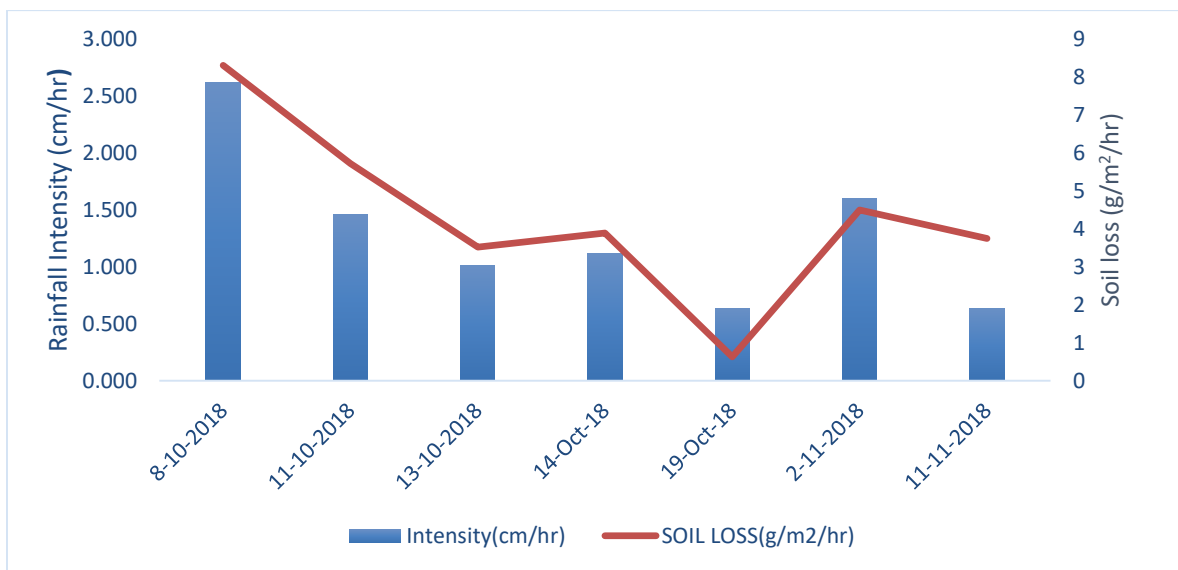


Fig. 4.8 Rainfall fluctuations and variability of soil loss from MFM Plot

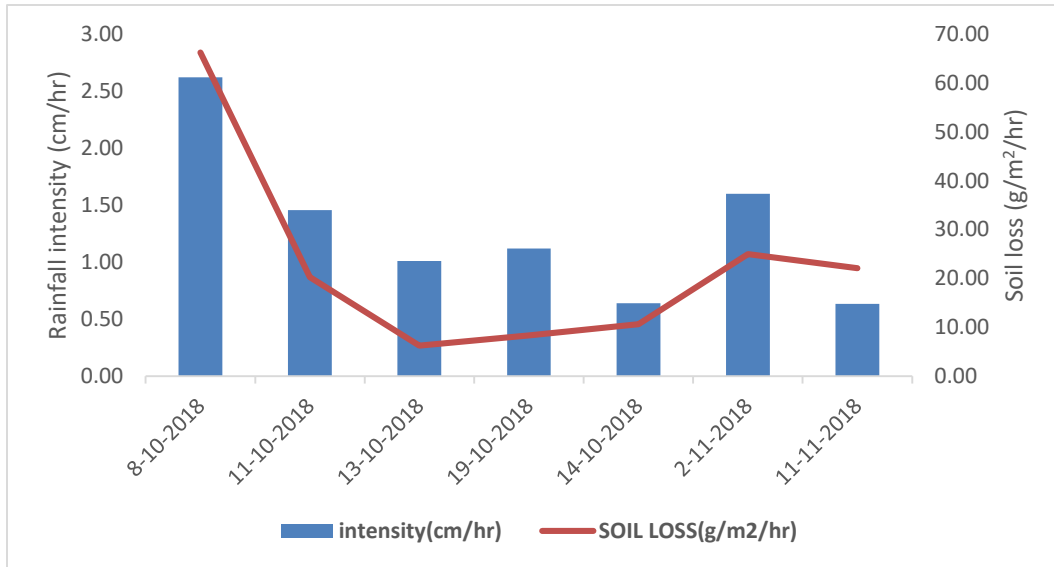


Fig. 4.9 Rainfall fluctuations and variability of soil loss from MF Plot

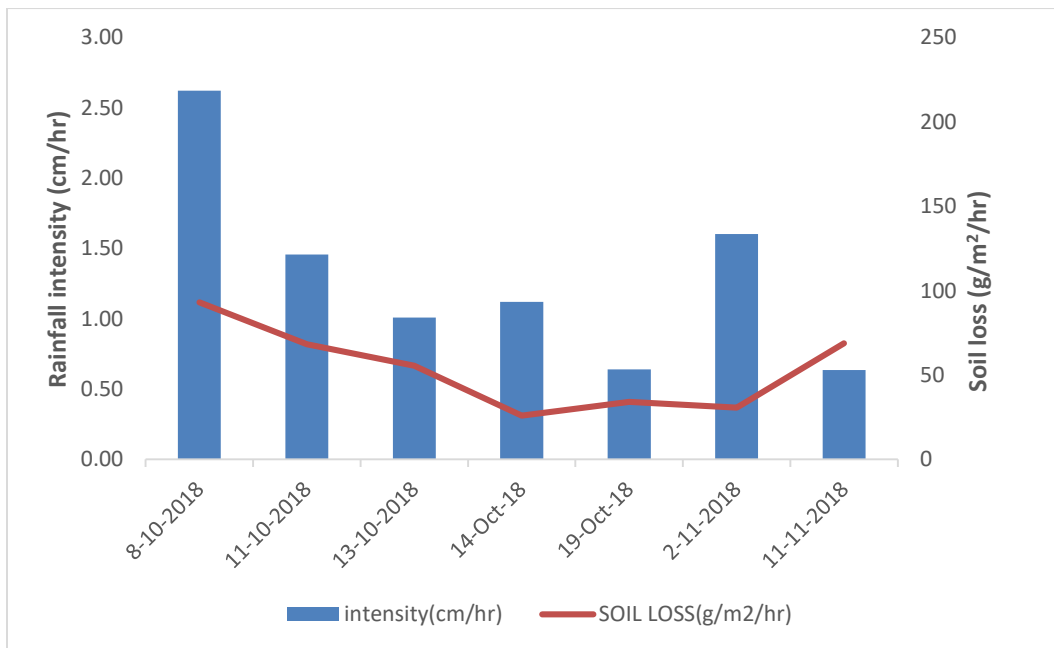


Fig. 4.10 Rainfall fluctuations and variability of soil loss from BS Plot

A.2.3.7 Effect of rainfall on soil crusting

Land cover and topography, soil type, antecedent soil moisture conditions, rainfall duration and rainfall intensity are major factors affecting runoff coefficient. For all 3 plots, Fig. 4.11, 4.12 and

4.13 revealed that the runoff coefficient increase is not in linear relationship with the increase of rainfall intensity. For agricultural fields exposed on similar conditions, the runoff coefficient increases with the increase of rainfall intensity (Wenbin et al., 2015). The research carried out by (Arjmand Sajjadi & Mahmoodabadi, 2015) stated that runoff coefficients increase with increasing crust development and decrease with vegetation cover development. Under the same rainfall intensities, the present study found that the decrease in runoff coefficient was depending on ground cover from BS plot which was fully exposed to MFM plot which was fully covered. The higher values of runoff coefficients recorded in the bare soil were attributed to lack of protective cover and the degree of crusting.

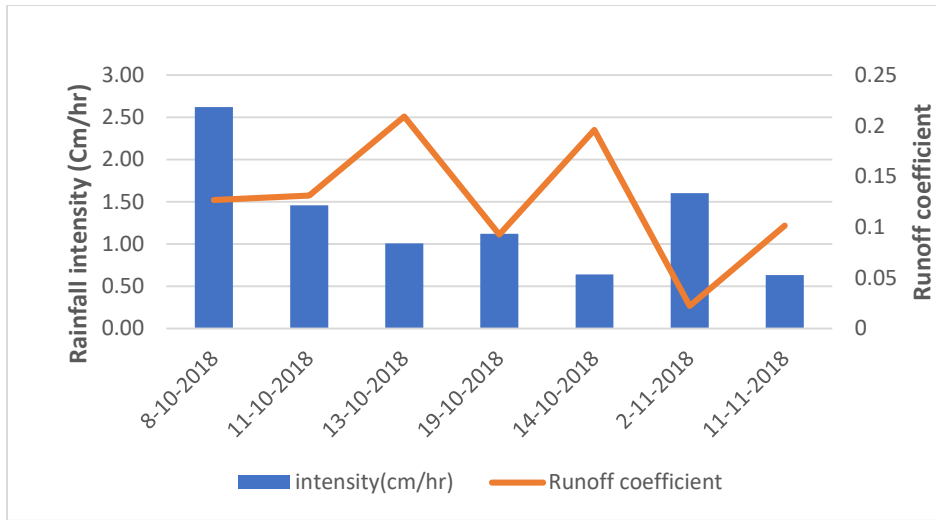


Fig. 4.11 Rainfall fluctuations and variability of runoff coefficients for MFM Plot

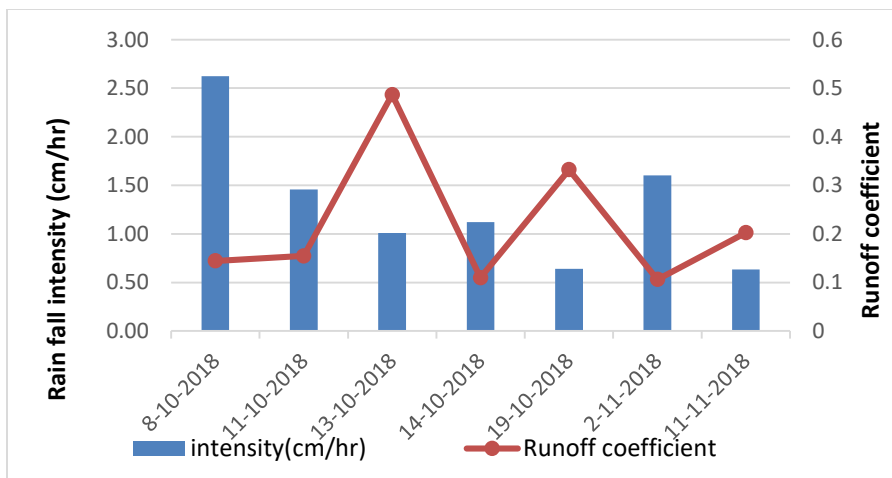


Fig. 4.12 Rainfall fluctuations and variability of runoff coefficients for MF Plot

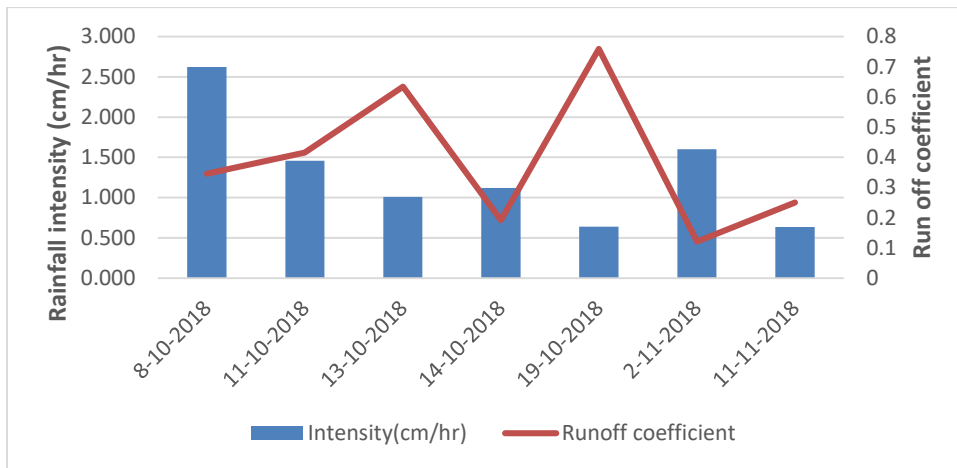


Fig. 4.13 Rainfall fluctuations and variability of runoff coefficients for BS Plot

A.2.3.8 Benefits from investigations in erosion plots to the farmers in the Sebeya catchment

Often, laboratory and field plots are used to obtain experimental data for predicting and evaluating soil erosion and sediment yield.

In this study, field experimentations in erosion plots have been conducted for getting data that can illustrate the knowledge on various techniques used for soil conservation. Field demonstrations have regularly done to local farmers and to other visitors while exhibiting the benefits of soil and water conservation measures in reducing soil loss. Throughout the growing phases of maize crop, various erosion processes (interrills and rills development, soil surface crusting and development of runoff and soil loss) have been observed and evaluated for different scenarios of land cover. As a final result of this research, farmers should be aware that erosion is much less from a plot which has a good vegetative cover than from a bare plot.

A.2.4 Concluding remarks

The present study aimed to assess various preventive measures against soil surface crusting and development of runoff coefficients in order to minimize the soil loss. Field experimentations in erosion plots have been conducted for getting data that can illustrate the knowledge on various techniques used for soil conservation. When exposed on the same rainfall intensity, the responses from the 3 plots showed similar variability in the following order: $R_{MFM} < R_{MF} < R_{BS}$ and $A_{MFM} < A_{MF} < A_{BS}$. The largest runoff coefficient (0.751) observed in BS plot was associated with largest

soil loss of 93.067 gr/m²/hr compared to the observed largest soil loss of 66.249 gr/m²/hr and 8.318 gr/m²/hr from MF and MFM plots respectively. Soil erosion was much less from a plot which has a good vegetative cover than from a bare plot. This means that vegetative cover and mulching have high performance in soil loss reduction. This research highly recommends to combine the cropping techniques with mulching and application of fertilizers in order to improve the soil stability while preventing runoff and soil loss.

4.A.3 ASSESSMENT OF THE SEBEYA RIVER SEDIMENT TRANSPORT AND ITS IMPACTS IN RELATION TO RAINFALL EVENTS

A.3.1 Introduction

Surface water plays a significant role in the development of a country and individual citizens as sources of food, water, transport, hydropower and recreation (Amasi et al., 2021). Thus, high concentration of sediments in water retrogrades the economy of a country and the polluted water affect the livelihoods of people living in the vicinity and can kill aquatic life.

Globally, soil erosion increases the amount of sediment transported in rivers at a rate of 2.3 billion tons per year (Wohl, 2015). In most catchments of Rwanda, sediment transported in rivers varies proportionally to the rate of erosion, river runoff and the land slope (Karamage et al., 2016) while soil nutrients (organic materials, nitrogen, phosphorus and potash) were lost due to soil erosion at rates of 945200, 41210, 200 and 3055 tons/year respectively (Mupenzi et al., 2012). For the case of the Sebeya river in the Western part of Rwanda, the transported sediments lead to scour on bridge, increase pollutants in water bodies and reduce the performance of hydro power plants (Munyaneza et al., 2015).

Recently, water quality was monitored by Rwanda Water Resources Board (RWB) at the outlet of the Sebeya river flowing into Lake Kivu. The measurements revealed excessive turbidity and Total Suspended Solids (TSS) of 1102 NTU and 4414.5 mg/L respectively (IWRM, 2018).

Actually, there is no specific study which has been conducted to monitor sediment transport in the Sebeya river and its impacts. The objectives of the present study were to estimate the Sebeya river sediment loading rates and propose mitigation measures to minimize its impacts on Lake Kivu, Gihira water treatment and various hydropower plants along the Sebeya river.

A.3.2 Methodology

To assess the impacts of the Sebeya river sediment load on various socio-economic projects along its length, bed load samples and water samples were hand-collected from five different sampling

points along the Sebeya river during rainy and dry seasons. The details on the sampling and testing procedures are presented in chapter 3.

A.3.3 Research outcomes

A.3.3.1 The Sebeya river water quality fluctuations

Storm water is a leading cause for water pollution. It runs off solid surfaces and collects pollutants such as oil, pesticides, sediments, bacteria, and other chemicals, and then deposits them into rivers, reservoirs and lakes. With its 7 tributaries, the Sebeya river is the only one river draining the Sebeya catchment and is the source of water for Gihira water treatment plant and for hydropower generation of Keya, Gihira and Gisenyi hydropower plants (RNRA, 2014). In flood condition, more sediments from illegal mining along the Sebeya river, the extraction of sand from the Sebeya river and from the hillside agriculture are seasonally generated and rejected by the Sebeya river into Kivu Lake.

A.3.3.2 Monitoring discharge, bed load rates and water quality of the Sebeya river

- *The Sebeya river discharge fluctuation*

Sebeya river discharge measurement was performed at Nyamugari bridge situated at Kanama Sector in order to determine the value of the surface outflow generated by the Sebeya catchment and its temporal variability. Knowing the discharge Q (m^3/s) and TSS (mg/l), the mass of TSS (kg) passing through the river per day can be deduced. The measurement of discharge has also high impact on sediment transport that leads to hydropower and water treatment plants damages (Yüce et al., 2018). For low water level at about 60 cm, a current meter was used to measure the stream velocity at each selected interval and the corresponding discharges were calculated as presented in Table 4.9. Considering all sampling dates as shown in the Table 4.9, the average the Sebeya river discharge was $2.245m^3/s$. During heavy rainfall event, the discharge was found to be high in the Sebeya river and reduced significantly after rainfall event.

Table 4.9 Monitoring of the Sebeya river discharge

Date	Discharge (m ³ /s)
27-Sep 18	2.005
07-Oct-18	1.853
03-Nov-18	2.946
17-Nov-18	2.178
Mean	2.245

Water resources occupy 8% of the total area of Rwanda but due to lack of data, it is difficult to estimate at which extent the climate change has impacted on water resources (REMA, 2010). The following statements stand for the sediments loading rates and water quality in the Sebeya river (Table 4.10):

- *Sediments loading rates in the Sebeya river*

In broadest context, soil erosion is responsible for increasing river sediment loading rates with two major types of pollution related to the physical and chemical composition of the sediment (DeVere 2010; Ezugwu 2013).

- *Quantification of Total Suspended Solids (TSS) in the Sebeya river*

An important parameter for the analysis of water quality is the concentration of Total Suspended Solids (TSS) because these types of solids are good indicators of physical and aesthetic degradation of surface water quality (Hannouche et al., 2011; Kusari and Ahmedi, 2013)

- *Turbidity fluctuation in the Sebeya river*

Due to soil erosion, the top soil and soil nutrients are carried into rivers, lakes and water reservoirs resulting in high turbidity. In general, water is more turbid during rainy season as compared to dry season (Table 4.10). The turbidity is an important parameter which helps to judge the water quality and it gives the idea on purification work to be carried out (Hersch, 2012).

- *Nutrients loading rates in the Sebeya river*

Nutrients lost from agricultural fields due to soil erosion, particularly nitrogen and phosphorus, become common pollutants in waterbodies and are largely responsible for what is known as “eutrophication”. Eutrophication is a process in which excess fertility in a waterbody leads to excessive plant growth, low dissolved oxygen, bad odors and the production of toxic substances by blue-green algae which may cause human diseases or kill fishes and other aquatic animals (Cook, 2014; Bagalwa, 2015).

Table 4.10a Sediments loading rates and water quality in the Sebeya river

Sampling points	Bed load (kg/hr)		NPK of Bed load					
			N%		P%		K%	
	RS	DS	RS	DS	RS	DS	RS	DS
NYB	10.4	5.3	0.76	0.32	0.81	0.26	0.14	0.10
KY	8.0	3.3	0.56	0.44	0.55	0.41	0.34	0.17
GH	6.0	4.6	0.59	0.14	0.68	0.26	0.16	0.08
GSH	11.1	0.7	1.80	0.34	1.59	0.26	0.39	0.18
SO	3.7	0.0	0.15	0.00	0.28	0.00	0.15	0.00
Mean	7.84	2.78	0.77	0.25	0.78	0.24	0.24	0.11

Table 4.10b Sediments loading rates and water quality in the Sebeya river

Sampling points	TSS (mg/l)		Turbidity (NTU)		NPK of water samples					
					N%		P%		K%	
	RS	DS	RS	DS	RS	DS	RS	DS	RS	DS
NYB	2790	227	880	208	0.29	0.12	0.58	0.37	0.56	0.45
KY	3033	220	667	242	0.45	0.26	0.62	0.32	0.60	0.4
GH	1904	546	778	598	0.44	0.35	0.69	0.33	0.58	0.25
GSH	2160	263	872	801	0.24	0.19	0.72	0.37	0.60	0.36
SO	2092	423	693	440	0.29	0.18	0.38	0.18	0.60	0.28

Mean	2395	336	778	458	0.34	0.22	0.60	0.31	0.59	0.35
------	------	-----	-----	-----	------	------	------	------	------	------

Sampling dates: [RS: Rainy Season (26/4/2019, 3/5/2019 and 18/5/2019);
DS: Dry Season (26/7/2019, 2/8/2019 and 8/8/2019)]

A.3.3.3 Impacts of the Sebeya river sediments on Keya, Gihira and Gisenyi hydropower plants

- *The Sebeya river bed load*

The variation in mass flow rates of bed load was studied during the two seasons. The table 4.10 and Fig. 4.14 show that higher values of bed load sediments were observed during rainy season and decreased significantly during dry season. Sedimentation affects the stability of dams, reduces the reservoirs storage and the carrying capacity of rivers which consequently reduces the hydropower production and flood attenuation capabilities. Large scour may be developed at bridge piers and abutments threatening their structural integrity (Brandimarte et al., 2012).

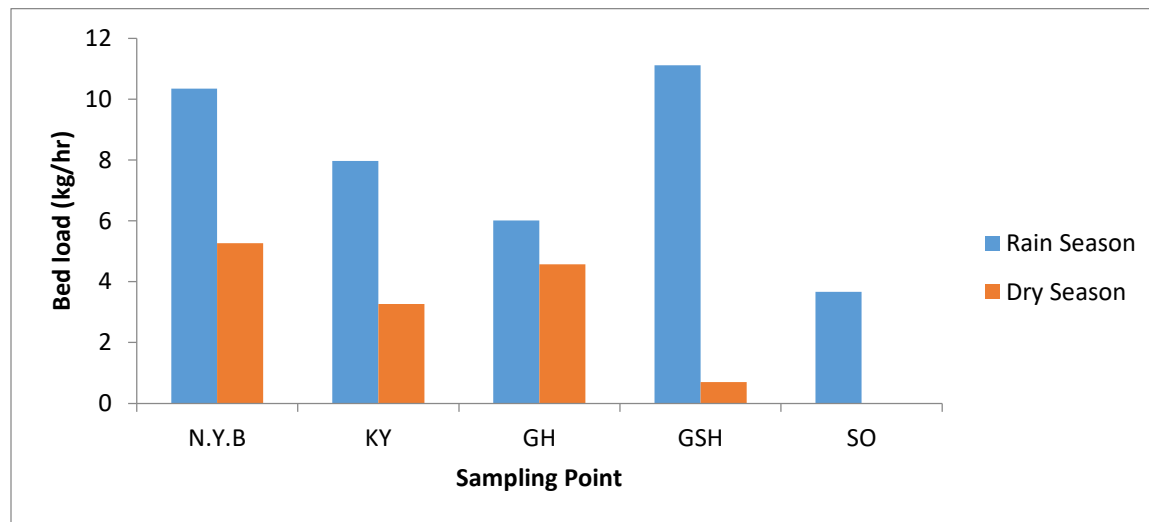


Fig. 4.14 Variation of bed load mass flow rates

- *Composition of bed load aggregates*

In Table 4.11, sieve analysis results showed that almost all bed load samples were mainly composed of high proportions of fine sand during dry season at more 70%. Other remaining portions such as silt, clay, coarse sand, gravel, and medium sand showed low percentages. Sand materials cause abrasion on the hydraulic turbines and consequently reduce the performance of the hydropower plant in producing electricity (Munyaneza et al., 2015, Thapa et al., 2017).

After comparing sediment concentration at the inlet and outlet of the sediment basin, it was found that the basin removed only 22% of sediment from diverted water toward the turbine. This means that 78% of sediment escapes the basin to cause erosion on the turbine components resulting in reduction of the plant capacity from 2.2 MW to 900 KW (Munyaneza et al., 2015). It is therefore important to enforce erosion control measures within the Sebeya catchment in order to mitigate the impacts of sedimentation by reducing the volume of sediment that is brought to the hydropower intakes by the Sebeya river. Alternatively, a sediment basin can be built for trapping suspended sediments before they reach the turbine components. Developments in achieving a more sustainable sediment management strategy are of high interest for HPPs, owners, environmental agencies and local government (Reisenbüchler et al., 2020).

Table 4.11 Sieve analysis results of bed load sediment during rainy and dry season

Sampling point	Bed load composition (%)									
	(Silt + Clay)		Fine Sand		Medium Sand		Coarse Sand		Gravel	
	(< 0.06mm)		(0.2- 0.06 mm)		(< 0.6- 0.2mm)		(2-0.6mm)		(60-2mm)	
	RS	DS	RS	DS	RS	DS	RS	DS	RS	DS
NYB	5.41	17.57	69.68	74.68	22.21	6.40	1.20	0.98	1.50	0.36
KY	6.37	8.10	57.20	70.30	33.33	18.8	2.20	2.10	0.90	0.70
GH	6.00	7.68	55.55	71.76	33.84	18.8	3.43	1.30	1.18	0.50
GSH	5.49	14.40	54.61	70.20	31.30	13.5	4.90	1.54	3.70	0.40
SO	4.06	0.00	67.504	0.00	21.60	0.00	2.48	0.00	4.44	0.00

Sampling dates: [RS: Rainy Season (26/4/2019, 3/5/2019 and 18/5/2019); DS: Dry Season (26/7/2019, 2/8/2019 and 8/8/2019)]

A.3.3.4 Impacts of soil erosion on Gihira water treatment plant

Storm water is a main leading cause of water pollution. Along this study, water quality was monitored at 5 different points along the Sebeya river during rainy and dry season and the results are presented in the following sections.

- ***Suspended Solids***

From the Table 4.10, the average Total Suspended Solids (TSS) for both seasons are plotted in the same graph as shown in Fig. 4.15. The higher values of suspended solids were observed in the rainy season at all sampling points comparatively to dry season. Spatially, there is a small increase of TSS from Nyamugari bridge to its downstream Keya hydropower due to a frequent illegal mining of sand and unimproved agriculture practices between these 2 river sections. However, from the inlet of Gisenyi HPP to the Sebeya river outlet, the river bed is flat which allows water to flow at a small velocity and then facilitates suspended particles to settle down.

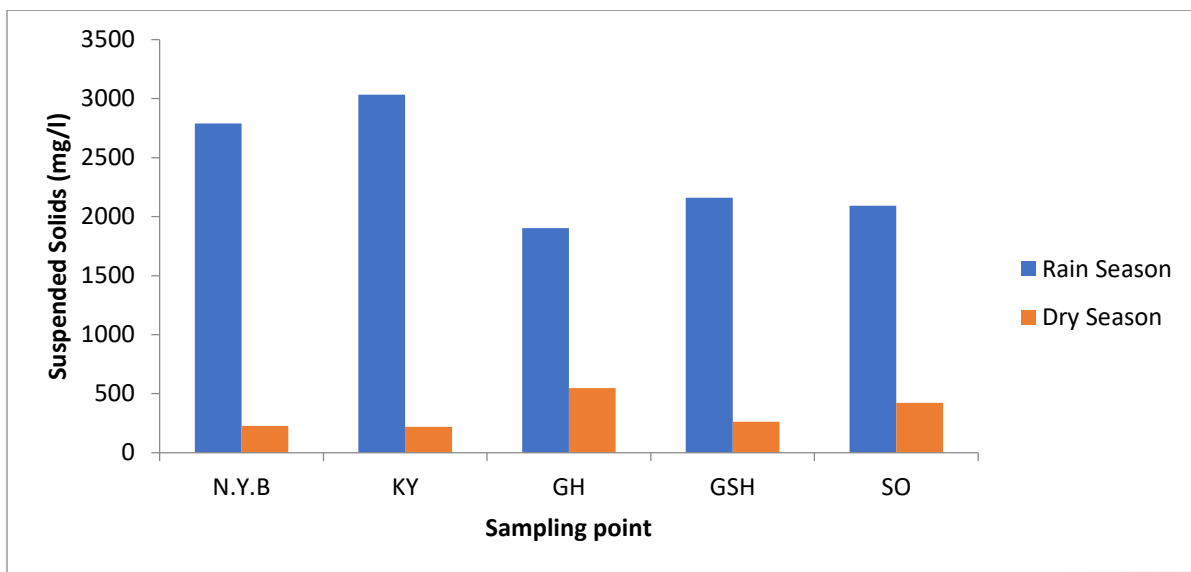


Fig. 4.15 Variation of Suspended Solids

- ***Turbidity***

Turbidity is proportional to the availability of clay, silty and sand from organic and inorganic matters (Serajuddin et al., 2019). The Table 4.10 and Fig. 4.16 illustrate the variation of the measured turbidity in the Sebeya river along rainy and dry seasons. During rainy season, both suspended sediments and turbidity increase due to soil erosion and low conservation measures in the Sebeya catchment. All turbidity values in two seasons are above permissible limit for drinking water at every sampling point. This is one of the issues faced by Gihira water treatment plant in terms of excessive costs of reagents for treating high turbid raw water (Table 4.12).

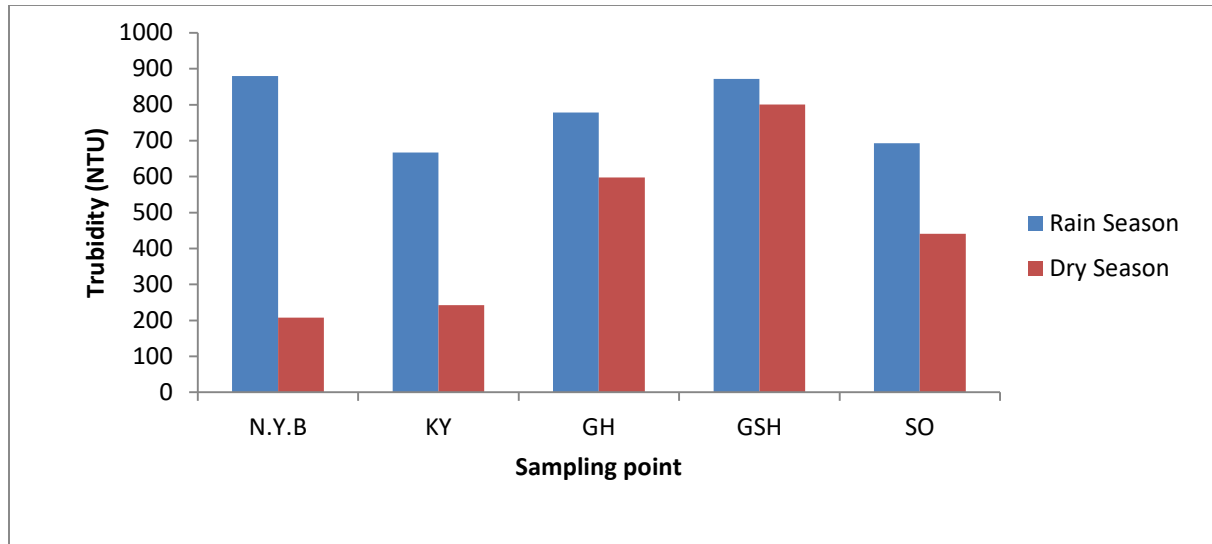


Fig. 4.16 Variation of Turbidity

A.3.3.5 Estimation of Nutrients (NPK) in the Sebeya river

Eroded soil carries away vital plant nutrients such as nitrogen, phosphorus, potassium, and calcium. In this study, samples of water and bed load were collected to determine NPK content present in the Sebeya river. All nutrients parameters were found to be high during rainy season and decreased during dry season (Table 4.10 and Fig. 4.17). The increase of nutrients in the Sebeya river is directly linked with the presence of sediments. Nutrients are mainly associated with agricultural effluent (Bagalwa, 2015).

It is very necessary to treat water and make water sources suitable for human consumption through the removal and killing of pathogenic organisms and removal of the taste, smell, and other undesirable chemical and physical constituents. Various treatment processes which are used to take out impurities from raw water may be arranged in a treatment sequence as: flocculation, sedimentation, filtration, and disinfection of water.

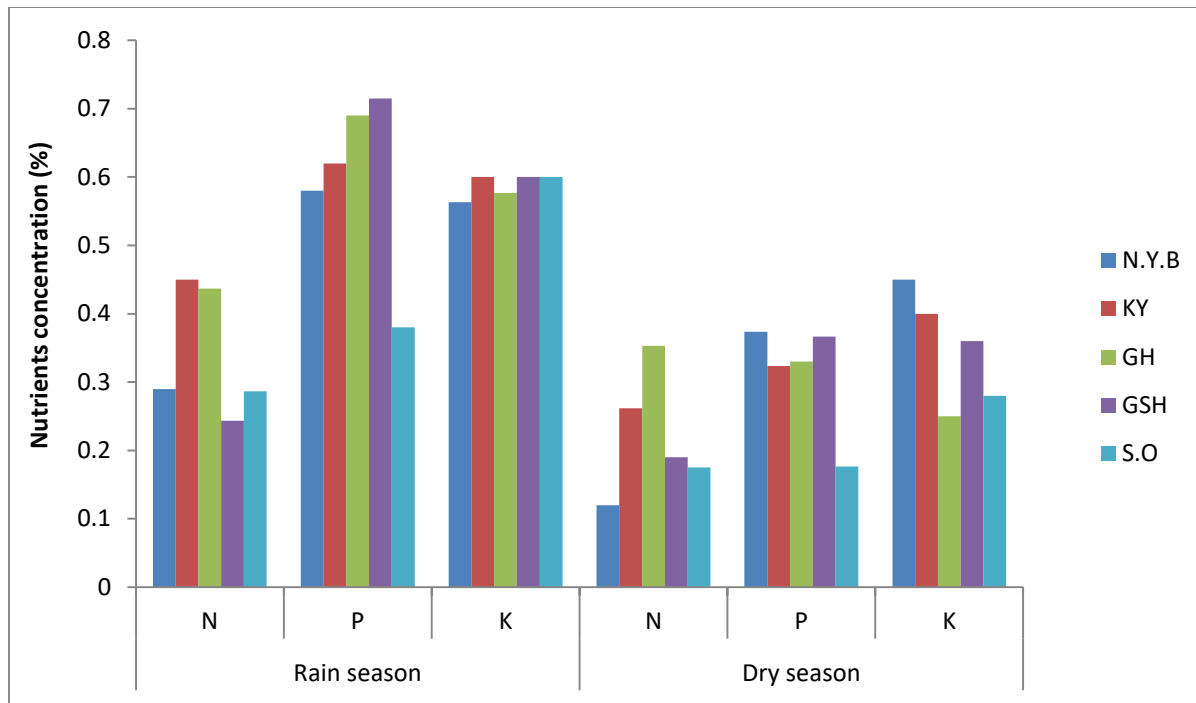


Fig. 4.17 NPK variation in the Sebeya river water samples

A.3.3.6 Effects of sediment load on the performance of Gihira WTP

The effects of sediments load on the performance of a water treatment plant are: high turbidity, high cost of coagulants to be used, low quantity of water to be supplied, damage of valves and taps, filters blockages, fills of tanks and pipes with mud and silt and it can also be causing the delay in water treatment process.

In this study, the effect of soil erosion on Gihira WTP was assessed while considering raw water quality in terms of turbidity and sulfloc consumed seasonally. Received from Rwanda Water and Sanitation Corporation (WASAC), the Table 4.12 quantifies various parameters of raw water and treated water at Gihira WTP from 2011 to 2017. Explicitly, the impact of soil erosion on Gihira WTP can be illustrated by the following statements:

- The turbidity due to high river sediment loads is more in rainy season than in dry season.
- The removal efficiency of turbidity is very high (about 99%). All turbidity values of the treated water comply with World Health Organization (WHO) and Rwanda drinking water standards of 5-25 NTU (Herschey, 2012).
- If the turbidity of raw water increases, the sulfloc consumption will also increase for the same quantity of raw water to be treated.

Table 4.12 Monthly volume of water with its turbidity and südfloc consumed (WASAC, 2018)

Year	RW	Rainy season (March-May)			Dry season (June-September)		
	or TW	Discharge (m ³)	Turbidity (NTU)	südfloc (kg)	Discharge (m ³)	Turbidity (NTU)	südfloc (kg)
2011	RW	175718.3	875.33		189876.3	204.67	
	TW	149959.0	2.07	3696.67	180024.7	1.03	2681.67
2012	RW	144704.7	599.00		186975.7	159.67	
	TW	129699.7	1.20	3003.00	177898.0	0.70	2943.33
2013	RW	257365.3	656.57		277667.3	181.33	
	TW	248676.3	1.68	3915.00	275565.0	1.96	2950.00
2014	RW	269065.0	108.27		274755.0	891.63	
	TW	267926.7	2.30	5316.67	271919.3	1.87	6441.67
2015	RW	295026.0	451.94		298780.0	577.88	
	TW	268205.7	1.50	5621.67	271618.3	1.62	4000.00
2016	RW	259426.0	1378.13		288549.2	1106.53	
	TW	247072.7	2.21	2030.00	278805.0	400.32	1470.00
2017	RW	266478.2	1609.67		291115.3	1164.77	
	TW	253788.7	1.65	5183.33	280746.0	1.62	5060.00

RW: raw water, **TW:** treated water

(1) Impacts of soil erosion on Lake Kivu

- *Estimation of daily sediment load rejected into Lake Kivu by the Sebeya river*

The Sebeya river water depths are automatically recorded by the hydrometric station installed at Nyundo Sector by Rwanda Water Forest Authority. Based on the available data, the channeling capacity of the Sebeya river was estimated at 100 m³/s (IWRM, 2017).

In this study, the Table 4.10 and Fig. 4.13 say that 4 kg/hr of sediment bed load are rejected by the Sebeya river into Lake Kivu which is negligible compared to the storage capacity of Lake Kivu of V = 500 km³. However, in flood condition, more sand sediments are seasonally generated and if no preventive measures are taken, the useful storage of Lake Kivu at Gisenyi beach location can be reduced significantly and swimming uses can be negatively affected. High sediment load into the Lake Kivu can make water less recreational and destroy aquatic habitats (Table 4.13).

Table 4.13 Sediment concentrations and risk to fish (Chang et al., 2013)

SN	Sediment (mg/l)	increase	Risk to fish and their habitat
1	0		No risk
2	<25		Very low risk
3	25-100		Low risk
4	100-200		Moderate risk
5	200-400		High risk
6	>400		Unacceptable risk

- *Estimation of daily nutrients rejected into Lake Kivu by the Sebeya river*

The Table 4.10 and Fig. 4.17 describe the variation on NPK in water samples taken from the Sebeya river during the 2 seasons of sampling while the Table 4.10 and Fig. 4.18 indicate the variation of NPK detected from the bed load samples. No bed load sediments were found in the samplers at the Sebeya river outfall during dry season.

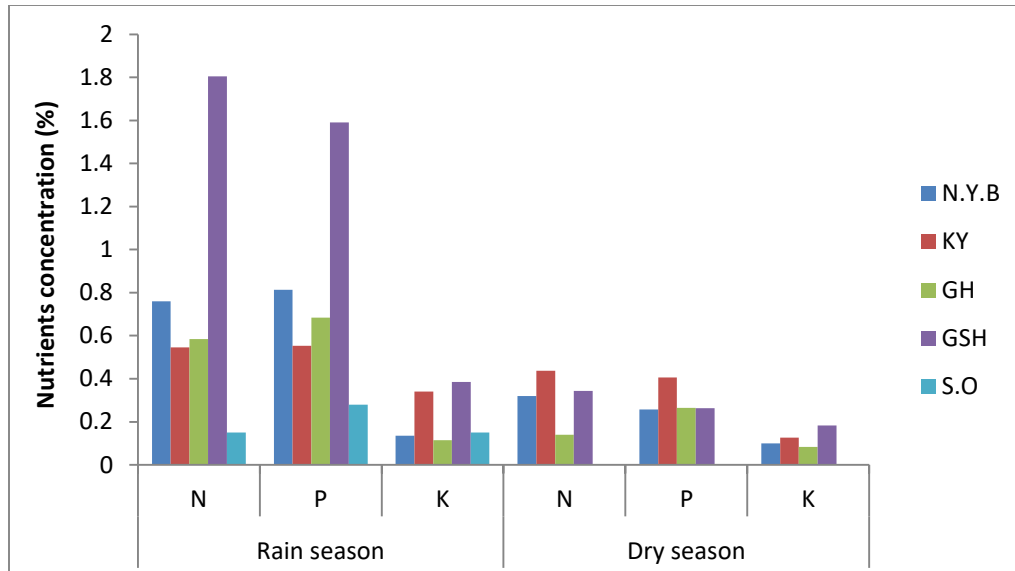


Fig. 4.18 NPK variation in the Sebeya river bed load samples

At the Sebeya river outlet, nutrients loadings into Lake Kivu are mainly linked to heavy rainfall which is influenced by the rapid growth of population, deforestation and soil erosion in the Sebeya catchment. At the Sebeya river outfall, nutrients load could be prevented.

- ***Aesthetic value of Lake Kivu***

The aesthetic value of lakes has been acknowledged by many researchers (Robby and Jian-Ping, 2017) who developed the Aesthetic Quality Index (AQI) while considering the following four parameters: taste, odor, turbidity and color.

High turbidity can significantly reduce the aesthetic quality of lakes and streams, having a harmful impact on recreation and tourism. It can harm fish and other aquatic life by reducing aquatic food supplies, degrading spawning beds of lakes and rivers and affecting the gill function of fishes (Kjelland et al., 2015).

Obviously (Fig. 4.14 and Fig. 4.15), high values of turbidity and TSS at all 5 sampling points can be associated with unstable mining and poor agricultural practices favoring erosion that results in high sediment loads in the Sebeya river.

A.3.3.7 Environmental mitigation measures of the Sebeya river sediment load impacts

Any mitigation measure reflecting the erosion control within the catchment would mitigate the adverse impacts of the Sebeya river sediment load by reducing the volume of sediment that is brought to the intakes of the 3 hydropower plants, to the inlet of Gihira WTP or to the location of other structures like bridges across the river. There are only two options of reducing the amount of sediment that enters in the reservoirs: to prevent soil erosion or to trap the eroded sediment before it reaches the reservoir (Kondolf et al., 2014). In order to minimize the Sebeya river sediment loading rates, the present study strongly recommends the improvement of the existing soil erosion and sediment control measures for high effective performance. As indicated by different research findings, this study also propose to increase the implementation of soil erosion control measures including terraces (Mupenzi et al., 2012), mulching (Patil et al., 2013), contour bunds (Savadogo et al., 2017), forestation and conservation tillage (Gattinger et al., 2011), various slopes stabilization measures, cover crops and vegetation (Mu et al., 2019b) various riverbanks stabilization measures like riverbank stone revetment, grassed waterways (Fiener and Auerswald, 2009) and specific sediment control measures such as buffer zones, sediment fences, sediment basins and check dams (Pravat et al., 2013; Fang et al., 2015; Bugg et al., 2017). These measures have to be adopted basing on the specific area criteria in the Sebeya catchment like land slope, soil depth and other essential characteristics.

A.3.4 Concluding remarks

The present study was designed to estimate the Sebeya river sediment load and assess its impacts on Lake Kivu, Gihira water treatment plant and various hydropower plants constructed in the Sebeya catchment.

This research revealed that the total suspended solids, turbidity, bed load materials and NPK nutrients were found to be high during rainy season compared to dry season. Fine sand proportion was found dominant in the composition of the Sebeya river bed load materials which adversely causes damages on hydropower turbines and the effect of high soil erosion rates on Gihira water treatment plant was traduced by high turbidity of raw water and excessive costs of reagents. At the Sebeya river outlet, nutrients load and high turbidity reduce significantly the aesthetic quality of Lake Kivu, having a harmful impact on recreation and tourism, aquatic life and affect the livelihoods of people living in the vicinity.

Researchers recommend two options of reducing the amount of sediment load in the Sebeya river: either to prevent soil erosion or to trap eroded sediment at the upstream of the hydropower and the water treatment plants.

4.A.4 PROPOSAL OF FUTURE-BASED REMEDIAL MEASURES ON AGRICULTURAL LAND AGAINST SOIL EROSION IN THE SEBEYA CATCHMENT

A.4.1 Introduction

Soil erosion is an environmental hazard that affects all landforms. Its causes and effects should be studied in order to control it. In Europe, suitable soil erosion control measures have been developed to improve agricultural productivity (Virto et al., 2015).

It is reported that soil erosion is the major cause of land degradation with serious impacts on agricultural productivity (Bakoji, 2017). Human activities were blamed to cause storm runoff and accelerate soil erosion (Karamage et al., 2016). An essential part of soil and water conservation is to control soil erosion, particularly through comprehensive land and water management techniques and to develop methods and techniques for mitigating harmful effects of soil loss and sediment movement (Lal, 2012).

Explicitly, water quality degradation is a challenge in this catchment. The current sedimentation in the Sebeya river impacts on hydropower and water treatment plants (Munyaneza et al., 2015). Recently, the study conducted by Rwanda Ministry of Environment highlighted a very high risk of erosion in the North-Western part of Rwanda, covering areas of the Sebeya catchment (Karamage et al., 2016; MoE, 2018). However, there is no specific research on how T-value (allowable soil loss tolerance) can be reached by means of soil erosion remediation measures in the Sebeya catchment.

The objectives of the present study were: (1) to assess the actual status of soil erosion control in the Sebeya catchment; (2) to assess the performance and the suitability of various soil erosion control measures in the Sebeya catchment; (3) to propose suitable and best management practices for erosion control in the Sebeya catchment.

A.4.2 Methodology

Literature review, site visits, questionnaire and interviews were used to get sufficient information on the existing soil erosion control measures, their performance and suitability within the Sebeya catchment. The information related to the current situation of soil erosion rates and soil erosion control in the Sebeya catchment have been obtained from published journal articles and different reports of government bodies. Comparatively and from literature review, a number of individual and combinations of conservation practices showed high percentages of soil loss reduction when

applied in agricultural fields. This research was intended to recommend these BMPs of high performance for their adoption and implementation in the Sebeya catchment.

DEM data have been collected from Center of Geographical Information System (CGIS Rwanda) for delineation and slope analysis of the Sebeya catchment. Also, a soil data shapefile has been used to assess the soil depth within the catchment.

The designed questionnaire is attached in the appendices of this PhD thesis while the details and procedures for this interview are presented in chapter 3.

A.4.3 Research outcomes

A.4.3.1 Existing soil erosion control measures in the Sebeya catchment

It is reported that various soil erosion control measures including trees planting, agro-forestry and terraces have been applied to rehabilitate 1,373 hectares in the Sebeya catchment (IWRM, 2017). This means that there is a need of improvement of soil conservation measures in the Sebeya catchment. Soft BMPs are those measures that are implemented easily with low cost including: mulching, cover crops and vegetation, trees planting, protective grasses on river banks, no tillage method and buffer zones. Existing hard BMPs in the Sebeya catchment are mainly terraces and anti-erosive ditches. Radical terraces and progressive terraces are still few; they were implemented to reduce the impact of topographic factor that influences soil erosion in this catchment (IWRM, 2016).

A.4.3.2 Improvement needed for implementing soil erosion control measures in the Sebeya catchment

The interview results in Table 4.14 indicate that among the 22 listed erosion control measures, about 4.57% of farmers confirmed their existence while 95.43% expressed the need of their implementation in the Sebeya catchment.

Adding the number of voices from farmers who need improvement and the number of voices which don't need improvement on the existing soil erosion measures, the following steps describe the computations in the Table 4.14 as shown below. Let's X_n be the percentage of farmers who need the implementation of a soil erosion remedial measure and X_p the percentage of farmers confirming the existence of a soil erosion control measure in the Sebeya catchment. Then $X_n - X_p = NG$ is the Needed Gap. As a result, IN will be Improvement Needed if $NG > 0$ while INN will be

Improvement Not Needed if $NG \leq 0$. The data in the Table 4.14 revealed that the Needed Gap (NG) values for all the 22 items of 6 categories ranged from 4.76 up to 2.86 and were all positive. This indicated that farmers needed improvement in all the 22 cultural practices in soil erosion prevention and control in the Sebeya catchment. The results of the study showed that farmers of the Sebeya catchment need improvement on various BMPs of erosion control (in agricultural fields, for slope and river bank stabilization, for sediments control and in reducing the velocity and volume of the Sebeya river and its tributaries).

In absence of BMPs, soil erosion rates continue to increase. That's why improvement on soil erosion control will be always needed because reaching T-value (allowable soil loss tolerance rate) seems to be an idealization. A similar study in Nigeria revealed that farmers needed improvement in all the existing soil erosion control measures in Kogi state (Onu and Mohammed, 2014).

Table 4.14 Improvement needed in the implementation of BMPs in the Sebeya catchment

SN	Measures category	BMP	Xn(%)	Xp(%)	(Xn - Xp)% = NG	Remark
1	In agriculture field	Mulching	4.13	0.63	3.49	IN
		Terraces	4.63	0.13	4.51	IN
		Anti-erosive ditches	4.76	0.00	4.76	IN
		Contour bunds	4.44	0.32	4.13	IN
2	For slope stabilization	Trees	4.76	0.00	4.76	IN
		Vetiver grass planting	4.19	0.57	3.62	IN
		Reed	4.63	0.13	4.51	IN
		Cetaria	4.76	0.00	4.76	IN
		Tripsacum	4.32	0.44	3.87	IN
		Paspalum	4.44	0.32	4.13	IN
		Grevillea	4.38	0.38	4.00	IN
3	For river banks stabilization	Use of gabions	4.57	0.19	4.38	IN
		Protective grasses	4.76	0.00	4.76	IN
		Stone revetment: use of riprap and gabions	4.76	0.00	4.76	IN
		Use of sand bags	4.76	0.00	4.76	IN

4	BMPs of sediments control	Sand trap	4.57	0.19	4.38	IN
		Sediment basin	4.36	0.18	4.18	IN
5	BMPs to reduce the velocity of runoff	Check Dam	4.70	0.06	4.63	IN
		Grass-lined channel	4.63	0.13	4.51	IN
		Stones blocks in a channel	3.81	0.95	2.86	IN
6	BMPs to reduce the volume of runoff	Hillside water pond	4.63	0.13	4.51	IN
		Roof runoff and cisterns	4.76	0.00	4.76	IN
TOTAL			95.43	4.57		

A.4.3.3 Performance assessment of various erosion control measures

From literature review, various conservation practices were assessed and presented showing their capabilities of reducing soil loss when applied in agricultural fields (section 2.4).

A.4.3.4 Suitability and proposal of BMPs for soil erosion control in the Sebeya catchment

- *Average slope of the Sebeya catchment*

Generally, the Sebeya catchment is characterized by high steep slopes which accelerate the rate of soil erosion (IWRM, 2018). Slope steepness is one of the important factors influencing soil erosion. Greater the slope more is the erosion. Based on the classification proposed by the Ministry of Environment (MoE) of Rwanda in 2018, the level of soil erosion in the Sebeya catchment can be grouped into 5 classes: Areas of very low risk of erosion have the slope varying 0-6%; Areas of low risk of erosion have the slope varying between 6-16%; Areas of medium risk of erosion have the slope varying between 16-40%; Areas of high risk of erosion have the slope varying between 40-60% and areas of very high risk of erosion have the slope >60%. In order to get more information on slope ranges with associated covered areas, DEM data collected from Center of Geographical Information System (CGIS Rwanda) have been used to generate the slope map for slope analysis of the Sebeya catchment (Fig. 4.19). Following to this classification, the Table 4.15

shows that 16-40% represents the slope range comprising the largest portion of the Sebeya catchment (55.8%) and the average slope in the Sebeya catchment has been estimated to 24.137%.

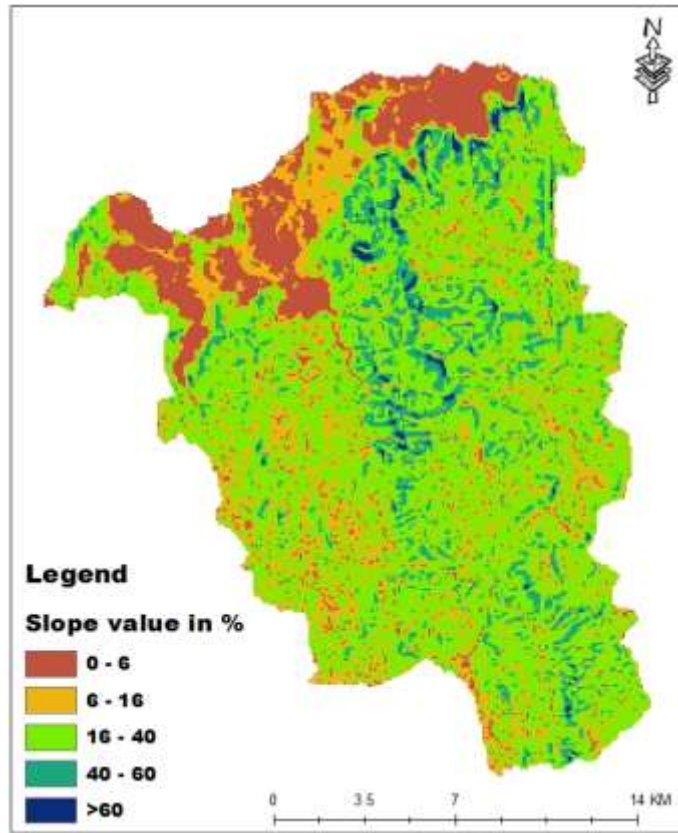


Fig. 4.19 The Sebeya catchment slope map

Table 4.15 Calculation of average slope of the Sebeya catchment

Slope Classes (%)	Area covered (ha)	% of covered area	Average slope Si (%)	Weighted slopes: Ai*Si (ha)
0--6	4620.871	12.72	3	13862.612
6 --16	7292.557	20.08	11	80218.126
16--40	20271.042	55.8	28	567589.181
40--60	3819.932	10.51	50	190996.581

60--90	322.08	0.89	75	24155.998
Total	36326.481	100	Weighted average	876822.498
			= 24.137	

- ***Soil depth and crops to be grown in the Sebeya catchment***

The soil depth from which a growing crop can easily extract most of water needed may be shallow or deep. That's why it is imperative to proceed for a careful analysis of crops to be grown with their rooting depths and the available soil depths (IWRM, 2016).

The Table 4.16 shows an indicative list of main crops growing in the Sebeya catchment with their rooting depths as experienced by many researchers.

Using the soil data shapefile from the University of Rwanda's Center of Geographical Information System (UR-CGIS), the soil depth map (Fig. 4.20) was obtained by clipping from Rwanda soil data map. This soil data map can be useful for more details with other crops to be grown in the Sebeya catchment.

Table 4.16 Crops grown in the Sebeya catchment

SN	List of crops	Rooting depth (cm)	
1	Tea plantation	0-50	(Sadeeka et al, 2019)
2	Beans	0-30	(FAO, 1983)
3	Banana plantation	0-20	(FAO, 1983)
4	Maize	0-10	(Plessis, 2003)
5	Irish potatoes	0-20	(Nedunchezhiyan et al, 2012)
6	Soybeans	0-30	(FAO, 1983)
7	Groundnut	0-35	(FAO, 1983)
8	Cassava	0-80	(FAO, 1983)
9	Sugar cane	0-20	(FAO, 1983)
10	Rice	0-40	(FAO, 1983)
11	Carrots	0-45	(Lott and Hammond, 2013)
12	Celery	0-30	(Lott and Hammond, 2013)

13	Eggplant	0-45	(Lott and Hammond, 2013)
14	Cabbage	0-45	(Lott and Hammond, 2013)

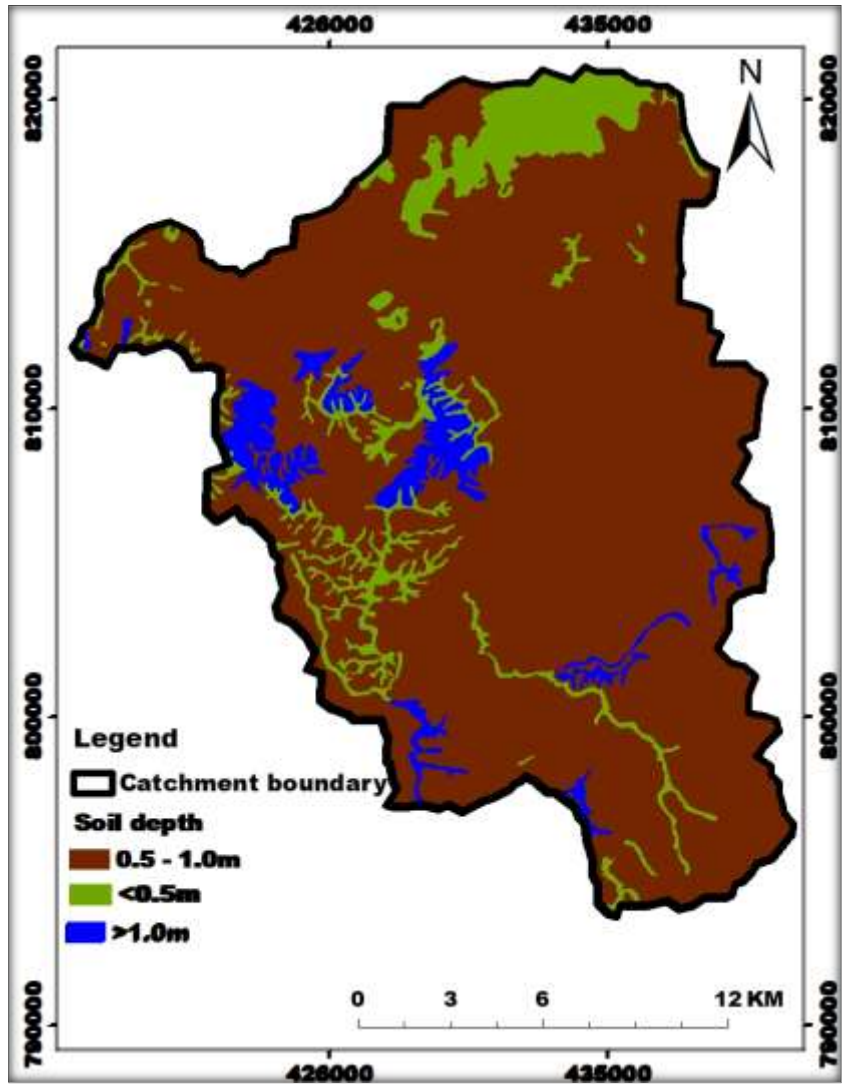


Fig. 4.20 The Sebeya catchment soil depth map

- *Proposal of BMPs for soil erosion control in the Sebeya catchment*

Terraces are more favorable in agricultural land with steep slopes ranging from 16% to 40% while progressive terraces and contour bunds are suited to flat areas of slopes less than 16% (IWRM, 2016). Erosion control measures in the Sebeya catchment were proposed based on land slope range (MoE, 2018). The Table 4.17 presents details and requirements on how various BMPs for soil erosion control can be effectively implemented in the Sebeya catchment according to slope range.

By combination of various physical measures, it is recommended that biological measures such as planting trees and grasses as well as lime and compost applications can be undertaken.

Table 4.17 Proposed BMPs for soil erosion control in the Sebeya catchment
[adapted from (IWRM, 2016)]

Land slope	Soil depth		
	1: (>1m)	2: (0.5-1m)	3: (<0.5 m)
(0-6%)	Agroforestry + Contour ploughing + Mulching + Grass strip	Agroforestry + Contour ploughing + Mulching + Grass strip	Agroforestry + Contour ploughing + Mulching + Grass strip
(6 - 16%)	Progressive terraces + Mulching or Contour bund + Mulching	Progressive terraces + Mulching or Contour bund + Mulching	Progressive terraces + Mulching or Contour bund + Mulching
(16- 40%)	Bench terraces	Bench terraces	Progressive terraces or Contour bund
(40-60%)	Bench terraces	Bench terraces	Afforestation
(> 60%)	Afforestation	Afforestation	Afforestation

A.4.3.5 Constraints for implementation of soil erosion measures in the Sebeya catchment

- *Social constraints*

The farmers need trainings on implementing the best management practices of soil erosion control due to the fact that the majority of farmers have a low educational level and trainability. The poor knowledge about the benefits of soil and water conservation (SWC) could be the limiting factor to adopt such erosion control measures (Okoba and De Graaff, 2005; Debebe et al., 2013).

In the Sebeya catchment, farmers are not motivated to provide enough space from their fields to waterways and they do not want to adopt hard BMPs of erosion control such as terraces and anti-erosive ditches. The reason for farmers to refuse adoption of terracing is that for shallow soil, terraces expose sub soil which is infertile (Kituku et al., 2011). The Table 4.18 shows the proportions of socio-constraints.

Table 4.18 Social constraints against the implementation of BMPs in the Sebeya catchment

No.	Limiting social factors on soil protection measures implementation	Number	Percentage (%)
1	Farmers are not motivated to provide enough space from their fields to waterways	16	21.43
2	Farmers do not want to adopt mechanical measures of soil erosion like radical terraces	18	24
3	Few farmers access to socio-medias on soil erosion control measures	12	16
4	Farmers resist to vote for crop rotation	9	12
5	Low educational level and trainability	20	28.57
Total		75	100

- *Economic constraints*

Most of SWC techniques (terraces, contour bunds, retaining walls, check dams, sediment basins, etc.) are costly to build. This statement is in agreement with Bizoza and De Graaff (2012) Who reported that the limiting factors of the adoption of soil and water conservation techniques are related to poverty and limited knowledge

In the Sebeya catchment, the number of farmers that access microfinance credit is estimated at 24% (Table 4.19). Some farmers (21.33%) do not have sufficient energy or income to adopt hard soil erosion control measures like: radical terraces and anti-erosive ditches. This

study revealed that challenges faced in adopting soil protection measures are poverty which is in agreement with (Oosterveld & Galand, 2012) who is the main reported that lack of money factor limiting the adoption of soil water conservation (SWC) techniques in Java (Bidogeza et al., 2015) reported that most of SWC techniques are costly and they are hence less adopted in Rwanda by poor resources farmers.

Table 4.19 Economic factors against the implementation of BMPs in the Sebeya catchment

No.	Limiting economic factors on soil protection measures implementation	Number	Percentage %
1	Few farmers access to microfinance credit	18	24
2	Few farmers access to inputs (inorganic fertilizer)	12	16
3	Some farmers do not have sufficient energy or income to adopt hard soil erosion control measure like: radical terraces and anti-erosive ditches	16	21.33
4	Others	29	41.67
Total		75	100

- ***Institution constraints***

The Table 4.20 shows that the farmers support in getting pesticides by Government and Non-Government institutions are limited to 29.33%. Seeds and fertilizers reach farmers over time (22.66%) and this research is highlighting lack of farmers trainings in soil conservation measures at 18.66%. This shows that the supports from the Government and Non-Government institutions are not sufficient for implementing the soil protection measures in the Sebeya catchment. (Bizoza, 2011) confirmed that sharing knowledge among farmers through trainings could enhance adoption of soil protection measures in Rwanda.

Table 4.20 Institutional factors against BMPs in the Sebeya catchment

No.	Limiting institutional factors on soil protection measures implementation	Number	Percentage %
1	Pesticides from Government and Non-Government institutions are to support a limited number of farmers	22	29.33
2	Seeds and fertilizers reach farmers over time	17	22.66
3	Lack of motivation to farmers who are applying well the BMPs in their farming system	10	13.33
4	Lack of farmers trainings in soil conservation measures	14	18.66
5	Other(s)	12	16.02
Total		75	100

- ***Government responsibility in improving farming system in the Sebeya catchment***

To cope with the problem of soil erosion, the government of Rwanda set a long-term program of transforming agriculture that includes conservation of soils, reducing soil erosion and restoring soil fertility (MINAGRI, 2009). It is reported that the government support led to the adoption of soil conservation techniques in Ethiopia (Kassa et al., 2013). This was furthermore supported by the findings of (Mgbenka et al., 2012) who reported about the government support to farmers to adopt SWC techniques in Nigeria.

The Table 4.21 indicates farmers views on what can be the Government responsibility in improving farming system in the Sebeya catchment. The majority of farmers suggest trainings and mobilization of a specialized technical team to assist them in implementing soil conservation measures and to generalize the application of fertilizers in the whole catchment. Also, the Government should facilitate farmers access to microfinance credit. These results are not far from those of (Oosterveld & Galand, 2012) who said that farmers knowledge about a practice cannot allow its adoption unless they understand its expected costs and benefits. Furthermore, (Solomon, 2016) indicated that when farmers did not have more information about a Soil Conservation Measure, they cannot be expected to adopt it.

Table 4.21 Government responsibility in improving farming system in the Sebeya catchment

No.	Government duty	Number	Percentage (%)
1	Trainings and mobilization of a specialized technical team to assist in implementation of soil conservation measures	17	22.67
2	Sensitization of farmers on the benefits of the land use consolidation and the selection of suitable cover crops which will minimize soil erosion	5	6.67
3	To generalize the application of fertilizers in the whole catchment	11	14.67
4	To facilitate farmers access to microfinance credit	10	13.33
5	Others way	26	34.67
Total		75	100

A.4.4 Concluding remarks

This research proposed suitable BMPs for soil erosion control on each slope of the Sebeya catchment. Soil erosion control measures including agro-forestry, terraces, mulching, tree planting, contour bunds, vegetative measures for slopes and buffer zones, check dams, riverbanks stabilization were proposed in the Sebeya catchment and recommended to be improved or implemented. This research finally recommended Government agencies and NGOs to be extensively involved in soil erosion management and to generalize supports to all farmers in the Sebeya catchment.

4.A.5 DEVELOPMENT OF AN EROSION CONTROL MODEL FOR FARMING SYSTEMS AND SOIL LOSS IN THE SEBEYA CATCHMENT

A.5.1 Introduction

This research intends to apply USLE-type model in order to make recommendations that will build sustainability into soil erosion management in the Sebeya catchment located in Western Province of Rwanda. Holden et al in 2014 defined sustainable development as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. All USLE-type models such as Universal Soil Loss Equation (USLE), Modified Universal Soil Loss Equation (MUSLE) and Revised Universal Soil Loss Equation (RUSLE) need information related with soil type, land use, landform, climate and topography to estimate soil loss. They are designed for a specific set of conditions in a particular area (Devatha et al., 2015). Presently, USLE is the most widely used model to predict soil erosion rates (Djoukbala et al., 2018), but its applicability is limited to sheet and rill erosion without any consideration of gully erosion (Alewell et al., 2019). Soil erosion management can be facilitated by using simulation and modelling. Modelling is a useful tool for soil erosion scenarios assessment that enables the adequate selection of soil erosion control measures (Panagopoulos et al., 2015). Soil erosion models can be understood as a virtual laboratory which brings together all data, observations and knowledge of different fields for sustainable environment (Alewell et al., 2019).

The main objective of this study was to develop a USLE-type erosion model to be used in predicting soil loss for sustainable environmental management in the Sebeya catchment at the level of parcels. The followings were the specific objectives of this research: (1) an estimation of the actual soil erosion rates in the Sebeya catchment; (2) a proposal of suitable best management practices for soil erosion control in each parcel of the Sebeya catchment; (3) a print out of relationships between soil erosion rates and soil productivity at the parcel level and (4) the development of a soil erosion control model which will help farmers in the Sebeya catchment to improve their farming system.

A.5.2 Data and methods

(1) Model choice and suitability

A complete overview in a recent review on soil erosion models identified 82 models (Karydas et al., 2014). In choosing the soil erosion model to be applied, it is always necessary to know the

availability of input data and the type of output data needed (Nearing, 2013). Modelling cannot be an alternative to measurement and monitoring but might be a powerful tool for simulation and prediction of the soil erosion potential (Alewell et al., 2019). Soil erosion models can be understood as a virtual laboratory which brings together all data, observations and knowledge of different fields (Alewell et al., 2019). USLE-type models were not designed to predict gully erosion nor sediment delivery ratios but each of the five USLE parameters might be evaluated separately even by non-expert stakeholders increasing thus transparency and objectiveness of evaluation. One reason for the popularity of USLE-type modelling is certainly that it is a good compromise between applicability in terms of required input data and relatively good reliability of obtainable soil loss estimates (Djoukbala et al., 2018). As such, it has become the standard technique of many soil conservationists and environmental managers (Nahayo et al., 2016).

This research aims to apply USLE-type model such as USLE, MUSLE or RUSLE. Presently, USLE is the most widely accepted method for estimating the annual soil loss because of less data demand (Alewell et al., 2019). It has been originally proposed in 1958 and actually modified to its present form in 1978 (Wischmeier and Smith, 1978). The empirical equation of this model is given by the equation Eq.(2.1). As described in the next section, the designed Soil Loss and Crop Yield (SOLCY) model is based on the USLE concept.

(2) SOLCY model design

From the Center of GIS of University of Rwanda (UR-CGIS) parcels data, a parcels map and an Excel sheet containing 259,673 parcels each of them having a specific location (District, Sector, Cell and Village) were first made available. Each parcel is characterised by a Universal Parcel Identification code abbreviated as parcel UPI. The shapes of parcels are diversified: triangular, square, rectangular and many irregular shapes (Fig. 4.21).

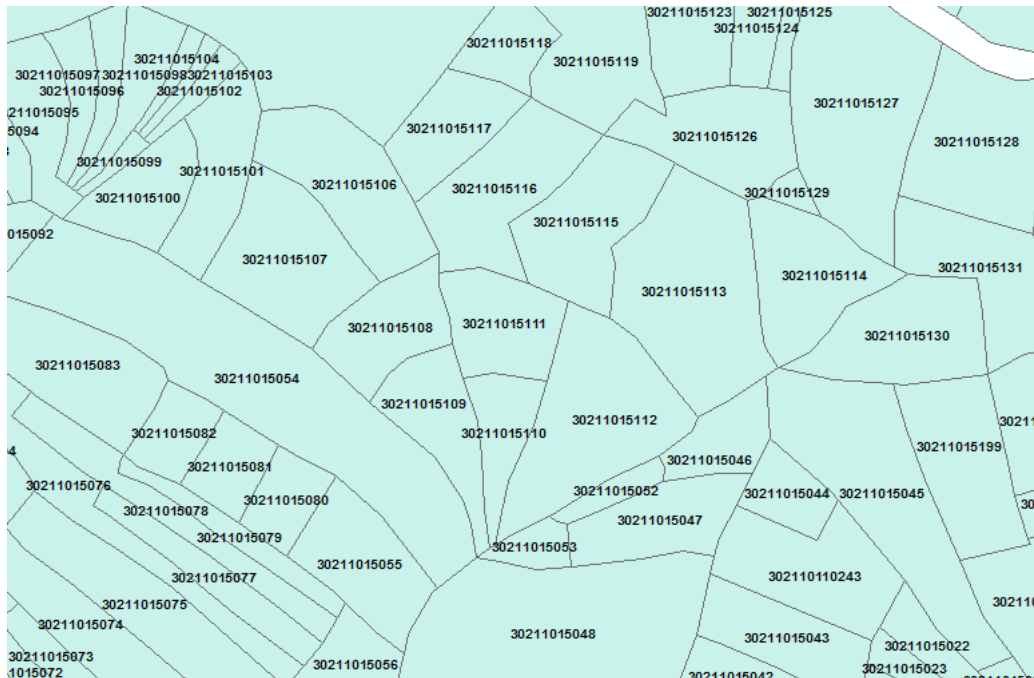


Fig. 4.21 Extract of a region from the parcels map

At the large-scale application of USLE model, the catchment area has been discretized into a series of 259,673 parcels having relatively independent land use. The Fig. 4.22 shows diversified processes used by Soil and Crop Yield (SOLCY) mode designed to predict soil loss and correlatively estimated crop yields.

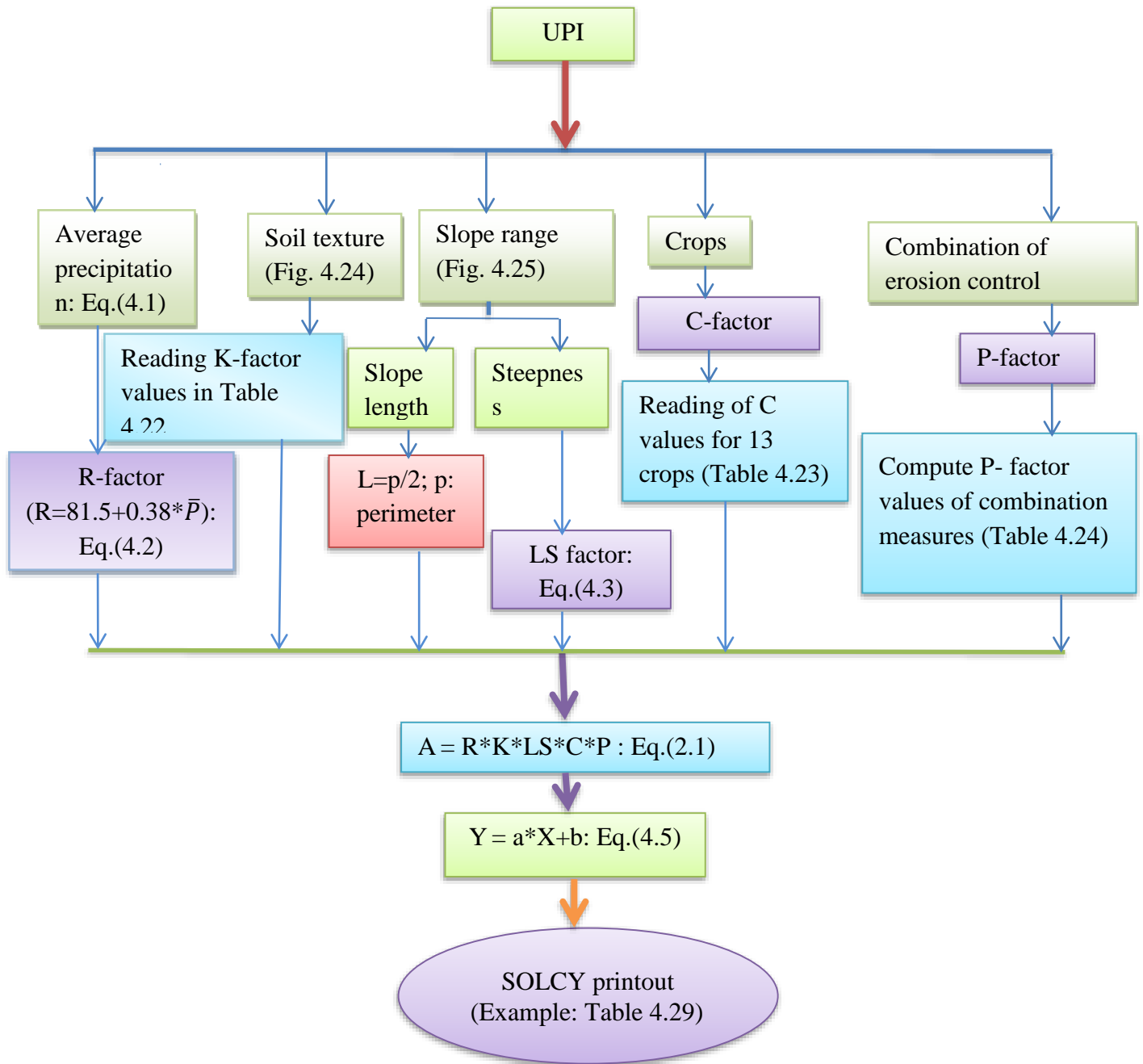


Fig. 4.22 SOLCY model flow diagram

(3) Rainfall data

Using rainfall data from the University of Rwanda's Center of Geographic Information Systems (UR-CGIS), the average precipitations in the Sebeya catchment in 2018 were 1187 mm, 1336 mm, 1538 mm, and 1233 mm at Tamira, Pfunda, Kanama, and Nyundo rainfall stations, respectively. By mapping, the rainfall distribution varies between 1076 mm and 1653 mm (Fig. 4.23). Knowing the minimum and maximum values for each range as shown in the legend of the rainfall map in Fig. 4.23, the reading of average annually precipitation on each parcel in the Sebeya catchment was made possible by overlapping the administrative boundaries map and the parcels map of the Sebeya catchment on the obtained rainfall map.

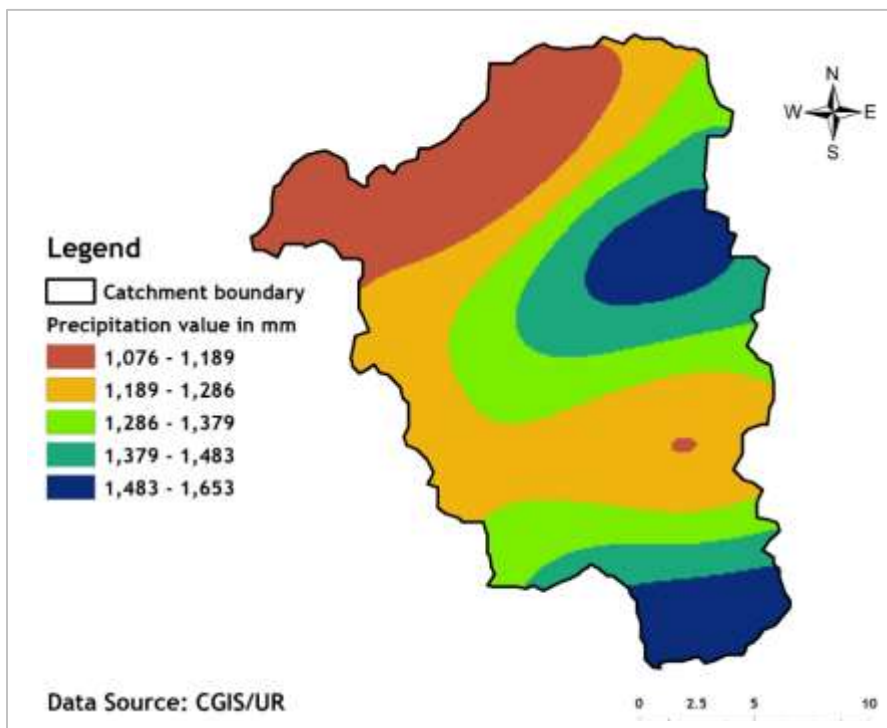


Fig. 4.23 Rainfall map of the Sebeya catchment

(4) Soil and topographic data

In this present study, a shapefile of soil was obtained from the Center of GIS of University of Rwanda (UR-CGIS) to produce soil texture map (Fig. 4.24) while Digital Elevation Model was used to generate the slope range map of the Sebeya catchment (Fig. 4.19).

In order to detect the slope range of each parcel, the administrative boundaries map and parcels map were overlapped on the slope range map of the Sebeya catchment.

To determine the soil texture for each parcel within the Sebeya catchment, the administrative boundaries map and the Sebeya catchment parcels map were overlapped to the soil texture map.

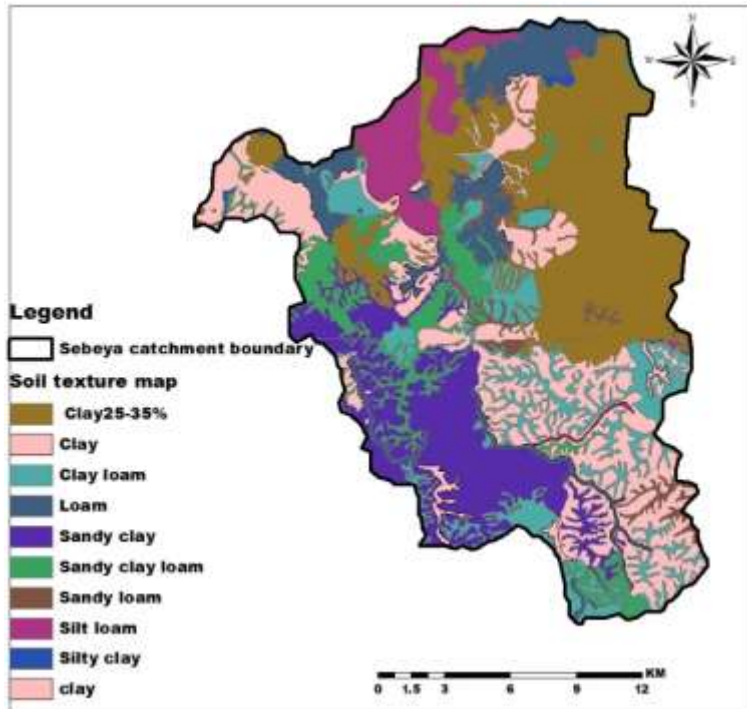


Fig. 4.24 Soil texture map of the Sebeya catchment

(5) Management data

Terraces are more favorable in agricultural land with steep slopes ranging from 16% to 40% while progressive terraces and contour bunds are suited to flat areas of slopes less than 16% (IWRM, 2016). Erosion control measures in the Sebeya catchment were proposed based on land slope range (IWRM, 2016). The Table 4.25 presents details on various combinations of soil erosion measures simulated on each parcel in this study.

(6) Land use / land cover data

From the data collected at UR-CGIS, the Fig. 4.25 shows that the Sebeya catchment is characterized by seven land cover types. In the determination of the type of land cover and land use on each parcel within the Sebeya catchment, the administrative boundaries map and the Sebeya catchment parcels map were overlapped on the land cover map.

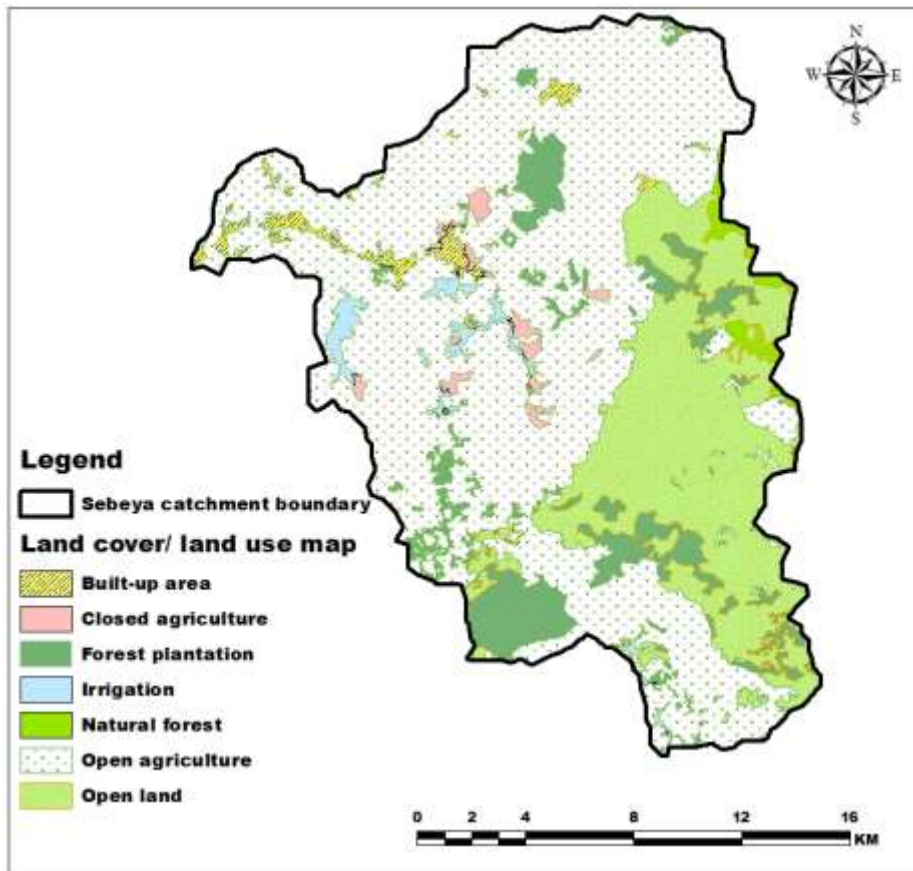


Fig. 4.25 LULC map of the Sebeya catchment

A.5.3 Research outcomes

A.5.3.1 Actual status of soil erosion in the Sebeya catchment

In determining the actual soil loss in the Sebeya catchment, all USLE parameters were mapped and maps integrated in GIS. The estimated soil loss of 130.724 t/ha/yr was categorized extremely high according to MoE (2018).

A.5.3.2 Values of USLE parameters for each parcel in the Sebeya catchment

- ***R-factor determination***

R-factor is the long term annual average of the product of rainfall kinetic energy (KE) in MJ.ha⁻¹ and the maximum rainfall intensity in 30 minutes (I₃₀) in mm.h⁻¹ (Yin et al., 2015). The rainfall factor can vary from year to year, so an average over a number of years is usually used (Ffolliott et al., 2013).

Referring to the Fig. 4.22, the average precipitation on each parcel was calculated based on the minimum and maximum precipitations as:

$$\bar{P} = (P_{\min} + P_{\max})/2 \quad \text{Eq.(4.1)}$$

It followed that the average rainfall values were varying from 1132.5 mm to 1568 mm and were inserted in the SOLCY Excel spreadsheet with respect to each parcel UPI.

If \bar{P} (mm) denotes the average precipitation, the value of R factor ((Hassan, 2011) can be estimated by the following formula recommended by Khare et al. (2017):

$$R=81.5+0.38\bar{P} \quad \text{Eq.(4.2)}$$

Where: R = rainfall erosivity in MJ.mm.h⁻¹.year⁻¹; \bar{P} = average precipitation on the parcel in mm.

Applicable for areas where annual precipitation ranges from 340 and 3500mm, the equation Eq.(4.2) was selected because its range of validity includes all precipitation events of this study.

By inserting all calculated values for all parcels in the SOLCY Excel sheet, the R-factor in the Sebeya catchment ranges from 511.85 to 677.34 MJ.mm.ha⁻¹.h⁻¹.year⁻¹.

- ***K-factor determination***

The soil erodibility factor (K) indicates the susceptibility of soil to erosion where it reflects the effect of soil properties and soil profile characteristics on soil loss (Manyiwa & Dikinya, 2013). The soil erodibility is the resistance of the soil to both detachment and transportation. It can be determined through the measurement of soil loss from a standard runoff plot (called “Standard USLE Plot”). A “Standard USLE Plot” is a field experimental plot having 9% slope along 22.13 m length which is kept fallow (bare soil) with periodic tillage (Lal, 1994). In this case, LS = C = P = 1, the soil loss becomes a function of R and K. Then from a known R and soil loss measurement, K can be estimated. The soil erodibility factor (K) rates from 0 to 1, where 0 indicates soils with the least susceptibility to erosion and 1 for soils which are highly susceptible to soil erosion by water.

From literature, different researchers have identified the variability of the soil erodibility values with the soil texture (Table 4.22). The soil erodibility factor is determined by soil texture and organic matter content (DeVere, 2010). Referring to the Fig. 4.23, the determination of K-factors for all parcels within the Sebeya catchment was determined by reading in the Table 4.22 and inserted in the SOLCY Excel sheet.

Table 4.22 Soil texture and corresponding soil erodibility values

Soil texture	K-factor	References
Silt loam	0.05	(Zisu and Nasui, 2015)
Loam	0.30	(Oruk et al., 2012)
Clay	0.22	(Oruk et al., 2012)
Sand clay	0.20	(Oruk et al., 2012)
Clay (20-35)%	0.76	(Belasri et al., 2017)
Sand clay loam	0.20	(Oruk et al., 2012)
Clay loam	0.31	(Oruk et al., 2012)
Sandy loam soil	0.23	(Chaudhary and Kumar, 2018)
Sand	0.05	(Ausseil and Dymond, 2010)
Silt	0.35	(Ausseil and Dymond, 2010)

- ***LS-factor determination***

The topographic factor LS is defined as the ratio of soil loss under the given conditions to that at the site with the “standard” slope steepness of 9% and the slope length of 22.13 m (Ganasri and Ramesh, 2016).

The topographic erosivity factor LS accounts for the effect of slope length (L) and slope steepness (S) on soil erosion. The steeper and longer the slope is, the higher is the risk of soil erosion. A higher slope gradient creates a higher flow velocity which causes more detachment and transport of soil particles (Kiani-Harchegani et al., 2019).

Wischmeier and Smith in 1978 defined the slope length (L) as: “the distance from the point of origin of the surface flow to the point where each slope gradient (S) decreases enough for the beginning of deposition or when the flow comes to concentrate in a defined channel”. When the slope length increases, the soil erosion by water also increases as due to the greater accumulation of surface runoff (Bera, 2017). In general, soil loss increases exponentially with slope steepness for tropical soils (Byizigiro et al., 2020). Further researches extend the LS-factor to topographically complex units using a method that incorporates contributing area and flow accumulation (Panagos et al., 2015). USLE method of calculating the LS factor uses slope length, angle, and a parameter that depends on the steepness of the slope in percent (Wischmeier and Smith, 1978).

Generally, to come up with the result of a slope length factor of each parcel, the following equation has been found appropriate to be used (Kassam et al., 1992):

For the slope less than 20%:

$$LS = (L)^{0.5} \times (0.0138 + 0.00965S + 0.00138S^2) \quad \text{Eq.(4.3)}$$

Where: L = slope length (m) and S = slope gradient (%).

And when the slope is greater than 20%:

$$LS = (L/22.2)^{0.6} \times (S/9)^{1.4} \quad \text{Eq.(4.4)}$$

Referring to the map in Fig. 4.24, another approximation to this process was to take the maximum slope of each slope range as the slope steepness while the largest path of travel $p/2$ was attributed to the slope length (L) for each parcel in the Sebeya catchment where p is the parcel perimeter.

Finally, the equations Eq.(4.3) and Eq.(4.4) were applied to estimate the LS-factors for all parcels of the Sebeya catchment and the obtained values were inserted in the SOLCY Excel sheet. For all parcels, the minimum and maximum observed slope lengths (and slope length factors) are 0.014 m (0.032) and 24707.00 m (559.798) respectively while the following Table 4.15 shows the percentages of areas covered in each slope range. There are many small parcels observed in the obtained shapefile for the overall 259,673 parcels in the Sebeya catchment. In true sense, a parcel having a physical perimeter of $p = 0.028$ m should be for no sense. However, most of those small parcels represent the physical portions inside the catchment but each one belonging to an entire parcel which has its main area outside the Sebeya catchment. By observing the diversified shapes of parcels in the Fig. 4.21, some parcels may be of very long physical parameters and then showing a very long slope length. As a recommendation, the designed SOLCY model should be validated to adjust and remove these types of errors made by attributing $p/2$ to the slope length of each parcel.

- ***C-factor determination***

The cropping-management factor can vary according to farming practices. In USLE-type equations, C-factor measures the combined effects of all interrelated cover and management measures. Its value includes the effects of crop cover, crop sequence, and length of growing season, tillage practices, residue management and the expected time distribution of erosive rainstorms (DeVere, 2010). It is expressed as the ratio of the soil loss from a cropped land under specified field conditions and the soil loss from a continuously clean-tilled bare soil surface over a given

period of time. One way to reduce soil loss is to choose a crop that provides cover during the year when rainfall is most erosive.

The Fig. 4.25 shows the different LULC types in the Sebeya catchment where the Table 4.23 indicates various C-factors for 13 main crops selected with high suitability of growing in the Sebeya catchment (Malesu et al., 2010). In this simulation, the Table 4.26 briefly describes a typical crop rotation suggested for one-year cultivation in the Sebeya catchment. All C-factors for 13 main cultivated crops in the Sebeya catchment were inserted in SOLCY Excel sheet for all 195,533 arable parcels. IWRM in 2016 suggests to not grow crops on slopes above 60%.

Table 4.23 C-factors for 13 main crops cultivated in the Sebeya catchment

Crops	C-factor	References
Irish potatoes	0.22	(Young, 1989)
Maize	0.38	(Panagos et al., 2015)
Beans	0.41	(Huffman et al., 2011)
Soya	0.28	(Morgan, 2005)
Wheat	0.20	(Panagos et al., 2015)
Sorghum	0.33	(Zhang et al., 1992)
Peas	0.41	(Huffman et al., 2011)
Groundnuts	0.55	(Balasubramanian, 2017)
Sweet potatoes	0.23	(Young, 1989)
Yam	0.45	(Morgan, 2005)
Banana	0.30	(Nill et al., 1996)
Vegetables	0.46	(Huffman et al., 2011)
Fruit trees	0.15	(Borrelli et al., 2016)

- ***P-factor determination***

The P-factor represents the effect of various support practices such as contour farming, terracing and strip cropping for arresting soil erosion being taken up in the area (Panagopoulos et al., 2015; Chaudhary and Kumar, 2018). It is the ratio of soil loss from a land where conservation practices (like: contouring, strip cropping, terracing, etc.) are adopted to soil loss from a land where soil erosion control measures were not implemented. The value of P-factor ranges from 0 to 1. The value of P-factor for a water body is 0 while the value of P-factor is taken as 1 for no conservation

practice (Adormado et al., 2019). From literature, the Table 4.24 indicates typical values of P-factors of various soil erosion control measures.

Table 4.24 Various soil erosion control measures and their corresponding P-factors

Erosion control measures	P-factor	References
Mulching	0.260	(David, 1988)
Anti-erosive ditches	0.290	(Tangtham and Korporn, 2004)
Bench terraces	0.128	(Kuok et al., 2013)
Contour bunds	0.600	(Kuok et al., 2013)
Drainage channels	0.800	(Chen et al., 2019)
Afforestation	0.001	(Bagarello et al., 2015)
Contour tillage	0.430	(Kuok et al., 2013)

Various combinations of soil erosion control measures to be implemented in the Sebeya catchment have been proposed based on the land slope range (IWRM, 2016). As simulated by SOLCY model, the Table 4.25 summarizes various combinations of soil erosion control measures applied on each parcel of the Sebeya catchment to predict soil loss and crop yields.

The 1st step was to assign a slope range to each parcel before calculating P-factor corresponding to each proposed combination of the soil erosion measures. The product of 2 or more P-factors gives a P-factor which represents the effects of the combined soil erosion control measures to be implemented. The Table 4.24 gives all P-factors for all soil erosion control measures to be used in calculating the P-factors corresponding to various combinations of soil erosion control measures simulated in SOLCY model and presented in Table 4.25.

Table 4.25 Proposed combinations of soil erosion control measures in SOLCY model (Adapted from IWRM, 2016).

Slope range (%)	$P_0 = P_i0 = P$ for no erosion control measure in any cultivated parcel	$P_1 = P_i1 = P$ for one measure acting alone in each cultivated parcel in the Sebeya catchment	$P_2 = P_i2 = P$ for a combination of 2 erosion measures in each cultivated	$P_3 = P_i3 = P$ for a combination of 3 erosion measures in each cultivated

	in the Sebeya catchment		parcel in the Sebeya catchment		parcel in the Sebeya catchment	
(0 - 6)	P ₁₋₀ : Contour tillage + Crop cover.	P ₁₋₁ : Contour tillage + Crop cover	P ₁₋₂ : Contour tillage + Mulching	P ₁₋₃ : Contour tillage + Mulching + anti-erosive		
(6 - 16)	P ₂₋₀ : Contour tillage + Crop cover	P ₂₋₁ : Contour tillage + Contour bund + Crop cover	P ₂₋₂ : Contour tillage + Contour bund + Mulching	P ₂₋₃ : Contour tillage + Contour bund + Mulching + anti-erosive		
(16 - 40)	P ₃₋₀ : Contour tillage + Crop cover	P ₃₋₁ : Bench terraces + Contour tillage + Crop cover	P ₃₋₂ : Bench terraces + Contour tillage + Mulching	P ₃₋₃ : Bench terraces + Contour tillage + Mulching + drainage channels		
(40 - 60)	P ₄₋₀ : Contour tillage + Crop cover	P ₄₋₁ : Bench terraces + Contour tillage + Crop cover	P ₄₋₂ : Bench terraces + Contour tillage + Mulching	P ₄₋₃ : Bench terraces + Contour tillage + Mulching + drainage channels		
(> 60)	P ₅₋₀ : Afforestation	P ₅₋₁ : Afforestation	P ₅₋₂ : Afforestation	P ₅₋₃ : Afforestation		

A.5.3.3 SOLCY Model assembly in Excel sheet

At this stage, respective values of all the 5 USLE parameters have been determined and inserted in SOLCY Excel sheet for all 259,673 parcels of the Sebeya catchment.

- ***Acceptable maximum soil loss tolerance limit (T-value)***

In many developed countries, the best management practices (BMPs) for soil erosion management have been technologically implemented. These techniques helped greatly to meet the tolerable soil loss criterion (Sakinatu and Muhammad 2017). T-value is a concept used to judge if a soil has a potential risk of erosion, productivity loss and off-site damages as a river or reservoir

sedimentation (Liu et al., 2010). Throughout the world, many investigations have proposed the soil loss tolerance ranging from 5 to 11.5 t/ha/yr (Bagarello et al., 2015). The generally accepted maximum limit of soil loss or T-value is 11.5 t ha⁻¹ year⁻¹ (Bagarello et al., 2015). The aim of soil conservation strategies is to limit rilling using a threshold soil loss value. But the occurrence of soil loss equal to or lower than 11.5 t ha⁻¹ year⁻¹ does not ensure absence of rills. The procedure used in assigning T-value has relied on multiple judgments of various researchers.

- ***Predicting soil loss with SOLCY model in the Sebeya catchment***

According to NISR in 2017, the 3 recognized agricultural seasons in Rwanda are: Season A (September-February); Season B (March-June) and Season C (July-September). The Table 4.26 gives a typical crop rotation simulated for soil loss prediction in the Sebeya catchment with SOLCY model.

SOLCY model is a USLE-type model at each parcel level. In other words, the empirical equation Eq.(2.1) can be applied to estimate the soil loss at each parcel where R, K, LS were already determined and now considered as physical constants in nature at each parcel. The only remaining variables are C-factor which will change according to the type of the seasonally cropping patterns and P-factor which will depend to the combinations of soil erosion measures to be simulated.

Table 4.26 Sowing dates and simulated crop rotation in SOLCY model (NISR, 2017).

Slope range (%)	Season A	Season B	Season C
0 - 6	Maize (between 01-15/09)	Irish potatoes (between 01-15/03)	Soy beans (between 01-30/06)
6 - 16	Maize (between 01-15/09)	Beans (between 01-15/03)	Irish potatoes (between 01-31/07)
16 - 40	Beans (between 01-15/09)	Maize (between 16-28/02)	Irish potatoes (between 01-31/07)
40 - 60	Irish potatoes (between 16-31/09)	Wheat (between 1-15/03)	Beans (between 01-31/07)

The 1st part in developing this SOLCY model was to simulate how soil loss can be reduced if suitable combinations of soil erosion control measures are applied specifically to well-known site conditions at all parcels in the Sebeya catchment. Comparatively by cultivating any type of the 13 main crops on any parcel, each annually average soil loss which can be predicted with SOLCY model will lay between 2 extreme values: minimum and maximum soil loss as $A_{min} < A < A_{max}$. The 1st step of simulation was done with the typical crop rotation described in Table 4.25, the 2nd step simulated 3 seasonally crops which have a minimum C-factor of $C = 0.15$ and the 3rd step simulated 3 seasonally crops which have a maximum C-factor of $C = 0.55$. Referring to the combinations of soil erosion control measures defined in Table 4.25, the results for these 3 steps are presented in the Table 4.27 below.

Table 4.27 Range of soil loss rates in the Sebeya catchment for various C-factors

Soil loss (t/ha/yr)	$P_0 = P_{i0}$	$P_1 = P_{i1}$	$P_2 = P_{i2}$	$P_3 = P_{i3}$
with C_{min}	164.43	49.55	40.78	15.62
with C_{max}	1400.19	218.67	127.13	39.04

- ***Relationship between soil loss and crops yield***

The 2nd part in developing SOLCY model was to apply successively a set of soil erosion control measures (P_{i1} , P_{i2} and P_{i3}) as defined in Table 4.25 in order to predict the resulting soil loss and crop yield on each arable parcel in the Sebeya catchment. The Table 4.28 gives an estimate of the minimum and maximum crop yields for the 13 main cultivated crops in the Sebeya catchment.

Table 4.28 Ranges of crop yields in the Sebeya catchment (MINAGRI, 2009; NISR, 2009).

Main cultivated crops in the Sebeya catchment	Min crop yields from all Rwanda Districts (kg/ha)	Max crop yields from Districts of the Sebeya catchment (kg/ha)
Irish potatoes	4,000	15,000
Maize	776	2,154
Beans	700	1,000
Soy beans	575	875
Wheat	437	2,154

Sorghum	222	1071
Peas	367	1438
Groundnut	260	1495
Yam	465	8,834
Sweet Potatoes	3,856	13,246
Banana	3,500	11,038
Vegetables	5,650	16,000
Fruits trees	9,000	16,000

Many researchers have proposed linear relationships between soil loss and crop yields (Obalum et al., 2012). In order to predict the crop yields, a linear relationship was assumed by considering the 1st point (x_1 = the maximum soil loss; y_1 = the minimum crop yield) and the 2nd point (x_2 = the minimum soil loss; y_2 = the maximum crop yield). From literature, the maximum soil loss has been fixed by previous researchers at 137 t/ha/yr (Obalum et al., 2012) while the minimum soil loss can be taken as the maximum acceptable limit of soil loss or T-value of 11.5 t/ha/yr (Bagarello et al., 2015). Having 2 points in plane XY Cartesian coordinates at this stage, a linear relationship becomes well defined for each crop in the form:

$$Y = a*X+b \quad \text{Eq.(4.5)}$$

Where a and b are known constants for each crop yield prediction; X = A = soil loss and Y = crop yield.

- ***SOLCY model printout***

The soil loss for each of the 13 crops simulated on each arable parcel of the Sebeya catchment and the value of the crop yield correlatively predicted using the above linear relationship (equation 4.5) were already simulated for each of the combination of soil erosion control measures Pi1, Pi2 or Pi3 as defined in the Table 4.25 and now available in SOLCY Excel spreadsheet. The results as shown in Table 4.29 were extracted from SOLCY Excel spreadsheet by using the INDEX-MATCH type lookup formula. Taking an example of the parcel of UPI = 30305034908, the user has to type only the parcel UPI and the soil loss with its corresponding crop yield are extracted for all 13 main cultivated crops in the Sebeya catchment to be printed in the Table 4.29 as shown below.

Table 4.29 SOLCY printout for UPI = 30305034908

UPI =	30305034908					
Slope range (%) =	0 - 6					
Crops	P1 = Pi1		P2 = Pi2		P3 = Pi3	
	Soil loss (t/ha/yr)	Yield (kg)	Soil loss (t/ha/yr)	Yield (kg)	Soil loss (t/ha/yr)	Yield (kg)
Irish Potatoes	11.17	15,028.83	5.70	15,507.95	1.63	15,865.16
Maize	19.29	2,048.78	9.85	2,152.62	2.82	2,230.03
Beans	20.82	977.68	10.63	1,002.02	3.04	1,020.17
Soya	14.22	868.44	7.26	885.07	2.07	897.46
Wheat	10.15	2,166.57	5.19	2,211.83	1.48	2,245.57
Sorghum	16.75	1,021.34	8.56	1,076.76	2.44	1,118.07
Peas	20.82	1,358.05	10.63	1,444.93	3.04	1,509.70
Groundnuts	27.92	1,333.31	14.26	1,467.75	4.07	1,567.99
Sweet Potatoes	11.68	8,149.49	5.96	8,484.69	1.70	8,734.61
Yam	22.85	11,985.57	11.67	13,124.76	3.33	13,974.11
Banana	15.23	10,878.36	7.78	11,086.20	2.22	11,241.17
Vegetables	23.35	15,022.38	11.93	15,964.74	3.41	16,667.35
Fruit trees	7.62	16,217.07	3.89	16,424.91	1.11	16,579.88

- **Who can use SOLCY model?**

Farmers, District agriculture planners and technicians in the Sebeya catchment can use SOLCY model. Most of the cases, an agriculture technician may be available at each sector and ready to facilitate farmers who will need SOLCY model guidance on how they can improve their farming systems. Also, researchers can develop similar models in other catchments based on SOLCY design concept. For 13 simulated crops, a District planner can take advantage of SOLCY to get advice in proposing a crop to be cultivated in a sector or a region based on its productivity and by suggesting BMPs for an appropriate farming system.

A.5.3.4 SOLCY Model validation

Model validation is a process that verifies if the model is performing properly as expected according to its design objectives and intended uses. It also identifies potential limitations and assumptions, and assesses its possible impact (Alewell et al., 2019). Validation refers to the testing of the model output to confirm if the produced results reflect the reality (Miller, 1974).

- ***Innovative aspect of SOLCY model***

Initially, the estimation of soil loss using USLE model with GIS applications on the Sebeya catchment was done at large-scale. In order to get more precise results and flexibility in assessing soil loss at parcel level, USLE model itself was limited to measure the soil loss at the outlet of the catchment but it was very difficult to print all the results of soil loss at the outlet of each of 259,673 parcels in the Sebeya catchment. That's why an improvement was proposed to apply analytically the USLE model on each parcel by simulating the cultivation of 13 main crops in the Sebeya catchment with selected combinations of soil erosion control measures. A such designed SOLCY model is estimating the soil loss at each parcel and prints results of soil loss for all 259,673 parcels and results of the predicted crop yields for all 195,533 arable parcels of the Sebeya catchment in an Excel sheet for each combination of soil erosion control measures.

- ***Comparing SOLCY model with USLE-GIS results***

By simulating the combination Pi1 of soil erosion control measures in each parcel (Table 4.25), the soil loss from the entire catchment by SOLCY model was 143.27 t/ha/yr compared to 130.72 t/ha/yr of soil loss using USLE with GIS applications. In order to judge the significance of the difference between the means of these 2 populations, a sample of 30 parcels was selected randomly from 259,673 parcels of the Sebeya catchment. The Table 4.30 shows the estimates of soil loss using GIS in comparison with the predicted soil loss by SOLCY model for which one-way ANOVA technique was applied.

One-way ANOVA technique uses F-test (Stockemer, 2019). Using an Excel tool for a significance level $\alpha = 5\%$, the F-test results obtained and shown in the Table 4.31 allow us to draw the conclusion that the two samples have been extracted from populations having the same mean.

Table 4.30 Comparison of USLE with GIS applications and SOLCY model results

Parcel UPI	Slope range (%)	Soil loss using GIS (t/ha/yr)	Soil loss using SOLCY model (t/ha/yr)
30308021403	16 - 40	0.00	0.03
3031003768	16 - 40	11.41	11.57
30310033137	16 - 40	14.55	14.15
30310033060	16 - 40	10.91	11.26
30305033163	16 - 40	113.62	119.79
3030502187	16 - 40	15.03	17.75
3030705248	0 - 6	13.35	12.99
30307051055	0 - 6	11.20	14.69
30308011805	0 - 6	16.92	18.42
30305031735	0 - 6	8.42	10.42
30307052557	0 - 6	12.45	17.19
30306041754	0 - 6	11.71	8.67
30305066406	40 - 60	38.15	35.37
30305052814	40 - 60	0.00	0.08
30401061089	40 - 60	101.89	101.87
30305063237	40 - 60	34.68	33.17
30401061093	40 - 60	92.31	105.21
30401062417	40 - 60	116.03	111.76
30401064300	6 - 16	49.87	50.11
30308043228	6 - 16	41.36	45.97
30308043265	6 - 16	67.97	60.32
30308043260	6 - 16	55.46	51.00
30308042445	6 - 16	39.43	42.23
30308041102	6 - 16	40.96	44.41
3040101710	>60	696.83	726.72
3040101687	>60	665.65	778.48
30305023516	>60	334.76	283.29

30305022701	>60	341.76	350.76
30401061118	>60	397.03	390.89
30306051612	>60	59.12	58.09

Table 4.31 F-test results for the 2 samples of the Table 4.30

ANOVA: Single factor				
Item	Sample size	Average (t/ha/yr)	Variance	Value
Soil loss by SOLCY model	30	117.55	39,526.18	
Soil loss using GIS	30	113.76	34,313.79	
Significance level (α)				0.050
F				0.006
Critical value of F (F_{crit})				4.007
Pearson correlation				0.939

Null hypothesis: H_0 = Population means are equal

Alternative hypothesis: H_1 = Population Means are different

Because $F < F_{crit}$, the null hypothesis is accepted (Stockemer, 2019).

- ***Comparison of soil loss from MF- field plot using SOLCY model and USLE-GIS***

This research used the USLE model to estimate soil loss from each of the 3 soil erosion plots which were installed in Kizi village, Muhira cell of Rugerero sector, purposively to investigate on soil erosion rates under different scenarios of LULC. The sieve analysis results showed that the soil of the experimental plots is a gravelly sand with (sand: 56.27%; clay and silt: 3.24% and gravel: 40.49%) (Table 4.32)

Table 4.32 Typical K values for different soil texture for field plot

Soil texture	K	References
Silt Clay	0.260	(Gitas et al., 2009)
Sand	0.050	(Ausseil & Dymond, 2010)
Coarse sand	0.0023	(Bouguerra et al. 2017)

K-factor is soil erodibility factor which represents both susceptibility of soil to erosion and the rate of runoff, as measured under the standard unit plot condition. From the Table 4.32, K-factor of the gravelly-sandy soil of the field plot is ranging between 0.023 and 0.05. Without excessive absolute error, let's attribute a midway value of K-factor around 0.036 to this gravelly-sandy soil of the field plot.

Using the average precipitation obtained from Fig. 4.22 in the equation Eq (4.2) the average R factor for the Sebeya catchment area is $582.34 \text{ MJ.mm.h}^{-1} \cdot \text{yr}^{-1}$.

Simulating using the USLE model, for the same parcel (UPI = 30312043470) and for the same cultivated plot without mulching (Plot FM), the predicted value of soil loss is 15.35 t/ha/yr using SOLCY model while the soil loss value predicted using USLE model is 17.54 /ha/yr (Table 4.33). Comparatively, the predicted values are in the same order if inserting the field conditions in using USLE model with GIS applications or using the SOLCY model.

Table 4.33 Estimating soil loss from field plots.

SN	Plot name	R	K	LS	C	P	Soil loss (t/ha/yr)
1	MFM	582.34	0.036	4.403	0.38	0.26	9.12
2	FM	582.34	0.036	4.403	0.38	0.5	17.54
3	BS	582.34	0.036	4.403	1	1	94.61

*: the value of C and P are taken as 1 for a bare soil plot (Chuenchum et al., 2019)

- **Limitations of SOLCY model**

Fertilizer has effects on soil loss and crop yield because it changes the organic matter of soil. However, its doses were not indicated in SOLCY model. Finally, SOLCY model is limited to the Sebeya catchment but this study provides an appropriate methodology and procedures to be duplicated to other catchments.

A.5.4 Concluding remarks

The present study aimed to design a model which can help to improve farming system in the Sebeya catchment. As an Excel spreadsheet containing all calculations related to USLE parameters, soil loss and crop yields, the designed SOLCY model stands as Soil Loss and Crop Yield prediction in the Sebeya catchment. This research has proven high improvement in soil loss reduction if increasing the number of soil erosion control measures in the applied combinations on each of 259,673 parcels of the Sebeya catchment. This study suggests field investigations in soil erosion plots to validate SOLCY model in predicting crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya catchment.

Farmers, District agriculture planners and technicians in the Sebeya catchment can use SOLCY model to focus on the parcel soil loss and predicted crop yield for sustainable land management decisions. The development of soil erosion rates greater than the acceptable soil loss tolerance limit (T-value) should be prevented by the affected people and landholders who are capable of identifying rill erosion at its early stage through some adaptive measures based on their indigenous knowledge. Finally, SOLCY model is limited to the Sebeya catchment but this study provides an appropriate methodology and procedures to be duplicated to other catchments.

PART B. PUBLISHED PAPERS

Paper 4.B.1 ANALYZING VARIOUS FACTORS AFFECTING FARMERS' WILLINGNESS TO ADOPT SOIL EROSION CONTROL MEASURES IN THE SEBEYA CATCHMENT

Title: Analyzing Various Factors Affecting Farmers' Willingness to Adopt Soil Erosion Control Measures in the Sebeya Catchment, Rwanda.

Authors: Félicien Majoro* and Umaru Garba Wali

Affiliation: University of Rwanda, College of Science and Technology, Department of Civil, Environmental and Geomatics Engineering, P.O. Box 3900, Kigali, Rwanda

*Corresponding Author Address: University of Rwanda, Department of Civil, Environmental and Geomatics Engineering, P.O. Box 3900, Kigali, Rwanda. Felicien Majoro, E-mail: majoro.felicien@yahoo.fr; Cell phone: +250 788484054; Orchid ID: 0000-0002-3679-3925.

Journal: *Sustainability* **2022**, 14, 1-16.

Layout: The format of the paper has been revised to have the same format as the thesis.

Abstract: Soil erosion is a worldwide environmental problem leading to low agricultural productivity and water quality degradation. Improving soil erosion control measures is essential. This study reports the results of a survey of 75 farmers, using structured interviews, field observations, and focus groups to analyze farmers' perceptions concerning current and future efforts to adopt Soil Erosion Control (SEC) measures in the Sebeya catchment located in the Western Province of Rwanda. Various factors influencing farmers' perceptions of soil erosion causes, effects, and willingness to adopt SEC measures were analyzed using descriptive statistics and SPSS (Version 20), including t-tests, chi-square tests, and a binary logistic regression model. Chi-square test results indicate that gender, farmer age, land ownership, farmland size, social media access, and credit access were strongly associated ($p < 0.05$) with the adoption of SEC measures, while marital status and education were not. A binary logistic regression model showed that among farmers' socioeconomic characteristics, farming experience ($B = 0.749$; $p = 0.020$) and access to socio media ($B = 2.107$; $p = 0.027$) were positively correlated, while age ($B = -0.642$; $p = 0.035$) and gender ($B = -2.034$; $p = 0.032$) were negatively correlated ($p < 0.05$) with the adoption of SEC measures. In order to mitigate high soil erosion rates and increase food production, there is a need for the government to support farmers, and train them. A highly skilled technical team should be mobilized to assist in implementing SEC measures in the Sebeya catchment.

Keywords: Sebeya catchment; soil erosion; soil erosion control; farmers' perceptions; Rwanda

B.1.1 Introduction

The effects of soil erosion are among the most significant environmental problems today, leading to low agricultural productivity and water quality degradation (Simeneh and Getachew, 2015; Tegegne and Biniam, 2016; Chen et al., 2019).

Rainfall is the main natural factor causing soil erosion through many phenomena: Disintegration, detachment, transport, and deposition (Sakinatu and Muhammad, 2017). Geomorphologic soil erosion is one of the most important processes in soil morphology. Human activities such as deforestation, overgrazing, tillage, improper agricultural practices, and changes in LULC affect water movement on the earth's surface (Borrelli et al., 2016). Topsoil and nutrient losses due to soil erosion lead to a decrease in the soil's water-holding capacity and, ultimately, the reduction of soil productivity. River sediments, mainly constituted by eroded soil materials and accompanying pollutants from agriculture, adversely impact various projects that use the river as a source of water supply.

In developing countries, poor farming techniques and a lack of financial resources for the agricultural systems make farmlands vulnerable to erosion (Pravat et al., 2015). Strategically, SEC measures are important adaptation measures for farmers to improve their productivity (Falcao et al., 2020; Huang et al., 2020). However, the limiting factors to the farmers' adoption of some SEC techniques, such as hillside water reservoirs, terraces, contour bunds, check dams, retaining walls, and sediment basins, are mostly linked to poverty and limited knowledge of agronomic practices (Bizoza and De Graff, 2012; Debebe et al., 2013).

In several developed countries, suitable SEC measures have been efficiently implemented, and these strategies helped substantially to reach the soil loss tolerance limit (Sakinatu and Muhammad, 2017). Soil loss tolerance (or T-value) is a soil loss value used to anticipate that the predicted soil erosion will not cause a significant reduction in soil productivity or excessive river sedimentation (Liu et al., 2010). Based on the literature, the soil loss tolerance ranges from 1 to 11.5 tons per hectare per year (Bagarella et al., 2015). Practically, many studies have used $11.5 \text{ t ha}^{-1} \text{ year}^{-1}$ as the maximum acceptable soil loss tolerance value (Bagarella et al., 2015).

In Rwanda, 80% of the economy is principally supported by agriculture, whereas the land is being exposed to high rates of soil erosion due to the conversion of land to agriculture (Munyaneza et al., 2016). Caused by several influential factors such as heavy rainfall, population pressure, and agricultural expansion on steep lands, Rwanda is highly vulnerable to soil erosion, rated at $250 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ (Karamage et al., 2016; IWRM, 2018; MoE, 2018a). Due to this commitment, the government has implemented plans to control soil erosion and floods in all nine level-1 catchments covering the entire territory of Rwanda.

The Sebeya catchment is highly prone to soil erosion resulting in excessive soil loss from agricultural land and sedimentation of the Sebeya river (IWRM, 2018). The eroded sand materials decrease the hydraulic efficiency of the turbines within the Keya hydropower plant installed on the Sebeya river. The abrasion of turbines leads to a decrease in power production and sometimes imposes the replacement of some of the turbine components, especially during the rainy season

(Munyaneza et al., 2015; Thapa et al., 2017). At the same time, the high turbidity of the Sebeya river imposes a high cost of coagulants on the Gihira water treatment plant. This problem of soil erosion at the Sebeya catchment outlet has a significant negative impact on the aesthetic and quality of Lake Kivu's water, which harms both recreational and aquatic life on the lake. Therefore, controlling soil erosion is crucial to increasing soil productivity while reducing the downstream Sebeya river and Lake Kivu sedimentation.

SEC measures are required for farmers to cope with and resist the potential risks of soil erosion (Falcao et al. 2020; Huang et al., 2020). However, factors affecting farmers' willingness to adopt SEC measures were not studied in the Sebeya catchment. For this research gap, the objective of this study was to examine farmers' perceptions of the actual soil erosion status and strategically assess various factors affecting the adoption and implementation of SEC measures in the Sebeya catchment.

B.1.2 Methodology

B.1.2.1 Study Area

As shown in Fig. 4.26, the Sebeya catchment area is shared by four country subdivisions: Rubavu, Nyabihu, Rutsiro, and Ngororero Districts. Sebeya is the main river in this catchment, originating from the Rutsiro mountains, and is 48 km long.

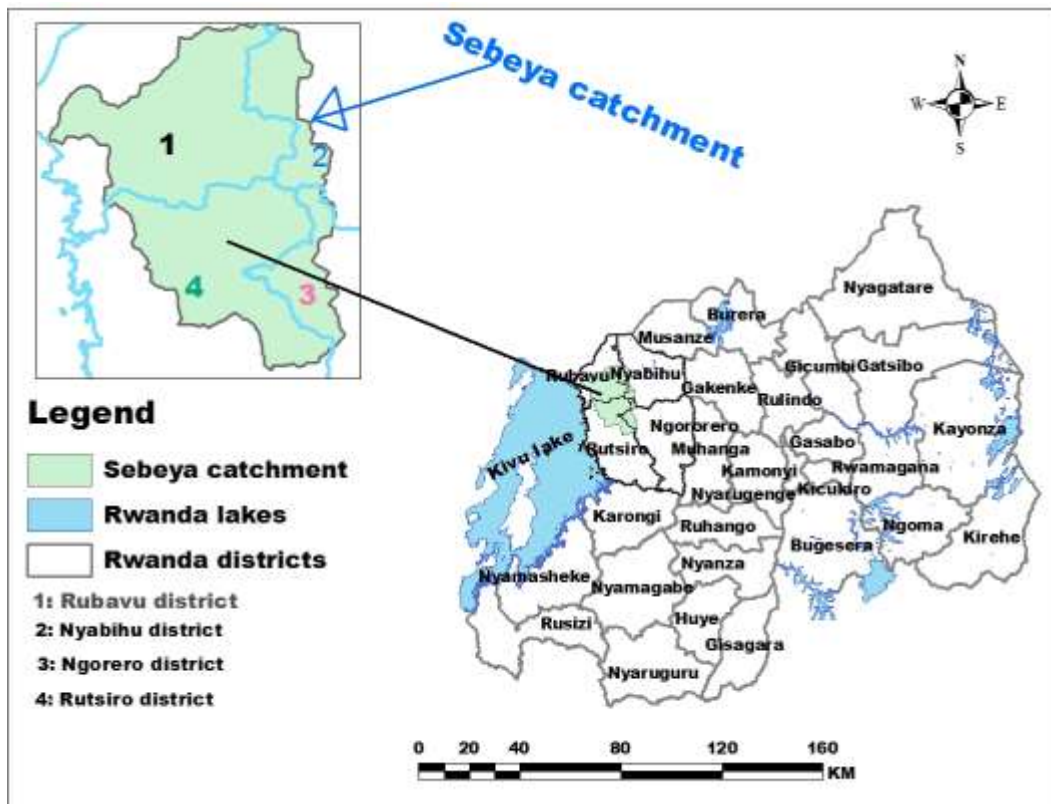


Fig. 4.26 Rwanda map showing the Sebeya catchment.

The superficial area and the estimated population density of the Sebeya catchment area are 363.1 km² and 644 inhab/km², respectively, compared to 26,338 km² and 415 inhab/km² on a country scale (NISR, 2014; IWRM, 2018). This catchment provides suitable conditions for agriculture because it has significant infiltration rates while being rich in minerals, except for clay soils on flat topography. Steep slopes also characterize this catchment, with the altitude and yearly average rainfall varying from 1462 m to 2979 m and 1200 mm to 1700 mm, respectively (IWRM, 2018). Based on all these factors, the Sebeya catchment is exposed to high-rated soil erosion (MoE, 2018a).

B.1.2.2 Determining the Sample Size and Sampling Procedures

The main objective of a research survey is to provide insight into how the findings from a sampled population can be generalized to the population as a whole (Taherdoost, 2016). The sample size in sampling analysis may be manageable; it must be optimum (Faber and Fonseca, 2014). If a survey is just for information on the research trends, small sample sizes can be selected, while large sample sizes are required for high-precision studies (Kumar, 2011). The required sample size depends on the margin of error and the significance level of the research (Taherdoost, 2016).

In this study, a sample of farmers was selected using a systematic random sampling at a 91.6% confidence level, with 0.5 degrees of variability, and a 10% margin of error as a level of precision while using the Cochran formula (Taherdoost, 2016) as shown in the following Eq(4.3)

$$n = \frac{Z^2 \hat{p} \hat{q}}{e^2} = \frac{(1.73)^2 (0.50)(0.50)}{(0.10)^2} = 75 \text{ farmers} \quad \text{Eq(4.3)}$$

In this equation, **n** stands for the required sample size; \hat{p} is the estimated proportion of an attribute that is present in the population (in this study, \hat{p} is the percentage of farmers who are supposed to adopt the practice, hence: $\hat{p}= 50\%$ and $\hat{q} = 1-\hat{p} = 50\%$); **e** is the acceptable margin of error; **Z** is the statistical value representing the confidence level; and **α** is the value chosen by the researcher to determine the statistical significance of the random sampling. It represents an acceptable probability of a Type I error (Kim, 2015).

In this investigation, study tours were executed to collect primary first-hand data about cultivated crops, topography, soil characteristics, hydrographic network, and the existing SEC measures in the Sebeya catchment.

Interviews of farmers from six identified sectors (Gisenyi, Rugerero, Nyundo, Nyakiriba, Kanama, and Nyabirasi) were conducted in order to attain scientific and practical insights into farmers' perceptions of the causes and effects of soil erosion, as well as their perceptions and actions regarding the adoption and implementation of soil erosion control measures in the Sebeya catchment.

B.1.2.3 Data Collection

Multifarious published journal articles and government reports have provided secondary data about erosion rates, causes, effects, and control in the Sebeya catchment. Therefore, the authors used this method to synthesize various researchers' views on this topic. The Digital

Elevation Model (DEM) data used to delineate the Sebeya catchment were obtained from CGIS Rwanda (Center of Geographical Information System).

B.1.2.4 Data Analysis

Descriptive statistics using SPSS (Version 20) were used along with the t-test, the chi-square test, and the binary logistic regression model to describe farmers' socioeconomic characteristics and tie their perceptions of soil erosion and various explanatory variables. As part of this study, the following variables were analyzed: Gender, age, marital status, education, farmland size, land ownership, amount of livestock, experience in agriculture, total income from the farm, main occupation, off-farm activities, access to media, and access to credit. All these variables were chosen based on the literature and the researchers' opinions (Tsfahunegn et al., 2021).

This study utilized the following steps to understand farmers' perceptions of adopting SEC measures in the Sebeya catchment (Table 4.34).

Table 4.34 Research design.

Case study	Research questions	Methods	Results
A sample of 75 farmers in the Sebeya catchment.	What is the actual status of various farmers' socioeconomic characteristics in the Sebeya catchment?	Scoring of various socioeconomic characteristics of farmers.	Actual status on various socioeconomic characteristics of farmers in the Sebeya catchment.
	What are various farmers' perceptions of various causes of soil erosion and its effects?	Assessing farmers' views on various causes and effects of soil erosion on agricultural lands.	A collection of farmers' views on main causes and effects of soil erosion in the Sebeya catchment and their assessment.
	How do farmers express their needs to improve the existing and implement new soil erosion control measures?	Scoring of various proposed SEC measures.	Farmers' views on the improvement and implementation of the existing and new proposed SEC measures in the Sebeya catchment.
	How do different farmers' socioeconomic	Using the binary logistic regression	Level of the statistical significance of the nine

Case study	Research questions	Methods	Results
	characteristics affect the adoption of SEC measures?	model to analyze the statistical significance of nine socioeconomic factors influencing the adoption of SEC measures.	factors influencing the adoption of SEC measures in the Sebeya catchment.

In this research, the binary logistic regression model was involved because the dependent variable (adoptability or willingness to adopt the proposed SEC measures) is a binary consisting of two values, 1 and 0, for an adopter and a non-adopter, respectively. The expected value is simply the probability p . Practically, the dependent variable is modeled indirectly as the logistic transformation of p , as shown in Eq(4.4) (Kleinbaum and Klein, 2010; Park, 2013; Sakinc and Ugurlu, 2013).

$$\text{logit}(p) = \ln\left(\frac{p}{1-p}\right) = B_0 + B_1 * X_1 + B_2 * X_2 + B_3 * X_3 + B_4 * X_4 + \quad \text{Eq(4.4)}$$

where B_i represents the coefficients of the logistic regression model and $\text{odds} = \frac{p}{1-p}$. In this context of binary logic regression, the language of odds is used more than the language of probability.

B.1.3 Results

B.1.3.1 Estimating Soil Loss from the Sebeya Catchment

Data on soil erosion and its controlling factors can be collected in the field or from simulated conditions in the laboratory. Field measurements provide more realistic data on soil loss because many factors are controlled in laboratory experiments. Three methods are commonly used to estimate or predict soil erosion: Erosion pins, bounded field erosion plots, and empirically based equations to predict soil loss and sediment yields from a catchment. Erosion models often use secondary data available in a geographic information system as an alternative approach because measuring soil erosion is expensive and time-consuming (Karamage et al., 2016).

As a result, this paper presents a classification of soil erosion in the Sebeya catchment area into six categories: Very low risk (0–5 tons/ha/year), low risk (5–10 tons/ha/year), moderate risk (10–25 tons/ha/year), high risk (25–50 tons/ha/year), very high risk (50–100 tons/ha/year), and extremely high risk (>100 tons/ha/year). Approximately 8000 hectares are at high risk, while approximately 6000 ha are at very high risk. In total, approximately 4500 ha of the Sebeya catchment land was found to be highly vulnerable to soil erosion (MoE, 2018b). This study estimated the soil loss from the Sebeya catchment area at 130.724 tons/ha based on the Universal Soil Loss Equation (USLE) combined with GIS applications. In the Sebeya catchment, soil erosion is accelerated by heavy rainfall, insufficient SEC measures, and human activities.

B.1.3.2 Farmers' Socioeconomic Characteristics

The results of the SPSS analysis of different farmers' socioeconomic characteristics are shown in Table 4.35. Statistical comparisons were made based on the percentage of respondents who answered each question similarly.

Table 4.35 Qualitative results of different farmers' socioeconomic characteristics as analyzed using SPSS in the Sebeya catchment ($n = 75$).

Attribute	Frequency	Attribute	Frequency
1. Gender		5. Land ownership	
Male	43(57.3%)	Farmland inherited	27(36%)
Female	32(42.7%)	Farmland bought	30(40%)
2. Age		Farmland hired	10(13%)
18–25	8(11%)	Not owner but a daily laborer	8(11%)
26–30	13(17%)	6. Total farmland size	
31–40	27(36%)	≤ 0.1ha	15(20%)
41–55	21(28%)	>0.1ha	60(80%)
>55	6(8%)	7. Main occupation	
3. Marital status		Farmer but not the owner	5(7%)
Married (live together)	59(79%)	Owner but not farm laborer	10(13%)
Single	7(10%)	Owner & daily laborer	60(80%)
Divorced	4(5%)	8. Access to social media	
Widowed	5(6%)	Yes	13(17%)
4. Education		No	62(83%)
Illiterate (no formal education)	11(15%)	9. Access to credit	
Can read and write	4(5%)	Yes	18(24%)
Primary education	42(55%)	No	57(76%)
Secondary education	15(20%)		
University	4(5%)		

The researchers used Table 4.36 to collect the quantitative information and the statistical analysis results with a t-test to compare the data.

Table 4.36. Quantitative results on different farmers' socioeconomic characteristics as analyzed using SPSS in the Sebeya catchment ($n = 75$).

Parameter	Sample			Country Mean (μ) (NISR, 2021)	t-Test Ho: $\bar{X} = \mu$
	Min	Max	Mean (\bar{X})		
Age (years)	18	67	38.40	-	N.A.
Farming experience (years)	1	48	17.95	-	N.A.
Total farmland size for Irish per household (m ²)	75	90,000	2540	165	DD
Total farmland size for maize per household (m ²)	48	41,160	1887	615	DD
Total farmland size for beans per household (m ²)	60	25,290	1814	778	DD
Income from Irish potatoes per household (kg/season)	40	4000	255	127	DD
Income from beans per household (kg/season)	10	30,000	821	67	D.D.
Income from maize per household (kg/season)	10	4000	198	88	D.D.
Number of cows per household	1	6	0.31	0.67	NS
Number of pigs per household	2	9	0.33	0.52	SS
Number of goats per household	1	5	0.60	0.72	SS
Number of poultry per household	2	13	0.69	1.64	NS
Number of rabbits per household	7	15	0.29	0.31	SS

DD: The sample mean and the country means are distinctly different. No t-test is needed. **NS:** The sample and country mean are not statistically the same. **S.S.:** The sample mean and the country means are statistically the same.

Based on the interview results in Table 4.36, this study depicted that the total farmland size per household (m²) for Irish potatoes, maize, and beans ranged between 75 and 90,000; 48 and 41,160; and 60 and 25,290; with average values of 2540, 1887, and 1814 m²/H.H, respectively. In addition, farmers in the Sebeya catchment reported that the income per household from Irish potatoes, beans, and maize ranged between 40 and 4000; 10 and 30,000; and 10 and 4000; with average values of 255, 821, and 198 kg/season/H.H., respectively.

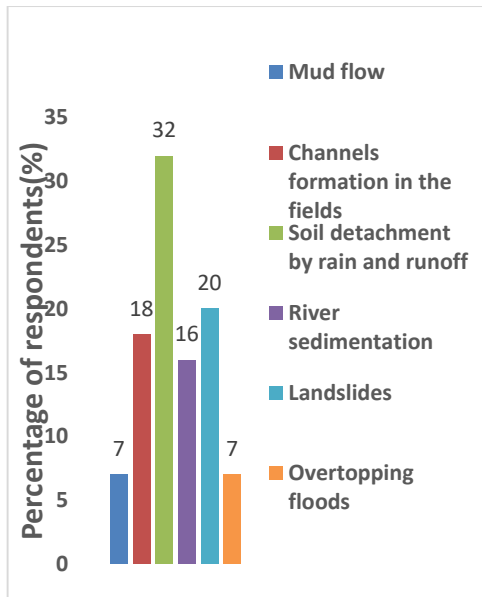
Quantitatively, this research revealed that the number of domestic animals per household varied between 1 and 6 cows, 2 and 9 pigs, 1 and 5 goats, 2 and 13 poultry, and 7 and 15 rabbits, with an average value per household of 0.31 cows, 0.33 pigs, 0.60 goats, 0.69 poultry, and 0.29

rabbits in the Sebeya catchment. In comparison with the mean values estimated per household countrywide (NISR, 2021) in Table 3, a t-test was applied to test the significance of the mean of this random sample, as illustrated in (Stockemer, 2019). As indicated in Table 3, the sample and the country means were statistically the same for pigs, goats, and rabbits. At the same time, the t-test revealed that the two values of the mean were statistically different for cows and poultry.

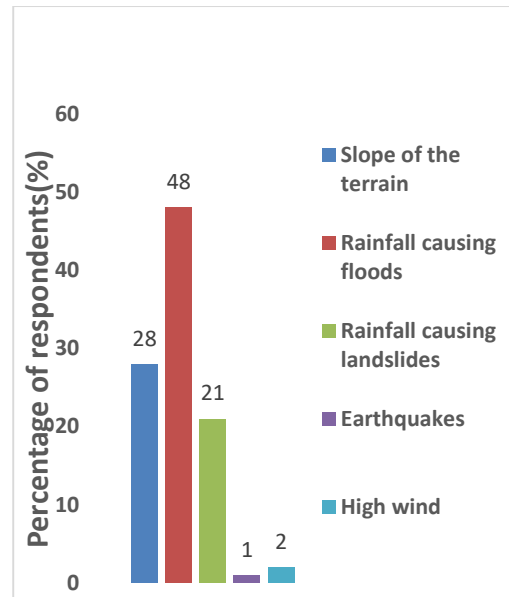
B.1.3.3 Farmers' Perceptions of Causes and Effects of Soil Erosion

In Fig. 4.27, farmers were asked to identify the indicators, major causes, and effects to assess the severity of soil erosion and causes of the agricultural productivity decline in their farmlands.

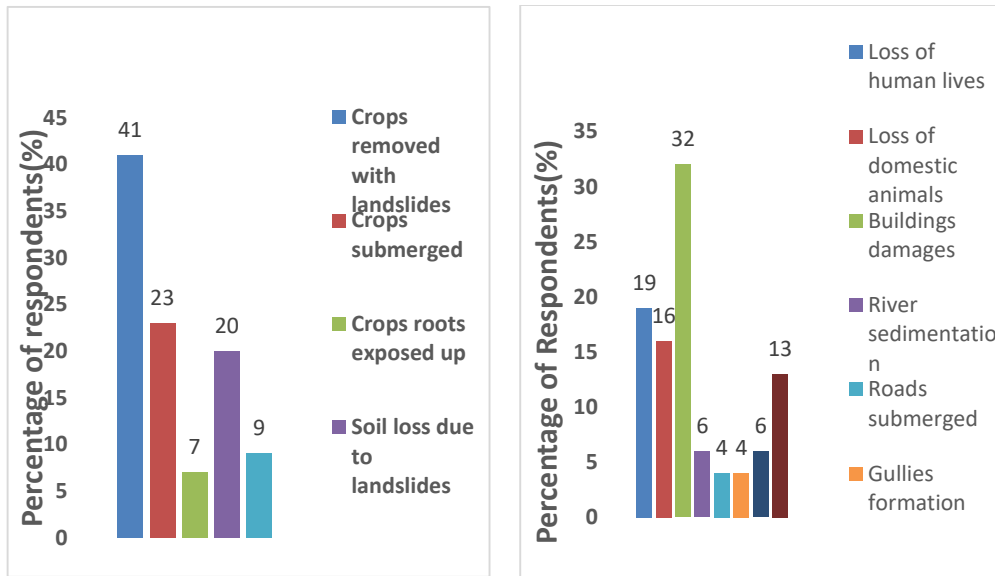
Various soil erosion signs given in Fig. 4.27a indicate that, in the Sebeya catchment, soil erosion is approximately known by 80.67% of farmers. Similarly, Biratu and Asmamaw (Biratu and Asmamaw, 2016) reported that (93.1%) of respondents recognized excessive soil erosion in their farmlands.



(a) Signs of soil erosion



(b) Natural causes of soil erosion



(c) Onsite effects of soil erosion

(d) Offsite effects of soil erosion

Fig. 4.27 Assessment of farmers' perceptions of soil erosion in the Sebeya catchment based on indicators, causes, and effects.

In this study, farmers in the Sebeya catchment could recognize four types of soil erosion: Gully erosion (42.6%), rill erosion (20%), stream bank erosion (18.7%), and sheet erosion (18.7%). The results of this research are backed by a recent study (Misebo, 2018), which affirms that sheet and rill erosion are the main types of erosion that occur on cultivated hillsides of Rwanda.

According to Fig. 4.27b, heavy rainfall combined with high runoff is the most important natural factor contributing to soil erosion in the Sebeya catchment. This finding is supported by Munyaneza et al in 2014, who reported that human activities caused storm runoff and accelerated soil erosion in the Sebeya catchment. Generally, the main causes of soil erosion perceived by farmers in the Sebeya catchment were the slope of the land, deforestation, continuous cultivation of land without fallow, high intensity of rainfall, and absence of appropriate SEC measures. The same causes were reported by Belay in 2020; Amenu and Megersa in 2021, while Pravat et al. in 2015 confirmed that soil erosion's first and second causes were heavy rainfall and slope steepness, respectively. The lack of land for agriculture and settlements is one of the major reasons for the persistence of deforestation in the Sebeya catchment (IWRM, 2019). Soil and nutrient losses (Fig.4.27c) constitute the main onsite damages due to soil erosion, adversely impacting soil productivity. Similarly, Biratu and Asmamaw in 2016 stated that almost all respondents acknowledged the decline in soil fertility due to soil erosion through farmers' interviews.

Fig. 4.27d illustrates soil erosion with considerable offsite damage in the Sebeya catchment. Furthermore, the eroded soil materials and the accompanying pollutants are among the harmful effects of soil erosion in the three hydropower plants, the Gihira water treatment plant, and disturbances to aquatic ecosystems and human recreation in Lake Kivu (Thapa et al., 2017).

B.1.3.4 Needs for the Implementation of SEC Measures in the Sebeya Catchment

Soil erosion is one of the most pressing environmental problems worldwide. It is one of the ecological phenomena to which the adage “Prevention is better than cure” is most applicable. Erosion control is any action to prevent soil erosion from detaching soil surface particles while elucidating the necessity of implementing SEC measures (Bagarello et al., 2015).

Table 2.3 lists 35 BMPs practices mostly applied to control soil erosion on agricultural lands as classified into six groups according to their respective purposes. With high percentages of soil loss reduction, if applied on agricultural lands, the 22 SEC measures table 4.14 were found suitable and proposed to be implemented in the Sebeya catchment.

In this investigation, the interview results revealed that the level of implementation of the 22 proposed SEC measures had reached 4.57%. In contrast, 95.43% effort is required for better controlling soil erosion to the acceptable soil loss rates in the Sebeya catchment. Furthermore, the Integrated Water Resources Management department in Rwanda (IWRM) in 2017 reported that the rehabilitation of 1373 ha in the Sebeya catchment was successful by applying various SEC measures, including tree plantation, agroforestry, and terraces. Therefore, the improvement of SEC measures is strongly needed in the Sebeya catchment. Among different soft BMPs (Table 4), trees and protective grasses should be planted along the river banks, and buffer zones should be established. The no-tillage method, cover crops, crop rotation, mulching, agroforestry, and stabilizing grasses on farm bunds are the soft BMPs that farmers can easily implement on their farmlands. Soft BMPs are those agronomic measures easily implemented at a low cost. At the same time, terraces (which are still few) and anti-erosive ditches constitute the main hard BMPs in the Sebeya catchment (IWRM, 2016). Similarly, Onu and Mohammed in 2014 reported that farmers needed to systematically improve all the existing SEC measures in Kogi state (Nigeria).

Technologically, bench terraces are earth embankments constructed to transform long slopes into a series of shorter slopes to intercept the surface runoff. Their implementation is mainly needed to control soil erosion on agricultural lands with slopes ranging from 16% to 60%, while progressive terraces and contour bunds are suitable on slopes less than 16% (IWRM, 2016). Based on slope ranges, various SEC measures were initially proposed in the Sebeya catchment by the Ministry of Environment (MoE, 2018). Table 4.37 shows how various proposed SEC measures can be efficiently implemented in the Sebeya catchment within slope ranges.

Table 4.37 Proposed combinations of SEC measures in the Sebeya catchment.

Land Slope	Soil Depth		
	(>1 m)	(0.5–1) m	(<0.5 m)
(0–6%)	AG+CC+CT+DC+M+	AG+CC+CT+DC+M+	AG+CC+CT+DC+M+
	SG	SG	SG
	CC+CT+DC+M+PT+S	CC+CT+DC+M+PT+	M+PT
(6–16%)	G	SG	CB+DC+M+SG
	Or	Or	Or
	CB+CC+CT+DC+M+	CB+CC+CT+DC+M+	CB+CC+CT+DC+M+
	SG	SG	SG

			CC+CT+DC+M+PT+
			SG
(16–40%)	BT+CC+CT+DC+M+	BT+CC+CT+DC+M+	or
	SG	SG	CB+CC+CT+DC+M+
			SG
(40–60%)	BT+CC+CT+DC+M+	BT+CC+CT+DC+M+	AF
	SG	SG	
(> 60%)	A.F.	A.F.	A.F.

A.F.: Afforestation; **AG:** Agroforestry; **B.T.:** Bench terraces; **C.B.:** Contour bunds; **CC:** Crop cover; **CT:** Contour tillage; **DC:** Drainage channels; **M:** Mulching; **P.T.:** Progressive terraces; **S.G.:** Stabilizing grasses on farm bunds.

B.1.4 Discussion

B.1.4.1 Actual Status of Soil Erosion and its Control in the Sebeya Catchment

In order to clarify the severity of soil erosion in the Sebeya catchment, this study classified this region as a very high-risk zone of soil erosion with an annual average soil loss of 130.724 tons/ha/year due to insufficient SEC measures, heavy rainfall, and human activities accelerating soil erosion. Among the greatest worldwide environmental concerns is soil erosion because it not only causes soil nutrient deprivation and land degradation but also leads to many notable offsite environmental problems such as flooding, water siltation, and pollution (Issaka and Ashraf, 2017). This research assessed various SEC measures (Table 4) and recommended their implementation in the Sebeya catchment. However, some SEC techniques, such as terraces, contour bunds, and drainage channels, are costly to build (Issaka and Ashraf, 2017; Debebe et al., 2013).

B.1.4.2 Adoptability of SEC Measures in the Sebeya Catchment

The chi-square test is a statistical measure used in sampling analysis to assess the relationship between two attributes (variables) (Turhan, 2020). It is symbolized as χ^2 . In this study, the significance of the chi-square value [χ^2 (calculated)] was determined by using the suitable degree of freedom [$df = (r-1)(c-1)$] and the degree of significance ($\alpha = 0.05$) in comparison with the chi-square value from a table [χ^2 (critical)]. Table 4.38 shows the chi-square test results to find relationships between variables (adoption factors) and the four selected SEC measures (terraces, mulching, anti-erosive ditches, stabilizing grasses on the farm bunds) in the Sebeya catchment.

Table 4.38. Significance of variables (adoption factors) for the four selected SEC measures.

S.N.	Variables (Adoption Factors)	df (r-1)(c-1)	χ^2 (Calculated)	χ^2 (Critical)	p-Value	χ^2 (Ho) *	test
1	Age of a farmer (yr)	12	26.762	21.026	0.0084	S	
2	Gender of a farmer	3	13.480	7.815	0.0037	S	
3	Marital status	9	1.170	16.919	0.9989	NS	
4	Education	12	0.310	21.026	0.9999	NS	
5	Farmland size (ha)	3	8.350	7.815	0.0393	S	
6	Main occupation	6	13.330	12.592	0.0380	S	
7	Access to media	3	8.580	7.815	0.0353	S	
8	Access to credit	3	11.870	7.815	0.0078	S	

* **Ho:** There is no relationship between the selected independent variable (adoption factor) and the dependent variable (the adoptability of the four proposed SEC measures: Terraces, mulching, anti-erosive ditches, and stabilizing grasses on the farm bunds). **S** = the adoption factor is statistically significant for the proposed SEC measures. **N.S.** = the adoption factor is statistically not significant for the proposed SEC measures. **r** = number of rows. **c** = number of columns.

This study also uses the Binary Logistic Regression Model (Park, 2013; Asfaw and Neka 2017) to investigate if there is a statistical significance between explanatory variables (independent variables) and the adoption of SEC measures in the Sebeya catchment. The nine variables commonly associated with SEC adoption are listed in Table 4.39 (Tesfahunegn et al., 2021).

Table 4.39 Compiled results from the binary logistic regression model (*).

Parameter	B	S.E.	Wald	df	Sig.	Exp (B)
Gender	-2.034	0.949	4.594	1	0.032	0.131
Age	-0.642	0.319	2.231	1	0.035	1.719
Marital status	-0.220	0.488	0.203	1	0.652	0.803
Education	-0.507	0.409	1.532	1	0.216	0.602
Total farmland size	-2.225	1.222	3.318	1	0.069	0.108
Main occupation	-0.335	0.852	0.155	1	0.694	0.715
Farmers experience	0.749	0.321	5.440	1	0.020	2.115
Access to social media	2.107	0.954	4.880	1	0.027	8.223
Access to credit	-0.521	0.841	0.384	1	0.536	0.594
Constant	3.420	4.823	0.503	1	0.478	30.572

* While assessing the effect of the nine explanatory variables (adoption factors) on the adaptability of the four selected SEC measures (terraces, mulching, anti-erosive ditches, and stabilizing grasses on the farm bunds), the following notations and meanings were used (Park, 2013; Asfaw and Neka 2017): **B**: Regression coefficient in the binary logistic regression model. **S.E.**: Standard error. **Exp (B)**: Odds ratio. **Sig.:** *p*-values (in the column of Sig.). **Wald**: A Wald chi-square test was used to determine whether the coefficients within the model are statistically significant. **df**: Degree of freedom (for the Wald chi-square test).

Many studies have shown that various socioeconomic characteristics affect farmers' adoption behavior of SEC measures (Tsefahunegn et al., 2021; Amenu and Megersa, 2021). In analyzing the impacts of the nine independent variables on the dependent variable (adoption of SEC measures in the Sebeya catchment), the following summary presents the results and interpretation using the chi-square test and the Binary Logistic Regression Model.

Gender of a farmer

Based on the socioeconomic characteristics of the respondents (Table 2), 57% were male, and 43% were female. Many researchers have reported large numbers of males in farmers' interviews (70%) and (78%), whereas women respondents constituted 30% and 22%, respectively, for Senkoro (Senkoro, 2010) and Pravat et al. in 2015. The chi-square test (Table 6) also indicates that the gender of the respondents is associated with their participation in adopting SEC measures

at ($\chi^2 = 13.480$; $df = 3$ and $p = 0.0037$). However, this finding differs considerably from that of Biratu and Asmamaw in 2016. They stated that the chi-square test did not indicate an association between respondents' gender and the extent to which they participated in SEC activities.

The gender of respondents is negatively correlated with the adoption of SEC measures and is statistically significant at the 0.05 level ($B = -2.031$; p -value = 0.032), which is also confirmed by the Wald statistics (4.591). These results reflect that males and females are likely to be engaged in implementing and maintaining SEC measures. However, male farmers may have better perceptions of soil erosion because they have more access to information-sharing events at farmer conferences than female farmers (Nigussie et al., 2017).

Age of a farmer

Some published findings have revealed that the age of a farmer is one factor influencing the farmers' adoption of SEC measures (Biratu and Asmamaw 2016; Nigussie et al., 2017).

In this study (Table 4.35), respondents were categorized into five age ranges as follows: 18–25 (11%), 26–30 (17%), 31–40 (36%), 41–55 (28%), and above 55 (8%). This study recorded a very small percentage of farmers aged between 18 and 25 (11.2%) because many young people are still at school and are not interested in farming once they have completed their secondary education. Most respondents were in the age ranges 31–40 and 41–55, indicating that the involved farmers were still in their economically active age for better advancements in their farming activities. They may buy or hire new hectares of farmlands and pay much attention to SEC measures. Moreover, the farmers in these age ranges are more engaged in fulfilling their family needs, such as food security and school fees for their children. They have more family responsibilities than the young and old farmers.

The chi-square test (Table 4.38) indicated that the age of farmers and adoption of the SEC measures have a significant association ($\chi^2 = 26.762$, $df = 12$; $p = 0.0084$). Similarly, Alemu in 2019 confirmed that the age of farmers significantly influenced their knowledge of the proposed SEC measures ($\chi^2 = 9.686$, $p = 0.046$).

Among the socioeconomic characteristics, the age of the respondents correlated negatively with the adoption of SEC measures. It was statistically significant at the 0.05 level ($B = -0.642$ and p -value = 0.035), and the Wald statistics (4.050) also showed its significant relationship. This finding is in line with Asfaw and Neka in 2017 and Belachew et al. in 2020, who confirmed that age is relevant in adopting SEC measures with $B = -0.067$, p -value = 0.045, and Wald statistics of 4.016. The negative sign indicates that as the age of farmers increases, the probability of participating in SEC practices decreases. Old farmers do not have enough energy to implement SEC measures in their farmlands. The younger the farmer, the more he or she tends to adopt SEC measures. Young farmers are usually more educated, physically apt, and highly adaptive to innovations concerning SEC technologies. Throughout the literature, Nadhomi et al. in 2013 reported that the maximum age to adopt SEC practices would be approximately 51 years. In this study, the average age of the respondents was 38 years, an age below the calculated age limit for the adoption potential of SEC measures. This age (38 years) suggests that farmers in the Sebeya catchment would tend to adopt new SEC measures.

Marital status of the respondents

Among the farmers' socioeconomic characteristics (Table 4.35), marital status was categorized into four groups, married (79%), single (10%), divorced (5%), and widowed (6%). Similarly, Alemu in 2019 reported a comparatively high percentage (94.6%) of married respondents in a farmers' interview.

However, the chi-square test indicates that there is no significant relationship between the marital status of farmers and their perceptions of adopting SEC measures in the Sebeya catchment ($\chi^2 = 1.170$, $df = 9$; $p = 0.9989$).

In this study, the binary logistic analysis depicted that the marital status of the respondents correlated negatively with the adoption of SEC measures and was statistically insignificant at the 0.05 level ($B = -0.220$, p -value = 0.652), where the Wald statistics (0.203) also revealed the same insignificance.

Education level of the farmers

In order to analyze the impact of the farmers' education level on the willingness to adopt SEC measures, respondents were grouped into five categories as shown in Table 4.35: Illiterate (who cannot read and write), who can read and write, primary, secondary, and university education with 15%, 5%, 55%, 20%, and 5%, respectively. However, the chi-square test does not show a significant relationship between farmers' education level and their participation in SEC activities ($\chi^2 = 0.310$, $df = 12$, $p = 0.9999$). Similar studies (Biratu and Asmamaw, 2016) also reported a chi-square test result that does not show a significant relationship between farmers' education and the level of participation in SEC activities ($\chi^2 = 3.155$, $p = 0.206$). The educational level of respondents correlated negatively with the adoption of SEC measures at the 0.05 level ($B = -0.1507$; p -value = 0.216) but statistically insignificant. The Wald statistics (1.532) also revealed its insignificant association with adopting SEC measures. Similarly, Betela and Wolka in 2021 reported that education status was negatively correlated at an insignificant level.

On the contrary, our result does not corroborate the findings of recent studies, which documented the positive and significant effect of education in fostering the adoption of SEC measures (Asfaw and Neka, 2017; Belachew et al., 2020; Mango et al., 2017). Education determines farmers' management ability and awareness of all the available and newly proposed SEC measures. An illiterate farmer would likely be less motivated to try out new technologies for a better livelihood since he or she will not have the opportunity to obtain, understand, or use more information from social media, such as radio and television.

Farmland size

Table 4.35 shows that the majority of farmers (80%) have large farm sizes (> 0.1 ha) compared to the other portion of farmers (20%) who have small farmland sizes (≤ 0.1 ha). A larger farmland size could push farmers to worry about soil erosion and its effects. Thus, it could positively influence their perceptions and adoption of SEC measures. Moreover, the chi-square test results showed a statistically significant relationship between farmland size and the adoption of SEC measures ($\chi^2 = 8.350$, $df = 3$; $p = 0.0393$). Similar studies in Ethiopia found that farmland

size positively affected farmers' perceptions and investment in SEC measures (Belachew et al., 2020; Teshome et al., 2016; Moges and Taye, 2017; Sileshi et al., 2019). Furthermore, farmland size was found to exert a positive and significant effect on adopting SEC measures in Uganda (Alemu, 2019; Mugonola et al., 2013).

Moreover, the binary logistic regression analysis revealed that the cultivated farmland size has a negative and insignificant impact on farmers' adoption of SEC measures ($B = -2.225$, p -value = 0.69). Throughout the literature (Asfaw and Neka, 2017), the size of farmlands had a negative and insignificant impact on farmers' adoption of SEC measures ($B = -0.325$, p -value = 0.849). The negative sign indicates that as the farmland size increases, the probability of adopting the SEC measures decreases (Asfaw and Neka, 2017; Alufah et al., 2012). Generally, large farmlands belong to old farmers who are not physically apt to execute the excessive labor required to implement SEC measures.

Main occupations in the farming system

In this study, 40% of farmers are engaged in farming for the agricultural business, 37.33 % for lack of other employment opportunities, and 22.67% for food security concerns. Table 4.35 shows three main farming jobs recognized among the interviewed farmers. They were grouped into three classes: A class of farmers who are not owners (7%), a class of farmers who are owners but not farm laborers (13%), and a class of farmers who are owners and daily laborers (80%). At the same time, the chi-square test indicates that the main occupation and the adoption of SEC measures have a significant association ($\chi^2 = 13.330$, $df = 6$, $p = 0.0380$).

In this study, farmers in the owner and daily laborer class (80%) should be more motivated to participate fully in protecting their farms against soil erosion while reflecting the positive effects of adopting SEC measures. In summary, farmers who earn a higher income from agriculture tend to have a better perception of soil erosion as this influences their field practices to be more appropriate. Still, the main occupation in the present study was negatively and insignificantly correlated with the adoption of SEC measures with $B = -335$, p -value = 0.694, and the Wald statistics of 0.155.

Farming experience of respondents

Farmers' experience is another important factor to consider when improving farming practices and technologies. Our study revealed that the farming experience of respondents was positively correlated with the adoption of SEC measures in the study area and statistically significant at the 0.05 level ($B = 0.749$, p -value = 0.020). This assertion of significance was confirmed by the Wald statistics (5.440). More experienced farmers better understand the importance of improving SEC measures than less experienced farmers (Wordofa et al., 2020). Similarly, Fekadu et al. in 2013 reported that farmers with more farming experience were more likely to participate in SEC initiatives.

Access to social media

In this study (Table 4.35), 17% of farmers have access to social media, against 83% with no access. Still, the chi-square test showed a significant relationship between access to social media and the farmers' adoption of SEC measures ($\chi^2 = 8.580$, $df = 3$, $p = 0.0353$). This survey indicates that a reasonable proportion of farmers can use social media and obtain sufficient information on implementing SEC technologies. In a similar study, Betela and Wolka in 2021 reported the same result. Access to social media was associated positively and significantly with the adoption of SEC measures with $B = 2.107$, p -value = 0.027, and the Wald statistics of 4.880.

Farmers' access to credit

Practically, the accessibility of farmers to credit should indicate a greater likelihood of adopting SEC technologies than those without access. Credit availability may encourage farmers to invest more in yield-enhancing activities, such as adopting and implementing SEC measures in their farmlands. Throughout the literature, Wordofa et al. in 2020 reported access to credit of up to 66%, while 34% of farmers had no access to credit. In this study, only 24 % of farmers reported having obtained credit, while a large portion of the respondents (76%) needed it (Table 4.35). Furthermore, the chi-square test revealed that adopting SEC measures is significantly influenced by access to credit facilities ($\chi^2 = 11.870$, $df = 3$, $p = 0.0078$).

However, access to credit correlated insignificantly and negatively with the adoption of SEC measures ($B = -0.521$, p -value = 0.536), as confirmed by the Wald statistics (0.384). Similarly, Karidjo et al. in 2018 reported that despite its significance at ($p < 0.001$), the access to credit variable was negatively correlated with the adoption of SEC measures. These results suggested that farmers who had access to credit from financial institutions were less likely to invest in adopting SEC technology.

To this end, the research question was: "Are there significant factors affecting farmers' willingness to adopt SEC measures in the Sebeya catchment"? The answer to this question necessitated using the chi-square test and the binary logistic regression model. Using the chi-square test on eight explanatory variables, gender, age of a farmer, land ownership, farmland size, access to social media, and access to credit were the remarkable influential factors strongly associated with SEC measures. At the same time, marital status and education did not. For deep analysis, some farmers' socioeconomic characteristics showed significant correlation while using the binary logistic regression model. In this study, farming experience and access to social media were positively correlated, while age and gender were negatively correlated with the adoption of SEC measures. However, other socioeconomic characteristics such as marital status, education level, farmland size, and access to credit revealed insignificance in adopting SEC measures.

B.1.4.3 SWOT Analysis

Table 4.40 exhibits the SWOT analysis of the performance and adoption of SEC measures in the Sebeya catchment.

Table 4.40 SWOT analysis of the performance and adoption of SEC measures in the Sebeya catchment.

Strength	Weaknesses
Reduction of topsoil and nutrients losses, soil compaction, and runoff	Insufficient data for adequate planning
Increase of organic matter while keeping high the soil depth and soil infiltration	Lack of technical training in planning and implementing SEC measures
Reduction of soil and water pollution with direct implications on the preservation of biodiversity	Lack of incentives for sustainable implementation of SEC measures
The intervention of the government and NGOs in promoting the BMPs of soil erosion control	The control of soil erosion is not perfect: persistence of soil erosion (indicators and its effects)
Opportunities	Threats
Improvement and implementation of new SEC measures	Climate change impacting crop yield expectations
Large scale adoption	Excessive rainfall
Increase in environmental awareness and support	Financial restrictions
Significant improvement in communication through social media	Some technologies such as bench terraces, check dams, hillside water tanks, retaining walls, and sediment basins, require high capital to invest in SEC measures. They are not affordable by an individual farmer.

B.1.4.4 Future Work

Farmers are the most direct perceivers of the development of soil erosion processes in their farmlands (Guo et al., 2017). Therefore, many authors (Aniah et al., 2013; Peprah et al., 2016; Tesfahunegn et al., 2011; Kusimi and Yiran, 2011) have found that analyzing farmers' perceptions of soil erosion causes, effects, and control can provide quick and practical information for sustainable farmlands management (Aniah et al., 2013; Peprah et al., 2016).

The performance of the 22 SEC measures (written in *italic* in Table 4) was assessed, and SEC measures were proposed for implementation while including farmers' perceptions. The emphasis was on the adoptability of structural SEC measures and the afforestation of hillsides.

Relatively little work has systematically and simultaneously examined all three aspects (planning, adoption, and implementation) of SEC measures in the Sebeya catchment. In order to address this research gap, the current research presented an explorative investigation of various causes and effects of soil erosion, adoption, and implementation of SEC measures in the Sebeya

catchment from the farmers' perspectives. In addition, further studies were proposed to assess various factors affecting farmers' willingness to participate in the planning process, implementation, and maintenance of SEC measures in the Sebeya catchment.

B.1.5 Conclusion and Recommendations

The main consequences of soil erosion in the Sebeya catchment are the reduction of agricultural productivity and water quality pollution. Therefore, its control is essential. This research was initiated to assess farmers' perceptions of soil erosion causes, effects, and control in the Sebeya catchment. It used a detailed survey of 75 farmers with structured interviews, field observation, and focus groups.

Various factors affecting farmers' adoption of SEC measures were assessed using SPSS (Version 20), the t-test, the chi-square test, and the binary logistic regression model. The chi-square test indicated that gender, the age of a farmer, land ownership, farmland size, access to social media, and access to credit were associated ($p < 0.05$) with SEC measures, while marital status and education were not. Moreover, the binary logistic regression model revealed that farming experience and social media access positively correlated significantly. In contrast, age and gender were negatively correlated at a 0.05 degree of significance with adopting SEC measures. On the other hand, marital status, education status, farmland size, and access to credit negatively influenced the adoption insignificantly.

In order to mitigate the high-rated soil erosion in the Sebeya catchment, this study suggests combining more than three soil erosion control measures on the same farmland. Moreover, the government should mobilize a skilled technical team to assist in implementing SEC measures within the Sebeya catchment.

To this end, this research recommends further studies to assess various factors affecting farmers' willingness to participate freely in the planning process, implementation, and maintenance of SEC measures in the Sebeya catchment.

Author Contributions: Both authors contributed to the conception and development of the manuscript as follows: Felicien Majoro was the designer of the manuscript. He carried out data analysis and interpretation, and wrote the manuscript. Umaru Garba Wali supervised all the writing activities of the manuscript. He reviewed and edited the manuscript. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors express their gratitude to the University of Rwanda (U.R.) and wish to acknowledge the UR-Sweden program's financial support in collecting data for this research. Lastly, the authors cannot fail to laud and emphasize the work of different authors on which the present study was based.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Paper 4.B.2 SUSTAINABILITY ANALYSIS OF SOIL EROSION CONTROL IN RWANDA: CASE STUDY OF THE SEBEYA CATCHMENT

Title: Sustainability Analysis of Soil Erosion Control in Rwanda: Case Study of the Sebeya Catchment

Authors: Félicien Majoro^{1,*}, Umaru Garba Wali¹, Omar Munyaneza¹, Francois-Xavier Naramabuye²

Affiliation: ¹University of Rwanda, College of Science and Technology, Department of Civil, Environmental and Geomatics Engineering, P.O. Box 3900, Kigali, Rwanda

²University of Rwanda, College of Agriculture Science and Veterinary Medicine, P.O. Box 3971, Kigali, Rwanda.

*Corresponding Author Address: University of Rwanda, Department of Civil, Environmental and Geomatics Engineering, P.O. Box 3900, Kigali, Rwanda. Felicien Majoro, E-mail: majoro.felicien@yahoo.fr; Cell phone: +250 788484054; Orchid ID: 0000-0002-3679-3925.

Journal: *Sustainability* **2023**, *14*, 151969.

Layout: The format of the paper has been revised to have the same format as the thesis.

Abstract: Soil erosion is a complex process that results in soil and fertility losses from agricultural land and, ultimately, leads to river sedimentation. This study aimed to assess various influential factors and processes affecting soil erosion and to recommend suitable site-based Soil Erosion Control Measures (SECM) for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya catchment of Rwanda. The present research used a literature review, site visits, and focus groups to assess various SEC measures within the Sebeya catchment. As a result, various site-based SEC measures were evaluated, recommended, and simulated to alleviate high soil loss rates in the Sebeya catchment using the Universal Soil Erosion Equation (USLE) model. Simulating existing and proposed SEC measures, soil loss was reduced significantly from 73 t/ha/yr to 29 t/ha/yr. To highlight the implication of the site-based recommended SEC measures in improving agricultural productivity, this study suggests field investigations in soil erosion plots and prediction of crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya catchment. For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya catchment, the present research recommends implementing the site-based recommended SEC measures with mulching and drainage channels on the same farmland. However, lack of money and knowledge are the main limitations in implementing SEC measures in the Sebeya catchment. Therefore, governmental and non-governmental organizations should technically and financially help farmers in the Sebeya catchment.

Keywords: Sebeya catchment; soil erosion causes; soil erosion effects; soil erosion control measures; crop yields; Rwanda

B.2.1 Introduction

Globally, soil erosion threatens agricultural and environmental sustainability (Igwe et al., 2017). Approximately 99.7% of the world's food is produced by agriculture, while only 0.3% comes from aquatic ecosystems, with direct implications for adopting various soil conservation measures to protect limited land resources (Pimentel and Michael, 2013).

Water erosion is a natural geomorphologic process characterized by compaction, disintegration, detachment, transport, and deposition (Sarathi and Padmini, 2015; Sanogo et al., 2021). Based on its severity, water erosion can be classified into five types: splash, sheet or interrill, rill, gully, and streambank erosion (Telkar et al., 2015). Vegetation, amount and intensity of rainfall, physical and chemical properties of soil, and land topography are the main natural causes of soil erosion. In addition, human activities have been blamed for highly influencing soil erosion (Farayi, 2011).

The degradation of soil quality (soil and nutrient losses and lower infiltration rates), and the downstream river and lake sedimentation, are the main on-site and off-site damages of water erosion. In addition, there are numerous consequences, such as food security and agricultural sustainability, water supply, reservoir storage capacity, and the ecology of freshwater bodies, that are adversely affected (Sharma et al., 2011; Kalambukattu and Kumar, 2017; Bashagaluke et al., 2018). Therefore, soil erosion control is the best option for enhancing agricultural productivity while preventing river and lake sedimentation (Huffman et al., 2011).

Using the USLE model to evaluate soil erosion in Rwandan level-1 catchments between 1990 and 2015 (NISR, 2019), soil loss trends (t/ha/yr) for the Mukungwa catchment were reported between 60 and 130; Upper Nyabarongo, between 60 and 90; Lower Nyabarongo, between 60 and 90; Kivu, between 30 and 70; Rusizi, between 50 and 60; Muvumba, between 45 and 60; Akanyaru, between 43 and 50; Upper Akagera, between 15 and 30; and Lower Akagera, between 15 and 20. In general, soil erosion rates increased between 1990 and 2015 due to deforestation for firewood, agriculture, and settlement, urbanization which has increased imperviousness, heavy rains in mountainous areas caused by climate change, and ineffective SECM.

As a level-2 catchment within Kivu level-1, the Sebeya catchment is experiencing severe soil erosion resulting from steep slopes and excessive rainfall (IWRM, 2018). Consequently, soil fertility has declined, and sedimentation in the Sebeya river has increased due to soil erosion. The large population accelerates this erosion. As mentioned earlier, anthropogenic erosion refers to different forms of soil erosion induced by human activity, such as deforestation to create new settlements, mining, road construction, steep slope reclamation, and firewood cutting. The Keya hydropower plant faces the challenge of difficult operation and maintenance because of an extremely large amount of sediment entering the plant with hard and abrasive minerals, especially during rainy seasons (Munyaneza et al., 2015). In addition, the excessive turbidity of the Sebeya river increases the coagulant consumption at the Gihira water treatment plant. It also harms the recreational and aquatic life of Lake Kivu.

There are several USLE-type models to assess and evaluate soil erosion rates (Alewell et al., 2019). Due to its simplicity, the USLE model will be used in this investigation to simulate the actual and predicted soil erosion rates within the Sebeya catchment for making suggestions and recommendations on long-term development and sustainability (Devatha et al., 2015). However, it does not include gully erosion, as it only considers sheet and rill erosion (Alewell et al., 2019). Modeling is a useful tool for assessing different scenarios associated with soil erosion, allowing the selection of the most effective SEC measures (Panagopoulos et al., 2015).

This study aimed to assess soil erosion's status and recommend appropriate site-based SEC measures for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya catchment.

B.2.2 Methodology

B.2.2.1 Study area

Located in Africa, Lake Kivu is among the East African Rift valleys. Its total surface area is 2700 km², at an altitude of 1460 m above sea level, and a maximum depth of about 480 m. It is shared by Rwanda and the Democratic Republic of Congo (DRC). The total number of 127 rivers flowing from the Congo Nile Crest into Lake Kivu includes the Sebeya river (Muvundja et al., 2009).

Situated in the Congo River Basin that flows into the Atlantic Ocean, the Sebeya catchment is one of the small catchments draining the western slopes of the Nile Congo catchment of Rwanda between 1°50'57.15" and 1°42'21.99" degrees South (22.984 km) latitude and 29°23'52.04" and 29°25' 06.14" degrees East (27.455 km) longitude (Guo et al., 2017).

This study is focused on the Sebeya catchment, which drains its water into Lake Kivu (Birdlife International, 2018) in the Western Province of Rwanda, as presented in Fig.4.28. The main river flowing in this catchment is Sebeya, which originates in the mountains of the Rutsiro District. The Sebeya river runs in a north–westerly direction along 48 km from its source in the mountains of the Congo-Nile divide at an altitude of 2660 m (above mean sea level) of Gishwati forest to its outfall at Lake Kivu at an altitude of 1470 m. As shown in Fig. 4.28, the Sebeya catchment is shared by four administrative units: Rubavu, Nyabihu, Rutsiro, and Ngororero.

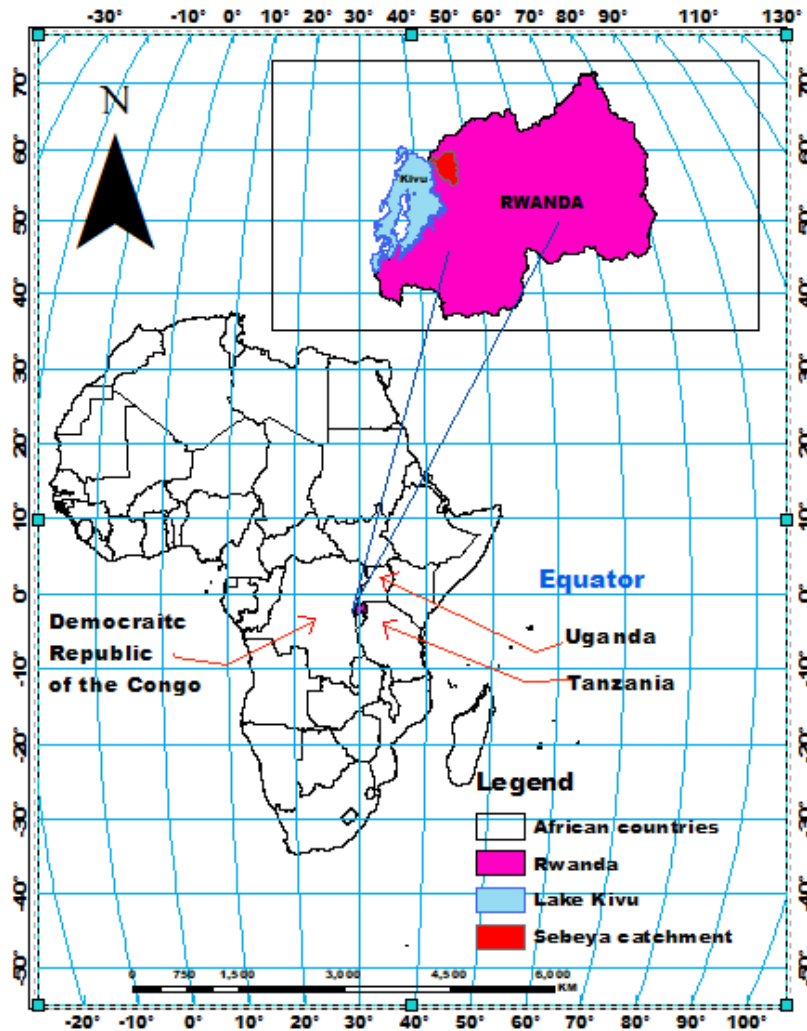


Fig. 4.28 The Sebeya catchment localization.

The Sebeya catchment covers 363.1 km², compared to the Rwandan territory area of 26,338 km² (NISR, 2014). Compared to Rwanda's average population density of 415 inhabitants/km², the Sebeya catchment has 644 inhabitants/km² (IWRM, 2018).

Butare complex and the volcanic rocks of the Virunga Mountains are two main geological formations in the Sebeya catchment, and nitosol, acricol, alisol, and lixisol are the main soil classes (IWRM, 2018). The clumping of the soil textural components of sand, silt, and clay forms aggregates, and the further association of those aggregates into larger units forms soil structures. The soil in this catchment favors agriculture due to its high infiltration rates and mineral content, except for the case of clay soils on flat topography.

As shown in Fig. 4.29, the topography of the Sebeya catchment is among the mountainous chain of the Congo-Nile river divide extending north-south from the Nyungwe forest in the south to the Gishwati forest in the north. This mountainous chain divides the country into two catchments. The catchment is characterized by steep slopes and complex topography (abrupt altitude changes at small distances).

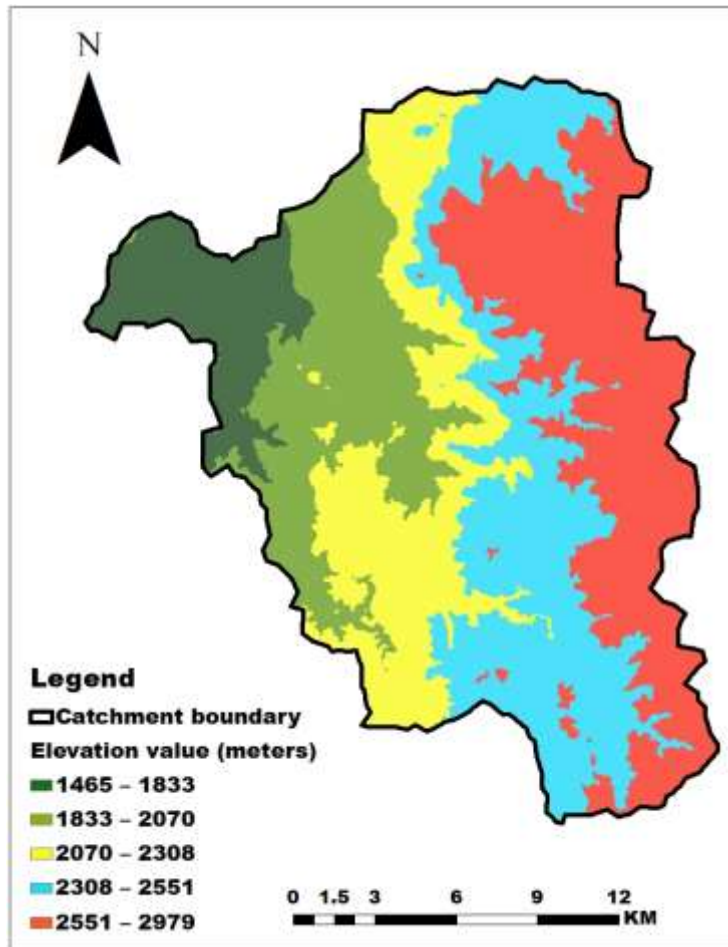


Fig. 4.29 The Sebeya catchment topographic map.

The rainfall pattern of Rwanda is bi-modal, i.e., it has two distinct rainy seasons. A heavy rainy season (March, April, and May), and a light rainy season (September, October, November, and December). The Sebeya catchment is characterized by high rainfall (1200 mm/year and above) and a relatively short dry season in June–August. Erratic showers continue in January–February, the second dry season in the country (NISR, 2017). Using rainfall data from the University of Rwanda’s Center of Geographic Information Systems (UR-CGIS), the average precipitations in the Sebeya catchment in 2018 were 1187 mm, 1336 mm, 1538 mm, and 1233 mm at Tamira, Pfunda, Kanama, and Nyundo, respectively. By mapping, the rainfall distribution varies between 1187 mm and 1536 mm, while the digital display of this rainfall map indicates an average precipitation of $\bar{P} = 1318$ mm for the Sebeya catchment (Fig.4.30).

Rwanda has a climate with an average temperature of around 20 °C and low monthly variation, as the Sebeya catchment has various regions with a high elevation greater than 2000 m. In contrast, the annual average temperature is slightly lower at around 17 °C. Rwanda has a dry climate in the east (lower elevation) and a wet climate in the west (high altitude of mountains), resulting in a large and varied pattern of agro-ecological zones. This variation leads to a

complicated and uncertain picture of potential changes in Rwanda’s overall climate (Guo et al., 2017).

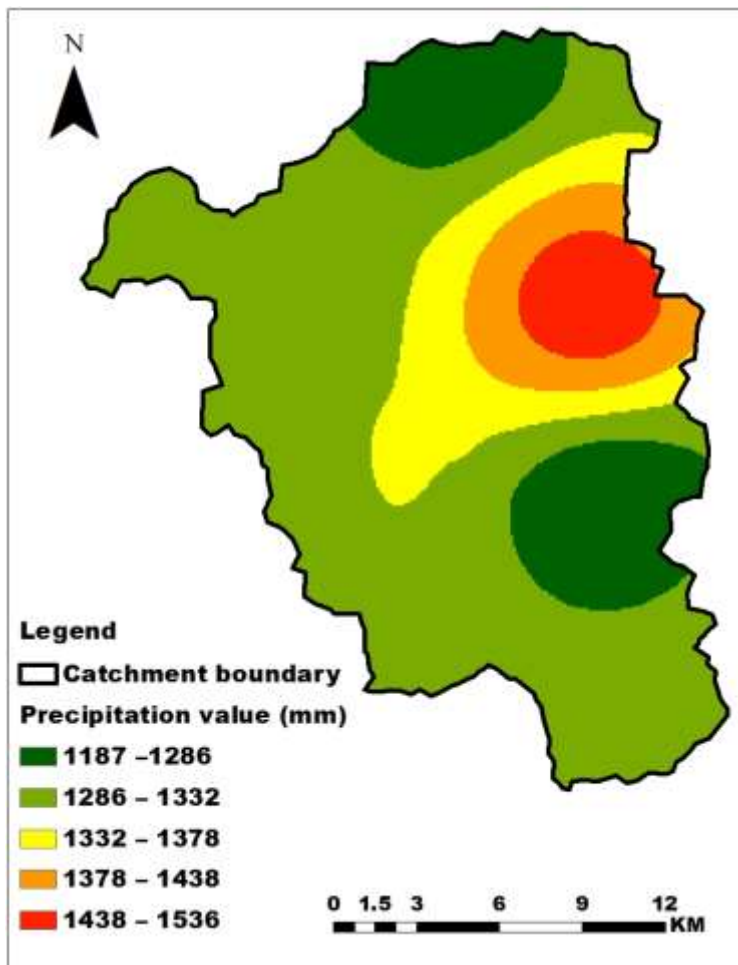


Fig. 4.30 Rainfall map of the Sebeya catchment

Land Use and Land Cover (LULC) are often referred to interchangeably, but they mean different things (Yang et al., 2018). The Sebeya catchment has four major classes (settlement and buildings, cattle grazing, agriculture, and forest plantation) and several land cover types, including natural and planted forests, herbaceous crops and plants, vegetation and shrubs, waterways and reservoirs, and built-up areas. The Sebeya catchment’s soil erosion is retarded by excessive trees and vegetation.

To this end, several factors accelerate water erosion in the Sebeya catchment, including its high elevation (1462–2979 m above sea level), steep topography, and excessive precipitation (1200–1700 mm) (IWRM, 2018; MoE, 2018).

B.2.2.2 Data collection

This study used government reports and journal articles to synthesize various researchers' views on the water erosion process, its causes, effects, and control in the Sebeya catchment.

In this investigation, site visits were carried out to collect detailed information on the study area. Observations of LULC, soil characteristics, the topography of the site, hydrographic network, agricultural practices, and main crops. Furthermore, monitoring the sedimentation, water quality, and flooding issues of the Sebeya river, together with the SEC measures in the Sebeya catchment, were also conducted. In addition, focus group discussion was frequently organized to guess the farmers' knowledge on water erosion and its control.

The University of Rwanda's Center of Geographic Information Systems (UR-CGIS) provided rainfall, soil, and topographic data for generating rainfall erosivity, soil texture, and topographic maps.

In this investigation, researchers used Landsat images (Sultana and Satyanarayana 2018) acquired in September 2008 and August 2018 to assess the LULC's influence on water erosion in the Sebeya catchment.

In order to determine high-risk erosion areas already affected by erosion features (gullies, landslides, rill erosion), the National Institute of Statistics of Rwanda (NSIR) used World View images of 30 to 50 cm resolution. As a result, existing SEC measures were identified, unprotected areas visualized, and future site-based SEC measures to eradicate high soil erosion rates were recommended based on this knowledge and judgment (MoE, 2020). Advantageously, this study took this opportunity to collect different shapefiles for the existing and the site-based recommended SEC measures from Rwanda Water Resources Board (RWB).

This study used government reports and journal articles to synthesize various researchers' views on the water erosion process, its causes, effects, and control in the Sebeya catchment.

In this investigation, site visits were carried out to collect detailed information on the study area, observations of LULC, soil characteristics, the topography of the site, hydrographic network, agricultural practices, and main crops. Furthermore, monitoring of the sedimentation, water quality, and flooding issues of the Sebeya river, together with the SEC measures in the Sebeya catchment, was also conducted. In addition, focus group discussion was frequently organized to guess the farmers' knowledge on water erosion and its control.

The University of Rwanda's Center of Geographic Information Systems provided rainfall, soil, and topographic data for generating rainfall erosivity, soil texture, and topographic maps.

In this investigation, researchers used Landsat images (Sultana and Satyanarayana, 2018) acquired in September 2008, September 2015, August 2018, and September 2022 to assess the LULC's influence on water erosion in the Sebeya catchment.

In order to determine high-risk erosion areas already affected by erosion features (gullies, landslides, rill erosion), the National Institute of Statistics of Rwanda (NISIR) used World View images of 30 to 50 cm resolution. As a result, existing SEC measures were identified, unprotected areas visualized, and future site-based SEC measures to eradicate high soil erosion rates recommended based on this knowledge and judgment (MoE, 2020). In July 2018, NISR (MoE, 2020) developed a Rwandan soil erosion risks map and proposed erosion prevention measures. The Ministry of Environment (MoE) is using the "Catchment Restoration Opportunity Mapping" (CROM) model created by the Environmental Systems Research Institute (ESRI) Rwanda Ltd. to classify soil erosion risks in Rwanda (Table 4.41). Advantageously, the study took this opportunity

to collect different shapefiles for the existing and site-based recommended SEC measures from the Rwanda Water Resources Board (RWB).

Table 4.41 Classification of erosion risks in Rwanda (MoE, 2020).

Soil loss (t/ha/yr)	<5	5–10	10–25	25–50	50–100	>100
Risk severity	very low	low	moderate	high	very high	extremely high

The following five steps explain the adopted procedures for determining the five USLE parameters to estimate soil erosion rates A (t/ha/yr), using the USLE model defined with its five parameters by Eq(2.1) (Parveen and Kumar, 2012).

Step1: Determining R factor for the Sebeya catchment

From the spatial distribution of rainfall Fig. 4.30, the average precipitation in the Sebeya catchment was estimated as $\bar{P} = 1318$ mm while using Eq(4.4), the induced R factor for the Sebeya catchment was averaged as 582.34 MJ x mm/h/y.

Step2: Determining K factor for the Sebeya catchment

Varying from 0 to 1 (Benavidez et al., 2018), Table 4.22 illustrates the erodibility of the soil texture throughout the literature.

Step3: Determining LS factor for the Sebeya catchment

The slope length factor LS can be determined using field erosion plots (Hrabalikova and Janecek, 2017). More practically, if A_s (m/m width) denotes the upstream area, β the inclination angle (radian), and “m” and “n” the coefficients, many researchers(Hrabalikova and Janecek, 2017) suggested using the following equation to estimate the slope length factor:

$$LS = \left(\frac{A_s}{22.13}\right)^m \times \left(\frac{\sin\beta}{0.0896}\right)^n \quad \text{Eq(4.5)}$$

Using Eq(4.5), Fig.4.31 shows that the results vary from 0 to 470.882, with an average value of LS of 5.737 (dimensionless).

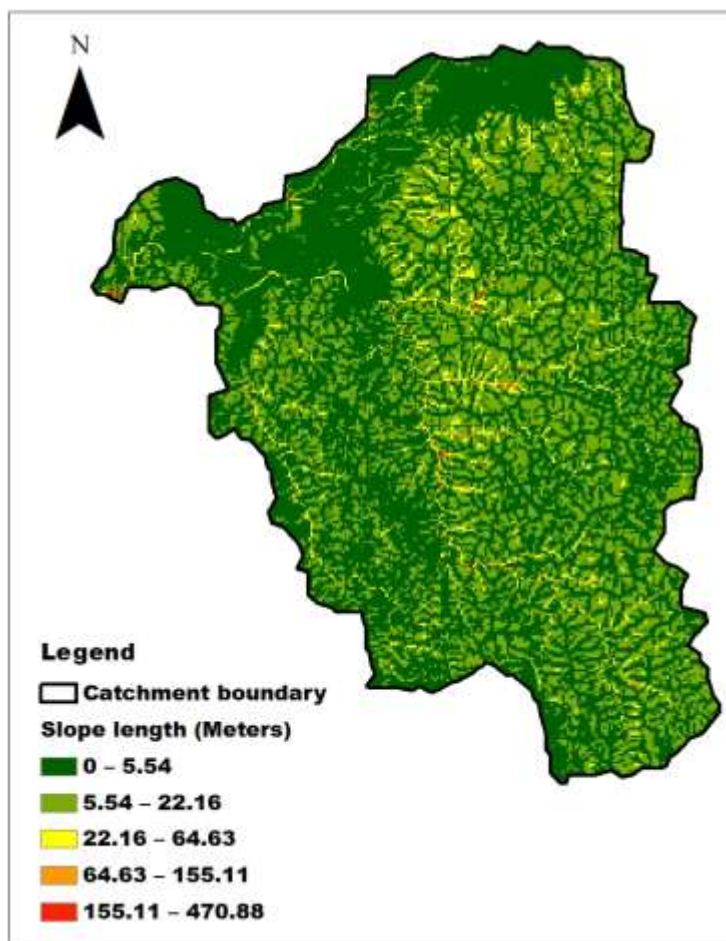


Fig. 4.31 The Sebeya catchment slope length factor map.

Step4: Determining C factor and P factor associated to various LULC types in the Sebeya catchment

Table 4.42 displays typical values of C and P recommended by various researchers for different LULC types.

Table 4.42 Crop management factor (C) and erosion control factor (P) for different land use/land cover types.

S.N.	LULC	C	References	P	References
1	Built-up	0.200	(Devatha et al., 2015)	0.500	(Kumar and Kushwara, 2013)
2	Closed agriculture	0.340	(Devatha et al., 2015)	0.001	(Lu et al., 2010)
3	Forest plantation	0.020	(Kumar and Kushwara, 2013)	0.300	(Kumar and Kushwara, 2013)
4	Irrigation	0.340	(Devatha et al., 2015)	0.500	(Kumar and Kushwara, 2013)

5	Natural forest	0.008	(Kumar and Kushwara, 2013)	0.001	(Lu et al., 2010)
6	Open agriculture	0.340	(Devatha et al., 2015)	0.020	(Tegegne and Biniam, 2016)
7	Open land	0.340	(Devatha et al., 2015)	0.500	(Kumar and Kushwara, 2013)

Step 5: Determining C factor and P factor for various SEC measures in the Sebeya catchment

C factor measures the implication of crop cover and BMPs in controlling soil erosion (Panagos et al., 2015). In this simulation, Table 4 exhibits different values of C proposed by various researchers throughout the literature.

The erosion control factor (P) measures the implication of SECM, BMPs, and cropping patterns in decreasing soil erosion (Panagopoulos et al., 2015; Oruk et al., 2012). It varies from 0 to 1 in the cases of water bodies and efficient soil conservation practices on farmlands (Adormado et al., 2019). Throughout the literature, Table 4.43 reveals typical values of P factors for different SEC measures to alleviate the excessive erosion rates in the Sebeya catchment.

Table 4.43 Crop management factor (C) and erosion control factor (P) for different soil erosion control measures.

SN	Recommended SECM	C	References	P	References
1	Afforestation	0.02	(Kumar and Kushwara, 2013)	0.001	(Bagarella et al., 2015)
2	Agroforestry	0.08	(Panagos et al., 2015)	0.500	(Sanchez-Bernal et al., 2013)
3	Bamboo to close gullies	0.01	(Endalamaw et al., 2021)	0.500	(Tardio et al., 2018)
4	Bench terraces	0.15	(Endalamaw et al., 2021)	0.128	(Kuok et al., 2013)
5	Contour bank terraces	0.15	(Endalamaw et al., 2021)	0.150	(Kuok et al., 2013)
6	Contour banks	0.50	(Shannon, 2017)	0.600	(Kuok et al., 2013)
7	Grassed waterways	0.20	(Endalamaw et al., 2021)	0.100	(Fiener and Auerswald, 2009)
8	Hedgerows	0.20	(Endalamaw et al., 2021)	0.000	(*)
9	No-till	0.25	(Panagos et al., 2015)	0.100	(Fiener and Auerswald, 2009)
10	Perennial crops	0.23	(Panagos et al., 2015)	0.800	(Duguma, 2022)
11	Reforestation	0.02	(Kumar and Kushwara, 2013)	0.001	(Bagarella et al., 2015)
12	River side bamboo	0.01	(Endalamaw et al., 2021)	0.500	(Tardio et al., 2018)

13	Silvopastoralism	0.09	(Panagos et al., 2015)	0.000	(*)
14	Rainwater harvesting tanks	0.00	(*)	0.800	(Chen et al., 2019)
15	Drainage channels	0.58	(Gao et al., 2022)	0.800	(Chen et al., 2019)
16	Dense forest and water bodies	0.00	(*)	0.000	(*)

* Similar to dense forest or water body.

Finally, this study intended to predict the efficiency of the site-based recommended SEC measures in increasing crop yields. Similar to the existing literature (Obalum et al., 2012), the largest soil loss can be fixed at $x_2 = 137$ t/ha/yr, while the maximum soil loss tolerance, $x_1 = 11.5$ t/ha/yr, can be considered as the lowest observable soil loss rate. Based on the minimum crop yield from all Rwandan districts and the maximum crop yield from the four districts overlapping the Sebeya catchment (NISR, 2009), Table 4.44 displays the ranges of crop yields assumed at the minimum and maximum soil losses ($x_1 = 11.5$ and $x_2 = 130$ t/ha/yr) in the Sebeya catchment.

Table 4.44 Possible ranges of crop yields in the Sebeya catchment (NISR, 2009).

Crops	$y_2 =$ Lowest Yield (t/ha)	$y_1 =$ Highest Yield (t/ha)
Maize	0.776	2.154
Irish potatoes	4.000	15.000
Beans	0.700	1.000
Soybeans	0.575	0.875
Wheat	0.437	2.154
Peas	0.367	1.438
Groundnut	0.260	1.495
Sweet Potatoes	3.856	13.246
Banana	3.500	11.038

B.2.2.3 Data Analysis

Various soil erosion indicators, causes, and effects were identified and assessed based on the existing literature, site observations, and focus groups.

This research used Landsat images acquired in 2008, 2015, 2018, and 2022 to compare and find out how two or more different scenarios of LULC affect water erosion in the Sebeya catchment. Studies of soil erosion dynamics using sequential aerial photographs and remote sensing techniques, in combination with LULC analyses, have revealed a positive change of 54% from 1990 to 2015, indicating a significant increase in soil erosion on the Rwandan landscape (NISR, 2019).

The actual water erosion rates were estimated using different shapefiles obtained from the Rwanda Water Resources Board on the nature and efficiency of existing SEC measures in the Sebeya catchment.

Predicting water erosion rates using the USLE model has allowed assessment of the impact of LULC on soil erosion and deducing the efficiency of the site-based recommended SEC measures in the Sebeya catchment. Correlatively, crop yields were predicted using a linear relationship between soil losses and crop yields. USLE parameters were adopted referring to the previously-published studies and USLE parameters mapping. Analyzing data in figures and tables was done using ArcGIS map and Microsoft Excel.

B.2.3 Results

B.2.3.1 Hydrological Processes in the Sebeya catchment

The main hydrologic parameters affecting water erosion within a catchment are precipitation, interception, infiltration, runoff, soil moisture changes, groundwater storage changes, and river flows. When rain falls, it causes soil detachment and transport by raindrop splashes or runoff. The complexity of erosive processes depends on many factors, such as soil type, slope, terrain size, LULC, and solar radiation within the catchment (Kinnel, 2010). Fig.4.30 exhibits the spatial distribution of rainfall, while Fig. 4.32 illustrates the rainfall patterns within the Sebeya catchment at Gisenyi airport station. The yearly precipitations in the Sebeya catchment are known to induce high water erosion rates (IWRM, 2016).

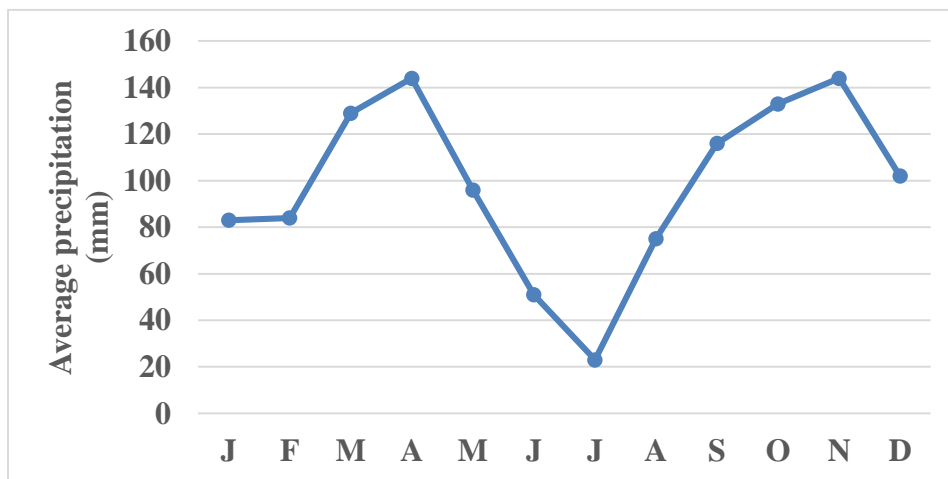
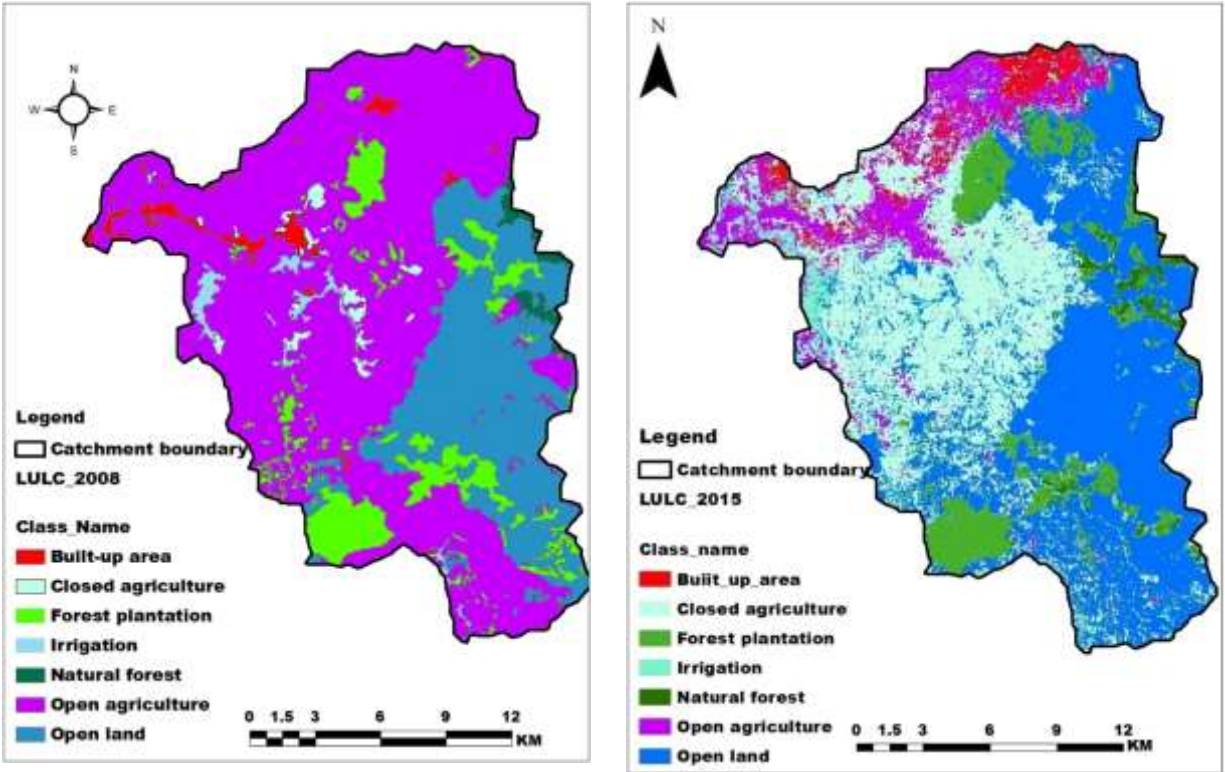


Fig. 4.32 Typical monthly precipitations at Gisenyi airport station (IWRM, 2016).

B.2.3.2 Impact of LULC on Water Erosion in the Sebeya catchment

Due to its multiple effects on soil, land cover contributes to soil erosion control by decreasing the direct impact of raindrops, increasing organic matter, raising infiltration rates, and decreasing the runoff velocity, while controlling the sediment transport and yield.

In most developing countries like Rwanda, demographic pressure and associated demand for human activities have been the major cause of LULC changes (Dibaba et al., 2020; Sisay et al., 2021; Belaya and Mangistua, 2019). Therefore, it is particularly important to pinpoint the aspects causing LULC changes in the Sebeya catchment. Fig.4.33 shows LULC detection in the Sebeya catchment for four years (2008, 2015, 2018, and 2022), while Tables 4.45 and 4.46 reveal the percentage of area covered by each LULC type.



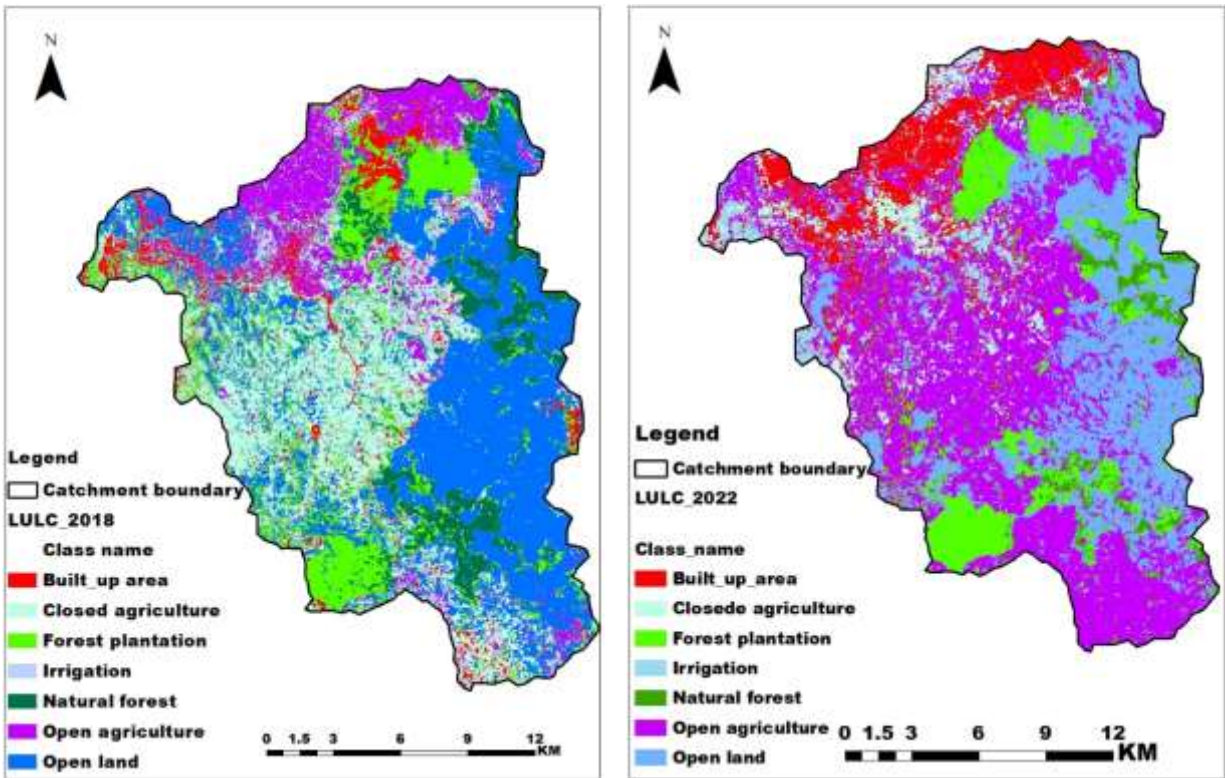


Fig.4.33 Land use/land cover detection for 2008, 2015, 2018 and 2022 in the Sebeya catchment.

Table 4.45 Area covered by each land use/land cover type in the Sebeya catchment (2008 and 2015).

SN	LULC Type	Covered Area in 2008		Covered Area in 2015	
		(km ²)	(%)	(km ²)	(%)
1	Built-up	6.96	1.92	10.97	3.02
2	Closed agriculture	4.97	1.37	107.31	29.51
3	Forest plantation	34.91	9.61	33.75	9.28
4	Irrigation	5.52	1.52	16.30	4.48
5	Natural forest	4.16	1.14	6.01	1.65
6	Open agriculture	224.40	61.75	37.71	10.37
7	Open land	82.45	22.69	151.63	41.69
Total		363.38	100.00	363.38	100.00

Table 4.46 Area covered by each land use/land cover type in the Sebeya catchment (2018 and 2022).

SN	LULC Type	Covered Area in 2018		Covered Area in 2022	
		(km ²)	(%)	(km ²)	(%)
1	Built-up	11.38	3.13	39.64	10.90
2	Closed agriculture	0.05	0.01	22.51	6.19
3	Forest plantation	55.57	15.28	35.54	9.77
4	Irrigation	7.96	2.19	16.62	4.57
5	Natural forest	13.58	3.74	11.67	3.21
6	Open agriculture	185.63	51.04	147.38	40.52
7	Open land	89.50	24.61	90.32	24.84
Total		363.38	100.00	363.38	100.00

These results on LULC detection in the Sebeya catchment revealed that LULC change in the study area primarily comprised a decrease in open agriculture area, accompanied by an increase in closed agriculture, built-up area, and open land (Table 4.45). Table 4.45 and Table 4.46 show that the land in the Sebeya catchment is mostly used for agriculture with seasonal crops in an area of about 53.4% (2008: 64.6%; 2015: 44.4%; 2018: 53.2%; 2022: 51.3%). This status of LULC exposes the land to splash erosion, and further detachment as the land is not permanently covered. Forests with high canopy density occupy an area of only about 2.4% (2008: 1.1%; 2015: 1.7%; 2018: 3.7%; 2022: 3.2%), and comparatively, built-up areas occupy about 4.7% (2008: 1.9%; 2015: 3.0%; 2018: 3.1%; 2022: 10.9%) of the total area of the Sebeya catchment (363.4 km²). Therefore, the Sebeya catchment's land will continue to be eroded if no serious measures are taken in agricultural lands. In addition, built-up areas accelerate water velocity, runoff, and flow accumulation, creating severe gullies downstream. In such areas, stormwater management facilities, such as rainwater harvesting infrastructures and drainage channels, should be established to collect stormwater from houses in agglomerated zones.

Table 8 illustrates the adopted procedures for assessing soil erosion rates A (t/ha/yr) induced by LULC, using the USLE model defined with its five parameters by Eq(2.1).

Table 4.47 Effect of land use/land cover on water erosion within the Sebeya catchment in 2008, 2015, 2018 and 2022.

(a) Erosion rates induced by the land use/land cover in 2008

S.N.	LULC type	K	R	LS	C	P	Soil loss Ai (t/ha/yr)	Covered area ai (ha)	Weighted (Ai x ai)
------	-----------	---	---	----	---	---	---------------------------	-------------------------	-----------------------

1	Built-up	0.405	582.34	5.73	0.200	0.500	135.141	696	94,057.95
2	Closed agriculture	0.405	582.34	5.73	0.340	0.001	0.459	497	228.36
3	Forest plantation	0.405	582.34	5.73	0.020	0.300	8.108	3491	28,306.58
4	Irrigation	0.405	582.34	5.73	0.340	0.500	229.739	552	126,816.10
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.011	416	4.50
6	Open agriculture	0.405	582.34	5.73	0.340	0.020	9.190	22,440	206,213.90
7	Open land	0.405	582.34	5.73	0.340	0.500	229.739	8245	1,894,200.0
Total								36,337	2,349,827

Average soil loss is $2,349,827/36,337 = 65$ t/ha/yr

(b) Erosion rates induced by the land use/land cover in 2015

S.N.	LULC type	K	R	LS	C	P	Soil loss Ai(t/ha/yr)	Covered area ai (ha)	Weighted area(Ai x ai)
1	Built-up	0.405	582.34	5.73	0.2	0.5	135.1407	1097	148,203.90
2	Closed agriculture	0.405	582.34	5.73	0.34	0.001	0.459478	10,731	4930.81
3	Forest plantation	0.405	582.34	5.73	0.02	0.3	8.108444	3375	27,365.38
4	Irrigation	0.405	582.34	5.73	0.34	0.5	229.7392	1630	374,369.20
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.010811	601	6.49
6	Open agriculture	0.405	582.34	5.73	0.34	0.02	9.18957	3771	34,658.22
7	Open land	0.405	582.34	5.73	0.34	0.5	229.7392	15,163	3,483,612.00
Total								36,368	4,073,146

Average soil loss is $4,073,146/36,368 = 112$ t/ha/yr

(c) Erosion rates induced by the land use/land cover in 2018

S.N.	LULC type	K	R	LS	C	P	Soil loss Ai (t/ha/yr)	Covered area ai (ha)	Weighted area(Ai x ai)
1	Built-up	0.405	582.34	5.73	0.200	0.500	135.141	1991	269,084.10
2	Closed agriculture	0.405	582.34	5.73	0.340	0.001	0.459	8003	3673.51
3	Forest plantation	0.405	582.34	5.73	0.020	0.300	8.108	5203	42,187.51

4	Irrigation	0.405	582.34	5.73	0.340	0.500	229.739	1474	338,545.40
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.011	2710	29.81
6	Open agriculture	0.405	582.34	5.73	0.340	0.020	9.190	4167	38,294.22
7	Open land	0.405	582.34	5.73	0.340	0.500	229.739	12,818	2,944,847.0
Total								36,366	3,636,661

Average soil loss is $3,636,661/36,366 = 100$ t/ha/yr

(d) Erosion rates induced by the land use/land cover in 2022

S.N.	LULC type	K	R	LS	C	P	Soil loss Ai (t/ha/yr)	Covered area ai (ha)	Weighted (Ai x ai)
1	Built-up	0.405	582.34	5.73	0.2	0.5	135.1407	3964	535,700.30
2	Closed agriculture	0.405	582.34	5.73	0.34	0.001	0.459478	2251	1034.41
3	Forest plantation	0.405	582.34	5.73	0.02	0.3	8.108444	3554	28,817.55
4	Irrigation	0.405	582.34	5.73	0.34	0.5	229.7392	1662	381,821.00
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.010811	1167	12.61
6	Open agriculture	0.405	582.34	5.73	0.34	0.02	9.18957	14,738	135,435.50
7	Open land	0.405	582.34	5.73	0.34	0.5	229.7392	9032	2,075,074.0
Total								36,368	3,157,895

Average soil loss is $3,157,895/36,368 = 87$ t/ha/yr

The results on LULC detection in the Sebeya catchment (Table 4.47 and Fig. 4.34) revealed that soil erosion increased from 65 t/ha/yr (2008) to 112 t/ha/yr (2015) due to deforestation for firewood and shelter, urbanization, intense rainfall (climate change) in mountainous areas, over-cultivation, and the lack of SECM. Comparatively, the decreased soil erosion rates from 112 t/ha/yr (2015) to 100 t/ha/yr (2018) and from 100 t/ha/yr (2018) to 87 t/ha/yr (2022) are attributed to the particular attention paid to implementing SEC measures in different Rwandan catchments and particularly in the Sebeya catchment, including afforestation, land consolidation, anti-erosive ditches and terraces programs (NISR, 2019).

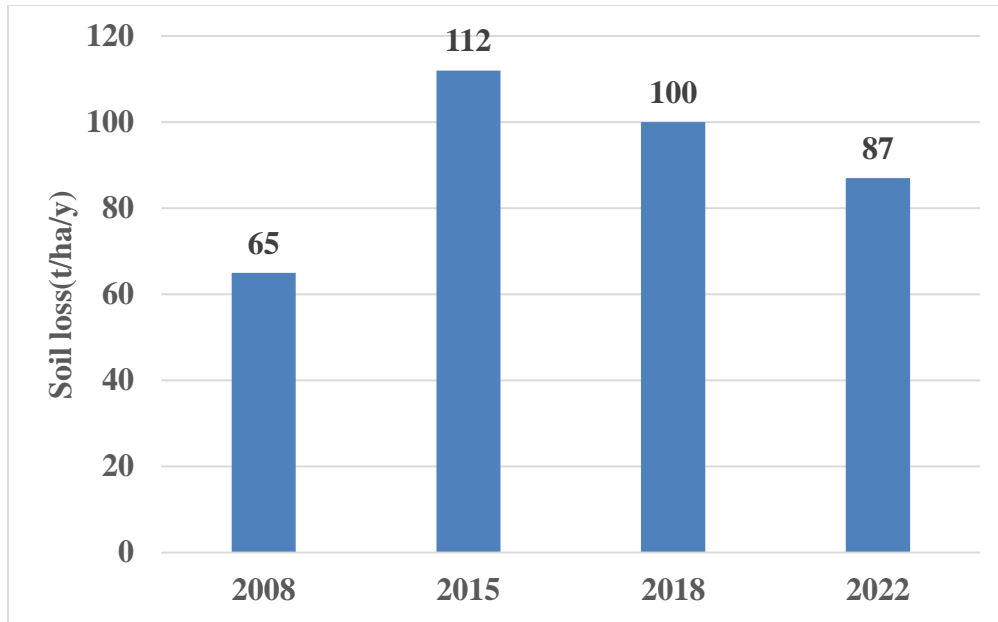


Fig.4.34 Historical variation of soil erosion rates induced by the land use/land cover in the Sebeya catchment.

B.2.3.3 Estimating the Actual Soil Erosion Rates in the Sebeya catchment

Using different shapefiles obtained from the Rwanda Water Resources Board, Fig. 4.35 shows various existing SEC measures and the spreading of erosion rates in the Sebeya catchment. Finally, Table 9 indicates that about 73 t/ha/yr of soil is lost from the Sebeya catchment annually.

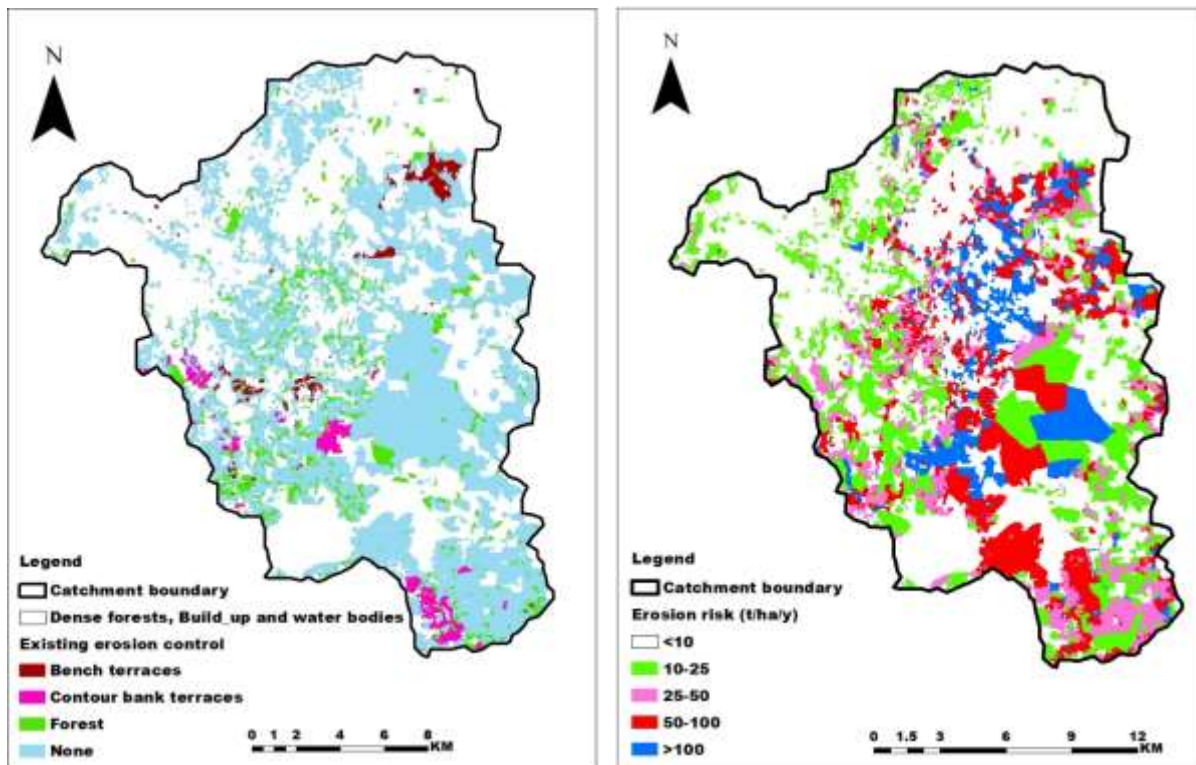


Fig. 4.35 Existing soil erosion control measures and soil loss ranges in the Sebeya catchment (RWB, 2018).

Table 4.48 Existing soil erosion control measures and their induced soil loss rates in the Sebeya catchment (RWB, 2018).

(a) Existing SECM			(b) Calculation of the actual soil loss				
Existing SECM	Area covered (ha)	%	Erosion risk (t/ha/yr)	Peak value (t/ha/yr)	Ai Coverage ai (ha)	% of area covered	Weighted value (Ai x ai)
None	15,319	42	<10	10	18,009	50	180,087
Forest	1959	5	25-Oct	25	6936	18	173,408
Contour terraces	bank 606	2	25–50	50	3484	10	174,195
Bench terraces	442	1	50–100	100	4917	14	491,707
Dense forest and water bodies	and 18,009	50	>100	600	2989	8	1,791,702
Total	36,335	100	Total		36,335	100	2,654,323

The actual soil loss from the Sebeya catchment is $2,654,323/36,335 = 73$ t/ha/yr

In this study, the purpose of estimating soil loss based on LULC was to quantify the implications of LULC on water erosion within the Sebeya catchment (Table 4.47). However, in practice, soil loss estimation includes the action of the existing SEC measures within the catchment (Table 4.48). In 2018, for example, the soil loss induced by LULC (100 t/ha/yr) was excessively greater than 73 t/ha/yr, which is the estimated soil loss by taking account of the existing SEC measures in the Sebeya catchment. Therefore, SEC measures are essential to alleviate high soil erosion rates.

B.2.3.4 Soil Nutrients Depletion Due to Water Erosion in the Sebeya catchment

The availability of nutrients in soils for the growth of plants defines their fertility. In many cases, farmers must increase soil nutrient levels by applying chemical fertilizers, animal manures, and compost to ensure crop growth (Van Beek et al., 2016). Practically, nutrient testing provides results with an interpretive guide defined as high, medium, or low (Table 4.49).

Table 4.49 Quantifying various nutrients available in a soil (Niaz et al., 2022; Suchithra and Pai, 2020).

Nutrients Level	Nitrogen (N) (ppm)	Phosphorus (P) (ppm)	Potassium (K) (ppm)	Organic Carbon (C) (%)	Calcium (Ca) (%)
Low	<430	<7	<80	<0.40	<0.50
Medium	430–600	7–15	80–180	0.40–0.60	0.50–0.75
High	>600	>15	>180	>0.60	>0.75

Although soil erosion threatens agriculture sustainability (Baptista et al., 2013), few researchers have studied the spatial-temporal availability of soil nutrients within the Sebeya catchment (Table 4.50).

Table 4.50. Availability of soil nutrients within the Sebeya catchment (ppm).

S.N.	Soil Nutrient	Sampled Value at Nyamyumba Sector in 2017 (Kabirigi et al., 2017)	Tested Samples from Mulinga Sector in 2021 (MINAGRI, 2021)
1	P	7.000	<7 ppm
2	K	0.003	<180 ppm
3	C	75,560	<0.60 ppm
4	Ca	-	<0.75%
5	pH *	-	<7 (acidic)

* The soil pH was also assessed.

B.2.3.5 Sediments and Nutrients Dynamics in the Sebeya catchment

Most Rwandan catchments are affected by erosion, river runoff, and land slope, and river sediment transport varies proportionally to these factors (Karamage et al., 2016). Throughout the literature, soil erosion is washing away 945,200 tons of organic materials, nitrogen, phosphorus, and potash each year (Mupenzi et al., 2012). Challengingly, the amount of nutrients per unit weight of eroded soil is about three times higher than the nutrients in the remaining soil (Narendar et al., 2017), agriculture being the main contributor to nutrients found in the Sebeya river (Bagalwa., 2015). In addition, the eroded sediments in the Sebeya river cause scouring on bridges, add pollutants to the river, and cause abrasion on hydropower turbines (Munyaneza et al., 2015). Therefore, it is essential to prevent excessive sedimentation and nutrient loading in the Sebeya river.

B.2.3.6 Site-Based Recommended Soil Erosion Control Measures and Associated Soil Loss Rates in the Sebeya catchment

Without proper Best Management Practices (BMPs), soil erosion will continue to increase over the years (NISR, 2019). Consequently, soil erosion control will always need improvement, and achieving the T-value (the maximum soil loss tolerance rate) will appear as a perfectionism concept within the catchment. For example, a farmer's interview in Nigeria revealed that farmers required improvement of all SEC measures in the Kogi region (Onu and Mohammed, 2014).

Using different shapefiles obtained from the Rwanda Water Resources Board, Fig. 4.36 relates the simulated site-based recommended SEC measures intended to alleviate the excessive erosion rates in the Sebeya catchment. The following subsections explain the adopted procedures for predicting soil erosion rates A (t/ha/yr) using the USLE model defined with its five parameters in Equation (1).

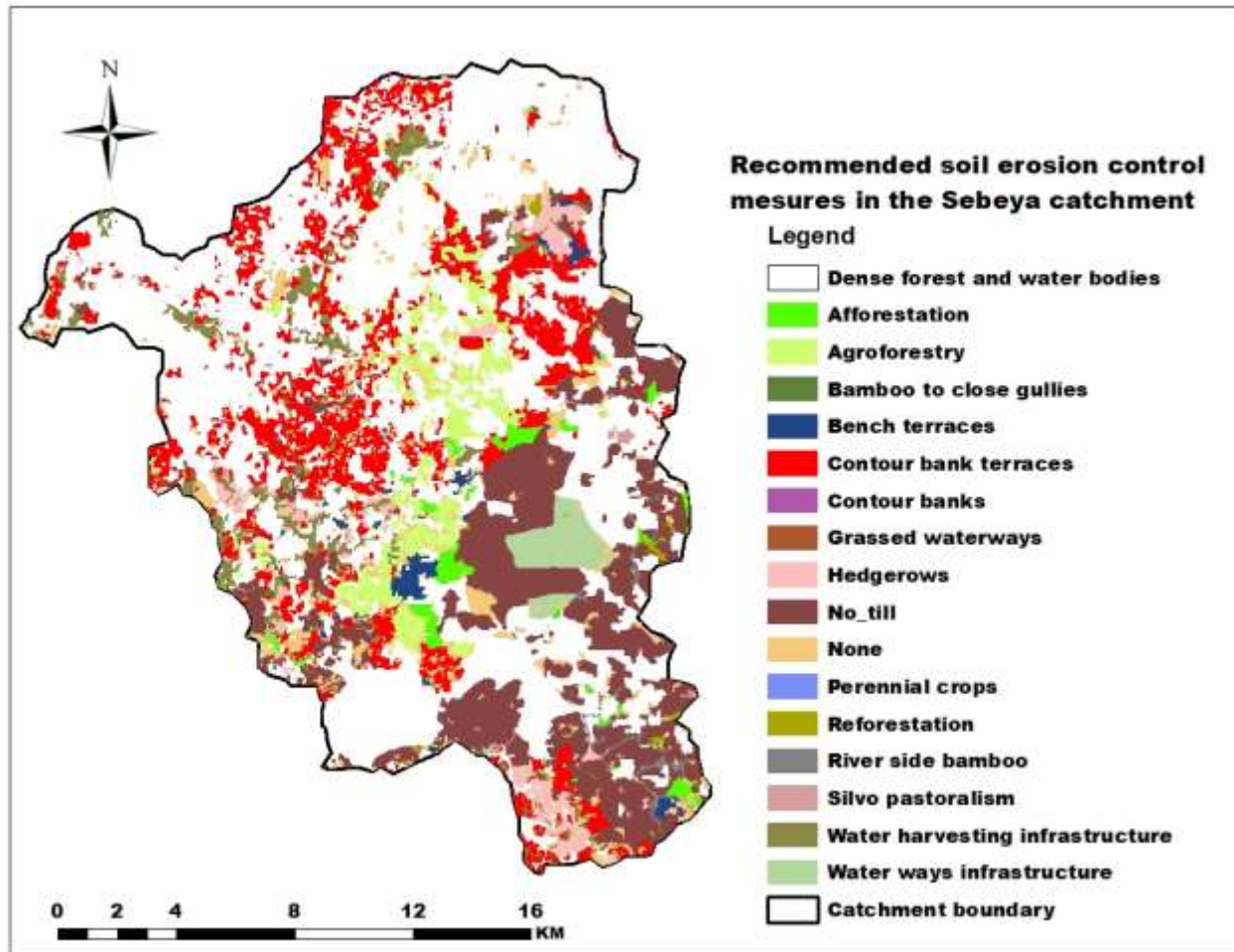


Fig. 4.36 Recommended soil erosion control measures in the Sebeya catchment (RWB, 2018).

Fig. 4.36 shows various site-based SEC measures recommended to alleviate the excessive erosion rates of 73 t/ha/yr revealed by Table 4.48, while Table 4.51 reveals the extent of the areas for each site-based soil erosion control measure.

Tables 4.43 and 4.47 have estimated the values of all five USLE parameters, as displayed in Table 4.51. In addition, Table 4.51 illustrates the estimation of erosion rates associated with the suggested SECM in the Sebeya catchment.

Comparatively, the proposed SEC measures reduced soil loss significantly from 73 t/ha/yr (Table 9) to 29 t/ha/yr (Table 4.51), raising the efficiency of SEC measures to 61%. For effective action to eradicate the excessive erosion rates within the Sebeya catchment, the present study emphasizes the implementation of the site-based recommended SEC measures with mulching and drainage channels on the same farmland.

Table 4.51 Erosion rates induced by the site-based recommended soil erosion control measures in the Sebeya catchment.

S.N.	Recommended SECM	K	R	LS	C	P	Soil Loss Ai (t/ha/yr)	Area ai (km ²)	Weighted (Ai x ai)
1	Afforestation	0.405	582.34	5.73	0.02	0.001	0.027	4.792	0.130
2	Agroforestry	0.405	582.34	5.73	0.08	0.500	54.056	17.500	945.966
3	Bamboo at gullies	0.405	582.34	5.73	0.01	0.500	6.757	0.284	1.919
4	Bench terraces	0.405	582.34	5.73	0.15	0.128	25.947	3.208	83.241
5	Progressive terraces	0.405	582.34	5.73	0.15	0.150	30.407	49.428	1502.934
6	Contour bunds	0.405	582.34	5.73	0.50	0.600	402.179	0.065	26.030
7	Grassed waterways	0.405	582.34	5.73	0.20	0.100	27.028	0.072	1.938
8	Hedgerows	0.405	582.34	5.73	0.20	0.000	0.000	8.714	0.000
9	No-till	0.405	582.34	5.73	0.25	0.100	33.785	58.323	1970.455
10	Existing SECM*	0.405	582.34	5.73	0.22	0.341	99.539	20.419	2032.489
11	Perennial crops	0.405	582.34	5.73	0.23	0.800	251.146	0.002	0.475
12	Reforestation	0.405	582.34	5.73	0.02	0.001	0.027	1.024	0.028
13	River side bamboo	0.405	582.34	5.73	0.01	0.500	6.757	1.767	11.943
14	Silvopastoralism	0.405	582.34	5.73	0.09	0.000	0.000	0.357	0.000
15	Rainwater tanks	0.405	582.34	5.73	0.00	0.800	0.000	12.653	0.000
16	Drainage channels	0.405	582.34	5.73	0.58	0.800	627.053	6.052	3794.661
17	Dense forest and water bodies	0.405	582.34	5.73	0.00	0.000	0.000	178.694	0.000
Total								363.352	10,372.209

Predicted soil loss from the Sebeya catchment = $10,372.209/363.352 = 29$ t/ha/yr

* (C = 0.216 and P = 0.341) are averages based on the existing SEC measures in Table 4.48.

B.2.3.7 Implications of Soil Erosion Control Measures on Crop Productivity in the Sebeya catchment

About 80% of the Rwandan population depends on agriculture (NISR, 2015). Due to Rwanda's high population density, soil erosion threatens the nation's food security and agricultural

sustainability (Bidogeza et al., 2007). Therefore, adopting SEC measures is required to mitigate these effects and improve soil productivity.

The simulated efficiency of the site-based recommended SEC measures in reducing the high soil loss rates from 73 t/ha/yr to 29 t/ha/yr should be accompanied by an increase in crop yields ranging between the smallest (y_2) and the largest (y_1) values of the observed yields displayed in Table 4.44. In practice, the implication of the site-based recommended SEC measures in improving agricultural productivity should be highlighted by field investigations in soil erosion plots and the prediction of crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya catchment (Bidogeza et al., 2007).

B.2.4 Discussion

B.2.4.1 Erosion Process and Its Damages in the Sebeya catchment

Raindrops striking the soil surface dislodge fine soil particles. The resulting overland flows erode soil particles of varying sizes, which slide along the land's surface and get transported to streams, channels, rivers, water reservoirs, and lakes. There are three distinct processes of water erosion: loosening and dislodging (displacement), transportation, and deposition of soil particles. Organic matter, silt, and finer sand particles will be washed away by runoff, but heavier rainfalls will also displace larger material components. Lands with high slopes will facilitate the process of water erosion (Chen et al., 2011). With considerable damage, water erosion reduces soil fertility and water storage capacity. In addition, it increases sediment concentration in the runoff with possible depositions to increase the risk of flood disasters (Xungui and Xia, 2014).

Many visible signs reflect the persistence of erosion in the Sebeya catchment, including accumulated transported sediment in depressions and above obstacles, rills or gullies on roadsides or upper slopes, exposure of roots, changes in soil color and texture, and excessive sediment loading rates in rivers and reservoirs. In addition, if the soil is tested regularly, a reduction in organic soil matter levels may indicate soil loss by erosion (Nenadovic et al., 2013).

For proper land use management, researchers recommend launching various studies to identify mechanisms and driving forces of soil erosion, including precipitation, vegetation, land use type, and physical soil properties (Leta and Megersa, 2021; IWRM, 2017). For instance, many factors accelerating soil erosion in the Sebeya catchment include excessive rainfall, soil cultivation without fallow, bare ground, insufficient SECM, artisanal mining, overgrazing, and deforestation (Guo et al., 2017). Furthermore, in areas with expanding populations, diversified human activities for construction, agricultural production, and urbanization are the major contributors to soil erosion (Ding et al., 2015).

Various visual signs and information from social media (television, different websites, and newspapers) on causes, influential factors, and on-site and off-site effects of erosion within the Sebeya catchment inspired these investigations.

Due to declining soil fertility, erosion threatens agriculture sustainability (IWRM, 2018; Devatha et al., 2015; Balasubramanian, 2017). For deep analysis, farmers may lose income due to lower yields or purchase more fertilizers to compensate for fertility loss. As a result, the eroded sediments will be highly concentrated in fertilizers and pesticides, polluting downstream rivers and reservoirs. Therefore, erosion control is essential for boosting crop production and protecting rivers and lakes from sediment loading (Huffman et al., 2011).

In addition to depleting soil nutrients, water erosion causes land degradation, floods, silt buildup, and excessive pollution. The prevention and control of erosion are global issues targeted at ensuring food security and environmental sustainability (Dahal et al., 2016; Sakinatu and Muhammad, 2017; Debebe et al., 2013).

B.2.4.2 Implications of LULC Changes on Water Erosion within the Sebeya catchment

Land cover describes how the land surface is physically, chemically, or biologically classified. For example, grasslands, forests, roads, buildings, and water bodies belong to it. Typically, land use can refer to the use of that land – for instance, cattle ranches, recreation, housing (commercial, residential, industrial), and other human activities.

This study revealed seven different LULC types in the Sebeya catchment (Table 4.47): built-up area, closed agriculture, forest plantation, irrigation, natural forest, open agriculture, and open land. Despite the possibility of developing green agriculture and mining, there are some cases where unsustainable agricultural and mining activities are causing terrible sedimentation in the Sebeya river during rainy seasons (IWRM, 2018). To properly manage these landscapes, we must monitor their dynamic changes while minimizing the impacts caused by anthropogenic activities and natural phenomena (Zisu and Nassui, 2015; Twisa and Buchroithner, 2019; Rawat and Kumar, 2015; Hegaz and kaloop, 2015; Tewkesbury et al., 2015).

B.2.4.3 Future Work

In addition to reducing soil fertility, erosion compacts the soil and decreases aeration and permeability. Briefly, water erosion alters the soil physically, chemically, and biologically (Bossio et al., 2010).

In the Sebeya catchment, water erosion results in agricultural soil and nutrient losses, landslides removing crops, exposed roots, eroded materials covering crops or getting deposited in roads, and silting up of waterways. Ultimately, there is an increase in sediment concentration at Keya, Gihira, and Gisenyi hydropower plants and excessive turbidity at Gihira water treatment plant. It is also common for floods and landslides to occur during the rainy season, causing damage to buildings and sometimes killing livestock and people (MIDMAR, 2012).

Water erosion is a stressful environmental issue for which the proverb “Prevention is better than cure” may help to sensitize farmers and stakeholders in the Sebeya catchment to adopt and implement SEC measures in their farmlands. This study assessed the efficiency of the site-based recommended SEC measures to alleviate the excessive soil loss rates (Table 4.51). Money and knowledge are the main limitations in implementing SEC measures in the Sebeya catchment (Debebe et al., 2013).

For the ultimate objective of eradicating the high erosion rates in the Sebeya catchment, Majoro and Wali (2022) assessed various factors affecting farmers’ willingness to adopt SEC measures in the Sebeya catchment. However, there is a need to promote further studies intended to increase farmers’ willingness to participate in the planning process, implementation, and maintenance of SEC measures in the Sebeya catchment. Practically, lowering the high soil loss rates below the maximum soil loss tolerance rate of 11.5 t/ha/yr throughout the entire catchment should be the main target in implementing SEC measures (Sakinatu and Muhammad, 2017).

To this end, farmers are the most perceptive and can identify rill erosion at its early stage; therefore, researchers should focus on BMPs easily applied by indigenous knowledge to prevent soil erosion. Government grants, donor agencies, and non-governmental organizations (NGOs) should empower the affected people (landowners and farmers) to adopt and implement SEC measures. All farmers should be trained and sensitized through awareness and education programs to ensure their farmlands are protected from soil erosion for sustainable agricultural operations.

B.2.5 Conclusion and recommendations

This study aimed to assess various factors and processes affecting soil erosion to recommend suitable site-based SEC measures for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya catchment.

In this research, the actual soil loss was estimated to be very high at 73 t/ha/yr, due to various influential factors such as abrupt slopes and the natural soil's susceptibility to erosion, coupled with continuous cultivation and climatic conditions.

Using simulations and predictions with the USLE model, the proposed SEC measures reduced soil loss significantly from 73 to 29 tons per hectare annually, raising their efficiency to 61%. To highlight the implications of the site-based recommended SEC measures in improving agricultural productivity, this study suggests field investigations in soil erosion plots to predict crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya catchment.

For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya catchment, the present research suggests implementing the site-based recommended SEC measures with mulching and drainage channels on the same farmland. However, money and knowledge are the main limitations to implementing SEC measures in most of the Sebeya catchment farmlands. Therefore, the government should help farmers in the Sebeya catchment by providing technical and financial assistance for implementing SEC measures in their farmlands.

Funding: This research received no external funding.

Author Contributions: All authors contributed to the conception and development of the manuscript as follows: Felicien Majoro was the designer of the manuscript. He carried out data analysis and interpretation, and wrote the manuscript. Umaru Garba Wali supervised all the writing activities of the manuscript. He provided a deep analysis and edited the manuscript. Omar Munyaneza proposed and guided in implementing the writing methodology of this manuscript. Francois-Xavier Naramabuye contributed in typing and editing of our manuscript.

Acknowledgments: The authors recognize and appreciate the support from the cooperation between the University of Rwanda and the government of Sweden and the diversified authorship of journal articles and reports made available for this study.

Conflicts of Interest: The authors declare no conflict of interest.

PART C. GENERAL DISCUSSION

4.C.1 Variability of soil erosion in the Sebeya catchment

The results on LULC detection in the Sebeya catchment revealed that LULC change is accompanied with an unavoidable variability of soil erosion in the Sebeya catchment (Table 4.47). The impact of LULC on soil erosion can be positive or negative over years. In this research, the results on LULC detection in the Sebeya catchment (Table 4.47 and Fig. 4.34) revealed that soil erosion increased from 65 t/ha/yr (2008) to 112 t/ha/yr (2015) and decreased from 112 t/ha/yr (2015) to 100 t/ha/yr (2018) and from 100 t/ha/yr (2018) to 87 t/ha/yr (2022). Comparatively, studies of soil erosion dynamics using sequential aerial photographs and remote sensing techniques, in combination with LULC analyses, have revealed a variability of soil loss with a positive change and negative change of soil erosion on the Rwandan landscape (NISR, 2019). Without proper Best Management Practices (BMPs), soil erosion may increase year after year.

Soil erosion is one of the most pressing environmental problems worldwide to which the adage “Prevention is better than cure” is most applicable. Erosion control is any action to prevent soil erosion from detaching soil surface particles while elucidating the necessity of implementing SEC measures (Bagarello et al., 2015). Table 2.3 lists 35 BMPs practices mostly applied to control soil erosion on agricultural lands as classified into six groups according to their respective purposes while the chapter 2 has discussed how various soil conservation practices showed high percentages of soil loss reduction when applied in agricultural fields.

4.C.3 Modelling soil erosion in the Sebeya catchment

Modeling cannot be an alternative to measurement and monitoring but might be a powerful tool for the simulation and prediction of the soil erosion potential (Alewell et al., 2019). The present study aimed to design a model which can help to minimize soil erosion to tolerable soil loss rates at the level of each parcel in the Sebeya catchment and consequently to contribute to the sustainable agriculture while protecting the environment. The designed Soil Loss and Crop yield (SOLCY) model was used to simulate up to a combination of 3 soil erosion control measures on each of 259,673 parcels in the Sebeya catchment. The combination of more than 3 soil erosion control measures was found to be the most effective in reducing soil erosion on each parcel to tolerable soil loss rates.

Farmers, District agriculture planners, and technicians in the Sebeya catchment can use SOLY model to focus on the parcel soil loss and predicted crop yield for sustainable land management decisions. For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya catchment, the present research suggested implementing the site-based recommended SEC measures with mulching and drainage channels on the same farmland (Table 4.37). The development of soil erosion rates greater than the acceptable soil loss tolerance limit (11.5 t/ha/yr) should be prevented by the affected people and landholders who are capable of identifying rill erosion at its early stage through some adaptive measures based on their indigenous knowledge.

Finally, SOLCY model is limited to the Sebeya catchment but other researchers should develop similar models on other catchments based on SOLCY model design concept.

4.C.3 Future Work

This study assessed various factors and processes affecting soil erosion to recommend suitable site-based SEC measures for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya catchment.

Farmers are the most direct perceivers of the development of soil erosion processes in their farmlands. How do farmers perceive the soil erosion hazard and its control? With the aim of understanding the basic processes and factors affecting soil erosion and its control, the uniqueness of this research consists in a systematic and simultaneous examination of all the three aspects (planning, adoption, and implementation) of soil erosion control measures in the Sebeya catchment. The proposed methodologies were developed to clearly: (1) identify and interpret the indicators of soil erosion; (2) estimate the actual soil loss from the entire catchment; (3) assess the main causes and effects of soil erosion; (4) assess and propose suitable Best Management Practices (BMPs) of soil erosion control on all catchment farmlands; (5) propose the best combination of soil erosion control measures which can reduce the high rated soil erosion below the acceptable soil loss rates; (6) assess various factors affecting farmers' willingness to implement soil erosion control measures in their farmlands; (7) analyze the sustainability of soil erosion control in the Sebeya catchment. This study provided a clear knowledge to farmers on various Best Management Practices (BMPs). However, lack of knowledge and economic constraints are the main limitative factors against the implementation of soil erosion control measures in the Sebeya catchment (Ding et al., 2015). The majority of farmers suggest trainings and mobilization of a specialized technical team to assist them in implementing soil conservation measures and to generalize the application of fertilizers in the whole catchment.

For the ultimate objective of eradicating the high erosion rates in the Sebeya catchment, this study recommends further studies focusing on the analysis of various factors affecting farmers' willingness to participate in the planning process, implementation and maintenance of soil erosion control measures in their farmlands. Practically, lowering the high soil loss rates below the maximum soil loss tolerance rate of 11.5 t/ha/yr throughout the entire catchment should be the main target in implementing SEC measures (IWRM, 2017).

To this end, farmers are the most perceivers and can identify rill erosion at its early stage; therefore, researchers should focus on BMPs easily applied by indigenous knowledge to prevent soil erosion. Government grants, donor agencies, and non-governmental organizations (NGOs) should empower the affected people (landowners and farmers) to adopt and implement SECM. All farmers should be trained and sensitized through awareness and education programs to ensure their farmlands are protected from soil erosion for sustainable agricultural and environmental management in the Sebeya catchment

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

The main objective of this study was the assessment of the spatial-temporal distribution of soil erosion and future-based remedial measures to control soil erosion on agricultural land of the Sebeya catchment to contribute to sustainable agriculture and environment protection. This research started by gathering in a literature review various worldwide researchers views on various causes, effects and remedial measures of soil erosion in agricultural lands.

Focused on the Sebeya catchment, this study firstly held to explore the actual status of soil erosion in the Sebeya catchment. Qualitative and quantitative data were collected and analyzed. Specifically, 75 farmers living and having farm lands in the catchment were interviewed in terms of knowledge on soil erosion, causes and control measures. The results showed that streambank erosion is due to the erosive power of runoff from uplands areas as confirmed by 18.7% of the interviewed farmers. The main natural causes of soil erosion in the Sebeya catchment are heavy rainfall (69.33%) and the slope steepness (28%) (Section 4.A.1).

This study also assessed the various preventive measures against the soil surface crusting and the development of runoff coefficients in order to minimize the soil loss in the Sebeya catchment agricultural fields. The three experimental field plots were installed and named Maize-Fertilizer-Mulching (MFM), Maize-Fertilizer (MF) and Bare Soil (BS) which were set in Rugerero Sector of Rubavu District. The sieve analysis indicated that the soil in the experimental plots was a gravelly sand with (sand:56.27%; clay and silt: 3.24% and gravel: 40.49%) while the field experimental results showed that the mulched plot had high moisture content with low runoff and soil loss compared to 2 other plots. When exposed on the same rainfall intensity, the responses from the 3 plots showed similar variability of runoff coefficients (R) and soil loss (A) respectively in the following order: $R_{MFM} < R_{MF} < R_{BS}$ and $A_{MFM} < A_{MF} < A_{BS}$ (Section 4.A.2).

In the estimation of the Sebeya river sediment load and assessment of its impacts on Lake Kivu, Gihira water treatment plant and various hydropower plants constructed in the Sebeya catchment, the three designed bed load samplers were equidistantly installed along the entire width of the river against the flow in order to catch the sediment while water samples were hand-collected from five different sampling points along the Sebeya river during rainy and dry seasons (Section 4.A.3). Laboratory analysis for turbidity, total suspended solids, sieve analysis for bed load materials and NPK content of water and bed load samples were conducted. At all 5 sampling sites and during rainy season compared to dry season, the average mass flowrates of bed load materials were 7.84 and 2.96 kg/hr respectively. Sieve analysis results showed that all bed load sediments were mainly composed of high proportions of fine sand of more than 70% which adversely causes damages on hydropower turbines and the effect of high soil erosion rates on Gihira water treatment plant was traduced by high turbidity of raw water and excessive costs of reagents. At the Sebeya river outlet, nutrients load and high turbidity reduce significantly the aesthetic quality of Lake

Kivu, having a harmful impact on recreation and tourism, aquatic life and affect the livelihoods of people living in the vicinity.

Farmers in the Sebeya catchment have not yet implemented sufficient soil erosion control measures in such a way that the estimated average soil loss from the whole catchment area was 130.724 t/ha/yr in 2012 and 100 t/ha/yr in 2018, which is extremely high. Progressing with farmers interview, among the 22 existing soil erosion control measures, 4.57% of farmers confirmed their existence while 95.43% expressed the need of their implementation in the Sebeya catchment (Section 4.A.4). In this section, the performance of soil erosion remediation measures was assessed and the Best Management Practices (BMPs) proposed for soil erosion control in the Sebeya catchment based on the land slope.

By simulating a combination of 0, 1, 2 and 3 soil erosion control measures on each of 259,673 parcels, the simulated average annual soil loss from the Sebeya catchment was 849.94; 143.27; 88.64 and 28.59 t/ha/yr respectively. Correlatively on each of 195,533 arable parcels of the Sebeya catchment, the crop yield was predicted from the soil loss value using an established linear relationship. Soil Loss and Crop Yield (SOLCY) model has been developed to predict soil loss and crop yields for each of 13 main cultivated crops in the Sebeya catchment. The combination of 3 soil erosion control measures has been found to be the most effective in reducing soil erosion on each parcel (Section 4.A.5). Therefore, this research shows high necessity of improving soil erosion control practices. The development of soil erosion rates greater than the acceptable soil loss tolerance limit (T-value) should be prevented by the affected people and landholders who are capable of identifying rill erosion at its early stage through some adaptive measures based on their indigenous knowledge. Farmers, District agriculture planners and technicians in the Sebeya catchment can use SOLCY model to focus on the parcel soil loss and predicted crop yield for sustainable land management decisions.

Various factors influencing farmers' perceptions of soil erosion causes, effects, and willingness to adopt soil erosion control measures were analyzed using descriptive statistics and SPSS (Version 20), including t-tests, chi-square tests, and a binary logistic regression model. Chi-square test results indicate that gender, farmer age, land ownership, farmland size, social media access, and credit access were strongly associated ($p < 0.05$) with the adoption of SEC measures, while marital status and education were not. A binary logistic regression model showed that among farmers' socioeconomic characteristics, farming experience ($B = 0.749$; $p = 0.020$) and access to socio media ($B = 2.107$; $p = 0.027$) were positively correlated, while age ($B = -0.642$; $p = 0.035$)

and gender ($B = -2.034$; $p = 0.032$) were negatively correlated ($p < 0.05$) with the adoption of SEC measures (Section 4.B.1).

Simulating the existing and the site-based recommended soil erosion control measures, soil loss was reduced significantly from 73 t/ha/yr to 29 t/ha/yr. To highlight the implication of the site-based recommended SEC measures in improving agricultural productivity, this study suggests field investigations in soil erosion plots and prediction of crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya catchment. For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya catchment, the present research recommends implementing the site-based recommended soil erosion control measures with mulching and drainage channels on the same farmland (Section 4.B.2).

This research finally recommends government agencies and NGOs to be extensively involved in soil erosion management and to mobilize a specialized technical team to assist in implementation of soil erosion control measures in the Sebeya catchment. Also worldwide researchers should be encouraged through grants by governments and non-governmental organizations (NGOs) to develop similar models on other catchments for the quantitative computation of soil loss and the predictions of crop yield based on SOLCY design concept. Lastly, researches should be strengthened and extended to measurement and monitoring programs in order to build up validation data sets for soil erosion models.

REFERENCES

- Adeogun, A. G., Sule, B. F., and Salami, A. W. (2018). Cost effectiveness of sediment management strategies for mitigation of sedimentation at Jebba hydropower reservoir, Nigeria. *Journal of King Saud University Engineering Sciences*, 30(2), 141–149. <https://doi.org/10.1016/j.jksues.2016.01.003>
- Adormado, H. A., Appolineres, H. A., and Yoshida, M. (2019). Erosion vulnerability assessment in REINA, Quezon Province, Philippines with raster-based tool built within GIS environment. *Agricultural Information Research*, 18(1), 24-31.
- Ahmad, N., and Pandey, P. (2018). Assessment and monitoring of land degradation using geospatial technology in Bathinda district, Punjab, India. *Solid Earth*, 9(1), 75–90. <https://doi.org/10.5194/se-9-75-2018>
- Alemu, M. D. (2019). Farmers' Perception of Soil Erosion and Adoption of Soil Conservation Technologies at Geshy Sub-Catchment, Gojeb River Catchment, Ethiopia. *Agricultural Sciences*, 10(01), 46–65.
- Alewell, A., Borrelli, P., Meusburger, K., and Panagos, P. (2019). Using the USLE: chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research*, 7, 203-225.
- Alufah, S., Shisanya, C. A., and Obando, J. A. (2012). Analysis of Factors Influencing Adoption of Soil and Water Conservation Technologies in Ngaciuma Sub-Catchment, Kenya. *African Journal of Basic & Applied Sciences*, 4(5), 172–185.
- Amenu, L., and Megersa, T. (2021). Factors Influencing Soil Erosion Management Practices in Ejersa Lafo District, West Showa Zone, Oromia, Regional State, Ethiopia. *Journal of Applied Science and Environmental Management*, 5(1), 79-85.
- Aniah, P., Wedamb, E., Pukunyienc, M., and Yinimid, G. (2013). Erosion and livelihood change in North East Ghana. *International Journal of Sciences: Basic and Applied Research (IJSBAR)*, 7(1), 28-35.
- Arjmand Sajjadi, S., and Mahmoodabadi, M. (2015). Aggregate breakdown and surface seal development influenced by rain intensity, slope gradient and soil particle size. *Solid Earth*, 6(1), 311–321. <https://doi.org/10.5194/se-6-311-2015>
- Armenise, E., Simmons, R. W., Ahn, S., Garbout, A., Doerr, S. H., Mooney, S. J., Sturrock, C. J., and Ritz, K. (2018). Soil seal development under simulated rainfall: Structural, physical and hydrological dynamics. *Journal of Hydrology*, 556, 211–219. <https://doi.org/10.1016/j.jhydrol.2017.10.073>
- Asfaw, D., and Neka, M. (2017). Factors affecting adoption of soil and water conservation practices: The case of Wereillu Woreda (District), South Wollo Zone, Amhara Region, Ethiopia. *International Soil and Water Conservation Research*, 5(4), 273–279.
- Ausseil, A. E., and Dymond, J. R. (2010). Evaluating ecosystem services of afforestation on erosion-prone land: A case study in the Manawatu Catchment, New Zealand. *Conference paper, International Congress on Environmental Modelling and Software, 5th Biennial Meeting (July 2010)*, Ottawa, Canada, 1-10.
- Ayeni, I. F., Omotade, I., Olanrewaju, O. O., and Alatise, M. O. (2017). Constructed Wetlands, an Eco Friendly Technology for Soil and Water Remediation: a Review. *Proceedings of the 2017 Annual Conference of the School of Engineering & Engineering Technology (SEET), The Federal University of Technology, Akure, Nigeria, 11-13 July, 2017.*

- Bagalwa, J. J. (2015). *Sediment and nutrient loading into Lake Kivu: A case study of Lwiro micro catchment, Democratic Republic of Congo*. [MSc thesis]. Makerere University, Kampala, Uganda.
- Bagarella, G., Lazzarin, R., and Noro, M. (2015). On the activation strategy of the chiller in water-loop self-contained refrigeration system: An experimental analysis. *International Journal of Refrigeration*, 57, 94-102.
- Bagarello, V., Costanza, D. S., Ferro, V., and Pampalone, V. (2015). Establishing a soil loss threshold for limiting rilling. *Journal of Hydrologic Engineering*, 1-5. doi:10.1061/(ASCE)HE.1943.5584.0001056.
- Bai, J., Shengtian, Y., Yichi, Z., Xiaoyan, L., and Yabing, G. (2019). Assessing the impact of terraces and vegetation on runoff and sediment routing using the time-area method in the Chinese Loess Plateau. *Water*, 803(11), 1-20, doi:10.3390/w11040803.
- Bakoji, Y. (2017). *Soil erosion: Farmers perception and conservation measures in the Northern part of Taraba state*. [PhD thesis]. University of Malaya Kuala Lumpur. Taraba state, Nigeria.
- Balasubramanian, A. (2017). *Soil erosion-causes and effects*. [Report]. University of Mysore. Mysore, India.
- Bhandari, D., Joshi, R., Regmi, R. R., and Awasthi, N. (2021). Assessment of Soil Erosion and Its Impact on Agricultural Productivity by Using the RMMF Model and Local Perception: A Case Study of Rangun Catchment of Mid-Hills, Nepal. *Applied and Environmental Soil Science*, vol. 2021. Article ID 5747138. <https://doi.org/10.1155/2021/5747138>
- Bashagaluke, J. B., Logal, V., Opoku, A., Sarkodie-Addo, J., and Quansah, C. (2018). Soil nutrient loss through erosion: Impact of different cropping systems and soil different cropping systems and soil amendments in Ghana. *PLOS ONE*, 13(12), 1-17.
- Barsher, L., Moores, J., and Mclean, G. (2016). *Scientific basis for erosion and sediment control practices in New Zealand*. Landcare Research. Richmond, New Zealand.
- Batista, P. V. G., Silva, M. L. N., Davies, J., and Quinton, J. N. (2019). Erosion model testing – are doing enough? In FAO. (2019). Proceedings global symposium, on soil erosion, 15–17 May 2019. Fao headquarters, Rome, Italy, pp 665.
- Belachew, A., Mekuria, W., and Nachimuthu, K. (2020). Factors influencing adoption of soil and water conservation practices in the northwest Ethiopian highlands. *Int Soil Water Conserv Res*, 8, 80-89. <https://doi.org/10.1016/j.iswcr.2020.01.005>
- Belasri, A., Lakhouili, A., and Halima, O. I. (2017). Soil erodibility mapping and its correlation with soil properties of Oued El Makhazine catchment, Morocco. *Journal of Materials and Environmental Science*, 8(9), 3208-3215.
- Belay, T. T. (2020). Perception of Farmers on Soil Erosion and Conservation Practices in Dejen District, Ethiopia. *International Journal of Environmental Protection and Policy*, 2(6), 224-229.
- Belaya, T., and Mengistua, D. A. (2019). Land use and land cover dynamics and drivers in the Muga catchment, Upper Blue Nile basin, Ethiopia. *Remote Sensing Applications: Society and Environment*, 15, 1-10.
- Benavidez, R.; Jackson, B.; Maxwell, D.; and Norton, K. (2018). A review of the Revised Universal Soil Loss Equation (RUSLE): With a view to increasing its global applicability and improving soil loss estimates. *Hydrol. Earth Syst. Sci*, 22, 6059–6086.

- Bera, A. (2017). Estimation of soil loss by USLE model using GIS and remote sensing techniques: A case study of Muhuri river basin, Tripura, India. *Eurasian Journal of Soil Science*, 3(6), 206 - 215. doi: 10.18393/ejss. 288350
- Bidogeza, J., Berentsena, P. B., De Graaff, J., and Oude Lansinka, A. G. (2007). Multivariate typology of farm households based on socio-economic characteristics explaining adoption of new technology in Rwanda. *AAAE Ghana Conference Proceedings*, 175-281.
- Bidogeza, J. C., Berentsen, P. B. M., De Graaff, J., and Lansink, A. O. (2015). Potential impact of alternative agricultural technologies to ensure food security and raise income of farm households in Rwanda. *Forum for Development Studies*, 42(1), 133–157. <https://doi.org/10.1080/08039410.2014.972444>
- Bing, H., Wu, Y., Liu, E., and Yang, X. (2013). Assessment of heavy metal enrichment and its human impact in lacustrine sediments from four lakes in the mid-low reaches of the Yangtze River. *Journal of Environmental Sciences*, 25(7), 1300–1309.
- Biratu, A. A., and Asmamaw, D. K. (2016). Farmers’ perception of soil erosion and participation in soil and water conservation activities in the Gusha Temela catchment, Arsi, Ethiopia. *International Journal of River Basin Management*, 4(3), 1329–336.
- BirdLife International (2018). *Sediment fingerprinting in Sebeya catchment*. [Report]. Rwanda Water and Forestry Authority, Kigali, Rwanda.
- Birhanu, Z., Ramadjita, T., Bougouna, S., Fourter, N., and Suhan, P. (2014). *Assessment of contour bunding technology for improved land and water management in Mali*. [Report]. International Crops Research Institute for the Semi-Arid Tropics. Telangana, India.
- Bizoza, A. (2011). *Farmers, institutions and land conservation*. [PhD thesis]. Wageningen University. Wageningen, Dutch.
- Bizoza, A. R., and De Graaff, B. A. (2012). Financial cost–benefit analysis of bench terraces in Rwanda. *Land Degradation and Development*, 23, 103-115.
- Bossio, D., Geheb, K., and Critchley, W. (2010). Managing water by managing land: Addressing land degradation to improve water productivity and rural livelihoods. *Agricultural Water Management*, 97, 536–542.
- Bouguerra, H., Abderrazak, B., Kamel, K., Oussama, D., and Salah, E. T. (2017). Mapping Erosion Prone Areas in the Bouhamdane Catchment (Algeria) Using the Revised Universal Soil Loss Equation through GIS. *Journal of Water and Land Development*, 32(1):13–23. doi: 10.1515/jwld-2017-0002
- Borrelli, P., Diodato, N., and Panagos, P. (2016). Rainfall erosivity in Italy: a national scale spatio temporal assessment. *International Journal of Digital Earth*, 9(9), 835-850. doi:10.1080/17538947.2016.1148203.
- Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schutt, B., Ferro, V., Bagarello, V., Oost, K. V., Montanarella, L., and Panagos, P. (2013). An assessment of the global impact of 21st century land use change on soil erosion. *Nature communications*, 1-13. doi: 10.1038/s41467-017-02142-7
- Brandimarte, L., Paron, P., and Di Baldassarre, G. (2012). Bridge pier scour: A review of processes, measurements and estimates. *Environmental Engineering and Management Journal*, 11(5), 975–989. <https://doi.org/10.30638/eemj.2012.121>
- Brooks, K. N., Ffolliot, P. F., and Magner, J. A. (2013). *Hydrology and the management of catchments*. Wiley-Blackwell, Iowa, USA.

- Bugg, R. A., Donald, W., Zech, W., and Perez, M. (2017). Performance evaluations of three silt fence practices using a full-scale testing apparatus. *Water*, 502(9), 1-15.
- Byizigiro, R. V, Rwanyiziri, G., Mugabowindekwe, M., Kagoyire, C., and Biryabarema, M. (2020). Estimation of Soil Erosion Using RUSLE Model and GIS: The Case of Satinskyi Catchment, Western Rwanda. *Rwanda Journal of Engineering, Science, Technology and Environment*, 3(1). <https://doi.org/10.4314/rjeste.v3i1.2s>
- Carluer, N., Lauvernet, C., Noll, D., and Munoz-Carpena, R. (2017). Defining context-specific scenarios to design vegetated buffer zones that limit pesticide transfer via surface runoff. *Science of the Total Environment*, 575, 701–712. <https://doi.org/10.1016/j.scitotenv.2016.09.105>
- Chakravarty, S., Ghosh, S. K., Suresh, C. P., Dey, A. N., and Shukla, G. (2012). Deforestation: Causes, Effects and Control Strategies. *Global Perspectives on Sustainable Forest Management*. <https://doi.org/10.5772/33342>
- Chang, B., Page, F., and Losier, R. (2013). Variables affecting sediment sulfide concentrations in regulatory monitoring at salmon farms in the Bay of Fundy, Canada. *Aquaculture Environment Interactions*, 4(1), 67–79. <https://doi.org/10.3354/aei00074>
- Chaudhary, S., and Kumar, S. (2018). Soil erosion estimation and prioritization of Koshalya Jhajhara catchment in North India. *Indian Journal of Soil Conservation*, 46(3), 305-311.
- Chen, S.H.; Su, H.B.; Tian, J., Zhang, R.H.; and Xia, J. (2011). Estimating soil erosion using MODIS and T.M. images based on support vector machine and à trous wavelet. *Int. J. Appl. Earth Obs. Geoinf*, 13, 626–635.
- Chen, L., Sela, S., Svoray, T., and Assouline, S. (2013). The role of soil-surface sealing, microtopograph, and vegetation patches in rainfall-runoff processes in semiarid areas. *Water Resources Research*, 49(9), 5585-5599.
- Chen, G., Zhang, Z., Guo, X., and Wen, Q. (2019). Quantitative assessment of soil erosion based on CSLE the 2010 national soil erosion survey at regional scale in Yunnan province of China. *Sustainability*, 11, 3252-3275. doi:10.3390/su111235252
- Claman, D., and Way, L. (2021). Bank Stability Assessment Tool for Bridge and Abutment Infrastructure in Iowa. Transportation Department, Iowa, USA.
- Cook, M. R., Moss, N. E., Rogers, A. L., and McKinney, M. (2014). *Analysis of sediment loading rates and water quality for the Bon Secour river catchment Baldwin country, Alabama*. [Report]. Geological survey of Alabama, Tuscaloosa, Alabama.
- Dahal, G.; Holcomb, J., and Socci, D. (2016). Surfactant-Oxidant Co-Application for Soil and Groundwater Remediation. *Remediation*, 26, 101–108. <https://doi.org/10.1002/rem.21461>.
- David, W. P. (1988). Soil and water conservation planning: Policy issues and recommendations. *Journal of Philippine Development*, 15, 47-84.
- Debebe, W., Melaku, K., Menfese, T. and Tesfaye, G. (2013). Farmers perceptions and participation on mechanical soil and water conservation techniques in Kembata Tembaro zone: the case of Kachabirra Woreda, Ethiopia. *International Journal of Advanced Structures and Geotechnical Engineering*, 2(4), 118-131.
- Deng, C., Zhang, G., Liu, Y., Nie, X., Li, Z., Liu, J., and Zhu, D. (2021). Advantages and disadvantages of terracing: A comprehensive review. *International Soil and Water Conservation Research*, 9(3), 344–359. <https://doi.org/10.1016/j.iswcr.2021.03.002>

- Devatha, C. P., Deshpandeb, V., and Renukaprasad, M. S. (2015). Estimation of soil loss using USLE model for Kulhan catchment, Chattisgarh- A case study. *Aquatic Procedia*, 4, 1429-1436. doi:10.1016/j.aqpro.2015.02.185.
- Djoukbala, O., Hasbaia, M., Benselama, O., and Mazour, M. (2019). Comparison of the erosion prediction models from USLE, MUSLE and RUSLE in a Mediterranean catchment, case of Wadi Gazouana (N-W of Algeria). *Modeling Earth Systems and Environment*, 5(2), 725–743. <https://doi.org/10.1007/s40808-018-0562-6>
- DeVere, L. B. (2010). *Agri-science fundamentals and applications (5ed)*. Delmar Cengage Learning. Clifton Park, USA.
- Dibaba, W.K.; Demissie, T.A., and Miegel, K. (2020). Catchment Hydrological Response to Combined Land Use/Land Cover and Climate Change in Highland Ethiopia: Finchaa Catchment. *Water*, 12, 1801. <https://doi.org/10.3390/w12061801>.
- Ding, L.; Chen, K.; Cheng, C., and Wang, X. (2015). Water ecological carrying capacity of urban lakes in the context of rapid urbanization: A case study of East Lake in Wuhan. *Phys. Chem. Earth*, 89, 104–113. <https://doi.org/10.1016/j.pce.2015.08.004>
- Dollinger, J., Dagès, C., Bailly, J. S., Lagacherie, P., and Voltz, M. (2015). Managing ditches for agroecological engineering of landscape. A review. *Agronomy for Sustainable Development*, 35(3), 999–1020. <https://doi.org/10.1007/s13593-015-0301-6>
- Duguma, T. A. (2022). Soil erosion risk assessment and treatment priority classification: A case study on Guder Catchments, Abay River Basin, Oromia, Ethiopia. *Heliyon*, 1-14.
- Endalamaw, N. T., Moges, M. A., Kebebe, S. Y., Alehegn, B. M., and Sinshaw, B. G. (2021). Potential soil loss estimation for conservation planning, Upper Blue Nile basin, Ethiopia. *Environmental Challenge*, 1-12
- Eisazadeh, L., Sokouti, R., Homae, M., and Pazira, E. (2012). Comparison of empirical models to estimate soil erosion and sediment yield in micro catchments. *Eurasian Journal of Soil Science*, 1, 28–33.
- Ezugwu, C. (2013) Sediment deposition in Nigeria reservoirs: impacts and control measures. *Innovative Systems Design and Engineering*, 4, 54–62.
- Faber, J., and Fonseca, L. M. (2014). How a Sample Size Influences Research Outcomes. *Dental Press Journal of Orthodontics*, 19(4), 27–29. <https://doi.org/10.1590/2176-9451.19.4.027-029>
- Falcao, K. D., Panachuki, E. O., Monteiro, F. D., Menezes, R. D., Rodrigues, D. B., Sone, J. S., and Oliveira, P. T. (2020). Surface runoff and soil erosion. *Surface runoff and soil erosion in a natural regeneration area of the Brazilian Cerrado*, 8, 124-130.
- Fang, X., Wesley, C., and Christopher, P. L. (2015). Stormwater field evaluation and its challenges of a sediment basin with skimmer and baffles at a highway construction site. *Water*, 7, 3407-3430.
- Fang, H. (2021). Responses of runoff and soil loss to rainfall regimes and soil conservation measures on cultivated slopes in a hilly region of Northern China. *International Journal of Environmental Research and Public Health*, 18(4), 1–17. <https://doi.org/10.3390/ijerph18042102>
- FAO (1983). *Fertilizer use under multiple cropping system*. Food and Agriculture Organization of the United Nations. Rome, Italy.
- Farayi, D. (2011). *Spatial soil erosion hazard assessment and modelling in Mbire District, Zimbabwe*. [MSc thesis]. University of Zimbabwe, Mbire, Zimbabwe.

- Fekadu, B., Yenealem, K., Jema, H., and Belaineh, L. (2013). Impact of integrated soil and water conservation program on crop production and income in West Harerghe Zone, Ethiopia. *International Journal of Environmental Monitoring and Analysis*, 1(4), 111-120.
- Ffolliott, F. P., Brooks, N. K., Neary, G. D., Tapia, P. R., and Chevesich, G. P. (2013). *Soil erosion and sediment production on catchment landscapes: processes, prevention, and control*. UNESCO. Montevideo, Canada.
- Fiener, P., and Auerswald, K. (2009). Effects of hydrodynamically rough grassed waterways on dissolved reactive phosphorus loads coming from agricultural catchments. *Journal of Environmental Quality*, 38, 548-559.
- Fiener, P., Auerswald, K. (2017). Grassed Waterways. In: Delgado, J., Sassenrath, G., and Mueller, T. *Precision conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation*. Agron. Monogr. 59. ASA and SCCA, Madison, WI. p. 131-150. <https://doi.org/10.2134/agronmonogr59.2013.0021>
- Franz, E. P., Poala, F., Nuna, A., and Maria C. M. M. (2018). Performance evaluation of soil erosion control by geotextile materials on road cut slope. *The 2018 world congress on Advances in Civil, Environmental and Materials Research (ACEM18)*. Sangdo convensia, August 27-31. Incheon, Korea.
- Gali, R. K., Soupir, M. L., Kaleita, A. L., and Daggupati, P. (2015). Identifying potential locations for grassed waterways using terrain attributes and precision conservation technologies. *American Society of Agricultural and Biological Engineers*, 58(5), 1231-1239. doi:10.13031/trans.58.10995
- Ganasri, B. P., and Ramesh, H. (2016). Assessment of soil erosion by RUSLE model using remote sensing and GIS - A case study of Nethravathi Basin. *Geoscience Frontiers*, 7, 953-961.
- Gao, Z., Xu, Q., Si, Q., Zhang, S., Fu, Z., and Chen, H. (2022). Effects of Different Straw Mulch Rates on the Runoff and Sediment Yield of Young Citrus Orchards with Lime Soil and Red Soil under Simulated Rainfall Conditions in Southwest China. *Water* 2022, 14, 1119-1132.
- Gasore, G., Ahlborg, H., Ntagwirumugara, E., and Zimmerle, D. (2021). Progress for on-grid renewable energy systems: Identification of sustainability factors for small-scale hydropower in Rwanda. *Energies*, 14(4). <https://doi.org/10.3390/en14040826>
- Gattinger, A., Jawtusich, J., Müller, A., and Mäder, P. (2011). *No-till agriculture – a climate smart solution*. [Report]. Bishofliches Hilfswerk MISEREOR, Aachen, Germany.
- Ghimire, S. K., Higaki, D., and Bhattarai, T. P. (2013). Estimation of Soil Erosion Rates and Eroded Sediment in a Degraded Catchment of the Siwalik Hills, Nepal. *Land*, 2, 370-391; doi:10.3390/land2030370
- Gitas, I. Z., Kostas, D., Chara, M., and George, N. S. (2009). Multi-Temporal Soil Erosion Risk Assessment in Chalkidiki Using a Modified USLE Raster Model. *EARSeL EProceedings* 8(5), 40–52.
- Guo, X., Zhou, L., Chen, Y., Zhao, M., and Wang, R. (2017). Perception and adaption of ecological. *Journal of Arid Land Resources and Environment change for farmers in the typical desertification area: a case of Hangjin Banner in the Inner Mongolia autonomous region*, 31(3), 64-69.
- Guo, S., Zhu, Z., and Lyu, L. (2018). Effects of climate change and human activities on soil erosion in the Xihe river basin, China. *Water*, 10(85), 1-14. doi:10.3390/w10081085.
- Hajigholizadeh, M., Melesse, A. M., and Fuentes, H. R. (2018). Erosion and sediment transport modelling in shallow waters: A review on approaches, models and applications.

- International Journal of Environmental Research and Public Health*, 15(3).
<https://doi.org/10.3390/ijerph15030518>
- Hannouche, A., Chebbo, G., Ruban, G., Tassin, B., Lemaire, B. J., and Joannis, C. (2011). Relationship between turbidity and total suspended solids concentration within a combined sewer system. *Water Science and Technology*, 64(12), 2445–2452.
- Hassan, K. F. (2011). Application of rainfall intensity-kinetic energy relationship for soil loss prediction. *Mesopotamia J. of Agri*, 39(2), 40-51.
- Hegazy, I. R., and Kaloop, R.M. (2015). Monitoring urban growth and land use change detection With GIS and remote sensing techniques in Daqahlia governorate Egypt. *Int. J. Sustain. Built Environ*, 4, 117–124.
- Holden, E., Linnerud, K., and Banister, D. (2014). Sustainable development: our common future revisited. *Global Environmental Change*, 26, 130-139.
- Herschy, R. W. (2012). Water quality for drinking: WHO guidelines. *Encyclopedia of Earth Sciences Series*, 876–883. https://doi.org/10.1007/978-1-4020-4410-6_184
- Hrabalíková, M., and Janeček, J. (2017). Comparison of different approaches to LS factor calculations based on a measured soil loss under simulated rainfall. *Soil and Water Research*, 12(2), 1-12. doi:10.17221/222/2015-SWR
- Huang, X., Lu, Q., and Yang, F. (2020). The effects of farmers' adoption behavior of soil and water conservation measures on agricultural output. *International Journal of Climate Change Strategies and Management*, 12(5), 599-615.
- Huffman, R., Fangmeier, D., Elliot, W., and Workman, S. A. (2011). *Soil and water conservation engineering*. American Society of Agricultural and Biological Engineers. Michigan, USA.
- Igwe, P. U., Nwezi, C. C., Echendu, J. E., Chukwunyere, I. C., and Okonkwo, N. J. (2017). Adaptations to Soil Erosion: A Review. *International Journal of Advanced Engineering, Management and Science (IJAEMS)*, 1(12), 1126-1134.
- Issaka, S., and Ashraf, M. A. (2017). Impact of soil erosion and degradation on water. *Geol. Ecol. Landsc*, 1(1), 1–11. <https://doi.org/10.1080/24749508.2017.1301053>.
- IWRM (2016). *Feasibility study and detail design of the early implementation project on Sebeya catchment*. [Report]. Integrated Water Resources Management Department, Ministry of Natural Resources. Kigali, Rwanda.
- IWRM (2017). *Sebeya catchment plan 2017-2023*. [Report]. Ministry of Natural Resources. Kigali, Rwanda.
- IWRM (2018). *Sebeya catchment plan 2018-2024*. [Report]. Integrated Water Resources Management Department, Ministry of Natural Resources. Kigali, Rwanda.
- Jeong, A., Dorn, R. I., Seong, Y. B., and Yu, B. Y. (2021). Acceleration of soil erosion by different land uses in arid lands above natural background rates: Case study in the Sonoran desert, USA. *Land*, 10(8), 834. <https://doi.org/10.3390/land10080834>
- Julien, P.Y. (2011). Erosion and sedimentation. *Geological Magazine*, 148(4), 683-684.
- Kabir, M. A., Dutta, D., and Hironaka, S. (2011). Process-based distributed modeling approach for analysis of sediment dynamics in a river basin. *Hydrology and Earth System Sciences*, 15(4), 1307–1321. <https://doi.org/10.5194/hess-15-1307-2011>
- Kabirigi, M., Mugambi, S., Musana, S. B., Ngoga, T. G., Muhutu, J. C., Rutebuka, J., Ruganzu, V. M., Nzeyimana, I., Nabahungu, N. L., and Nabahungu, N. L. (2017). Estimation of soil erosion risk, its valuation and economic implications for agricultural production in Western part of Rwanda. *Journal of Experimental Biology and Agricultural Sciences*,

- 5(4), 525-536.
- Kalambukattu, G. J., and Kumar, S. (2017). Modelling soil erosion risk in a mountainous catchment of Mid Himalaya by integrating RUSLE model with GIS. *Eurasian Journal of Science*, 6(2),1-14.
- Karamage, F., Zhang, C., Ndayisaba, F., Shao, H., Kayiranga, A., Fang, X., Nahayo, L., Nyesheyija, M. E., and Tian, G. (2016). Extent of cropland and related soil erosion risk in Rwanda. *Sustainability*, 608(8), 1-19. doi:10.3390/su8070609
- Karydas, C. G., Panagos, P., and Gitas, I. Z. (2014). A classification of water erosion models according to their geospatial characteristics. *International Journal of Digital Earth*, 7(3), 229-250, doi:10.1080/17538947.2012.67138
- Kassa, Y., Beyene, F., Haji, J., and Legesse, B. (2013). Impact of integrated soil and water conservation program on crop production and income in West Harerghe zone, in Ethiopia. *International Journal of Environmental Monitoring and Analysis*, 1(4), 111-120.
- Kassam, A. H., Van Velthuis, H. T., Mitchell, J. B., Fischer, G. W., and Shah, M. M. (1992). *Agro ecological land resources assessment for agricultural development planning: a case study of Kenya*. [Report]. Agriculture Organization of the United Nations. Rome, Italy.
- Khare, M. D., Mondal, A., Kundu, S., and Kumar, P. (2017). Climate change impact on soil erosion in the Mandakini River Basin, North India. *Appl. Water Sci*, 7, 2373–2383. doi:10.1007/s13201-016-0419-y
- Kiani-Harchegani, M., Sadeghi, S. H., Singh, V. P., Asadi, H., and Abedi, M. (2019). Effect of rainfall intensity and slope on sediment particle size distribution during erosion using partial eta squared. *Catena*, 176, 65–72. <https://doi.org/10.1016/j.catena.2019.01.006>
- Kiggundu, N., Wanyama, J., Mfitumukiza, D., Twinomuhangi, R., Barasa, B., Katimbo, A., and Kyazze, F. B. (2018). Rainwater harvesting knowledge and practice for agricultural production in a changing climate: A review from Uganda’s perspective. *Agricultural Engineering International: CIGR Journal*, 20(2), 19–36.
- Kim, J. H. (2015). How to Choose the Level of Significance: A Pedagogical Note. *Minich personal RePEc archive*, 1-13.
- Kinnel, P. I. A. (2010). Event Soil Loss, Runoff and the Universal Soil Loss Equation Family of Models: A Review. *Journal of Hydrology*, 385, 384-397.
- Kituku, M. G., Muwanga, A., Poesen, J., and Deckers, J. A. (2011). *Farmer’s perception on Landslide occurrences in Bududa District, Eastern Uganda*. [Report]. National Environmental Management Authority. Kampala, Uganda.
- Kleinbaum, D. G., and Klein, M. (2010). *Logistic Regression: A Self-learning Text* (3rd ed.). Springer, Atlanta, USA.
- Kjelland, M. E., Woodley, C. M., Swannack, T. M., and Smith, D. L. (2015). A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications. *Environment Systems and Decisions*, 35(3), 334–350. <https://doi.org/10.1007/s10669-0159557-2>
- Kondolf, G. M., Gao, Y., Annandale, G. W., Morris, G. L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H., Wang, Z., Wei, Z., Wu, B., Wu, C., and Yang, C.T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth’s Future*, 2(5), 256–280. <https://doi.org/10.1002/2013ef000184>

- Kristin, B., and Steven, R. A. (2003). Sampler size and sampling time affect bed load transport rates and particle sizes measured with bed load traps in gravel-bed streams. *Proceedings of Oslo Norway Workshop on Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advance (June 2002)*, 126-133.
- Kumar, R. (2011). *Research methodology: a step-by-step guide for beginners*. New Dehli, India: SAGE publication Ltd.
- Kumar, S., and Kushwara, S. P. (2013). Modelling soil erosion risk based on RUSLE-3D using GIS in a Shivalik sub-catchment. *Journal of Earth System Science*, 12(6), 32-41. doi:10.1007/s12040-013-0276-0
- Kuok, K. K., Darrien, Y. S., and Chiu, P. C. (2013). Evaluation of C and P factors in Universal Soil Loss Equation on trapping sediment: Case study of Santubong river. *Journal of water resource and protection*, (5), 1149-1154.
- Kusari, L., Ahmedi, F. (2013). The use of turbidity and total suspended solids correlation for the surface water quality monitoring. *International Journal of Current Engineering and Technology*, 3(4), 1311–1314.
- Kusimi, J. M., and Yiran, G. A. (2011). Application of local knowledge in land degradation assessment in the Bawku East Municipality. *Ghana Journal of Geography*, 3, 88–125.
- Laker, M. C., and Nortjé, G. P. (2019). Review of existing knowledge on soil crusting in South Africa. In *Advances in Agronomy* (1st ed., Vol. 155, Issue March). Elsevier Inc. <https://doi.org/10.1016/bs.agron.2019.01.002>.
- Laksni, S., Suhardjorno, S., Ery, S., and Mohammad, S. (2017). Runoff velocity behaviour on smooth pavement and paving blocks surfaces measured by a tilted plot. *Journal of water and Land Development*, 33(4-6), 149–156.
- Lal, R. (1994). Soil erosion research method: laboratory and field plots for erosion research. *Philosophical Transactions of the Royal Society: Biological Sciences*, 352, 997-1010.
- Lal, R. (2012). Climate Change and Soil Degradation Mitigation by Sustainable Management of Soils and Other Natural Resources. *Agricultural Research*, 1(3), 199–212. <https://doi.org/10.1007/s40003-012-0031-9>
- Le Coz, J., Camenen, B., Peyrard, X., and Dramais, G. (2014). Uncertainty in open-channel discharges measured with the velocity-area method. *Flow Measurement and Instrumentation*, 26, 18-29.
- Leta, A., and Megersa, T. (2021). Factors Influencing Soil Erosion Management Practices in Ejersa Lafo District, West Showa Zone, Oromia, Regional State, Ethiopia. *Journal of Applied Sciences and Environmental Management*, 25(1), 79–85.
- Li, C., Pan, C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hydrology*, 558, 90–103. <https://doi.org/10.1016/j.jhydrol.2018.01.007>
- Li, G., Wan, L., Cui, M., Wu, B., and Zhou, J. (2019). Influence of canopy interception and rainfall kinetic energy on soil erosion under forests. *Forests*, 10(6). <https://doi.org/10.3390/f10060509>
- Li, C., Yang, M., Li, Z., and Wang, B. (2021). How will Rwandan land use/land cover change under high population pressure and changing climate? *Applied Sciences (Switzerland)*, 11(12). <https://doi.org/10.3390/app11125376>
- Liu, X.B., Zhang, X.Y., Wang, Y. X., Sui, Y.Y., Zhang, S. L., Herbert, S. J., and Ding, G. (2010). Soil degradation: a problem threatening the sustainable development of agriculture in Northeast China. *Plant Soil Environment*, 56 (2), 87-97.

- Lott, E. D., and Hammond, V. E. (2013). *Vegetable and Fruit Production*. University of Nebraska. Lincoln, UK.
- Ly, S., Charles, C., and Dégre, A. (2013). Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at catchment scale: a review. *Biotechnology, Agronomy, Society, and Environment*, 17(2), 392-406.
- Majoro, F., Wali, G. U., Munyaneza, O., Naramabuye, F. X., and Mukamwambali, C. (2020). Estimation of Soil Loss and Ranking Priority in Implementing Soil Erosion Control in Sebeya Catchment, Rwanda. *North American Academic Research (NAAR)*, 3(10), 13-27.
- Majoro, F., and Wali, U. G. (2022). Analysing various factors affecting farmers' willingness to Adopt soil erosion control measures in the Sebeya catchment, Rwanda. *Sustainability*, 14, 12895. <https://doi.org/103390/su141912895>
- Malesu, M. M. Raymonds, O. A., Cherogony, K., Douglas, N., Charles, G., Kipnetich, B. E., Mick, O., Ilyama, M., and Mogoi, J. (2010). *Rwanda irrigation master plan*. [Report]. Ministry of Agriculture and Animal Resources. Kigali, Rwanda.
- Mango, N., Makate, C., Tamene, L., Mponela, P., and Ndengu, G. (2017). Awareness and adoption of land, soil and water conservation practices in the Chinyanja Triangle, Southern Africa. *Int Soil Water Conserv Res*, 5(2), 122-129. <https://doi.org/10.1016/j.iswcr.2017.04.00>
- Manyiwa, T., and Dikinya, O. (2013). Using Universal Soil Loss Equation and soil erodibility factor to assess soil erosion in Tshesebe village, North East Botswana. *African Journal of Agricultural Research*, 30(8), 4170-4178, doi: 10.5897/AJAR2013.7081
- Mekuriaw, A., Heinimann, A., Zeleke, G., and Hurni, H. (2018). Factors influencing the adoption of physical soil and water conservation practices in the Ethiopian highlands. *International Soil and Water Conservation Research*, 6(1), 23-30.
- Mgbenka, R.N., Nicholas, O., Igbokwe, E. M. and Felix, E. (2012). Soil and water conservation capabilities among farmers and extension agents in Eastern region of Nigeria. *African Journal of Agricultural Research*, 7(1), 58-67.
- MIDMAR (2012). *Disaster High Risk Zones on Floods and Landslides*. [Report]. Ministry of Disaster Management and Refugee Affairs, Kigali, Rwanda.
- Miller, D. R. (1974). Sensitivity analysis and validation of simulation models. *Journal of Theoretical Biology*, 48(12), 345-360.
- MINAGRI (2009). *Crop assessment 2009B Season*. [Report]. Ministry of Agriculture and Animal Resources, Kigali, Rwanda.
- MINAGRI (2010). *Agriculture gender strategy*. [Report]. Ministry of Agriculture and Animal Resources, Kigali, Rwanda.
- MINAGRI (2021). *Annual report 2020-2021*. Ministry of Agriculture and Animal Resources, Kigali, Rwanda.
- Misebo, A. M. (2018). The role of agronomic practices on soil and water conservation in Ethiopia; Implication for climate change adaptation: A review. *Journal of agriculture Science*, 10(6), 227-237.
- MoE (2018). *Mapping of erosion in Rwanda and guidelines for erosion control*. [Report]. Ministry of Environment, Kigali, Rwanda.
- MoE (2020). *Soil erosion control mapping report*. Ministry of Environment, Kigali, Rwanda.
- Moges, D. M., and Taye, A. A. (2017). Determinants of farmers' perception to invest in soil and water conservation technologies in the North-Western Highlands of Ethiopia. *Int Soil Water Conserv Res*, 5(1), 56-61.

- Mohamadi, M. A., and Kavian, A. (2015). Effects of rainfall patterns on runoff and soil erosion in field plots. *International Soil and Water Conservation Research*, 3, 273–281.
- Mohammad, H., Assefa M, M., and Hector, R. F. (2018). Raindrop-Induced Erosion and Sediment Transport Modelling in Shallow Waters: A Review. *Journal of Soil and Water Science*, 1(1), 15–25. <https://doi.org/10.36959/624/427>
- Moriaque, T. A., Alladassi, F. K., Zoundji, C., and Julien, A. (2022). Impact of conservation tillage on runoff, soil loss and soil properties on acrisols and ferralsols in central Benin. *Canadian Journal of Soil Science*, 102, 1-14. doi: 10.1139/CJSS-2021-0080
- Morgan, R. P. C. (2005). *Soil erosion and conservation (3rd ed)*. Blackwell Publishing. Victoria, Australia.
- Mu, H., Yu, X., Fu, S., Yu, B., Liu, Y., and Zhang, G. (2019a). Effect of stem basal cover on the sediment transport capacity of overland flows. *Geoderma*, 337, 384-393. <https://doi.org/10.1016/j.geoderma.2018.09.055>
- Mu, H., Yu, X., Fu, S., Yu, B., Liu, Y., and Zhang, G. (2019b). Effect of stem cover on hydraulic parameters of overland flow. *Journal of Hydrology*, 577, 123964. <https://doi.org/10.1016/j.jhydrol.2019.123964>
- Mugisha, S. (2012). *MINIRENA Suspends Mining Activities Around River Sebeya*. [Report]. Ministry of Natural Resources, Kigali, Rwanda.
- Mugonola, B., Deckers, J., Poesen, J., Isabirye, M., and Mathijs, E. (2013). Adoption of soil and water conservation technologies in the Rwizi catchment of south western Uganda. *Int J Agric Sustain*, 11(3), 264-281.
- Munyaneza, O., Majoro, F., Mutake, S. and Hagenimana, E. (2015). Performance evaluation of sediments basins: Case study of Keya hydropower plant in Rwanda. *Journal of Water Resource and Protection*, 7,1387-1398.
- Munyaneza, O., Majoro, F., Hagenimana, E. and Usabyisa, W. (2016). Impact assessment of hillside rainwater harvesting ponds on agriculture income: Case study of Ntarama sector in Rwanda. *Journal of Water Resource and Protection*, 8, 844-854.
- Mupenzi, J. P., Li, L., Jiwen, G., Habumugisha, J. D., Habiyaremye, G., Ngamije, J. and Baragahoranye, I. (2012). Radical terraces in Rwanda. *East African Journal of Science and Technology*, 1(1), 53- 58.
- Musselman, R. (2012). *Sampling procedure for lake or stream surface water chemistry*. U.S. Department of Agriculture, Washington D.C, USA.
- Muvundja, A, F., Pasche, N., Bugenyi, W. B. F., Isumbisho, M., Müller, B., Namugize, J. P., Rinta, P., Schmid, M., Stierli, R., and Wüest, A. (2009). Balancing nutrient inputs to Lake Kivu. *Journal of Great Lakes Research*, 35, 406–418.
- Nadhomi, D. L., Tenywa, J. S., Musali, P., & Nakileza, B. R. (2013). Farmers' Perception of Erosion Risk and its Implication on the Adoption of Soil and Water Conservation Practices. *International Journal of Advanced Agricultural Sciences and Technology*, 2(1), 28–44.
- Nahayo, A., Pan, G., Joseph, S. D. (2016). Factors influencing the adoption of soil conservation techniques in Northern Rwanda. *Journal of Plant Nutrition and Soil Science*, 179(3), 1-13. doi: 10.1002/jpln.201500403
- Najeeb, S., Mahender, A., Anandan, A., Hussein, W., Li, Z., and Ali, J. (2021). Genetics and Breeding of Low Temperature Stress Tolerance in Rice. Rice improvement. https://doi.org/10.1007/978-3-030-66530-2_8

- Nambajimana, J. D., He, X., Zhou, J., Justine, M. F., Li, J., Khurram, D., Mind'je, R., and Nsabimana, G. (2020). Land use change impacts on water erosion in Rwanda. *Sustainability*, *12*(1), 1–23. <https://doi.org/10.3390/SU12010050>
- Narendar, M. K., Ramavtar, G., Prabhat, T., and Prashant, S. (2017). Nutrient losses in soil due to erosion. *Journal of Pharmacognosy and Phytochemistry*, *1*, 1009-1011.
- Ndagijimana, I., and Shukuru, H. (2015). *Flood control management - Case study of Sebeya River*. [B.Sc thesis]. University of Rwanda-College of Science and Technology. Kigali, Rwanda.
- Ndomba, P. M. (2010). Modeling of Sedimentation Upstream of Nyumba ya Mungu Reservoir in Pangani River Basin. *Nile Basin Water Science and Engineering*, *3*(2), 25-38.
- Nearing, G. S. (2013). *Diagnostics and generalizations for parametric state estimation*. [PhD thesis]. The University of Arizona. Tucson, Arizona.
- Nedd, R., Light, K., Owens, M., James, N., Johnson, E., and Anandhi, A. (2021). A synthesis of land use/land cover studies: Definitions, classification systems, meta-studies, challenges and knowledge gaps on a global landscape. *Land*, *10*(9), 1–33. <https://doi.org/10.3390/land10090994>
- Nedunchezhiyan, M., Byju, G., and Jata, K. S. (2012). Sweet potato agronomy. *Fruit, Vegetable and Cereal Science and Biotechnology*, *6*(1), 1-10.
- Nenadovic, S., Kljajevi, L., Nenadovi, M., Milanovi, M., and Markovi, S. (2013). Physico-chemical soil analysis of Rudovci region. *Geonauka*, *1*(2), 1-8.
- Niaz, A.; Sajjad, H.; Muhammad, A. A.; Minhas, A., Waheed, W., Danish, S., Sahad, F., Ghafoor, U., Baiq, K.S., and Sultan, H. (2022). Correlation of Soil Characteristics and Citrus Leaf Nutrients Contents in Current Scenario of Layyah District. *Horticulture*, *8*, 61. <http://doi.org/10.3390/horticulturae8010061>.
- Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Nohmi, M., and Tsubo, M. (2017). Farmers' perception about soil erosion in Ethiopia. *Land Degradation and Development*, *28*, 401-411.
- Nill, D., Schwertmann, U., Sabel-Koschella, U., Bernhard, M. and Breuer, J. (1996). *Soil erosion by water in Africa: Principles, prediction and protection*. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. München, Germany.
- NISR (2009). *Rwanda statistical yearbook*. [Report]. National Institute of Statistics of Rwanda, Kigali, Rwanda.
- NISR (2014). *Rwanda demographic and health survey 2014-15*. [Report]. National Institute of Statistics of Rwanda, Kigali, Rwanda.
- NISR (2015). *Seasonal agricultural survey 2015*. [Report]. National Institute of Statistics of Rwanda, Kigali, Rwanda.
- NISR (2017). *Seasonal agricultural survey*. [Report]. National Institute of Statistics of Rwanda, Kigali, Rwanda.
- NISR (2019). *Rwanda natural capital accounts – ecosystems*. [Report]. Ministry of Environment, Kigali, Rwanda.
- NISR (2021). *Agriculture Household Survey*. National Institute of Statistics of Rwanda, Kigali, Rwanda.
- Obalum, S. E., Buri, M. M., Nwite, J. C., Hermansah., Watanabe, Y., Igwe, C. A., and Wakatsuki, T. (2012). Soil degradation-induced decline in productivity of Sub Saharan African soils: The prospects of looking downwards the low lands with the Sawah

- ecotechnology. *Applied and Environmental Soil Science*, 1-10. doi: 10.1155/2012/673926.
- Okoba, O. B., and De Graaff, J. (2005). Farmers knowledge and perceptions on soil erosion and conservation measures in the Central Highlands, Kenya. *Land Degradation & Development*, 16, 475-487.
- Onu, F. M., and Mohammed, A. (2014). Competency improvement needs of farmers in soil erosion prevention and control for enhancing crop production: Case study of Kogi State, Nigeria. *Agricultural Sciences*, 5, 958-963.
- Oosterveld, W., and Galand, R. (2012). Justice reform, security sector reform and local ownership. *Hague Journal on the Rule of Law*, 4(1). <https://doi.org/10.1017/S1876404512000115>
- Oruk, E., Eric, J. N., and Ogogo, A. (2012). Influence of soil textural properties and land use cover type on soil erosion of a characteristic ultisols in Betem, cross river Sate, Nigeria. *Journal of Sustainable Development*, 5(7), 104-110. doi:10.5539/jsd.v5n7p104.
- Panagopoulos, T., Cakula, A., and Ferreira, V. A. (2015). Simulation model for predicting soil erosion in a large reservoir of Southern Portugal. *International Journal of Sustainable Agricultural Management and Informatics*, 1(1), 1-23.
- Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., and Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science and Policy*, 54, 438-447.
- Park, H. A. (2013). An introduction to logistic regression: From basic concepts to interpretation with particular attention to nursing domain. *J. Korean. Acad. Nurs.* 4, 57-61.
- Parveen, R., and Kumar, U. (2012). Integrated Approach of Universal Soil Loss Equation (USLE) and Geographical Information System (GIS) for Soil Loss Risk Assessment in Upper South Koel Basin, Jharkhand. *Journal of Geographic Information System*, 4(6), 1-9. doi:10.4236/jgis.2012.46061
- Patil, S, Tushar, K. S., and Bhalerao, S. A. (2013). Mulching: A soil and water conservation practice. *Research Journal of Agriculture and Forestry Sciences*, 1(3), 26-29.
- Peng, C., Yonggang, G., and Yongming, L. (2011). Soil erosion and sediment control effects in the three gorges reservoir region, China. *Journal of Resources and Ecology*, 2(4), 289-297.
- Peprah, J. A., Afoakwah, C., and Isaac, K. (2016). *Crop Yield Volatility among Smallholder Farmers in Ghana*. UNU-INRA, Accra, Ghana.
- Perera, E. N. C., Jayawardana, D. T., Jayasinghe, P., Bandara, R. M. S., and Alahakoon, N. (2018). Direct impacts of landslides on socio-economic systems: a case study from Aranayake, Sri Lanka. *Geoenvironmental Disasters*, 5(1). <https://doi.org/10.1186/s40677-018-0104-6>
- Pimentel, D., and Michael, B. (2013). Soil erosion threatens food production. *Agriculture*, 3, 443-463. <https://doi.org/10.3390/agriculture3030443>
- Plessis, J. (2003). *Maize production*. [Report]. Department of Agriculture, Pretoria, South Africa.
- Pravat, K. S., Gouri, B. S., and Ramkrishna, M. (2013). Assessing the performance of check dams to Control rill-gully erosion: small catchment scale study. *International Journal of Current Research*, 5(4), 899-906.
- Pravat, K. S., Gouri, S. B., and Ramkrishna, M. (2015). Farmers' perceptions of soil erosion and management strategies in South Bengal in India. *European Journal of Geography*, 6(2), 85-100.

- Prosdocimi, M., Tarolli, P., and Cerdà, A. (2016). Mulching practices for reducing soil water erosion: A review. *Earth-Science Reviews*, 161, 191–203. <https://doi.org/10.1016/j.earscirev.2016.08.006>
- Ramesh, R., Kalin, L., Hantush, M., and Chaudhary, A. (2021). A secondary assessment of sediment trapping effectiveness by vegetated buffers. *Ecological Engineering*, 159. <https://doi.org/10.1016/j.ecoleng.2020.106094>
- Ramsankaran, R., Kothiyari, U. C., Ghosh, S. K., Malcherek, A., and Murugesan, K. (2013). Modèle distribué à bases physiques d'érosion des sols et de production de sédiments (DREAM) pour la simulation d'événements particuliers. *Hydrological Sciences Journal*, 58(4), 872–891. <https://doi.org/10.1080/02626667.2013.781606>
- Rawat, J., and Kumar, M. (2015). Monitoring land use/cover change using remote sensing and GIS techniques: A case study of Hawalbagh block, Almora district, Uttarakhand, India. *The Egyptian Journal of Remote Sensing and Space Science*, 18(1), 77-84. <https://doi.org/10.1016/j.ejrs.2015.02.002>
- Raza, A., Ahrends, H., Habib-Ur-Rahman, M., and Gaiser, T. (2021). Modeling approaches to assess soil erosion by water at the field scale with special emphasis on heterogeneity of soils and crops. *Land*, 10, 457.
- Reisenbüchler, M., Bui, M., Skublics, D., and Rutschmann, P. (2020). Sediment management at run-off river reservoirs using numerical modelling. *Water*, 249(12), 1-17.
- REMA (2010). *Practical tools on land management-GPS, mapping and GIS*. [Report]. Rwanda Environment Management Authority, Kigali, Rwanda.
- RNRA (2012). *Consultancy services for development of Rwanda national water resources master plan*. [Report]. Rwanda Natural Resources Authority, Kigali, Rwanda.
- RNRA (2014). *Technical studies for designing a retention pond for controlling floods at Sebeya river*. [Report]. Rwanda Natural Resources Authority, Kigali, Rwanda.
- Robby, Y. T., and Jian-Ping, S. (2017). Measuring the aesthetic value of multifunctional lakes using an enhanced visual quality method. *Water*, 233(9), 1-11.
- Rogers, D. P., and Vladimir, V. T. (2013). *Weather and climate resilience: Effective preparedness through national meteorological and hydrological services*. The World Bank, Washington DC, USA.
- RWB. (2018). *Shapefiles on Soil Erosion Risks in Rwanda: Actual and Site-based Recommended Soil Erosion Control Measures*. Rwanda Water Resources Board, Kigali, Rwanda.
- Sadeeka, L., Kumar, L., and Sandamali, J. (2019). Assessment of potential land suitability for tea in Sri Lanka Using a GIS-based multi-criteria approach. *Agriculture*, 48(9), 1-26.
- Sakinatu, I., and Muhammad, A. (2017). Impact of soil erosion and degradation on water quality: a review. *Geology, Ecology and Landscapes*, 1(1), 1-11.
- Sakinc, I., and Ugurlu, E. (2013). Logistic Regression Analysis to Examine Factors Affecting Gender Diversity on the Boardroom: ISE Case. *International Journal of Business and Social Science*, 4(3), 57-61.
- Saleem, Y. S., Zahoor, U. I., and Shakeel, A. R. (2018). Engineering feasibility of gabion structures overreinforced concrete structures. *International Research Journal of Engineering and Technology*, 5(10), 990-994.
- Sanchez-Bernal, E., Ortega-Baranda, V., Domonguez-Hernandez, F., Ortega-Escobar, M., Can-Chulim, A., and Sarmiento-Bustos, D. (2013). Soil erosion control using agroforestry terraces in San Pedro Mixtepec, Oaxaca, Mexico. *International Journal of Agriscience*, 3(5), 423-439.

- Senkoro, A. J. (2010). *Impact of soil erosion control practices on household food security and income, A case of East Usambara Highlands, Tanzania*. [Msc thesis]. Sokoine University of Agriculture, Morogoro, Tanzania.
- Sanogo, K., Birhanu, B. Z., and Kizito, F. (2021). Vulnerability of landscape patterns from a multidisciplinary approach based on remote sensing and GIS in two agroecologies of Mali. *International Institute of Tropical Agriculture*, 1-12.
- Sarathi, S., and Padmini, B. (2015). Estimation of soil erosion using RUSLE and GIS techniques: a case study of Barakar River basin, Jharkhand, India. *Model. Earth Syst. Environ.*, 1(4), 1-13.
- Savadogo, P., Bayala, J., and Kalinganire, A. (2017). *Restoration of degraded lands in Mali: a review on lessons learnt and opportunities on scaling*. [Report]. European Commission, Bamako, Mali.
- Serajuddin, M. D., Chowdhur, A. I., Haque, M. D., and Haque, E. (2019). Using turbidity to determine total suspended solids in an urban stream: A case study. *Proceedings of the 2nd International Conference on Water and Environmental Engineering, Dhaka, Bangladesh, India*. 148-154.
- Seutloali, K. E., and Beckedahl, H. R. (2015). Understanding the factors influencing rill erosion on roadcuts in the south eastern region of South Africa. *Solid Earth*, 6(2), 633–641. <https://doi.org/10.5194/se-6-633>
- Shannon, D. R. (2017). *Effect of Contour Bunds on Surface Runoff and Soil Erosion in the Bokole Catchment, Southwest Ethiopia*. Utrecht University, New Delhi, India.
- Sharma, A., Tiwari, K. N., and Bhadoria, P. B. S. (2011). Effect of land use land cover change on soil erosion potential in an agricultural catchment. *Environmental Monitoring and Assessment*, 173, 789–801. doi 10.1007/s10661-010-1423-6.
- Shi, Q., Wang, W., and Feng, L. (2022). Response of the Headcut Erosion Process to Flow Energy Variation in the Loess Gully Region of China. *Water*, 14(19), 1–15. <https://doi.org/10.3390/w14193038>
- Shit, K., Bhunia, G. S., and Maiti, R. (2013). Assessing the performance of check dams to control rill-gully erosion: Small catchment scale study. *International Journal of Current Research*, 5(4), 899–906.
- Shortle, J. S., Mihelcic, J. R., Zhang, Q., and Arabi, M. (2020). Nutrient control in water bodies: A systems approach. *Journal of Environmental Quality*, 49(3), 517–533. <https://doi.org/10.1002/jeq2.20022>
- Sileshi, M., Kadigi, R., Mutabazi, K., and Sieber, S. (2019). Determinants for adoption of physical soil and water conservation measures by smallholder farmers in Ethiopia. *Int Soil Water Conserv Res*, 7(4), 354–361. <https://doi.org/10.1016/j.iswcr.2019.08.002>
- Simeneh, D., and Getachew, F. (2015). Evaluation of land use types and physical soil and water conservation structures in Wyebla catchment in Northern Ethiopia. *International Journal of Environmental Protection*, 6(1), 90-96.
- Sisay, G., Gitima, G., Mersha, M., and Alemu, G. W. (2021). Assessment of land use land cover dynamics and its drivers in Bechet Catchment Upper Blue Nile Basin, Ethiopia. *Remote Sensing Applications: Society and Environment*, 24, 1-11.
- Solomon, B. (2016). *Assessment of factors that determine farmer's adoption behaviour of soil and water conservation practices in Libo Kemkem Woreda*. [MSc thesis]. University of Addis Ababa. Addis Ababa, Ethiopia.

- Stockemer, D. (2019). *Quantitative methods for social sciences: A practical introduction with examples in SPSS and data*. Springer, Ottawa, Canada.
- Suchithra, M. S., and Pai, L. M. (2020). Improving the prediction accuracy of soil nutrient classification by optimizing extreme learning machine parameters. *Information Processing Agriculture*, 7, 72-82.
- Sultana, S., and Satyanarayana, A. N. (2018). Urban heat island intensity during winter over metropolitan cities of India using remote-sensing techniques: impact of urbanization. *International Journal of Remote Sensing*, 39, 1-39.
- Sun, T., Deng, L., Fei, K., Fan, X., Zhang, L., Ni, L., and Sun, R. (2021). Runoff characteristics and soil loss mechanism in the weathered granite area under simulated rainfall. *Water*, 13(23). <https://doi.org/10.3390/w13233453>
- Tajbakhsh, S.M., Memarian, H., Sobhani, M., and Aghakhani, A. H. (2018). Kinematic runoff and erosion model efficiency assessment for hydrological simulation of semi-arid catchments. *Global Journal of Environmental Science and Management*, 4, 127, 140.
- Taherdoost, H. (2016). Sampling Methods in Research Methodology; How to Choose a Sampling Techniques for Research. *International Journal of Academic Research in Management*, 5(2), 18-27.
- Tangtham, N., and Korporn, N. (2004). P-factors in Universal Soil Loss Equation (USLE) of various conservation practices on hillslope at Mae Sa integrated catchment and forest land-use project, Changwat Chiang Mai. *Kasetsart Journal-Natural Science*, 33, 41-51.
- Tardio, G., Mockoviski, S. B., Rauch, H. P., Fernandes, J. P., and Acharya, M. S. (2018). The use of bamboo for erosion control and slope stabilization: Soil bioengineering works. *Current and Future Prospects*, 106-132.
- Tegegne, M., and Biniam, S. (2016). Estimating Soil Erosion Risk and Evaluating Erosion Control Measures for Soil Conservation Planning at Koga Catchment, Highlands of Ethiopia. *Solid Earth Discuss*, 1-23. doi:10.5194/se-2016-120
- Telkar, S. G., Shivendu, P. S., Kumar, J. D., and Kant, K. (2015). Soil Erosion: Types and Their Mechanism. *International Journal of Economic Plants*, 2(4), 178-180.
- Tesema, T. A., and Leta, O. T. (2020). Sediment Yield Estimation and Effect of Management Options on Sediment Yield of Kesem Dam Catchment, Awash Basin, Ethiopia. *Scientific African*, 9, e00425. <https://doi.org/10.1016/j.sciaf.2020.e00425>
- Tesfahunegn, G. B., Ayuk, E. T., and Adiku, S. G. (2021). Farmers' perception on soil erosion in Ghana: Implication for developing sustainable soil management strategy. *Plos One*, 16(3), 1-26. doi:10.1371/journal.pone.0242444
- Teshome, A., De Graaff, J., and Kassie, M. (2016). Household-Level determinants of soil and water conservation adoption phases: evidence from North-Western Ethiopian highlands. *Environ Manage*, 57, 620–636. <https://doi.org/10.1007/s00267015-0635-5>
- Tewkesbury, P. A., Comber, J. A., Tate, J. N., Lamb, A., and Fisher, F. P. (2015). Critical synthesis of remotely sensed optical image change detection techniques. *Remote Sensing of Environments*, 160, 1–14.
- Thapa, B. S., Dahlhaug, O. G., and Thapa, B. (2017). Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine. *Renewable and Sustainable Energy Reviews*, 49, 1100-1113.
- Troxel, C. F. (2013). *Life cycle analysis of sediment control devices*. [MSc thesis]. Georgia Institute of Technology, Atlanta, USA.

- Turhan, N. S. (2020). Karl Pearson's chi-square tests. *Education Research and Reviews*, 15(9), 575-580. doi:10.5897/ERR2019.3817
- Twisa, S., and Buchroithner, F. M. (2019). Land-Use and Land-Cover (LULC) Change Detection in Wami River Basin, Tanzania. *Land*, 8, 1-15.
- USDA (2013). *Revised Universal Soil Loss Equation : Version 2 (RUSLE2)*. [Report]. United States Department of Agriculture, Washington D.C, USA.
- Van, T. T., Dafang, F., Tran, N. B., Eldon, R. R., Tang, T. T. S., and Rajendra, P. S. (2018). An investigation on performance and structure of ecological revetment in a sub-tropical area: A case study on Cuatien river, Vinh City, Vietnam. *Water*, 636(10), 1-18.
- Van Beek, C.L., Elias, E., Yihenew, G.S., Heesmans, H., Tsegaye, A., Feyisa, H., Tolla, M., Melmuye, M., Gebremeskel, Y., and Mengist, S. (2016). Soil nutrient balances under Diverse agro-ecological settings in Ethiopia. *Nutr. Cycl. Agroecosys*, 106, 257–274. <https://doi.org/10.1007/s10705-016-9803-0>.
- Virto, I., Imaz, M. J., Fernández-Ugalde, O., Gartzia-Bengoetxea, N., Enrique, A., and Bescansa, P. (2015). Soil degradation and soil quality in Western Europe: Current situation and future perspectives. *Sustainability*, 7(1), 313–365. <https://doi.org/10.3390/su7010313>
- WASAC (2018). *Raw and treated water characteristics at Gihira water treatment plant*. Water and Sanitation Corporation, Kigali, Rwanda.
- Wenbin, M., Fuliang, Y., Chuanzhe, L., Yuebo, X., Jiyang, T., Jia, L., and Nana, Z. (2015). Effects of rainfall intensity and slope gradient on runoff and soil moisture content on different growing stages of spring maize. *Water*, 7, 2990-3008. doi:10.3390/w7062990
- Wischmeier, W. H., and Smith, D. D. (1978). *Predicting rainfall erosion losses: A guide to conservation planning*. United States Department of Agriculture, Washington, D.C.
- Wohl, E. (2015). Legacy effects on sediments in river corridors. *Earth-Science Reviews*, 147, 30-53. <https://doi.org/10.1016/j.earscirev.2015.05.001>
- Wordofa, M. G., Okoyo, N. E., and Erkalo, E. (2020). Factors influencing adoption of improved structural soil and water conservation measures in Eastern Ethiopia. *Environmental System Research*, 2-11. doi: 10.21203/rs.3.rs-25734/v2
- Xungui, L., and Xia, W. (2014). Analysis of the relationship between soil erosion risk and surplus floodwater during flood season. *Journal of Hydrologic Engineering*, 19, 1294-1311. doi: 10.1061/(ASCE)HE.1943-5584.0000912
- Yang, C., Rottensteiner, F., and Heipke, C. (2018). Classification of land cover and land use based on convolutional neural networks. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 4(3), 251-258.
- Yin, S., Xie, Y., Liu, B., and Nearing, M. A. (2015). Rainfall erosivity estimation based on rainfall data collected over a range of temporal resolutions. *Hydrology and Earth System Sciences*, 19(10), 4113–4126. <https://doi.org/10.5194/hess-19-4113-2015>
- Young, A. (1989). *Agroforestry for soil conservation*. CAB International, Wallingford, UK.
- Yüce, M. İ., Sit, M. E., and Ercan, B. (2018). A relationship between flow discharges, sediment discharge and sub-basin areas in Ceyhan catchment. *13th International Congress on Advances in Civil Engineering (12-14 September 2018)*, Izmir, Turkey.
- Zermeño-Hernández, I., Pingarroni, A., and Martínez-Ramos, M. (2016). Agricultural land-use diversity and forest regeneration potential in human-modified tropical landscapes. *Agriculture, Ecosystems and Environment*, 230, 210–220. <https://doi.org/10.1016/j.agee.2016.06.007>

- Zhai, K. (2010). Reservoir water quality assessment based on Fuzzy evaluation method. *Journal of Hubei University for Nationalities*, 28, 10–12.
- Zhang, X. K., Xu, J. H., Lu, X. Q., Deng, Y. J., and Gao, D. W. (1992). A study on the soil loss equation in Heilangjian province. *Bulletin of soil and water conservation*, 12, 1-9.
- Zisu, I., and Nasui, D. (2015). Using universal soil loss equation for soil erosion assessment in agricultural land from Rugoj hills. *Geographica Timisiensis*, 24(2), 13-23.

PUBLICATIONS BY THE AUTHOR

The two PhD papers published in the Sustainability Journal (SCI journal) are presented here :

- (1) Majoro, F. & Wali, U.G. (2022). Analyzing Various Factors Affecting Farmers' Willingness to Adopt Soil Erosion Control Measures in the Sebeya Catchment. *Sustainability*, 14, 12895.
- (2) Majoro, F., Wali, U.G., Munyaneza, O. & Naramabuye, F.X. (2023). Sustainability of Soil Erosion Control in Rwanda: Case Study of the Sebeya Catchment. *Sustainability*, 14, 151969.

TRAININGS, WORKSHOPS, SEMINARS AND CONFERENCES

TRAININGS

- (1) Participant in a “**4 days Training in Small Hydropower Projects: Design, Construction, Operation Maintenance and Financial**” organized by ICH (International Centre for Hydropower of Norway) in UMUBANO Hotel – Kigali (11 -14 Dec 2017).
- (2) Participant in a “**5 days Training on the Capability and Use of WADISO**”. **WADISO** = Water Distribution Systems Software; **Organizer: GLS Consulting Company** from South Africa; **Venue: Beauséjour Hotel, Kigali; Dates: 16-22 July 2019.**

WORKSHOPS

- (1) Participation in “**a 1day validation workshop of Groundwater study in Eastern province**”. Organizer: RWB; Venue: ONOMO Hotel; Date: 19 Oct 2018.
- (2) Participation in a 2days “**Research Workshop on Integrated Water Resources Management**”. **Organizer: JV RWB/W4GR + SEAD.** Venue: Camp Kigali at UR-CST. Dates: 22-23 Aug 2018.
- (3) Participation in a “**Workshop with UR staff on Intellectual property Hosted by RDB Rwanda**”. **Organizer: RDB** in partnership with UR; Venue: **Online Workshop via Webex.** **Audience:** This workshop was reserved to the UR-CST academic staff, researchers in the centers and PhD students. **Date: Wednesday 23 Dec 2020 (14:00-15:00).**

SEMINARS

- (1) **Seminar presentation No.1: Presentation on my PhD Research Progress**
Topic: Majoro PhD Research Progress, challenges and way forward.

Audience: UR-DRI, budget officers and PhD students concerned with UR-Sweden PhD Grants. **Venue:** UR-Headquarter. **Date:** 13 Feb 2019.

(2) Seminar presentation No.2: Presentation of my PhD Research Proposal

Topic: Public Defence of Majoro PhD Research Proposal

Audience: The staff members of the Post-Graduate Committee in the Department of Civil, Environmental and Geomatic Engineering at UR-CST and all 3 supervisors of this PhD research. **Venue:** Masters Room of CEGE Department. **Date:** 20 November 2019.

(3) Seminar presentation No.3: An online seminar on one chapter of my PhD thesis

Topic: Soil Erosion Modelling for Sustainable Environmental Management in Sebeya Catchment. **Audience:** The staff members of the Department of Civil, Environmental and Geomatic Engineering (CEGE) at UR-CST and all 3 supervisors of this PhD research. **Date:** 05 August 2021 (14:00-15:00).

CONFERENCES

(1) Participation in a 4 Days Rwanda Water Week (and World Water Week conference in Rwanda on 22 March of every year). Organizer: RWB; Venue: UR-CST; Dates: 19-23 Mar 2018

(2) Participation in a 4 Days Rwanda Water Week (and World Water Week conference in Rwanda on 22 March of every year). Organizer: RWB; Venue: UR-CST; Dates: 18-22 Mar 2019.

(3) Paper presentation in a conference:

Title: Soil Erosion Modelling for Sustainable Environmental Management in Sebeya Catchment (Published Paper to gain other researchers comments for my PhD thesis).

Co-authors: Prof. Umaru Garba WALI (Main supervisor), Prof. Omar MUNYANEZA (co-supervisor), Prof. Francois-Xavier NARAMABUYE (co-supervisor).

Date: 1st November 2021; **Duration:** 45 min

Type of presentation: Oral with power point in the: International Conference on Civil Engineering Education – Rwanda 2021 under the theme “Repositioning Civil Engineering Education for Sustainable Development” (November 1st to 3rd 2021)

Venue / audience: Venue: INES-Ruhengeri (Rwanda); Audience: Worldwide researchers from different Universities (INES Ruhengeri, Royal Academic Engineering, University of ABERDEEN (UK), University of IBADAN (Nigeria), Catholic University of Cameroon, University of Botswana, University of MAKURDI (Nigeria), University of Ilorin (Nigeria), University of Rwanda).

ABOUT THE AUTHOR

Eng. Felicien MAJORO was born on 1st June 1964 in Manyagiro Sector, Gicumbi District, Northern Province of Rwanda and he is married to Mrs Concilie MUKAMWAMBALI. He obtained his Master's degree in Applied Sciences, Civil Engineering option in August 1993 from University of Sherbrooke, Quebec, Canada after having graduated for an Advanced Diploma in Mathematic Sciences from National University of Rwanda (NUR) in 1987. Before starting his Master's degree programme, Félicien MAJORO was requested to upgrade his undergraduate knowledge with a propaedeutic of 10 courses (30 credits): Computer Programming, Engineering Drawing, Fluid Mechanics, Strength of Material, Concrete Technology, Soil Mechanics, Hydraulics, Sanitary Engineering, Systems analysis and Planning and Statistical Analysis of Experiments.

In 2001, Felicien MAJORO has been recruited to work at University of Rwanda (UR) with the former Kigali Institute of Science and Technology (KIST) on 01 Mar 2001 as Assistant Lecturer in the Department of Civil and Environmental Technology where he got promoted on 05 January 2005 as Lecturer in the same department until now. He is teaching water resources related courses such as: Fluid Mechanics, Engineering Hydrology, Engineering Hydraulics, Soil mechanics, Groundwater Hydraulics, River engineering, Engineering of dams, Hydraulic structures, Water supply and distribution (Gravity water supply and Pumped water supply systems), Hydropower generation, Irrigation and drainage Engineering, Water resources planning and management, Soil erosion and sediment control.

As an independent consultant, Felicien MAJORO worked as a Technical Director in Hydraulics and Building Construction Company (ECOHYBA) at Kayonza, Rulindo and Musanze District in Rwanda from September 2008 to July 2013. Felicien MAJORO has worked also as a Consulting Engineer in Hydropower in KSB Group headquartered in Frankenthal (Germany) to produce a feasibility study of a micro-hydropower project at Rusumo river in Gicumbi District from April 2015 to June 2018.

Felicien MAJORO has participated in trainings and workshops: Between 1st Sept-3rd Dec 2002, a 3 months Training in Hydraulic research “*Nile Basin Capacity Building Network in River Engineering (NBCBN-RE)*” held in Cairo Egypt and a Validation Workshop of EIA guidelines for Rwanda organized by Rwanda Environmental Management (REMA) during 14-15 May 2009 at La Palisse Hotel in Kigali.

On 15 June 2017, Felicien has registered for a PhD per research at University of Rwanda on the topic title “Soil Erosion Potential in the Sebeya Catchment, Rwanda”. He investigated on the development of run-off coefficients and soil erodibility in relation to hydrology, he assessed land use and nutrients dynamics in relation to rainfall events, he assessed the suitability of BMPs of soil erosion control for Sebeya catchment agricultural land and finally he established an erosion control model for farming systems to minimize soil loss in the Sebeya catchment with the consequence of increasing the crop yields.

Along with these responsibilities, the findings of this PhD resulted in a number of two publications in a peer-reviewed journal.

**MAJORO'S PhD QUESTIONNAIRE FOR FARMERS INTERVIEW IN THE SEBEYA
CATCHMENT (Part A: English version)**

Majoro's PhD Research Topic Formulation

**“SPACE-TEMPORAL RESPONSE AND FUTURE-BASED REMEDIAL MEASURES
ON AGRICULTURAL LAND AGAINST SOIL EROSION IN SEBEYA_RIVER
CATCHMENT, RWANDA”**

Eng. MAJORO Félicien (M.Sc)

Lecturer at UR-CST

School of Engineering

Department of Civil, Environmental and Geomatics Engineering

Water Resources Engineering Programme

UNIVERSITY OF RWANDA

E-mail: majoro.felicien@yahoo.fr /Tel: (+250)788484054

Main supervisor: Prof. Umaru Garba WALI

Co-supervisor 1: Dr. Omar MUNYANEZA

Co-Supervisor 2: Prof. Francois Xavier NARAMABUYE

Dear Respondent,

I am glad you are here. I am a PhD student in University of Rwanda, Department of Civil, Environmental and Geomatics Engineering, conducting a PhD research project entitled: **“SPACE-TEMPORAL RESPONSE AND FUTURE-BASED REMEDIAL MEASURES ON AGRICULTURAL LAND AGAINST SOIL EROSION IN SEBEYA_RIVER CATCHMENT, RWANDA”**. Your input in this research is of high regard and I promise to use your information for academic purpose only. The results will be used to improve soil erosion control strategies for Sebeya catchment which will help in:

- increasing agricultural production because soil nutrients will not be washed out by erosion
- minimizing river and downstream reservoirs sedimentation
- minimizing the impact of the eroded materials on various socio-economic development projects (which are KEYA and GISENYI Hydropower projects, GIHIRA Water Treatment Plant and Bridges on Sebeya river and its tributaries).

Questionnaire & interview

- This questionnaire contains **38** questions.
- All questions are to be answered by Sebeya catchment farmers.
- In order to avoid overloading respondents with open questions, we have proposed the following types of questions:
 - (1) Filling gaps questions
 - (2) YES or NOT type questions
 - (3) Multiple choice questions

- The following interview questions search to clarify erosion causes and process, its effects and knowledge on Best Management Practices (BMPs) in Sebeya catchment agriculture fields. The socio-economic aspects of Sebeya catchment farmers are also investigated.

A. RESPONDENT IDENTIFICATION

- (1) **Names:**
- (2) **Sex:**
 - Male
 - Female
- (3) **Age (years):**
 - 18-25
 - 26-30
 - 31-40
 - 41-55
 - >55
- (4) **Marital Status:**
 - Married and live together
 - Single
 - Divorced or separated
 - Widow or widower
- (5) **Education Level:**
 - No formal education: Can't write & can't read
 - No formal education: read but can't write
 - Elementary
 - Secondary
 - University
- (6) **Function:**
 - Farmer but he/she isn't owner
 - Owner but he/she isn't farmer
 - Owner & farmer

B. HOUSEHOLD SOCIO-ECONOMIC CHARACTERISTICS

- (7) **When did you start farming?**
Ans: since
- (8) **What brought you into farming?**
 - Inheritance
 - Agriculture business
 - Food production
 - Lack of other job
 - Others (specify)
- (9) **How has your business of farming changed your lifestyle from last 2 years (2016-2017 and 2017-2018)?**
 - Improving
 - Declining
 - Improving and declining
 - Declining and improving
 - No change

(10) For married people:

- Both are farmers
- One of them is a farmer
- None of them is a farmer

(11) Source of income for a farmer who is not owner:

- Income from farming:Rwf/day (wage)
- Income from another job:Rwf/day
- How income is spent:
 - Food
 - School fees
 - Clothes
 - Domestic water
 - Electricity
 - House rent
 - Health care (insurance, medical services,)
 - Others(specify)

(12) For an owner:

a. Number of plots

- 1
- 2 or more

b. Total hectares

- Less than 0.1ha
- Greater than 0.1ha

c. Main source of land holding

- Inheritance
- Bought
- Hire

d. What are your main cultivated crops and why these particular ones?

• Types of crops growing

- Beans (.....m xm)
- Soybeans (.....m xm)
- Maize (.....m xm)
- Sweet potatoes (.....m xm)
- Irish potatoes (.....m xm)
- Cassava (.....m xm)
- Banana plantations (.....m xm)
- Vegetables:
 - eggplant (.....m xm)
 - tomatoes (.....m xm)
 - onions (.....m xm)
 - cabbage (.....m xm)
 - green beans (.....m xm)
 - pepper (.....m xm)
 - carrots (.....m xm)
- Groundnuts (.....m xm)
- Coffee (.....m xm)

- Tea plantations (.....m xm)
- Sugar cane (.....m xm)
- Wheat (.....m xm)
- Sorghum (.....m xm)
- Peas (.....m xm)
- Forage:
 - Reed (.....m xm)
 - Tripsacum (.....m xm)
 - Ceteria (.....m xm)
 - Other type of forage (specify) (.....m xm); specify:
- Other type of crops (specify) (.....m xm); specify:
- **What is your main reason to select these crops? :**
- Main source of livelihood income (agriculture business): specify:
- Main source of livelihood income (market for extra harvested products): specify:
- Easy to cultivate
- Regional crop
- Small crop period
- Forage for pastures
- Suitable crop for family food (food security):
 - high yield (in quantity per small area); specify:
 - quality (high nutritive value); specify:
 - preferred by family member (easy to cook); specify:
 - preferred by family member (taste); specify:
 - preferred by family member (easy to eat); specify:
 - preferred by family member (easy digestion); specify:
 - preferred by family member (sorghum: drink porridge)
 - preferred by family member (wheat: drink porridge)
 - preferred by family member (banana: drink juice)
 - preferred by family member (banana: drink banana beer)

e. Income generation

- **Agriculture (last season); (NK = Not Known); Season A (SA); Season B(SB)**

- Beans (..... x100 Kg); (1Kg = Rwf); SA or SB
- Soybeans (..... x100 Kg); (1Kg = Rwf); SA or SB
- Maize (..... x100 Kg); (1Kg = Rwf); SA or SB
- Sweet potatoes (..... x100 Kg); (1Kg =Rwf); SA or SB
- Irish potatoes (..... x100 Kg); (1Kg = Rwf); SA or SB
- Cassava (..... x100 Kg); (1Kg = Rwf); SA or SB
- Banana (..... x100 Kg); (1Kg = Rwf); SA or SB
- Vegetables:
 - eggplant (..... x 70 Kg); (1Kg = Rwf); SA or SB
 - tomatoes (..... x 130 Kg); (1Kg = Rwf); SA or SB
 - onions (..... x100 Kg); (1Kg = Rwf); SA or SB
 - cabbage (..... x60 Kg); (1Kg = Rwf); SA or SB
 - green beans (..... x100 Kg); (1Kg = Rwf); SA or SB
 - pepper (..... x30 Kg); (1Kg = Rwf); SA or SB
 - carrots (..... X120 Kg); (1Kg = Rwf); SA or SB

- Groundnuts (..... x100 Kg); (1Kg = Rwf); SA or SB
- Coffee (..... x90 Kg); (1Kg = Rwf); SA or SB
- Tea (..... x35 Kg); (1Kg = Rwf); SA or SB

- Sugar cane:
 - Harvest season (Last SA or SB):
 - Total harvested sugar cane: Rwf
 - Number of FUSO:
 - Number of DAIHATSU tracks(= 4xnumber of FUSO) =
 - Number of tons per DAIHATSU: 4tons
 - Total harvested tons:number of DAIHATSUx4tons =tons
- Wheat (..... x100 Kg); (1Kg = Rwf); SA or SB
- Sorghum (..... x100 Kg); (1Kg = Rwf); SA or SB
- Peas (..... x100 Kg); (1Kg = Rwf); SA or SB
- Forage:
 - Reed (..... xRwf/m²); SA or SB
 - Tripsacum (..... xRwf/m²); SA or SB
 - Setaria (..... xRwf/m²); SA or SB
 - Other type of forage (specify)
 - (..... xRwf/m²); SA or SB
- Other type of crops (specify)
- (..... x100 Kg); (1Kg = Rwf); SA or SB
- **Income from Pastures:**
- **Cows (last seasons A+B+C: Sept 2017 upto Aug 2018):**
 - Number of actual cows:
 - Number of sold cows:
 - Total amount of money for sold cows: Rwf
 - Number of milk liters per day:
 - Price of milk: 1L =Rwf
 - Total amount of money for sold manure:Rwf
- **Pigs (last seasons A+B+C: Sept 2017 upto Aug 2018):**
 - Number of actual pigs:
 - Number of sold pigs:
 - Total amount of money for sold pigs:Rwf
 - Total amount of money for sold manure:Rwf
- **Sheep (last seasons A+B+C: Sept 2017 upto Aug 2018):**
 - Number of actual sheep:
 - Number of sold sheep:
 - Total amount of money for sold sheep:Rwf
 - Total amount of money for sold manure:Rwf
- **Goats (last seasons A+B+C: Sept 2017 upto Aug 2018):**
 - Number of actual goats:
 - Number of sold goats:
 - Total amount of money for sold goats:Rwf
 - Total amount of money for sold manure:Rwf
- **Rabbits (last seasons A+B+C: Sept 2017 upto Aug 2018):**

- Number of actual rabbits:
- Number of sold rabbits:
- Total amount of money for sold rabbits:Rwf
- Total amount of money for sold manure:Rwf
- **Chickens (poultry) (last seasons A+B+C: Sept 2017 upto Aug 2018):**
 - Number of actual chickens:
 - Number of sold chickens:
 - Total amount of money for sold chickens:Rwf
 - Number of eggs per day:
 - Price of one egg: 1egg = Rwf
 - Total amount of money for sold manure:Rwf
- **Fishery (last season: SA or SB or SC ie. From Sept 2017 upto Aug 2018):**
 - Number of actual fish ponds:
 - Size of each fish pond:m xm; Volume = ...
 - Total Kg of last season sold fishes:Kg
 - Unit Price of fish: 1 Kg of fish =Rwf
 - Total amount of money for last season sold fishes:Rwf
- **How income is spent**
 - Food
 - School fees
 - Clothes
 - Agriculture investment
 - Domestic water
 - Electricity
 - Health care (insurance, medical services, ...)
 - Pastures investment
 - House rent
 - House rehabilitation
 - Others(specify)

C. **THE ENVIRONMENT**

(13) Is there any use of machine?

- Yes
- No

(14) How have advances in technology such as machinery affected your farming?

- Air pollution which affects environment
- Lack of original soil
- Man powers decrease
- Increased soil erosion
- Decrease in organic matter

(15) What types of fertilizers do you use?

- Organic matter (organic manure or compost)
- Industrial fertilizers

(16) How have chemical fertilizers affected your farm in regard to the initial production:

- Increasing
- Decreasing

(17) If no other chemical fertilizers are added, how was the production?:

- Increased
- Decreased to be estimated equal to the time before using chemical fertilizers
- Decreasing rather than before using chemical fertilizers

(18) What do you understand by soil erosion?

- Damaging Flood with mud flow
- Channels formation in the fields
- Soil detachment by rain and runoff
- Soil detachment, transport and deposition of soil materials
- Landslides
- Floods: High runoff which overtops channels and can damage agriculture crops, lives and properties
- Wind erosion: Soil detachment, transport and deposition by wind
- Other understanding (specify):

(19) What are natural causes of soil erosion in Sebeya catchment did you observe?

- Slope of the terrain; Location: ...
High rainfall (or Floods); Location: ...
- High rainfall or rainfall of long duration (or Landslides); Location: ...
- Earthquakes; Location:
- High wind; Location:

(20) Have you seen any negative impacts on the environment due to farming in Sebeya catchment?

- Yes
- No

(21) If yes, what are them?

- Deforestation for land agriculture; Location
- Soil disturbance by agriculture machinery; Location:
- Soil disturbance by agriculture terracing; Location:
- Soil disturbance by tea plantations channels; Location:
- Removal of vegetative cover (overgrazing); Location: ...
- Land becomes harden due to pastures; Location:
- Removal of soil due to soil erosion on agriculture land; Location: ...
- Water pollution (turbidity) due to erosion from agriculture fields; Location:
- Others (specify)

(22) Can you mention various anthropogenic activities causing soil disturbance for non agriculture purposes in Sebeya catchment:

- mining sites; Location
- roads construction sites; Location
- quarries for roads (Lateritic soil); Location
- quarries for roads (construction stones); Location
- Building sites; Location:
- quarries for building; Location
- borrow pits for power transmission lines; Location

(23) Have you taken any steps to make your farm more environmentally friendly?

- Yes
- No

(24) If yes, how have you done this?

- Avoiding of illegal trees cutting
- Avoiding of grasses burning
- Avoiding tillage cultivation
- Use of recommended chemicals for soil fertilization
- Cultivation of recommended crops
- Cultivation of slope stabilization grasses and trees
- Cultivation on recommended areas (eg Respecting buffer zones of rivers and roads)
- Others (specify)

D. SOIL CONSERVATION MEASURES

(25) What are various types of soil erosion you have observed on Sebeya catchment?

- Sheet erosion (or interrill erosion); Location: ...
- Rill erosion; Location: ...
- Gully erosion; Location:
- Streambank erosion; Location: ...

(26) Absence of soil erosion control measures can cause soil erosion:

- Yes
- No

(27) What are various damages due to water erosion in Sebeya catchment?

- Crops removed with landslides; Location: ...
- Crops covered by soil erosion materials; Location:...
- Crops roots exposed up due to erosion; Location: ...
- Soil loss due to landslides; Location:
- Agriculture soil and nutrient losses; Location: ...
- Loss of human lives; Location: ...
- Loss of domestic animals; Location: ...
- Buildings; Location: ...
- High turbidity on Gihira WTP
- High concentration of sediments in Keya and Gisenyi HEPPs waterways
- Various types of sediment materials on Keya and Gisenyi HEPPs turbines
- Silting up of waterways; Location: ...
- Deposit of erosion materials in roads; Location: ...
- Gullies formation on the side of a road; Location: ...
- Cutoff road access due to progressive gullies; Location: ...
- Abrasion of Bridges piers by various types of sediment; Location: ...
- Others, specify:

(28) What kind of soil conservation methods have you seen in Sebeya catchment?

1. Terraces; Location:
2. Mulching; Location: ...
3. Appropriately selected cover crops; Location: ...
4. Vertical ploughing instead of horizontal ploughing; Location: ...
5. Anti-erosion ditches; Location:
6. Tree planting on Sebeya catchment mountains; Location:
7. Strip cropping along rivers; Location:
8. Grazing lands; Location: ...
9. Storm sewer drains; Location:

10. Siltation Pond at the end of a storm sewer; Location:
 11. Hillside water pond; Location:
 12. Sand traps (eg. Manholes); Location:
 13. Roadside channels; Location:
 14. Culverts; Location: ...
 15. Contour bunds (Field bunding); Location: ...
 16. Roof runoff and cisterns; Location: ...
 17. Velocity or Energy Dissipaters:
 - a. Check dams; Location: ...
 - b. Hillside water ponds; Location: ...
 - c. Stones blocks in a channel; Location: ...
 18. Vegetative measures for slopes stabilization:
 - a. Vetiver grass planting; Location: ...
 - b. Reed; Location: ...
 - c. Cetaria; Location:
 - d. Tripsacum; Location:
 - e. Paspalum; Location: ...
 19. Retaining walls made of gabions for slope stabilization; Location:
 20. Grassed waterway; Location:...
 21. Buffer zones:
 - a. Reed; Location: ...
 - b. bamboo; Location: ...
 22. Protective sediment barrier (Erosion control fences for roads); Location: ...
 23. Riverbank stabilization:
 - a. Sand bags; Location: ...
 - b. Retaining wall made of gabions; Location: ...
 - c. Pavement of banks slopes by stones revetment at the location of a bridge; Location: ...
 - d. Protective riprap on the foot of river banks; Location: ...
 - e. Protective grasses (reed); Location: ...
 - f. Trees plantations (bamboo); Location: ...
 - g. Trees plantations (Grevillea); Location: ...
 24. Others (specify)
- (29) What are the needed soil conservation measures in Sebeya catchment?**
1. Terraces; YES or NOT
 2. Mulching; YES or NOT
 3. Appropriately selected cover crops; YES or NOT
 4. Vertical ploughing instead of horizontal ploughing; YES or NOT
 5. Anti-erosion ditches; YES or NOT
 6. Tree planting on Sebeya catchment mountains; YES or NOT
 7. Strip cropping along rivers; YES or NOT
 8. Grazing lands; YES or NOT
 9. Storm sewer drains; YES or NOT
 10. Siltation Pond at the end of a storm sewer; YES or NOT
 11. Hillside water pond; YES or NO
 12. Sand traps (eg. Manholes); YES or NOT

13. Roadside channels; YES or NOT
 14. Culverts; YES or NOT
 15. Contour bunds (Field bunding); YES or NOT
 16. Roof runoff and cisterns; YES or NOT
 17. Velocity or Energy Dissipaters:
 - a. Check dams; YES or NOT
 - b. Hillside water ponds; YES or NOT
 - c. Stones blocks in a channel; YES or NOT
 18. Vegetative measures for slopes stabilization:
 - a. Vetiver grass planting; YES or NOT
 - b. Reed; YES or NOT
 - c. Cetaria; YES or NOT
 - d. Tripsacum; YES or NOT
 - e. Paspalum; YES or NOT
 19. Retaining wall made of gabions for slope stabilization; YES or NOT
 20. Grassed waterway; YES or NOT
 21. Buffer zones:
 - a. Reed; YES or NOT
 - b. bamboo; YES or NOT
 22. Protective sediment barrier (Erosion control fences for roads); YES or NOT
 23. Riverbank stabilization:
 - a. Sand bags; YES or NOT
 - b. Retaining wall made of gabions; YES or NOT
 - c. Pavement of banks slopes by stones revetment at the location of a bridge; YES or NOT
 - d. Protective riprap on the foot of river banks; YES or NOT
 - e. Protective grasses (reed); YES or NOT
 - f. Trees plantations (bamboo); YES or NOT
 - g. Trees plantations (Grevillea); YES or NOT
 24. Others (specify:); YES or NOT
- (30) Do you have soil erosion control measures in your field?**
- Yes
 - No
- (31) If no, what is your main reason (Choice A) and what is your will on implementing soil erosion control measures in your field (Choice B)?**
- Choice A**
1. It is costly (High labor demanding)
 2. I didn't know the existence of this soil erosion control technique
 3. It disturbs the soil
 4. It reduces the crop land
 5. The land is not mine (labour)
 6. No land rights (rented)
 7. Others (specify)
- Choice B**
- a. He/she has money, he/she will try to implement
 - b. His money is not sufficient that's why he/she needs support for implementation

- c. He/she needs someone to fund all the implementation
- d. He/she refuses to adopt for erosion control measures in his/her field (for reason in A)
- e. Other(s), specify:

Answers:

- Terraces; Choice A: and Choice B:
- Mulching; Choice A:..... and Choice B:
- Appropriately selected cover crops; Choice A:..... and Choice B:
- Vertical ploughing instead of horizontal ploughing; Choice A:..... and Choice B:
- Anti-erosion ditches (channeling); Choice A:..... and Choice B:
- Tree planting on Sebeya catchment mountains; Choice A:..... and Choice B:
- Grazing lands; Choice A:..... and Choice B:
- Hillside water pond; Choice A:..... and Choice B:
- Sand traps; Choice A:..... and Choice B:
- Contour bunds (Field bunding); Choice A:..... and Choice B:
- Roof runoff and cisterns; Choice A:..... and Choice B:
- Velocity or Energy Dissipaters:
 - Check dams; Choice A:..... and Choice B:
 - Hillside water ponds; Choice A:..... and Choice B:
 - Stones blocks in a channel; Choice A:..... and Choice B:
- Vegetative measures for slopes stabilization:
 - Vetiver grass planting; Choice A:..... and Choice B:
 - Reed; Choice A:..... and Choice B:
 - Cetaria; Choice A:..... and Choice B:
 - Tripsacum; Choice A:..... and Choice B:
 - Paspalum; Choice A:..... and Choice B:
- Retaining walls made of gabions for slope stabilization; Choice A:..... and Choice B:
- Grassed waterways; Choice A:..... and Choice B:
- Riverbank stabilization (small rivers):
 - Sand bags; Choice A:..... and Choice B:
 - Retaining walls made of gabions; Choice A:..... and Choice B:
 - Protective grasses (reed); Choice A:..... and Choice B:
 - Trees plantations (bamboo); Choice A:..... and Choice B:
 - Trees plantations (Grevillea); Choice A:..... and Choice B:
- Other(s), specify:; Choice A:..... and Choice B:

E. GOVERNMENT'S ROLE IN FARMING

(32) What are the governmental institutions that support your farm?

- MINAGRI
- NAEB
- RAB
- Other(s), Specify: ...
- None.

(33) In positive case, what kind of farm supports?

- Fertilizers
- Pesticides

- Agricultural technicians or specialists
 - Money
 - Trainings
 - Other kind(s), (specify)
- (34) What are NGOs that support your farm?**
- W4GR
 - SEAD
 - DFID: Development Fund for International Department
 - UNDP
 - FAO
 - WFP
 - Other(s), specify: ...
 - None.
- (35) What do you think it would happen to your farm and family if the government stopped supports? (N/A if none)**
- Low productivity
 - Development decrease
 - Environment degradation
 - The farming would continue to grow positively
 - Other(s), specify:
- (36) Social, economic, political and institutional constraints on implementing soil conservation measures in Sebeya catchment**
- **Social**
 - Farmers are not motivated to provide enough space from their fields to waterways
 - Farmers do not want to adopt mechanical measures of soil erosion like radical terraces
 - Few farmers access to socio-medias on soil erosion control measures
 - Farmers resist to vote for crop rotation
 - Low educational level and trainability
 - Other(s), specify:
 - **Economic**
 - Few farmers access to microfinance credit
 - Few farmers access to inputs (inorganic fertilizer)
 - Some farmers do not have sufficient energy or income to adopt hard soil erosion control measures like: radical terraces and anti-erosive ditches
 - Other(s), specify:
 - **Political**
 - Politics of establishing trainings without priority on soil conservation measures
 - Politics of setting of laws governing agriculture without farmers willing
 - Other(s), specify:
 - **Institutional**
 - Subsidies from Government and Non-Government institutions are to support a limited number of farmers
 - Seeds and fertilizers reach farmers over time
 - Lack of motivation to farmers who are applying well the BMPs in their farming system
 - Lack of farmers trainings in soil conservation measures
 - Other(s), specify:

(37) **In your opinion, how the government should help to improve the farming systems in Sebeya catchment?**

- Trainings and mobilization of a specialized technical team to assist in implementation of soil conservation measures
- Sensitization of farmers on the benefits of the land use consolidation and the selection of suitable cover crops which will minimize soil erosion in agriculture fields
- Sensitization of farmers on the benefits of the land use consolidation and the selection of suitable cover crops which will minimize the impacts of soil erosion on agriculture fields
- To generalize the application of fertilizers in the whole catchment
- To facilitate farmers access to microfinance credit
- Other ways, specify:

MAJORO'S PhD QUESTIONNAIRE FOR FARMERS INTERVIEW IN THE SEBEYA CATCHMENT (Part B: Kinyarwanda version)

IBIBAZO BIGENEWE KUBAZWA KANDI BIGASUBIZWA IMBONANKUBONE N'ABAHINZI B'IMIRIMA INYURWAHO N'AMAZI YISUKA MU MUGEZI WA SEBEYA MU RWEGO RW'UBUSHAKASHATSI BWA MAJORO FELICIEN KU MPAMYABUSHOBOZI Y'IKIRENGA.

UBUSHAKASHATSI BWA MAJORO FELICIEN KU MPAMYABUSHOBOZI Y'IKIRENGA (PhD) MURI KAMINUZA Y'U RWANDA

“INGAMBA ZOSE ZISHOBOKA ZADUFASHA MU GUSIGASIRA NO KURINDA ISURI UBUTAKA BUHINGWAHO KANDI BUNYURWAHO N'AMAZI YISUKA MU MUGEZI WA SEBEYA, MU RWANDA”

**Injenyeri MAJORO Félicien (Impamyabushozi y'icyiciro cya 3 cya kaminuza: M.Sc)
Umwarimu muri Kaminuza y'u Rwanda (UR)
Koreji y'ubumenyi n'ikoranabuhanga (CST)
Ishuri ry'abenjenyeri (School of Engineering: SoE)
Ishami ry'ubwubatsi n'ibidukikije (Department of Civil, Environmental and Geomatics Engineering: CEGE)
Porogaramu y'amazi n'ibidukikije (Water Resources Engineering Programme)
E-mail: majoro.felicien@yahoo.fr /Tel: (+250)788484054**

**Umugenzuzi mukuru w'ubushakashatsi: Prof. Umaru Garba WALI
Umugenzuzi wungirije wa 1: Dr. Omar MUNYANEZA
Umugenzuzi wungirije wa 2: Prof. Francois Xavier NARAMABUYE**

Kuri mwe musubiza,

Nishimiye kubabona. Ndi umunyeshuri muri Kaminuza y'u Rwanda, ishami ry'ubwubatsi n'ibidukikij. Nkora ubushakashatsi bwo kumpesha impamwubushobozi y'ikirenga (PhD) muri Kaminuza y'u Rwanda ku mushinga witwa:

“INGAMBA ZOSE ZISHOBOKA ZADUFASHA MU GUSIGASIRA NO KURINDA ISURI UBUTAKA BUHINGWAHO KANDI BUNYURWAHO N'AMAZI YISUKA MU MUGEZI WA SEBEYA, MU RWANDA”

Uruhare rwanyu muri ubu bushakashatsi ni inkunga ikomeye kandi ndabasezeranya ko amakuru mumpa nzayakoresha ku mpamvu zo kwiga gusa. Ibisubizo mumpa bizakoreshwa mu gushaka izindi ngamba twakoresha mu kurwanya isuri muri aka gace Sebeya iherereyemo. Izo ngamba zizadufasha mu:

- Kwiyongera k'umusaruro w'ubuhinzi kuberako ifumbire yo mubutaka izaba itagitwarwa n'isuri.
- Kurwanya ibitaka n'imyanda byireka mu migezi n'ibishanga byo mu gace ka Sebeya no mu kiyaga cya Kivu.
- Kurwanya ingaruka mbi ziterwa n'isuri ku bikorwaremezo bishingiye ku mugezi wa Sebeya (ingomero z'amashanyarazi: urwa KEYA n'urwa Gisenyi, uruganda rutunganya amazi rwa GIHIRA n'ibiraro byubatswe mu gace ka Sebeya)

Ibibazo n'ibazwa mbonankubone

- Ibibazo bikurikira ni **37**.
- Ibi bibazo byose bigomba gusubizwa n'abahinzi b'imirima inyurwaho n'amazi yisuka mu mugezi wa Sebeya.
- Kugirango tworoherewe abasubiza, twabahitiyemo ibibazo bisaba ibisubizo bigufi by'ubwoko bukurikira:
- Ibibazo bisaba kuzuza ahateganijwe
- Ibibazo bisaba YEGO cyangwa OYA
- Ibibazo bisaba guhitamo ibisubizo biri byo
- **Ibi bibazo bikurikira bigamije kugaragaza neza ibitera isuri , uko yiyongera, ibyo yangiza n'uburyo bwo kuyirwanya no kuyirinda mu mirima inyurwaho n'amazi yisuka mu mugezi wa Sebeya.**

F. UMWIRONDORO W'USUBIZA

- (38) **Amazina:**
- (39) **Igitsina:**
- Gabo
 - Gore
- (40) **Imyaka ufite y'amavuko:**
- 18-25
 - 26-30
 - 31-40
 - 41-55
 - >55
- (41) **Irangamimerere:**
- Arubatse kandi abana n'uwo bashakanye
 - Ingaragu
 - Yatandukanye n'uwo bashakanye (bombi bariho)
 - Umupfakazi
- (42) **Amashuri yize:**
- Ntabwo yize: ntabwo azi gusoma no kwandika
 - Ntabwo yize: azi gusoma aliko ntazi kwandika
 - Abanza
 - Ayisumbuye
 - Kaminuza
- (43) **Icyo akora:**
- Ahingira abandi
 - Arahingisha ariko agakora akandi kazi
 - Arihingira

**G. IBIGIZE UBUKUNGU BW'URUGO BUTURUTSE KU BUHINZI
N'UBWOROZI:**

(44) Watangiye ryari ubuhinzi?

Igisubizo: Guhera

(45) Ni iki cyaguteye gukora umwuga w'ubuhinzi?

- Kubera imirima y'umurage
- Inyungu mu buhinzi
- Kongera umusaruro
- Kubura akandi kazi
- Izindi mpamvu (zivuge) ...

(46) Ni gute guhinga kwawe kwahinduye imibereho yawe muri iyi myaka 2 ishize (2016-2017 na 2017-2018)?

- Yariyongeye
- Yaragabanyutse
- Yabanje kwiyongera nyuma iragabanyuka
- Yabanje kugabanyuka nyuma iriyongera
- Nta mpinduka

(47) Ku bashatse:

- Bose ni abahinzi
- Umwe muri bo ni umuhinzi
- Nta n'umwe uhinga

(48) Inkomoko y'amafaranga ku umuhinzi utagira ubutaka bwe:

- Amafaranga akomoka mu buhinzi:Rwf/umunsi
- Amafaranga akomoka mu kandi kazi:Rwf/umunsi
- Ni gute ukoresha amafaranga winjije:
 - Guhaha ibiribwa
 - Kwishyura amashuri y'abana
 - Kugura imyambaro
 - Kwishyura amazi
 - Kwishyura amashanyarazi
 - Kwishyura ubukode bw'inzu
 - Kwita ku buzima (Mutiweri, serivisi zo kwivuza,)
 - Ibindi (bivuge)

(49) Ku ufite ubutaka:

a. Imirima afite:

- 1
- 2 cyangwa irenzeho

b. Ubuso bw'ubutaka afite:

- munsi ya 0.1 hegitare
- hejuru ya 0.1 hegitare

c. Inkomoko y'ingenzi y'ubutaka afite:

- Umurage

- Ubwo yaguze
- Ubwo akodesha (cyangwa bamutije)

d. Ni ibihe bihingwa mukunda guhinga? Kubera iki aribyo mwahisemo?

• **Ubwoko bw'ibihingwa**

- Ibishyimbo (.....m xm)
- Soya (.....m xm)
- Ibigori (.....m xm)
- Ibijumba (.....m xm)
- Ibirayi (.....m xm)
- Inyumbati (.....m xm)
- Urutoki (.....m xm)
- Imboga:
 - intoryi (.....m xm)
 - inyanya (.....m xm)
 - ibitunguru (.....m xm)
 - amashu (.....m xm)
 - imiteja (.....m xm)
 - urusenda (.....m xm)
 - karoti (.....m xm)
- Ubunyobwa (.....m xm)
- Ikawa (.....m xm)
- icyayi (.....m xm)
- Ibisheke (.....m xm)
- Ingano (.....m xm)
- Amasaka (.....m xm)
- Amashaza (.....m xm)
- Ubwatsi bw'amatungo:
 - Urubingo (.....m xm)
 - Tiripusakumu (.....m xm)
 - Setariya (.....m xm)
 - Ubundi bwoko bw'ubwatsi (buvuge:); (.....m xm)
- Ubundi bwoko bw'ibihingwa (buvuge:); (.....m xm)
- **Ni iyihe mpamvu wahisemo ibyo bihingwa? :**
- Ni yo soko y'ingenzi y'amafaranga ninjiza (Ubuhinzi butanga amafaranga); buvuge:
- Ni isoko y'ingenzi y'amafaranga ninjiza (Ubuhinzi busagurira amasoko); buvuge:
- Kubihinga biroroha
- Ni ibihingwa byemewe na Leta muri aka karere
- Byera vuba
- Ubwatsi bw'amatungo
- Ibihingwa ngandura rugo:
 - Bitanga umusaruro mwinshi; Ni ibihe?:
 - Bifite intungamubiri; Ni ibihe? :
 - Imirimo mike mu gutekwa; Ni ibihe? :
 - Biraryoha; Ni ibihe? :
 - Byorohera amenyo; Ni ibihe? :
 - Byorohera igogora; Ni ibihe? :

- Amasaka atanga igikoma.
- Ingano zitanga igikoma.
- Umutobe w'ibitoki.
- Inzoga y'urwagwa.

e. Ibitanga amafaranga

- **Ubuhinzi mu gihembwe cy'ihinga gishize; (NK = ntabizi; SA = igihembe cya mbere (A); SB = igihembwe cya B (SB))**

- Ibishyimbo (..... x100 Kg); (1Kg = Rwf); SA or SB
- Soya (..... x100 Kg); (1Kg = Rwf); SA or SB
- Ibigori (..... x100 Kg); (1Kg = Rwf); SA or SB
- Ibijumba (..... x100 Kg); (1Kg = Rwf); SA or SB
- Ibirayi (..... x100 Kg); (1Kg = Rwf); SA or SB
- Imyumbati (..... x100 Kg); (1Kg = Rwf); SA or SB
- Ibitoki (..... x100 Kg); (1Kg = Rwf); SA or SB
- Imboga:
 - Intoryi (..... x 70 Kg); (1Kg = Rwf); SA or SB
 - Inyanya (..... x 130 Kg); (1Kg = Rwf); SA or SB
 - Ibitunguru (..... x100 Kg); (1Kg = Rwf); SA or SB
 - Amashu (..... x60 Kg); (1Kg = Rwf); SA or SB
 - Imiteja (..... x100 Kg); (1Kg = Rwf); SA or SB
 - Urusenda (..... x30 Kg); (1Kg = Rwf); SA or SB
 - Karoti (..... X120 Kg); (1Kg = Rwf); SA or SB
- Ubunyobwa (..... x100 Kg); (1Kg = Rwf); SA or SB
- Ikawa (..... x90 Kg); (1Kg = Rwf); SA or SB
- icyayi (..... x35 Kg); (1Kg = Rwf); SA or SB
- Ibisheke:
 - Igihembwe cy'isarura gisherutse (SA cg SB):
 - Amafaranga yakomotse ku musaruro w'ibisheke: Rwf
 - Umubare w'ama FUSO:
 - Umubare wa za DAIHATSU (= 4xumubare w'ama FUSO) =
 - Umubare wa “tons” kuri buri DAIHATDU = 4tons
 - Tons zo mu bisheke byasaruwe =umubare wa za DAIHATSUx4tons =tons
- Ingano (..... x100 Kg); (1Kg = Rwf); SA or SB
- Amasaka (..... x100 Kg); (1Kg = Rwf); SA or SB
- Amashza (..... x100 Kg); (1Kg = Rwf); SA or SB
- Ubwatsi bw'amatungo:
 - Urubingo (..... xRwf/m²); SA or SB
 - Tiripusakumu (..... xRwf/m²); SA or SB
 - Setariya (..... xRwf/m²); SA or SB
 - Ubundi bwoko bw'ubwatsi bw'amatungo (buvuge:)
(..... xRwf/m²); SA or SB

- Ubundi bwoko bw'ibihingwa (buvuge:).
..... (..... x100 Kg); (1Kg = Rwf); SA or SB

- **Amafaranga akomoka ku bworozi:**

- **Inka (mu bihembwe bitatu bishize A+B+C: Nzeri 2017 kugera Kanama 2018):**

- Umubare w'inka afite ubu:
- Umubare w'inka mu mwaka ushize:
- Amafaranga yabonye ku nka zose yagurishijwe: Rwf
- Umubare w'amata ku muni:
- Igiciro cy'amata: 1L =Rwf
- Amafaranga yose yakomotse ku ifumbire: Rwf

- **Ingurube (mu bihembwe bitatu bishize A+B+C: Nzeri 2017 kugera Kanama 2018):**

- Umubare w'ingurube afite ubu:
- Umubare w'ingurube yagurishije mu mwaka ushize:
- Amafaranga yabonye ku ngurube zose yagurishijwe: Rwf
- Amafaranga yose yakomotse ku ifumbire: Rwf

- **Intama (mu bihembwe bitatu bishize A+B+C: Nzeri 2017 kugera Kanama 2018):**

- Umubare w'intama afite ubu:
- Umubare w'intama yagurishije mu mwaka ushize:
- Amafaranga yabonye ku ntama zose yagurishijwe: Rwf
- Amafaranga yose yakomotse ku ifumbire: Rwf

- **Ihene (mu bihembwe bitatu bishize A+B+C: Nzeri 2017 kugera Kanama 2018):**

- Umubare w'ihene afite ubu:
- Umubare w'ihene yagurishije mu mwaka ushize:
- Amafaranga yabonye ku ihene zose yagurishijwe: Rwf
- Amafaranga yose yakomotse ku ifumbire: Rwf

- **Inkwavu (mu bihembwe bitatu bishize A+B+C: Nzeri 2017 kugera Kanama 2018):**

- Umubare w'inkwavu afite ubu:
- Umubare w'inkwavu yagurishije mu mwaka ushize:
- Amafaranga yabonye ku nkwavu zose yagurishijwe: Rwf
- Amafaranga yose yakomotse ku ifumbire: Rwf

- **Inkoko (mu bihembwe bitatu bishize A+B+C: Nzeri 2017 kugera Kanama 2018):**

- Umubare w'inkoko afite ubu:
- Umubare w'inkoko yagurishije mu mwaka ushize:
- Amafaranga yabonye ku nkoko zose yagurishijwe: Rwf
- Umubare w'amagi agurisha ku muni:
- Igiciro cy'igi: 1gi = Rwf
- Amafaranga yose yakomotse ku ifumbire: Rwf

- **Amafi (mu gihembwe gishize (SA cg SB cg SC): Nzeri 2017 kugera Kanama 2018):**

- Umubare w'ibibyuzi by'amafi:
- Ingano ya buri kizenga:m xm; Volume =

- Ibiro byose by'amafi yagurishijwe:Kg
- Igiciro cy'ikiro cy'ifi: 1 Kg cy'ifi =Rwf
- Amafaranga yose yakomotse ku musaruro w'amafi mu gihembwe gihurutse:Rwf

• **Ni iki ukoresha amafaranga winjije:**

- Guhaha ibiribwa
- Kwishyura amashuri y'abana
- Kugura imyambaro
- Kuyashora mu buhinzi
- Kwishyura amazi
- Kwishyura amashanyarazi
- Kwita ku buzima (Mutiweri, serivisi zo kwivuzza,)
- Kuyashora mu bworozi
- Kwishyura ubukode bw'inzu
- Gusana inzu
- Ibindi (bivuge)

H. **IBIDUKIKIJE**

(50) Muhingisha imashini?

- Yego
- Oya

(51) Ni gute iterambere ryo gukoresha imashini ryahinduye ubuhinzi bwawe?

- Kwanduza ikirere
- Gutakaza umwimerere w'ubutaka
- Ibura ry'akazi ku bakora umurimo wo guhingisha amaboko yabo
- Isuri iboneraho ikiyongera
- Ifumbire y'ubutaka iragabanuka

(52) Ni ubuhe bwoko bw'ifumbire ukoresha?

- Imborera
- Imvaruganda

(53) Ni iyihe ngaruka ifumbire mvaruganda yagize ku murima wawe ugereranyije n'umusaruro waguhaga? :

- Wariyongeye
- Waragabanyutse

(54) Wabonye umusaruro umeze ute niba nta yindi mvaruganda wongeye gushyira mu murima wawe? :

- Wariyongeye
- Waragabanyutse usubira kuwo nahoranye mbere yo gukoresha imvaruganda.
- Waragabanyutse cyane ujya muni y'uwo nari mfite mbere yo gukoresha imvaruganda.

(55) Kuri wowe wumva isuri ari iki?

- Amazi menshi arimo ibyondo arenga kandi akangiza ibyo asanze ku nkombe z'imigezi n'indi miyoboro y'amazi
- Iyo imvura iciye imikoki mu mirima
- Iyo ubutaka buvanywe mu mwanya wabwo n'imvura cyangwa amazi atemba
- Iyo ubutaka buvuye mu mwanya wabwo, butwawe kandi bukagira aho burundwa n'amazi
- Itunguka ry'ubutaka bitewe n'imvura

- Umwuzure wuzura imigezi n'indi miyoboro y'amazi ukangiza ibihingwa, abantu n'ibintu biri ku nkombe.
 - Iyo umuyaga ukukumbye ibitaka ukabijyana mu kirere cyangwa ahandi hantu
 - Ukindi gisobanuro; kivuge:
- (56) Ni ibihe bintu bya kamere bitera isuri muri aka gace k'umugezi wa Sebeya waba warabonye?**
- Ubuhaname bw'ubutaka; Aho wayibonye hari ubuhaname:
 - Imvura nyinshi itera umwuzure; Aho wayibonye itewe n'imvura nyinshi:
 - Imvura itera ubutaka gutenguka; Aho wabonye ubutaka butenguka kubera imvura:
 - Umutingito; Aho wabonye ubutaka bwavuye mu mwanya wabwo kubera umutingito:
 - Umuyaga mwinshi; Aho wabonye ubutaka butwarwa n'umuyaga:
- (57) Haba haraho wabonye ingaruka mbi zo guhinga nabi ku bidukikije mu gace k'umugezi wa Sebeya?**
- Yego
 - Oya
- (58) Zivuge niba ari yego.**
- Gutema amashyamba bashaka ubutaka bwo guhinga; Aho ubizi:
 - Guhingagura ubutaka n'imashini; Aho ubizi: ...
 - Guhingagura ubutaka bubaka amaterasi; Aho ubizi:
 - Guhingagura ubutaka bubaka imiferege yo kuhira icyayi; Aho ubizi:
 - Kumaraho ibyatsi bashaka ubwatsi bw'amatungo; Aho ubizi: ...
 - Ubutaka bukomera bitewe n'amatungo yahacundaguye; Aho ubizi:
 - Ubutaka bwatwawe n'isuri kuberako bahahinze; Aho ubizi: ...
 - Amazi afata ibara ry'igitaka kubera isuri ituruka mu mirima yahinzwe; Aho ubizi: ...
 - Hari izindi (izihe:); Aho uzizi:
- (59) Vuga ibindi bikorwa bitari iby'ubuhinzi byangiza ubutaka muri aka gace ka Sebeya.**
- Aho bacukura amabuye y'agaciro; Aho uzi:
 - Aho bubaka imihanda; Aho uzi: ...
 - Aho bacukura ibitataka byo kubaka imihanda; Aho uzi:
 - Aho bacukura amabuye yo kubaka imihanda; Aho uzi:
 - Aho bubaka inzu; Aho uzi: ...
 - Aho bacukura amabuye yo kubaka inzu; Aho uzi:
 - Aho bacukura kugirango bubake imiyoboro y'amashanyarazi; Aho uzi:
- (60) Hari icyo wakoze ku butaka bwawe kugirango ubungabunge ibidukikije mu murima wawe?**
- Yego
 - Oya
- (61) Niba ari yego wabigenje ute?**
- Kwirinda gutema atabifitiye uruhushya
 - Kwirinda gutwika ibyatsi
 - Kwirinda guhingagura ubutaka
 - Gufumbiza ifumbire mvaruganda yemewe
 - Guhinga ibihingwa byemew na Leta
 - Gutera ibyatsi n'ibiti bifata ubutaka ku migugunzi

- Guhinga ahabugenewe nubahiriza inkengero z'imigezi n'izi imihanda
- Indi myitwarire; Yivuge:

I. INGAMBA ZO KUBUNGABUNGA UBUTAKA

(62) Ni ubuhe bwoko bw'isuri wabonye mu gace k'umugezi wa Sebeya?

- Iyo amazi akubura agataka ko hejuru k'ubutaka; Wayibonye he? :
- Iyo amazi aca uduferege mu mirima; Wayibonye he? :
- Imikoki yaciwe n'amazi; Wayibonye he?
- Iyo umugezi ucukuye inkombe ukaba wanayitengura; Wayibonye he? : ...

(63) Ahantu hatari imirwanyasuri hashobora kwibasirwa n'isuri?

- Yego
- Oya

(64) Vuga ibyangijwe n'isuri muri aka gace k'umugezi wa Sebeya?

- Ibihingwa byatwawe n'inkangu; Aho abizi: ...
- Ibihingwa byatwikiriwe n'ibitaka byazanwe n'isuri; Aho abizi: ...
- Isuri yanitse imizi y'ibihingwa; Aho abizi: ...
- Ubutaka bwatwawe n'inkangu; Aho ayizi: ...
- Ubutaka bwera bwatwawe n'isuri; Aho abuzi:
- Abantu batwawe n'inkangu; Aho abazi: ...
- Amatungo yatwawe n'inkangu; Aho ayazi: ...
- Inzu zatwawe n'inkangu; Aho azizi: ...
- Isuri yanduza amazi ajya mu ruganda rw'amazi rwa Gihira
- Isuri yongera ibitaka mu mazi ajya mu ngomero z'amazi (urwa Keya n'urwa Gisenyi)
- Isuri ikukumba kandi ikohereza ibitaka n'amabuye by'ubwoko bwose mu ngomero z'amazi (urwa Keya n'urwa Gisenyi)
- Inzira z'amazi zuzura ibitaka; Aho ubizi: ...
- Ibitaka by'isuri byirunda mu muhanda; Aho yabibonye: ...
- Inkangu icika ku nkombe y'umuhanda; Aho ayizi: ...
- Umuhanda ucikamo kabiri kubera inkangu; Aho yabibonye: ...
- Ibitaka by'isuri byangiza ibiraro; Aho yabibonye: ...
- Ibindi; Aho abizi: ...

(65) Ni ubuhe buryo bwo kubungabunga ubutaka wabonye bukoreshwa muri aka gace ka Sebeya?

25. Amatarasi; Aho wayabonye:
26. Gusasira ibihingwa; Aho uzi:
27. Guhinga ibihingwa bitwikira ubutaka kurusha ibindi; Aho ubizi: ...
28. Amayogi atambitse aho guhinga ayegetse ku musozi; Aho uyazi:
29. Imiferege irwanya isuri; Aho iri: ...
30. Ibiti biteye ku misozi ihanamye; Aho wabibonye: ...
31. Ibiti bifata ubutaka ku nkombe z'imigezi; aho biri: ...
32. Gutera ibyatsi bifata ubutaka; Aho biri: ...
33. Imiferege itwara amazi y'imvura (ruhurura y'imvura); Aho iri: ...
34. Ikizenga cyakira amazi y'imvura kigasigarana umucanga n'ibitaka mbere yo kuyohereza mu mugezi; Aho ukizi: ...
35. Ikizenga gifata amazi y'imvura ku musozi; Aho ukizi:

36. Akagega gafata umucanga n'ibitaka kakarekura amazi agakomeza akagenda; Aho wakabonye:
37. Imiferege y'amazi ku mihanda; Aho uyizi:
38. Igihombo kini bashyira mu mwanya w'ikiraro gito; Aho ukizi: ...
39. Udukuta bakikiza umurima ngo tubuze amazi kwingira cg gusohoka batabishaka; Aho watubonye: ...
40. Imireko n'ibigega bifata amazi ku mazu; Aho biri: ...
41. Ibigabanya ingufu n'umuvuduko by'amazi:
- d. Agakuta gatangira amazi kugera ku buhagarike bwako kakuzura agakomeza. Aho ukazi: ...
 - e. Ibizenga bireka amazi yo ku misozi; Aho ubizi: ...
 - f. Amabuye ashinyitse bubakiye mu muferege; Aho uyazi: ...
42. Ingamba zifashisha ibimera mu gufata ubutaka bw'imigunguzi:
- f. Icyatsi cya vetiveri; Aho ukizi: ...
 - g. Urubingo; Aho uruzi: ...
 - h. Icyatsi cya setariya; Aho ucyizi: ...
 - i. Icyatsi cya tiripusakumu; Aho ukizi: ...
 - j. Icyatsi cya pasiparumu; Aho kiri: ...
43. Inkuta zikozwe mu makoro na senyenge mu gufata imikingo; aho ziri: ...
44. Imiferege itewemo ibyatsi; Aho iri: ...
45. Ibyatsi bitrwa ku nkengero z'imigezi ngo bibuze ibitaka kujya mu mugezi; Aho biri: ...
46. Utuzitiro tw'imyanda ku nyubako z'imihanda no kubungabunga isuri ku mihanda; Aho utuzi: ...
47. Gukomeza inkombe z'imigezi:
- h. Ukoreshaje imifuka y'emicanga; Aho uyizi:
 - i. Inkuta zikozwe mu makoro afashwe na senyenge; Aho uzizi: ...
 - j. Amabuye akoteye impande y'ikiraro; Aho uyazi: ...
 - k. Amabuye arunze mu ndiba z'inkombe z'umugezi; Aho uyazi; ...
 - l. Urubingo ku nkombe z'umugezi; Aho uruzi: ...
 - m. Imigano ku nkombe z'umugezi; Aho uyizi: ...
 - n. Ibiti bya Gereveriya ku nkombe z'umugezi; Aho ubizi: ...
48. Ubundi buryo (buvuge:); Aho ubuze: ...

(66) Ni ubuhe buryo bukenewe bwo kubungabunga ubutaka muri aka gace ka Sebeya?

1. Amatarasi; YEGO cg OYA
2. Gusasira ibihingwa; YEGO cg OYA
3. Guhinga ibihingwa bitwikira ubutaka kurusha ibindi; YEGO cg OYA
4. Amayogi atambitse aho guhinga ayegetse ku musozi; YEGO cg OYA
5. Imiferege irwanya isuri; YEGO cg OYA
6. Ibiti biteye ku misozi ihanamye; YEGO cg OYA
7. Ibiti bifata ubutaka ku nkombe z'imigezi; YEGO cg OYA
8. Gutera ibyatsi bifata ubutaka; YEGO cg OYA
9. Imiferege itwara amazi y'imvura (ruhurura y'imvura); YEGO cg OYA

10. Ikizenga cyakira amazi y'imvura kigasigarana umucanga n'ibitaka mbere yo kuyohereza mu mugezi; YEGO cg OYA
 11. Ikizenga gifata amazi y'imvura ku musozi; YEGO cg OYA
 12. Akagega gafata umucanga n'ibitaka kakarekura amazi agakomeza akagenda; YEGO cg OYA
 13. Imiferege y'amazi ku mihanda; YEGO cg OYA
 14. Igihombo kini bashyira mu mwanya w'ikiraro gito; YEGO cg OYA
 15. Udukuta bakikiza umurima ngo tubuze amazi kwingira cg gusohoka batabishaka; YEGO cg OYA
 16. Imireko n'ibigeza bifata amazi ku mazu; YEGO cg OYA
 17. Ibigabanya ingufu n'umuvuduko by'amazi:
 - Agakuta gatangira amazi kugera ku buhagarike bwako kakuzura agakomeza; YEGO cg OYA
 - Ibizenga bireka amazi yo ku misozi; YEGO cg OYA
 - Amabuye ashinyitse bubakiye mu muferege; YEGO cg OYA
 18. Ingamba zifashisha ibimera mu gufata ubutaka bw'imigunguzi:
 - Icyatsi cya vetiveri; YEGO cg OYA
 - Urubingo; YEGO cg OYA
 - Icyatsi cya setariya; YEGO cg OYA
 - Icyatsi cya tiripusakumu; YEGO cg OYA
 - Icyatsi cya pasiparumu; YEGO cg OYA
 19. Inkuta zikozwe mu makoro na senyenge mu gufata imikingo; YEGO cg OYA
 20. Imiferege itewemo ibyatsi; YEGO cg OYA
 21. Ibyatsi bitrwa ku nkengero z'imigezi ngo bibuze ibitaka kujya mu mugezi; YEGO cg OYA
 22. Utuzitiro tw'imyanda ku nyubako z'imihanda no kubungabunga isuri ku mihanda; YEGO cg OYA
 23. Gukomeza inkombe z'imigezi:
 - Ukoresheje imifuka y'emicanga; YEGO cg OYA
 - Inkuta zikozwe mu makoro afashwe na senyenge; YEGO cg OYA
 - Amabuye akoteye impande y'ikiraro; YEGO cg OYA
 - Amabuye arunze mu ndiba z'inkombe z'umugezi; YEGO cg OYA
 - Urubingo ku nkombe z'umugezi; YEGO cg OYA
 - Imigano ku nkombe z'umugezi; YEGO cg OYA
 - Ibiti bya Gereveriya ku nkombe z'umugezi; YEGO cg OYA
 24. Ubundi buryo (buvuge:); YEGO cg OYA
- (67) Ufite imirwanyasuri mu murima wawe?**
- Yego
 - Oya
- (68) Niba ntayo, ni ku yihe mpamvu (Ihitamo A) kandi utubwire icyo uteganya gukora mu gushyira imirwanyasuri mu murima wawe (Ihitamo B)?**
- Ihitamo A**
8. Birahenze kuko bisaba imirimo myinshi n'abakozi benshi
 9. Ntabwo yari azi uko isuri irwanwa
 10. Byangiza ubutaka
 11. Bigabanya ubutaka buhingwa

12. Ubutaka ntabwo ari ubwe (akazi ke ni uguhinga gusa)

13. Akodesha ubutaka

14. Izindi mpamvu (zivuge:)

Ihitamo B

- f. Nta kibazo cy'amafaranga, yiyemeje kurwanya isuri ku buryo bushoboka mu mirima ye yose
- g. Afite ubushobozi bucye, akeneye ubwunganizi
- h. Nta bushobozi na bucye afite, akeneye umuterankunga
- i. Ntashaka gukoresha uburyo ubwo ari bwo bwose mu kurwanya isuri mu mirima ye ku mpamvu yavuze muri A.
- j. Indi migambi (yivuge:)

Ibisubizo:

- Amatarasi; Ihitamo A: ... cg Ihitamo B:
- Gusasira ibihingwa; Ihitamo A: ... cg Ihitamo B:
- Guhinga ibihingwa bitwikira ubutaka kurusha ibindi; Ihitamo A: ... cg Ihitamo B:
- Amayogi atambitse aho guhinga ayegetse ku musozi; Ihitamo A: ... cg Ihitamo B:
- Imiferege irwanya isuri; Ihitamo A: ... cg Ihitamo B:
- Ibityi biteye ku misozi ihanamye; Ihitamo A: ... cg Ihitamo B:
- Gutera ibyatsi bifata ubutaka; Ihitamo A: ... cg Ihitamo B:
- Ikizenga gifata amazi y'imvura ku musozi; Ihitamo A: ... cg Ihitamo B:
- Akagega gafata umucanga n'ibitaka kakarekura amazi agakomeza akagenda; Ihitamo A: ... cg Ihitamo B:
- Udukuta bakikiza umurima ngo tubuze amazi kwinjira cg gusohoka batabishaka; Ihitamo A: ... cg Ihitamo B:
- Imireko n'ibigege bifata amazi ku mazu; Ihitamo A: ... cg Ihitamo B:
- Ibigabanya ingufu n'umuvuduko by'amazi:
 - Agakuta gatangira amazi kugera ku buhagarike bwako kakuzura agakomeza; Ihitamo A: ... cg Ihitamo B:
 - Ibizenga bireka amazi yo ku misozi; Ihitamo A: ... cg Ihitamo B:
 - Amabuye ashinyitse bubakiye mu muferege; Ihitamo A: ... cg Ihitamo B:
- Ingamba zifashisha ibimera mu gufata ubutaka bw'imigunguzi:
 - Icyatsi cya vetiveri; Ihitamo A: ... cg Ihitamo B:
 - Urubingo; Ihitamo A: ... cg Ihitamo B:
 - Icyatsi cya setariya; Ihitamo A: ... cg Ihitamo B:
 - Icyatsi cya tiripusakumu; Ihitamo A: ... cg Ihitamo B:
 - Icyatsi cya pasiparumu; Ihitamo A: ... cg Ihitamo B:
- Inkuta zikozwe mu makoro na senyenge mu gufata imikingo; Ihitamo A: ... cg Ihitamo B:
- Imiferege itewemo ibyatsi; Ihitamo A: ... cg Ihitamo B:
- Ibyatsi biterwa ku nkengero z'imigezi ngo bibuze ibitaka kujya mu mugezi; Ihitamo A: ... cg Ihitamo B:
- Gukomeza inkombe z'imigezi (utugezi duto):
 - Ukoresheje imifuka y'imicanga; Ihitamo A: ... cg Ihitamo B:
 - Inkuta zikozwe mu makoro afashwe na senyenge; Ihitamo A: ... cg Ihitamo B:
 - Urubingo ku nkombe z'umugezi; Ihitamo A: ... cg Ihitamo B:
 - Imigano ku nkombe z'umugezi; Ihitamo A: ... cg Ihitamo B:

- Ibiti bya Gereveriya ku nkombe z'umugezi; Ihitamo A: ... cg Ihitamo B:
- Ubundi buryo (buvuge:); Ihitamo A: ... cg Ihitamo B:

J. URUHARE RWA LETA MU BUHINZI

(69) Ni ibihe bigo bya Leta bigufasha mu buhinzi bwawe?

- MINAGRI
- NAEB
- RAB
- Ahandi bwaturutse, havuge:
- Ntacyo.

(70) Niba hari ibigo bya Leta bigufasha, ni ubuhe bufasha uhabwa?

- Ifumbire
- Imiti yica udukoko
- Abatekinisiye b'ubuhinzi
- Amahugurwa
- Ubundi bufasha, buvuge:

(71) Ni ibihe bigo byigenga bigufasha mu buhinzi bwawe?

- W4GR
- SEAD
- DFID: Development Fund for International Department
- UNDP
- FAO
- WFP
- Ahandi bwaturutse, havuge:
- Ntacyo.

(72) Ku muntu ufashwa, vuga icyari guhinduka iyo Leta ihagarika inkunga iguha ku buhinzi.

- Umusaruro muke
- Iryari iterambere ryasubira inyuma
- Ibidukikije ntibyabungabungwa
- Ubuhinzi bwakomeza kugenda neza nk'ubusanze
- Ukundi byagenda, bivuge:

(73) Vuga imbogamizi uwaza gushyira mu bikorwa uburyo bwo kurwanya isuri mu gace ka Sebeya yahura na zo.

• **Imbogamizi ku mibereho myiza**

- Abahinzi bamwe na bamwe ntibashaka ko hacukurwa imiferege mu mirima yabo
- Abahinzi bamwe na bamwe barwanya uburyo ubwo aribwo bwose bubirindura ubutaka mu kurwanya isuri nk'amatarasi y'indinganire.
- Abahinzi bamwe na bamwe ntibagerwaho n'ibinyamakuru bigamije kwigisha kurwanya isuri.
- Abahinzi bamwe na bamwe ntibashaka gusimburanya igihingwa kimwe ku kindi uko igihembwe gitashye
- Ubumenyi buke n'amahugurwa adahagije ku mirwanyasuri
- Izindi. Ni izihe: ...

• **Imbogamizi ku bukungu**

- Abahinzi bake ni bo bagurizwa n'ibigo by'imari iciriritse

- Abahinzi bake ni bo bagerwaho n'ifumbire mvaruganda
- Abahinzi bamwe na bamwe ntibafite imbaraga cyangwa amafaranga bihagije byo gucukuzza amatarasi n'imiferege
- Izindi. Ni izihe: ...
- **Imbogamizi mu bya politiki**
 - Politiki itegura amahugurwa idashyize ku isonga imigambi yo kurwanya isuri
 - Politiki ishyiraho amabwiriza agenga ubuhinzi atitaye ku byifuzo by'abahinzi
 - Izindi. Zivuge:

- **Imbogamizi zirebana n'ibigo bya leta cyangwa ibyigenga**
 - Imfashanyo iva mu bigo bya leta cyangwa ibyigenga igera ku bahinzi bake
 - Imbuto n'ifumbire bigera ku bahinzi bitinze
 - Hagombye ishimwe ku bahinzi bose bitabira imirwanyasuri mu mirima yabo
 - Amahugurwa agamije kurwanya isuri yagombye kuba ku bahinzi bose
 - Izindi. Zivuge:
- (74) **Ni iki wumva leta yakora gishobora gufasha kuzamura ubuhinzi mu gace ka Sebeya?**
 - Gushyiraho amahugurwa menshi no kwegereza impuguke mu mirwanyasuri abahinzi bo mu gace ka Sebeya
 - Kwigisha abahinzi ibyiza byo guhuza ubutaka no guhinga ibihingwa birwanya isuri kurusha ibindi
 - Gushyiraho amabwiriza yo gufumbira imirima yose yo mu gace ka Sebeya
 - Korohereza abahinzi mu kubona inguzanyo mu bigo by'imari
 - Ikindi leta yakora. Kivuge: