ASSESSING THE ROLE OF ECOSYSTEM BASED APPROACHES FOR SOIL EROSION REDUCTION IN THE CATCHMENT OF BYABAGABO-JABANA, KIGALI-RWANDA

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February, 2016

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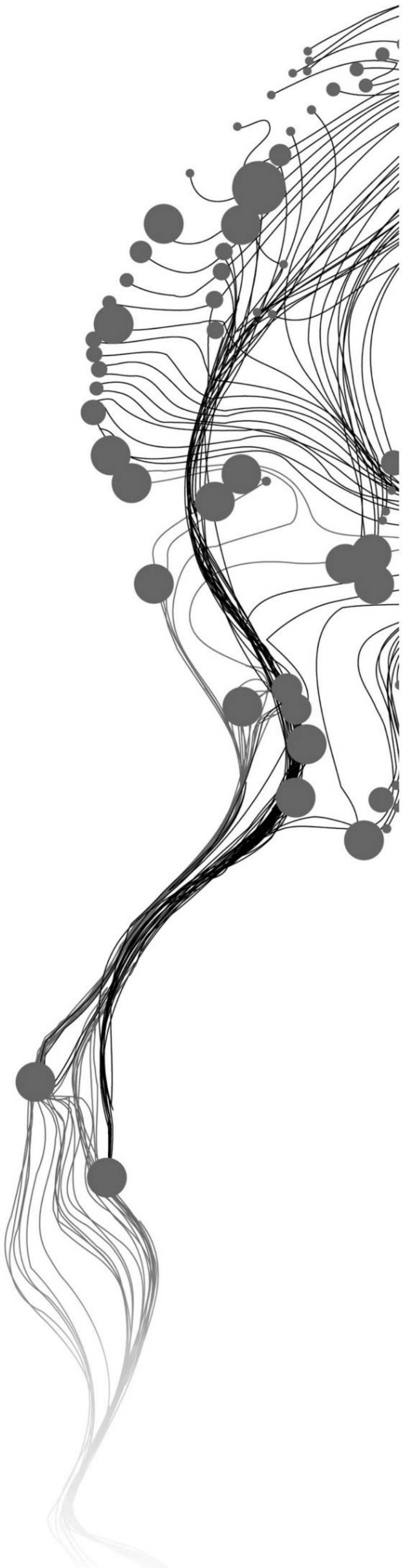

ASSESSING THE ROLE OF ECOSYSTEM-BASED APPROACHES FOR SOIL EROSION REDUCTION IN THE CATCHMENT OF BYABAGABO-JABANA, KIGALI-RWANDA

MARCELINE UWASE

Enschede, The Netherlands, [February, 2016]

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Natural Resources Management

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ABSTRACT

Soil erosion is a major environmental problem worldwide. Engineering measures are often used as mitigation measures but they require a high cost of implementation. Ecosystem based measures can be a measure to reduce soil erosion but their effects are less assessed for both onsite and offsite effect reduction. As a result, the total benefits provided by ecosystem-based measures, including a range of ecosystem services are underestimated. The objective of this research was (1) to assess the soil erosion for both onsite and offsite effects, (2) analyse the effects of engineering and ecosystem based approaches and (3) cost benefit analysis of both measures followed by a comparison of the measures to select the cost effective measure. In this research, assessment of driving factors of erosion, a comparison of engineering and ecosystem-based soil conservation measure, and a cost-benefit analysis of these measures was done to select the cost effective measure. I used the sub-catchment of Byabagabo-Jabana in Rwanda as a case study area for this research. The soil erosion was assessed using the model OpenLISEM and cost benefit analysis based on material, labour, and ecosystem service benefits was used to select the cost effective measure over time. The study shows that both rainfall and land use types contributed to the increase of soil loss and sedimentation in the areas. Both measures contributed to a decrease in soil loss and sedimentation, but bench terraces performed better. Similarly, both the engineering and ecosystem-based measures showed a recovery of the cost in a period of 20 years, but bench terraces measures revealed to be most profitable. The result of this can help to support soil conservation planning, and most importantly to value all the benefits of the ecosystem especially in Rwanda.

Key words: Soil erosion assessment, OpenLISEM, ecosystem-based approaches, engineering measures, soil loss and sedimentation, cost-benefit analysis

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1. INTRODUCTION

1.1. Background

Ecosystem services are the benefits that people get from the ecosystem (Dooley, 2005). Among these ecosystem services, there are provisioning services like food and timber; regulating services which include erosion control, floods prevention and climate regulation; cultural services such as recreational and spiritual place; as well as supporting services like nutrient cycling and soil formation (Millennium Ecosystem Assessment, 2005). Over the past 50 years, ecosystems have been extensively changed as compared to the past period due to the high demand of food, fresh water, timber and fuelwood; which has resulted to the depletion of biodiversity (Millennium Ecosystem Assessment, 2005). For this appraisal, the ecosystem services have been assessed by the United Nations, through Millennium Ecosystem Assessment in 2005 to understand, value, model and manage ecosystem services in a sustainable way.
A wide range of studies are been conducted to understand the importance of ecosystem services and their contribution to the community welfare. For example, Boojh (2012), has shown how ecosystem services can reduce the number of physical exposure acting as buffer to mitigate hazards impacts and/or provide natural protection against landslides, flooding and erosion.

Soil erosion is worldwide environmental problem. It can cause onsite erosion and offsite sedimentation effects which imply the decrease of soil productivity and economic damage to other properties. For example, onsite and offsite effects of erosion has cost $157 million in New Zealand in 2008 (Jones et al., 2008). In addition, a study conducted in Rwanda on cereals and tubers has shown that soil erosion resulted in estimated cost of $ 20 per hectare per year which is equal to an amount of $ 23 million at an area of 12 thousand square kilometre (Berry et al., 2003). Therefore, there is a need to assess the risk of erosion in order to take mitigation measures.

Models are useful tools to predict soil erosion for appropriate soil conservation planning (Shi et al., 2004). Different tools and methods are been applied all over the world to predict erosion rate among which we have process-based models such as LISEM (Limburg Soil Erosion Model) and OpenLISEM (Open source Limburg Soil Erosion Model) and empirical model such as USLE (Universal Soil Loss Equation), and RUSLE (Revised Universal Soil Loss Equation). OpenLISEM is an open source version of LISEM and is used to simulate runoff and erosion based on single rainstorm (De Roo & Jetten, 1999), however few studies have been conducted to predict soil erosion using process-based model due to high input data requirement (B. Liu & Nearing, 2000). The USLE model which is well known and most frequently used worldwide due to its simplicity, robustness and availability of input data (Grimm et al., 2002). Overall, most of the process-based models are being used because they provide detailed information on the soil erosion. Empirical models are being used all over the world for soil conservation due to the input data availability and simplicity but their output often lack accurate assessment. Predicting soil erosion provides information on highly affected area in which intervention are needed.

An appropriate soil conservation plan is required to reduce the negative effects of soil erosion. A lot of research has been conducted to investigate on the role of vegetation for hazards reduction. For example, a study has been conducted in a Mediterranean shrub lands; results indicated an important herbaceous layer for reducing soil erosion by maintaining the water retention capacity of the soil (Raventós et al., 2012). Furthermore, other research has shown how the disturbance of the ecosystem services results in a high decrease of their value. Dominati et al. (2014) assessed the total economic value of ecosystem services on uneroded steep slope, they showed that the removal of topsoil by erosion has dropped the ecosystem services value by 65%.

The loss and degradation of ecosystem services is still growing due to land use conversion by the human to meet their needs (Millennium Ecosystem Assessment, 2005). In addition, many ecosystem services lack value which can lead to degradation and inappropriate use of the ecosystem (Kareiva et al., 2011). Therefore, a clear understanding of the ecosystem economics can provide information to decision-makers on how much to conserve in the world of competing demands for resources (Kumar & Martinez-alier, 2011).
The quantification and valuation of ecosystem services is necessary for a sustainable management of the environment, as well as for future generations (TEEB, 2011). To ensure continuous flow of ecosystem benefits, strategies, such as creating markets for ecosystem services are developed (Willemen et al., 2013).

Various methods and tools to map and value ecosystem services have been developed to assess the trade-offs and ecosystem services values in the future (Nelson & Daily, 2010). The rationale for mapping ecosystem services has been adopted among different studies. It can refer to assigning a monetary unit to ecosystem services (Schägner et al., 2013), or analysing trends in ecosystem services (Maes et al., 2012) and/or estimating the cost benefit of ecosystem services (Naidoo & Ricketts, 2006). Tools have been developed to map ecosystem services such as INVEST (Integrated Valuation of Ecosystem Services) which aims at informing decision-makers about trade-offs associated with management choices and where to invest for a sustainable conservation (Tallis & Polasky, 2009). A blueprint has been developed to reduce uncertainty related to lack of transparent and systematic use of the data while trying to quantify ecosystem services (Crossman et al., 2013).

1.2. Problem statement

Rwanda is a steep sloped country where erosion risk has increased overtime. This can mainly be attributed to the changing of global weather pattern as well as local drivers which include farming practices (Kagabo et al., 2013). Moreover, the country also face some other environmental challenges such as deforestation, fragile soils and urban encroachment which accelerate the risk of erosion (City of Kigali, 2013).

Rainfall amount, intensity and frequency are climatic factors that also contribute to the increase of soil erosion risks. However, the gravity of these risks does not only depend on climatic factors alone, but also it is influenced by other factors like topography, soil, vegetation and land use and also triggering factors such as improper use of the land. The impacts of erosion cause on-site damage which implies the removal of the top soil and off-site damage resulting on the sedimentation of water body (USDA Natural Resources Conservation Service (NRCS), 2000). Therefore, there is a need to mitigate both onsite and offsite risks by implementing the right conservation measure.

Different measures have been applied to reduce soil erosion in Rwanda among which there are biological measures such as mulching, reforestation and agroforestry as well as engineering measures such as bench terraces and progressive terraces (Twagiramungu, 2006). The most commonly implemented engineering measure is bench terracing. For example, in a study conducted in Rwanda on soil conservation measures, results show that bench terraces cover 42% of all the measures implemented in Rwanda while other measures such as agroforestry cover around 10% (Bizoza & de Graaff, 2012).
Currently the government of Rwanda is investing in bench terraces construction, but bench terraces requires high implementation and maintenance cost. In addition, bench terraces can generate adverse environmental impacts and lead to a false sense of security (Boojh, 2012). Therefore, there is a need to select suitable

location to implement terracing measures or replace them with other conservation measures especially biological measures since terracing measures can involve negative effects.

Reforestation is a preventive measures for soil erosion measure but still its importance is not well assessed. Implementing reforestation measures can provide various benefits including erosion control, timber provision, recreation services and climate regulation (Twagiramungu, 2006). However, few studies have assessed the economic impacts of reforestation measures and compare the cost with engineering measures. In addition, there is a need to link the onsite and offsite effects of soil erosion with the economic impacts which can provide useful information on the extent of the problem especially to the stakeholders in order to take mitigation measures.

1.3. Research objectives

The main objective of this research is to assess the cost-effectiveness of reforestation measures in comparison with bench terraces measures for soil erosion risk reduction.

To address these objectives, study is conducted in predicting the soil loss and sedimentation based on existing data in a small catchment in Rwanda. In addition, a cost benefit approach is used to compare reforestation and bench terraces measures in which provisioning services (timber, fuelwood, food and forage) and regulating services (erosion control and carbon sequestration) provided by reforestation and bench terraces measures will be included. Soil loss is referred to onsite effects of erosion while sedimentation is the offsite effects of soil erosion.

Specific research objectives

1. To predict the current soil loss and sedimentation
2. To predict the reduced soil loss and sedimentation after reforestation and terracing in high risk areas
3. Comparison of the on and offsite costs and benefits of the two measures
   - Implementation and maintenance cost
   - Onsite benefits (avoided soil loss, and reforestation provision services)
   - Offsite benefits (avoided sedimentation and provision services)
4. To compare the internal rate of return (IRR)

Research questions

1. Which factors eg land cover or extreme rain govern the highest soil loss and sedimentation in the area?
2. Which conservation measures perform best between engineering measures and ecosystem based approaches?
3. What are the onsite and offsite benefits of implementing reforestation and terracing measures?
4. What is the cost of implementing and maintaining reforestation and bench terraces measures?
   - What is the cost effective measures based on Internal Rate of Return (IRR)?

2. LITERATURE

2.1. Soil erosion

Soil erosion is described as the detachment of soil particles, where the detached soil particles are transported by erosive agents such as flow of water; which results in the deposition process after the reduction of transport capacity (Morgan & Duzant, 2008). Soil erosion reduces the soil productivity through removal of top soil and plant nutrient. The removal of the topsoil is referred to soil loss which result in sedimentation after deposition as described in the Figure 1.

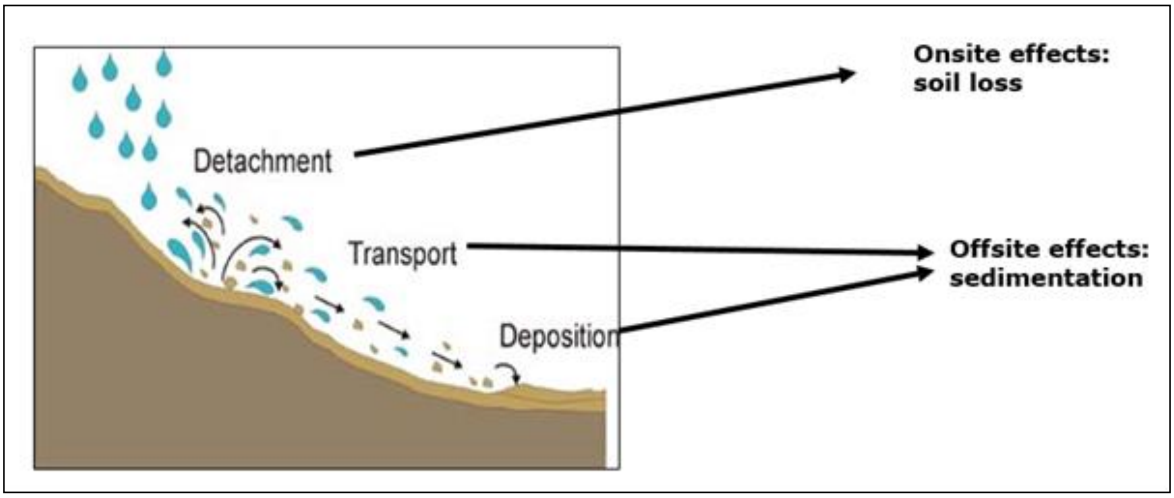


Figure 1 Soil erosion processes

There are different factors that contribute to erosion such as climatic characteristics, soil properties and topography. Those factors vary in space and time which makes erosion modelling a very difficult task. The primary cause of erosion are human activities such as deforestation and improper land management (Andrews & Tommerup, 1995) .

2.1.1. Soil erosion in Rwanda

Land degradation such as soil erosion has been reported to be environmental problem in Rwanda. Erosion is linked to the leaching of arable land and increase of transport material in the flood areas. According to Olson & Berry (2000), soil loss in Rwanda ranges from 34 to 246 tonnes per hectare per year. This could be attributed to high population density, lush vegetation and steep slopes.

2.1.2. Soil erosion factors

Erosion factors are all parameters that describe the magnitude of impacts. There are different parameters that can be used during erosion process modelling, but each model uses its own datasets. This is due to the fact that models are designed in a particular way to achieve a certain objective. Nevertheless, most of the parameters used in all model are the same as they are the main factors that contribute to soil erosion. Those main factors are soil, rainfall, topography and vegetation as explained below:

2.1.3. Rainfall factor

Rainfall is described as the amount of precipitation which falls within a certain area. Rain plays a big role in erosion process as detachment is a function of rainfall energy, soil detachability and rainfall interception by crops (Shrestha, 1997). This can be influenced by its amount, frequency and intensity. The kinetic energy of the rain can be considered as the available rainfall energy that is converted into erosion. The rainfall erosivity (Intensity and kinetic energy) is the most important factor which contribute to the soil detachment (Gifford, 2005). The amount of water flow contributes to the transport capacity of soil particles to flood plain.

2.1.4. Soil factor

Soil factor represents the tendency of the soil to erode which depends on the soil properties. Two energy flow namely, the raindrops impacts and the shear stress of the horizontal surface are known to erode the soil (FAO, 2002). Soil properties are mostly considered in the soil erosion processes. There are different soil properties among which we have soil texture, aggregate stability, organic matter, soil shear strength and bulk density. The properties of the soil that contribute to the soil erodibility are particle size of the soil, infiltration rate, cohesion and soil structure.

The structure of the soil is defined as the level at which the soil particles are compacted together to form pore space. The soil structure influences the soil ability to resist to erosion and to absorb water.
The soil cohesion is referred to the compulsory force between soil particles. Sandy soils are less cohesive, whereas the clay soil are very cohesive. Organic matter plays an important role as it can reduce the susceptibility of the detachment of the soil, increase the infiltration and hence decrease erosion.

2.1.5. Topography factor

The topography is commonly used to evaluate soil erosion especially in sloping terrain. The topography is mostly characterized by the slope steepness and the slope length. Slope gradient and slope length are related to soil detachment by runoff which depends upon the soil cohesion (Shrestha et al., 2004) The steeper the slope the higher the amount of runoff and the velocity; and the longer the slope length, the greater the accumulation of runoff in the floodplain (Morgan, 2009).

2.1.6. Cover Factor

Vegetation plays an important role by covering the soil and decreasing the effect of erosion. In addition, it can intercept the effects of the raindrops and reduces the surface runoff (Morgan, 2009). The impacts of vegetation is influenced by the ground cover percentage and the type of the cover.

The decline of vegetation cover due to deforestation, overgrazing and improper land management can expose the soil to erosion forces. In addition, a decline of vegetation can reduce the soil structure and cohesion which result in the removal of the topsoil and also decrease the soil nutrients.

2.2. Terracing and Reforestation measures

2.2.1. Bench terracing

Terracing is an agricultural method for collecting runoff water by controlling water erosion and increasing the infiltration rate (Zuazo et al., 2005). This technique is well known and implemented to transform landscape by reducing the slope in hilly and mountainous regions all over the world. Terracing is commonly applied in agricultural fields in developing countries in Africa like Ethiopia and Rwanda and also in Southern America or Asia such as Chinese Loess Plateau and India (Bizoza & de Graaff, 2012; Tenge et al., 2005).

Terraces are used to grow different types of crops such as rice, maize, apples, and grapes by using mechanization or traditional methods (Zuazo et al., 2005). The main objective of terraces is to improve the use of steep slopes and to increase the agricultural productivity. This function is achieved by creating the level surfaces according to contour lines of transformed slope (Bizoza & de Graaff, 2012). The bench platforms allows to spread the water runoff, slow down its speed and thus provide enough time for the infiltration of water into soil profile. Terraces can be used to control soil erosion in regions affected by soil erosion in combination with soil erodibility, climatic conditions and steep slopes.

There are different types of terraces, but the most worldwide known are bench terracing, stone wall terraces and Fanya Juu terraces (Tenge et al., 2005). In general, bench terraces consist of a set of platform level (bench) built along the contour lines of terraced slope. Those platforms are separated by riser (embankment) as described in the Figure 2.

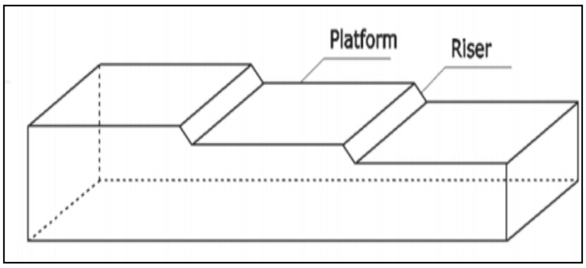


Figure 2 Bench terrace design

The main purpose of the bench is to decrease the slope length and steepness, as well as to reduce the amount and velocity of the runoff by retaining the surface water and allowing infiltration into top soil. Normally, bench terraces are constructed in hilly areas on slope up to 55% with stable soil.

2.2.2. Reforestation

Reforestation is an example of ecosystem-based measure and is defined as the establishment of forest on field that has recently also tree cover. Reforestation mostly influence the hydrological cycles as compared to other vegetation. Reforestation tends to consume water and reduce water runoff and soil erosion. The amount of water retained through evapotranspiration depends on the forest types (Thorsen et al., 2014).

In addition, reforestation and trees are suitable to reduce runoff especially to permeable soil structures which can be penetrated, store and filter water (Boojh, 2012). Furthermore, reforestation can protect soil from being eroded, and hence reduce sedimentation and flooding especially in sloping terrain ((Thorsen et al., 2014).

Reforestation has the ability to intercept the rain Savenije (2004) by reducing the runoff. This is considered as an important function of the ecosystem, especially in areas where erosion implies costs such as sedimentation and water quality reduction in the low lying areas. Reforestation measures can also provide other ecosystem services such as fruits, timber, and carbon sequestration but the real provision of a given reforestation is known after valuing all the ecosystem services provided by that reforestation.

2.3. Ecosystem services approaches

Ecosystem approach provides a framework which help to analyse and give a link between people and their environment (Millennium Ecosystem Assessment, 2005).

Ecosystem services have come to be a key concept to understand the interaction between the human and the natural environment. Ecosystem services represent what is understood as the benefits that humans get from the multitude and processes of natural resources (Thorsen et al., 2014). Table 1 shows the list of ecosystem services.

Table 1 List of ecosystem services (TEEB, 2010)

Provisioning Services are ecosystem services that describe the material outputs from ecosystems. They include food, water and other resources.

Food: Ecosystems provide the conditions for growing food – in wild habitats and in managed agro-ecosystems.

Raw materials: Ecosystems provide a great diversity of materials for construction and fuel.

Fresh water: Ecosystems provide surface and groundwater.

Medicinal resources: Many plants are used as traditional medicines and as input for the pharmaceutical industry.

Regulating Services are the services that ecosystems provide by acting as regulators eg regulating the quality of air and soil or by providing flood and disease control.

Local climate and air quality regulation: Trees provide shade and remove pollutants from the atmosphere. Forests influence rainfall.

Carbon sequestration and storage: As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues.

Moderation of extreme events: Ecosystems and living organisms create buffers against natural hazards such as floods, storms, and landslides.

Waste-water treatment: Micro-organisms in soil and in wetlands decompose human and animal waste, as well as many pollutants.

Erosion prevention and maintenance of soil fertility: Soil erosion is a key factor in the process of land degradation and desertification.

Pollination: Some 87 out of the 115 leading global food crops depend upon animal pollination including important cash crops such as cocoa and coffee.

Biological control: Ecosystems are important for regulating pests and vector borne diseases.

Habitat or Supporting Services underpin almost all other services. Ecosystems provide living spaces for plants or animals; they also maintain a diversity of different breeds of plants and animals.

Habitats for species: Habitats provide everything that an individual plant or animal needs to survive. Migratory species need habitats along their migrating routes.

Maintenance of genetic diversity: Genetic diversity distinguishes different breeds or races, providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial crops and livestock.

Cultural Services include the non-material benefits people obtain from contact with ecosystems. They include aesthetic, spiritual and psychological benefits.

Recreation and mental and physical health: The role of natural landscapes and urban green space for maintaining mental and physical health is increasingly being recognized.

Tourism: Nature tourism provides considerable economic benefits and is a vital source of income for many countries.

Aesthetic appreciation and inspiration for culture, art and design: Language, knowledge and appreciation of the natural environment have been intimately related throughout human history.

Spiritual experience and sense of place: Nature is a common element of all major religions; natural landscapes also form local identity and sense of belonging.

2.3.1. Ecosystem services valuation

The ecological and economics domain has seen a rise of interest for valuing of ecosystem services, goods and functions (De Groot et al., 2002). In addition, there is a need to know where ecosystem services located and how much benefits they provide (Willemen, 2010). For this appraisal, many studies have been conducted to explore the benefits of natural ecosystem to human society.

The valuation of ecosystem is undertaken for different reasons such as assessing the contribution of ecosystem to well-being; understanding why the actors use the ecosystem as they do, helping in decision making (Millennium Ecosystem Assessment, 2005). To increase the awareness of the benefits of ecosystem, stakeholder should be involved in the decision making (Willemen et al., 2015).

Valuation of ecosystem services is described as assigning monetary value to all ecosystem services, as well as those that lack values in the market such as recreational uses, aesthetics and climate regulation. A framework has been developed based on the Total Economic Value (TEV) to avoid redundancy while counting the benefits of the ecosystem services. The TEV is widely known to quantify the value of the ecosystem components by disaggregating the values into use and non-use values (Boojh, 2012).

The use values are defined as direct, indirect or future use of natural resources whereas non-use values are referred to values that are not associated to the actual use and do not require a person to carry specific cost to enjoy them (Kareiva et al., 2011).

Various methods are being used to assign value to ecosystems and the best way to value and assess ecosystems is to have a better understanding of ecosystem services. One of the method that is been used is the cost benefit analysis which is described in the sub-section below.

2.4. Cost-benefit analysis

The concept of cost-benefit analysis techniques has been adopted in 1930 and ever since, it was used in various fields. It is a tool used to facilitate the decision maker while trying to finance one project among many projects. Cost-benefit analysis is used to determine economic impacts of soil erosion and conservation (Kuhlman et al., 2010). The benefit are described as anything that will contribute to the achievement of the project while the cost is defined as anything that will decrease the objective of the project (Kuhlman et al., 2010).

The criteria used to determine the net benefits are the Net Present Value (NPV) and Internal Rate Return (IRR), and the value used to compute all the costs against benefits is a local currency (Gittinger, 1984). NPV describe how much value will add, which is what the project will maximize whilst the IRR describe the rate of return (Baccelli et al., 2012). Previous studies have argued on the best criteria to choose while selecting the cost effectiveness project (Faisalabad & Arshad, 2012) and they have concluded that in case of inconsistency the NPV should be considered. Therefore to make a conclusion, NPV should be given priority (Faisalabad & Arshad, 2012).

Nevertheless, IRR and NPV have been used in this study as a criteria of comparison, it refers to the growth rate of an investment. To assess a better option, the IRR must be higher than the discount rate and the NPV must be positive.

3. STUDY AREA

Rwanda is a sovereign state in central of Africa. It is located the south of equator and borders Uganda, Tanzania, Burundi and the Democratic of Congo Figure 3. The country is small, and dominated by mountainous mainly in western and northern part of the country. The geographic location of the country ranges between 1°04' and 2°51' latitude south and 28°45' and 31°15' longitude east. It is one of the most densely populated countries in Africa with a total population of about 12 million and a surface area of 26 thousands km².

Kigali is the largest city and the capital of Kigali which is located in the central part of Rwanda. Kigali covers a surface area of 712 km² with a population density of 1 556 persons per square kilometre (Government of Rwanda, 2012). Kigali has three main districts namely, Nyarugenge, Kicukiro and Gasabo. This study focuses on a catchment of Gasabo district in the Jabana sector.

The Jabana catchment have different sub-catchments, in this study, the sub-catchment of Byabagabo was selected. It covers an area of 7.8 km². The Byabagabo-Jabana sub-catchment is characterized by steep slopes which cause soil loss in the upper areas and sedimentation in the low areas.

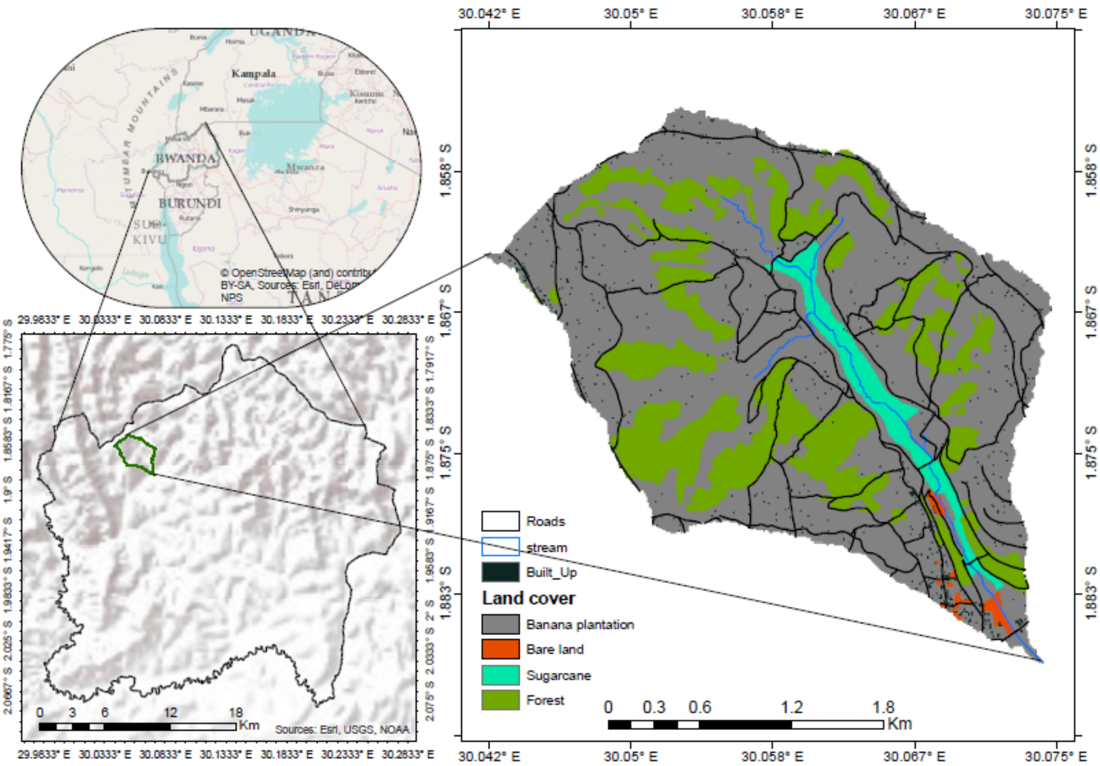


Figure 3 The location of the study area in Rwanda

3.1. Climate and topography

The climate of Byabagabo-Jabana sub-catchment has a tropical like the rest of the country. The sub-catchment of Byabagabo-Jabana has a mean daily temperature of 20.5° and a total annual precipitation of 1028 mm. The main rainy periods are from March to May, when occur the heavy and persistent rain occur. The short rainy period occurs in October and November. The dry period lasts from June to August. The topography of the Byabagabo-Jabana, sub-catchment varies between 1381 and 1763 m above sea level. The topography is characterised by steep slopes and low lying valleys see Figure 4

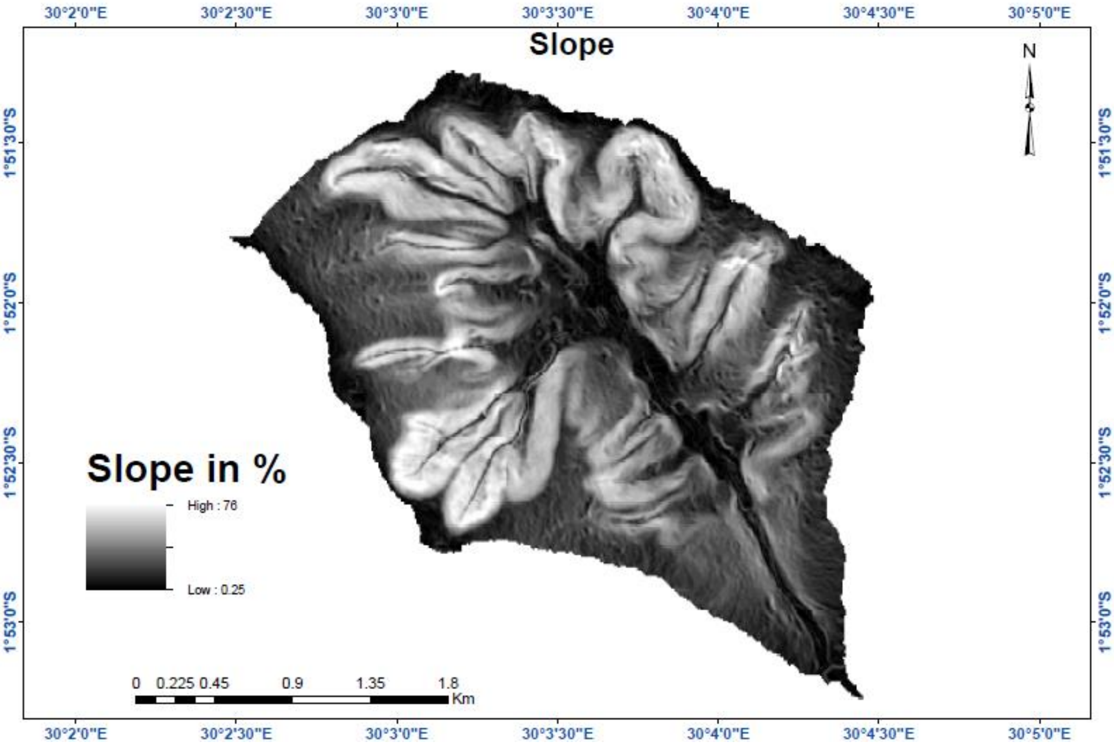


Figure 4 Slope map of Byabagabo-Jabana study area

3.2. Soil

The soil map of Byabagabo_Jabana catchment shows that the main soil classes of the area are Acrisols, Regosols, Alisols, Cambisols, Gleysols and Lixisols Figure 5. On the summit occurs alisols, regosols and lixisols, with soil texture ranging from clay loam to sandy clay loam. Acrisols, cambisols, Regosols are found on the mid-slope with soil texture varying between loam, clay loam and sandy loam. Gleysols and cambisols are found on the footslopes, with soil texture varying from silty clay and sandy clay loam.

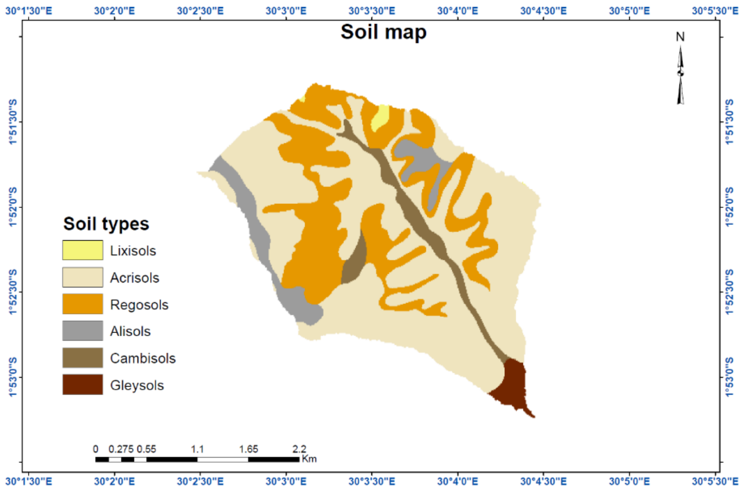


Figure 5 Soil map of the Byabagabo-Jabana study area

3.3. Land Use / Cover

The main land cover classes in the sub-catchment are forest, agriculture, built-up. The built-up class includes residential areas, schools and industries. The forest patches of the catchment is have Eucalyptus species and are mostly found in the upper areas of the Byabagabo-Jabana sub-catchment. The agriculture is predominant in the mid-slopes and is characterized by plantain (banana plantation). In the footslope, there is sugarcane plantation and vacant land which is defined as an area left without any other activity.

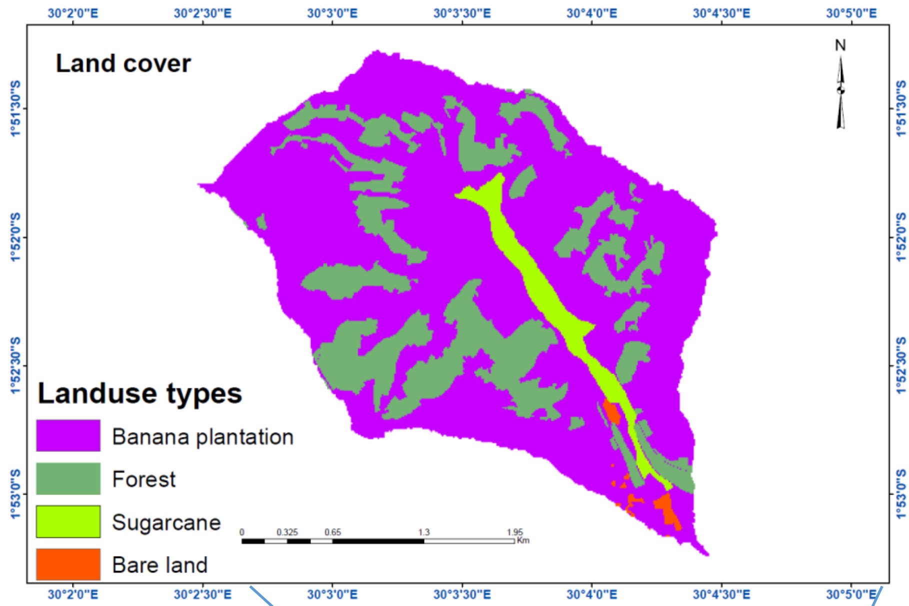


Figure 6 Land use of the Byabagabo-Jabana study area

Banana plantation

Sugarcane

Young Forest

Deforestation in the forest

Bare land

4. MATERIALS AND METHODS

This chapter gives the detail information about the data collection and methods used in this study. Figure 7 gives an overall workflow of the research project based on the research objectives. The green boxes stands for key research questions.

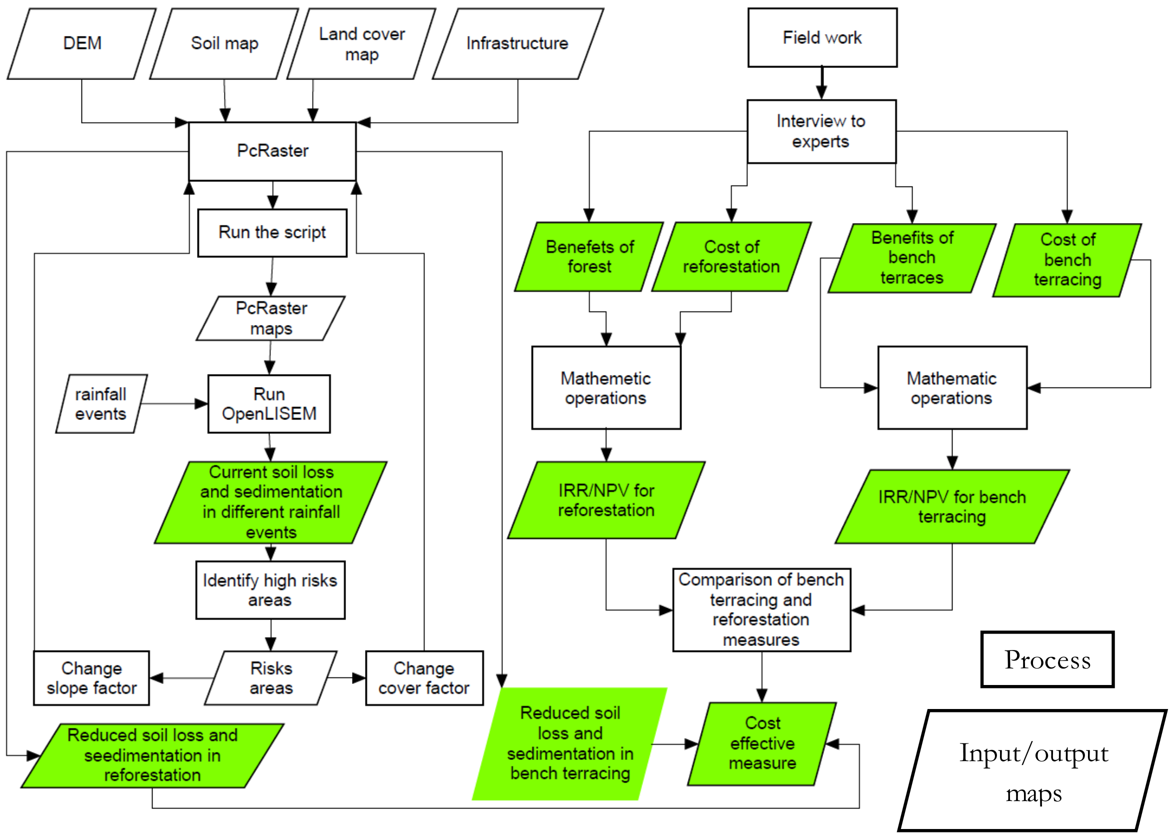


Figure 7 Flowchart

4.1. Methods for soil erosion assessment

OpenLISEM

To assess the driving factors of soil loss and sedimentation in the catchment and to compare the effects of reduced soil erosion after engineering and ecosystem-based measures, the OpenLISEM De Roo, (1996); Jetten et al. (2003) was applied. OpenLISEM was selected because it is used for planning and conservation purposes and can also be used to explore different soil conservation scenarios (De Roo & Offermans, 1995). Furthermore, the model has been applied in East African country that has similar environmental aspects as Jabana catchment (Hessel et al., 2006).

OpenLISEM is described as a hydrological and soil erosion model that has been developed by the Department of Physical Geography at Utrecht University in collaboration with the Soil Physics Division Centre in Wageningen (De Roo & Jetten, 1999). The model is founded on the original LISEM.

OpenLISEM is a raster based model which incorporates PCRaster as the GIS environment (Jetten et al., 2003). The incorporation of PCRaster means that the model is articulated in terms of GIS commands and that there is no conversion routine (De Roo & Offermans, 1995). The main reason of integrating GIS is that OpenLisem requires a large input data that cannot be entered by hand, but can rather be acquired from PCRaster.

The use of LISEM model in soil erosion simulation

The model is applied to temporally and spatially simulate the sediment transport and runoff in a watershed based on a single rainfall event (De Roo, 1996). The model can simulate detailed spatial erosion patterns and the result of the simulation can be used for soil erosion mitigation measures (Morgan & Nearing, 2011).

A research conducted for the model simulation has reported that the manning's and saturated hydraulic conductivity are the most sensitive variables in the OpenLISEM (De Roo & Jetten, 1999). This is due to the spatial variability of the saturated hydraulic conductivity and soil moisture storage at catchment level which result in model outputs far from perfect (Jetten et al., 2003). To improve the model results, high resolution and very detailed data are required.

The basic theory of OpenLISEM

OpenLISEM has two main processes namely, erosion and hydrological processes. Other processes incorporated in the model are rainfall, interception, surface storage in micro depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow Figure 8. Furthermore, the model takes into consideration the effects of paved roads and tractor wheeling which are smaller than the pixel size.

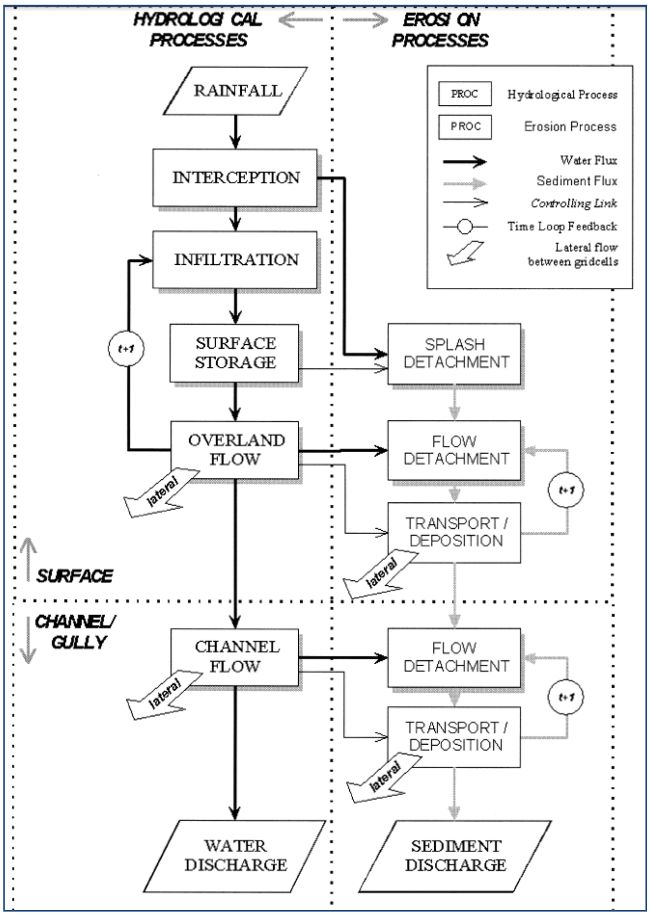


Figure 8 Flowchart for OpenLISEM (De Roo & Jetten, 1999)

The rainfall is considered as the basic input of the model. Recorded rainfall data from different rain gauges can be used in the model as time series file. For every time increase during a given simulation, the model generates a map with spatial distribution of the rainfall intensity by using the time series file and rain gauge (De Roo et al., 1996)

The interception by vegetation or crops is simulated by the computation of the maximum storage capacity filled during rainfall. There are different equations used to estimate the maximum storage capacity depending on the vegetation cover type. The example below shows one of the equation developed by Hoyningen-Huene, (1983) which is used for crops and vegetation:

$$\mathbf{SMAX = 0.935 + 0.498 * LAI - 0.00575 * LAI^2}$$

Where **SMAX** = Maximum Storage Capacity

LAI = Leaf Area Index

The interception is then subtracted from the rainfall. The amount of rainfall that is left, reaches the soil where infiltration and surface storage can occur Hessel (2005); as OpenLISEM is an event based model, water that has been infiltrated is considered as a loss as the water cannot reappear.

The infiltration and vertical transport of water in the soil are simulated using three different equations namely;

1. Swatre, model which is based on the Richard's equations (Morgan et al., 1998)
2. Green and Ampt model which considers Darcy's law (Kutilek & Nielsen, 2004)
3. Smith and Parlange model (Bastiaansen et al., 1996)

The Green Ampt model involves a detailed information of soil properties such as saturated hydraulic conductivity, soil thickness, initial soil moisture content and porosity. Roads are also considered in OpenLISEM. The model considers the roads width that are smaller than the pixel size for the simulation. However, the infiltration rate and splash detachment of the roads are considered as zero in the process. To compute the rate of erosion and deposition, the model adopt an assumption that the transport capacity of the runoff gives a balance between erosion processes and deposition.

When the model is run, the user can select the rainfall event, some relevant parameters and the location of the input and the output. The user can specify this information by using a command file authorized by the interface (De Roo et al., 1996).

PcRaster

PcRaster is a software tool that computes maps and tables that can be used as input and output of OpenLISEM. To generate those maps and tables, PcRaster comprises the tools that can be used to query and report time series, routing tools like drains, accumulate and kinematic wave (Soliman, 2011). In addition, PcRaster contains efficient scripting series of commands suitable to set up a model. When those commands are put together, an efficient run time mechanism remove redundant data transfer (De Roo et al., 1996). The PcRaster commands are used to produce all the required input data of OpenLISEM based on four basic maps, namely map of topographical, land use, soil and infrastructure variables. A minimum of 24 input maps in PcRaster format are necessary for the event simulation based on the user interest see Appendices 1.

4.2. Methods for analysing the effect of engineering and ecosystem-based measures

The design of conservation plans are essential not only after simulating the extent of the erosion risk, but also after identifying locations where those problem occur (Shrestha, Suriyaprasit, & Prachansri, 2014). For this appraisal, the implementation of bench terraces and reforestation measures were done after identification of the high risk areas from the simulated soil erosion rate.

The analysis of engineering and ecosystem-based measures was based on erosion reduction measures using the OpenLISEM. The erosion measures were assessed based on an assumed implementation in high risk areas. These areas were selected from the estimated current soil erosion map.

To select high risks areas, we used a threshold based on the soil loss tolerance. According to Wischmeier & Smith (1981), the soil loss tolerance is defined as the maximum level average allowable soil loss that will permit the level of productivity to be sustained economically. The soil loss tolerance equals 5 to 10 tonnes per hectare per year if the soil depth is more than 1m (Schertz, 1983). Based on that assumption, high risks areas were identified as greater than 5 tonnes per hectare per year as Rwanda has a soil depth of greater than 1 m.

The high risk areas were selected by extracting areas which are >= 5 tonnes per hectares using ArcGIS. Afterwards, the selected high risk areas were overlaid with the land use map to create a new class of erosion in the land use map. The land use map was reclassified and a class of high risk areas was added.

To simulate the reforestation measure, the cover map (obtained from NDVI map) was overlaid with the high risk areas and a value equal to forest map was assigned to those high risk areas. All the reclassified input

maps were exported into Pcraster. Furthermore, the reforestation measures improve the rate of infiltration, soil porosity and decrease the flow of water, for this purpose, the high erosion risk areas were extracted from the soil map. The map was then reclassified which has helped to assign new values of Ksat , Thetas (porosity) and n parameters to the soil class of those high risk zones.
The script was run in PcRaster to compute the reduced soil loss and sedimentation after reforestation measures using the PcRaster command below :

Pcrcalc luerosion.map=nominal(if(landuse.map eq 7, 4, landuse.map))

Where 7: class of high risk zone
4: class of forest

The command used was to generate a landuse erosion map where only the column seven which stands for a class of erosion was converted into forest class and no change was done to the remaining class.
The erosion high risks areas were assigned new Ksat, N, Thetas, RR values referring to forested classes, and afterwards different maps of erosion classes were created. The Ksat of forest was based on the literature (Renard et al., 1997).

The command applied was to reducing the slope factor, as terracing measures implies the reduction of the slope (see below). This implies that the high risk areas occurring in column seven where the slope factor is greater or equal to 0.16, the slope map should be changed to 0.16 and no changes should be made to the remaining slope. A slope factor of 16% was selected based on the findings from the field, the interviewee said that they implement bench terraces on slope >=16%. In addition, the new values has been given to manning's factor based on the literature. This was done due to the fact that in bench terracing, they plant some grasses around the bench which reduces the surface flow movement. The model was therefore run to predict reduced soil loss and sedimentation after bench terracing measures.

Pcrcalc grad.map=scalar(if(luerosion1.map eq 7 and grad. map ge 0.16 , 0.16,grad.map))

Where luerosion1.map = land use map with high risk areas
7 = risk areas
0.16 = slope factor

Afterwards, two scenarios were developed to predict the reduced soil loss and sedimentation. For the first, the reforestation measure was implemented by converting high risk areas into forest. For the second scenario, the slope factor was reduced using a command in PcRaster script and finally, OpenLISEM model was run to estimate the predicted reduced soil loss and sedimentation in comparison to no measures. Three rainfall events were used during the simulation to assess the impacts of the rainfall intensities on those conservation measures.

Statistical analysis

Analysis of variance (ANOVA) has been considered in this study to test if there is a significant difference between the reduced soil loss and sedimentation in reforestation measures and the reduced soil loss and sedimentation in bench terraces measures.

To achieve this, a total of thirty random points were selected from the erosion maps in the Byabagabo-Jabana catchment, which were later used to extract values in the two erosion maps (reforestation and bench terraces) after implementing the measures. The extracted values were exported into Excel to compute ANOVA. However, for the catchment level, to assess the reduced soil loss and sedimentation after implementation of both reforestation and bench terraces measures no statistics were needed, two values from the output of the map were used for the comparison.

4.3. Methods for the cost-benefit analysis

In this study a cost-benefit analysis was applied to compute the implementation and maintenance costs of reforestation and terracing measures and the benefits provided by the ecosystem. The benefits of reforestation considered in this study are reduced soil erosion and also provision of other services that are beneficial to wellbeing. For bench terraces, grasslands benefits are considered in this study because grasses are planted across the bench. These grasses help retain the water flow movement, but also provide other services to human being. In addition, the food services was also taken into consideration due to the fact that after implementing measures stakeholders gain more space for cultivation, and hence increase the yield. The benefits were estimated based on the increase in ecosystem services (timber, fodder, food, carbon sequestration, and fuel wood) and reduction of soil loss and sedimentation also an ecosystem services.

The valuation of reforestation services was based on benefits provided by the trees. The provisioning services considered were timber and fuelwood, whereas the regulation services considered were carbon sequestration. For the provisioning services, their values can be estimated in the market. For this appraisal, during the field work, interviews were conducted and following information were gathered in the field: the size of the plot, number of trees that can be planted on the same plot, estimated yield per year, and the corresponding monetary value in the market (Table 2). The estimation of some ecosystem services (Fodder and carbon sequestration) was not accurate due to limited data, therefore some assumptions have been made referring to the literature.

The cost was referred to implementation and maintenance cost of both reforestation and bench terraces measures. The implementation and maintenance cost of terracing and reforestation for onsite and offsite effects reduction was estimated based on the labour cost, number of people and number of days needed to finish the work in both reforestation and terracing measures (Table 3).

Table 2 Indicators for assessing costs and benefits of bench terraces and reforestation measures

	Costs & Benefits	Indicators
	Terraces/cost	Lifespan
	• Construction cost	Labour • number of people • manpower/day
	• Maintenance cost	Labour • number of people • manpower/day
	Terraces/benefits	Avoided damage (soil loss and sedimentation)
		Food
		Fodder
		Grass
	Reforestation/cost	Tree lifespan
		Seeds • Number of trees • Type of trees
	• Planting cost	Labour • number of people • manpower/day
		Mulching
		Pruning
	• Forest maintenance	Labour • number of people • manpower/day
		Annual pruning
	Reforestation benefits	Avoided damage (soil loss and sedimentation)
		Timber
		Fuel wood
		Carbon sequestration

Furthermore, the reduced soil loss and sedimentation after implementing the measures was considered as another benefits of the measures. However, the ecosystem services is difficult to value because has no direct –market. Therefore, in this research, the benefits of erosion control were not converted into monetary value but rather evaluated through the predicted reduced soil loss and sedimentation.

Cost of implementation and maintenance in bench terracing and reforestation measures

The cost in this study was estimated based on the implementation and maintenance cost of reforestation and terracing measures. The implementation and maintenance cost of bench terracing for onsite and offsite effects reduction was estimated based on the labour cost per day multiplied by number of person days needed to finish the work for both implementation and maintenance cost, the monetary value used are provided in Table 10. The same procedure was applied for reforestation and other cost of the number of trees was used to compute the cost of reforestation and the monetary values are given in Table 10. Microsoft Excel was the software used to calculate the cost of each measure.

Table 3 Monetary value for the cost of implementation and maintenance in both measures per ha

Bench terracing (ha)	Implementation	Maintenance
Person-days	1000	100
Labour cost per day	€ 6	€ 6
Total cost per hectare	€ 6223	€ 622

Reforestation (ha)	Implementation	Maintenance
Man-days	300	60
Labour cost per day	€ 6	€ 6
Total cost per hectare	€ 2065	€ 373

Benefits of reforestation and terracing measures

In this study, to estimate the benefits of ecosystem services in both measures, two types of ecosystem services were considered, namely; provisioning services and regulation services. In addition, the information on the year of which the benefits start to occur, was gathered and was considered in this study while computing the benefits.

For the bench terraces measures, the provisioning services considered was fodder and food while the regulations services considered was the carbon sequestration. For all services no monetary data was available during the fieldwork, hence values considered were retrieved from the literature. The monetary value used to assess the fodder services and carbon sequestration were retrieved from USDA Natural Resource Conservation Service, (2010) using grassland cover as reference and are provided Table 4. The monetary value used to estimate the food services are provided in Table 4 and were retrieved from the literature based on the profit of banana plantation in Rwanda (OneAcreFund, 2015).

For the reforestation measures, the provisioning services considered were timber and fuelwood and the values used were obtained from the fieldwork. For the carbon sequestration no data for the study area were available, therefore the values were retrieved from the literature referring to (Krieger, 2001). The value of each provisioning services was obtained by multiplying the total benefits of the provisioning services by the monetary value. In addition, the total value of a tree was divided by three as the expert interviewed said that farmers are only allowed to harvest 1/3 of the total production per year. The values used are provided in Table 4.

Table 4 Ecosystem services in monetary values per ha per year

Ecosystem services	Reforestation	Bench terraces
Carbon sequestration	€ 0.902	€ 0.05 /ha
Fodder	n.a	€ 0.12 /ha
Food	n.a	€ 6150 /ha
Timber	€ 5111/ha	n.a
Fuelwood	€ 1740 /ha	n.a
Total benefit value	€ 6852	€ 6150

After computing all the cost and benefits in reforestation and terracing measures for both onsite and offsite, the result was multiplied by the surface area of the identified high erosion risk areas which was equal to 25 hectares. Afterwards, a comparison was done based on the IRR and NPV. To assess if the implementation of the measure is worthy, the IRR was compared to the discounting rate; where the discount rate value was estimated by using the interest rate payable by stakeholders on bank loan (Bizoza & de Graaff, 2012). The NPV was assessed based on whether the monetary value is positive or negative. The time horizon of both measures was also used to compute the IRR. The information related to the time horizon in both measures was obtained through interviews in the field and a lifetime of bench terraces was estimated to range between 15 to 20 years while for reforestation does not have a lifetime. Therefore, a time horizon of 20 years was considered in this study. The high discount rate is 13% while the low discount rate is 8% (Atampugre, 2014). Normally, the following formula provided by FAO SAFR, (2002), is used to calculate the IRR:

IRR= ldr + ((hdr-ldr) * NPV at ldr / (NPV at ldr – NPV at hdr)

Where: IRR = Internal Rate Return

hdr = higher discount rate

ldr = lower discount rate

NPV = Net Present Value

NPV is used to calculate the amount invested in comparison with the future amount after deducting all the discounting rate. The equation below is used to compute the NPV

$$\mathbf{NPV = \Sigma\ (B\text{-}C)\ /\ (1+i)^{t}}$$

With B= gross benefit

T = total cost

t = time horizon

i = discounting rate

In this study, IRR was computed directly from Excel, after the computation of all cost of implementation, maintenance and benefits provided by the ecosystem, an incremental benefit was calculated. The incremental benefits are the sum of cost and benefits after taking into consideration of the period of flow. The incremental benefits are the net benefits and were obtained by subtracting the total cost of implementation and maintenance of both measures from the total benefits of all measures within a time period of 20 years.

4.4. Data collection

4.4.1. Data collection for soil erosion assessment

Available data

Various basic data required for OpenLISEM had been collected from different Institution as shown in the Table 5. The input data to simulate soil erosion are Land use/cover map, Rainfall data, Digital Elevation Model (DEM), Soil units and Infrastructure data. The infrastructure data include roads data, built-up density, channel data and discharge data.

The data of the land use, rainfall, DEM and soil units map were collected in different Institution of Rwanda through meetings. A soil map with a scale of 1:50,000 was obtained and the data constituted the physical properties of the soil profiles which are needed to run the OpenLISEM. A Digital Elevation Model (DEM) of 10m resolution was also collected.

For the rainfall data, rainfall event data with a temporal resolution of 10 minutes collected from January 2014 to April 2015 were collected. The data were recorded by Kigali-Kanombe Airport weather station using an automatic rain gauge. The daily rainfall of 30 years were collected and were recorded by Kigali-Kanombe Airport station. The station is located at 9 km from Jabana-Byabagabo sub-catchment.

I used the event based rainfall data from the satellite (Meteosat Second generation Multi-sensor Precipitation Estimate (MSGMPE). Based on the daily rainfall data, a day with high rainfall records was selected. Two days were selected from the daily rainfall data one of 28/02/2013 which had the highest records and the 23/10/2013 which also had a high rainfall intensity. Those days have been used to download the rainfall data from MSGMPE. However, the downloaded rainfall data of 28/02/2013 had some gaps and therefore the event of 23 October 2013 was selected. The data were acquired from a rainfall data receiver located at ITC.

Table 5 Available data

Map	Year	Map scale/spatial resolution	Source
DEM	2010	10 m	RNRA (Rwanda Natural Resources Authority)
Land use	2012	30 m	RNRA (Rwanda Natural Resources Authority)
Soil	2009	1/50000	MINAGRI (Ministry of Agricultural and Animal Resources)
Rainfall data daily	1984-2014		Rwanda Meteorological Agency
Satellite event based rainfall data	28/02/2013		(Meteosat Second generation Multi-sensor Precipitation Estimate (MSGMPE).

Field data collection

Field work was carried out from 21 September 2015 till 15 October 2015 to collect field observation on erosion and sedimentation feature, soil characteristics and to observe different types, heights of land cover within the catchment. Furthermore, an interview was done to obtain information on the cost and benefits of reforestation and bench terracing measures.

Prior to the fieldwork, the sample plots were determined based on the stratified purposive sampling strategy in which the Digital Elevation Model (DEM) and Land Cover maps were overlaid by the sum operation in the ArcGIS. An erosion susceptibility map indicating high, medium and low erosion risk areas was generated. The sampling points were selected on each units and priority was given to areas which were highly prone to erosion.

A total of 60 locations (Figure 9) within the catchment were visited during the field work, and the following features were recorded: GPS coordinates, sedimentation at the outlet of the watershed, cohesion of the soil surface, land cover types, plant height and the stream depth and width. In addition, soil samples were also collected for laboratory analysis.

In addition, 2 sites were visited to take GPS coordinates and pictures of gully erosion for the model validation. The Table 5 shows different parameters collected from field observation which have had been used to make the input maps for OpenLISEM model.

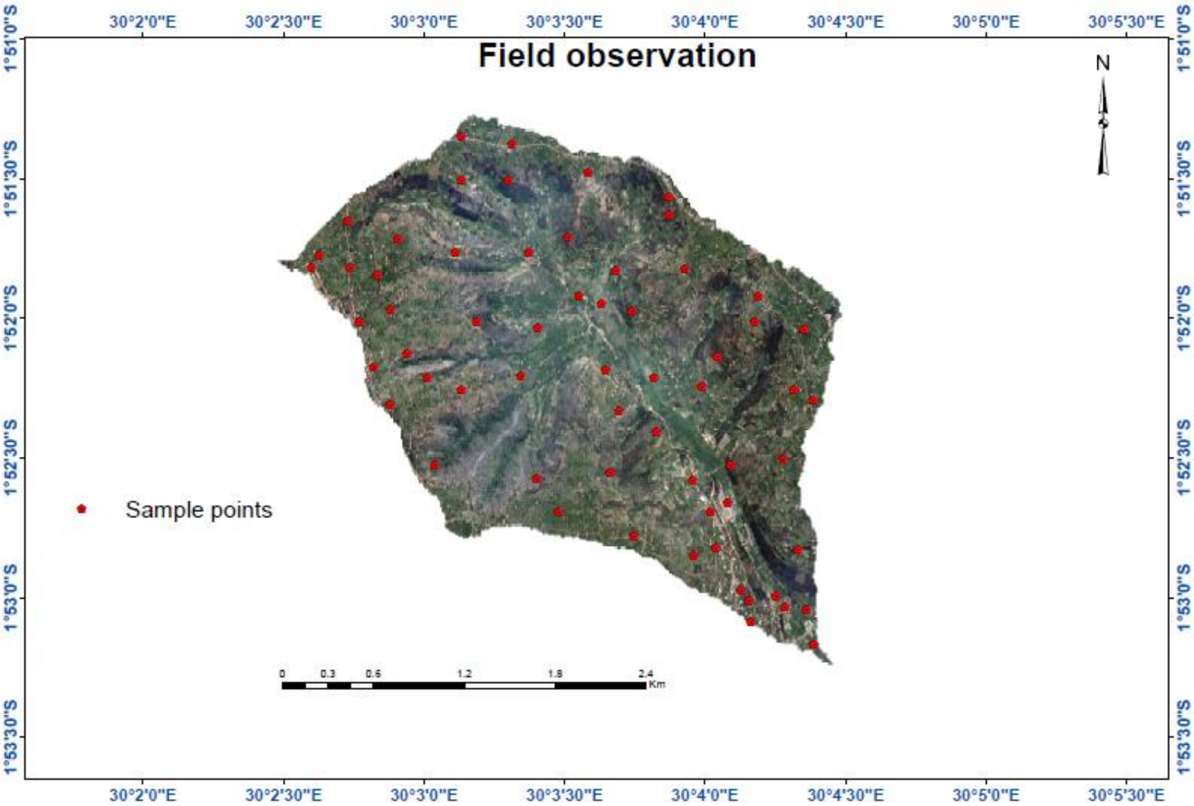


Figure 9 Sample points

Table 6 Field data

Data	Purpose	Source
Soil texture	Laboratory analysis (assessment of soil erodibility	Soil samples
Cohesion	Soil cohesion	Field measurement
Plant height	Estimated the throughfall kinetic energy	Field observation
Crop types	Estimated the throughfall kinetic energy	Field observation
Infrastructure	OpenLISEM	Field measurement
Cost and benefits of reforestation	Cost benefit analysis	Interview
Cost and benefits of bench terracing	Cost benefit analysis	Interview

Soil texture

Soil samples were collected from the field. The collected samples were taken to the laboratory for soil texture and organic matter analysis. The analysis of the soil was only focusing on the soil texture and organic matter content to help understand the soil erodibility of the catchment. According to Wischmeier & Smith (1981), the percentage of soil texture and organic matter together with the permeability can help in the estimation of the soil erodibility. The soil laboratory analysis was conducted using the pipette method (Reeuwijk, 2002). This is a standard method for the laboratory soil texture analysis Figure 10 Figure 10.

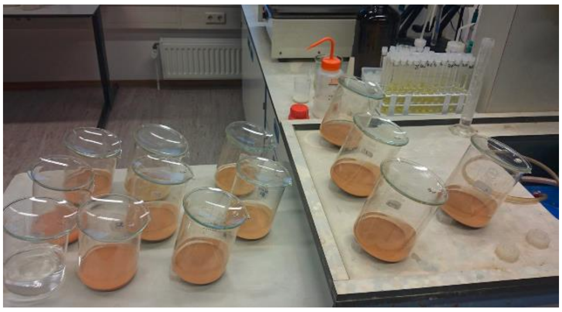



Figure 10 : Laboratory analysis of the soil

Cohesion of the surface soil

The vane taster was used to measure the cohesion of the soil surface see Figure 10. It was done following the method developed by (F.Richards, 1988) where the vane tester was implanted into the soil at about 2 cm and afterwards turned clockwise until the soil broke. The values of cohesion of the surface soil are expressed in kilo pascal (kpa). The cohesion measurement was done in 35 location in forest, sugarcane, banana plantation and bare land classes of the catchment. The average result for each class was considered as the value of the cohesion.

Figure 11 Vane taster (www.humboldtmfg.com)

Plant height / Crop types

The plant height and crop types are required for OpenLISEM. The data of the land use/cover map were not very detailed, the types of different agriculture crops were missing including the plant height. Therefore, a field observation were done on different land use types and the information was recorded. For the crop height, tree height was estimated using visual interpretation. The plant height and crop types are used in the model to calculate the through fall kinetic energy in the section of splash erosion.

Infrastructure (roads, stream and built-up density)

Data related to infrastructure are also required as input of the model. Field measurement was done to estimate the values to roads and stream

Figure 12. For the data related to stream, information was gathered by measuring the width and the depth of the stream in different location alongside the catchment by using a tape measurement of 8m. The data related to the roads were obtained by measuring the width of impermeable roads using tape measurement of 8m, which was given to the roads map and converted later into roadwidth map. The data related to built-up density had been given by the Kigali-city.

Figure 12 Stream measurements

4.4.2. Field interview data

To assess the on and offsite cost and benefits of the reforestation and terraces measures some interviews were carried. In total, three experts were interviewed among them, two were experts in reforestation and one in terracing measures.

To obtain information on the main costs of reforestation measures, an interview has been conducted in PAREF Be 2 (Support program to the development of the forestry sector), a project within the Rwanda Natural Resources Authority (RNRA). The following questions related to reforestation were asked during the interview: What is the construction cost, After how much time does erosion control occur after planting trees, What are the planting costs, What is the reforestation maintenance costs, What are the benefits of forest, What are the allowed number of trees to be harvested for sustainability, What is the land area lost for cultivation and what is the tree lifespan. The questionnaire used can be found in Appendices 2.

To obtain information on the main costs of the terracing measure, an interview was conducted with one expert of Land Husbandry, Water harvesting and Hillside Irrigation (LWH) project. The following questions were asked: Which type of terraces can be constructed in Kigali (Jabana watershed), What is the time required to finish the construction, What is the cost of terraces construction, What is the cost of terraces maintenance, What is the land area needed for terrace (Not available for cultivation anymore) and What is the lifespan of terraces. The questions included where they construct terraces at different stage of slopes. The questionnaire used is in Appendices 3

4.4.3. Data preparation for OpenLISEM

The main input data required to predict the rate of soil erosion and sedimentation of the watershed are DEM, Soil surface, Land use / cover map, Rainfall and Infrastructure data. The structure of the spatial input data is provided below:

The Catchment maps

The DEM is used for the catchment characteristics parameters. The DEM is not directly used in the model, but rather the maps that are derived from it. The model parameters derived from the DEM are Local Drainage Direction (LDD), slope gradient, outlet location and finally the catchment boundary. Those parameters have been generated from the PcRaster commands at a 10 meter resolution.
The LDD was created from the DEM using the PcRaster commands (Appendices 1). Afterwards, the LDD was used to generate the channel LDD, channel mask and the outlet.

Soil surface maps

The categories of maps generated from here are used to determine different processes such as infiltration, velocity of overland flow and surface storage. In this study the manning's coefficient, random roughness of soil surface and the road width had been considered to determine those processes. The land use types was used to assign values of manning's n (N map) and random roughness (RR map) based on the literature (Tennakoon, 2004) values as shown in the table below. Finally, the information was converted into PcRaster table format, which was later used in PcRaster commands to generate N and RR maps.

The width of impermeable road (Roadwidth map) was generated from the roads map by using PcRaster commands. The road is impermeable, this means that there is no infiltration during the process.

Table 7 Values of manning's n, random roughness and plant height

Land use/cover classes	Values of manning's	Values of random roughness	Plant height
Banana plantation	0.04	1.8	3.5
Forest	0.2	1.0	15
Sugarcane	0.04	1.8	3
Bare	0.06	1.9	n.a

Landsat Image

The Landsat imagery of 30m resolution has been downloaded from the internet as described in the table below, and was used to generate the Normalized Difference Vegetation Index (NDVI).

Map	Year	Resolution	Source
Landsat	13/06/ 2013	30m	USGS (glovis.usgs.gov)

The NDVI was produced using its near infrared (NIR) and red (R) bands respectively using the equation below :

$$NDVI = \frac{\rho NIR - \rho R}{\rho NIR - \rho R}$$

The obtained NDVI map has values which range from -1 to 1. The value 1 stands for presence of high green vegetation cover while -1 means low green vegetation cover. The obtained NDVI was used to generate the canopy cover map which was later used in PcRaster script.

Vegetation maps

The maps related to vegetation are used during the interception and splash detachment process in this model. The required parameters to model interception are the Leaf Area Index (LAI map), Plant height, and the Percentage of Canopy Cover (PER map). The canopy cover is used in the model to the fraction of soil covered by The values for fraction canopy cover were obtained from the NDVI map by using the following equation of (Knijff e al., 1999):

C= 1- Exp [-α * NDVI/ (β-NDVI)]

Where α=2 and β=1
C= Canopy cover

The Leaf Area Index was calculated from the canopy cover using the PcRaster commands as described in Appendix 1. The LAI map was later used to calculate the storage capacity. The plant height values were estimated from the field observation. An average value of plant height in meters was assigned to each land cover unit. Although, there was variability in the height within each class type, in this project, one average value was given to each land unit see Appendix 2. The assigned values were converted into PcRaster table format, which was then used in PcRaster commands to produce a plant height (Ch) map. The produced map (Ch map) was later used to calculate the throughfall kinetic energy of the splash detachment.

Infiltration maps

There are different options to model infiltration processes in the OpenLISEM, but in this study the Green Ampt infiltration was considered. The input parameters for running Green Ampt infiltration are the Initial soil moisture content (Thetai1 map), hydraulic conductivity (Ksat1 map), soil water at wilting capacity (PSI map) and saturated soil water content (Thethas1 map). The required values were generated from the SPAW model Saxton & Rawls (2006), using the fraction of the soil texture (clay and sand). Afterwards, the values of Ksat, Psi, Thethai and thethas were assigned to each soil class and the information was converted into PcRaster table format, which was later used in PcRaster commands to generate all those maps. The values used in this study are shown in the table below:

Table 8 Parameters of infiltration map

Soil types	Ksat (mm/hr)	Thetas	Psi (cm)	Thetai
Alisols	5.7	0.50	19.68	0.12
Acrisols	7	0.44	18.84	0.17
Cambisols	6	0.36	14.16	0.12
Lixisols	12	0.36	12.48	0.12
Regosols	6.8	0.45	20.08	0.21
Gleysols	5.9	0.37	17.76	0.27

Erosion / deposition related map

Four maps are required to calculate the sediment flow, using the deficit transport capacity. The aggregate stability (Aggrstab map) is used to determine the number of drops that are required to decrease the size of the aggregates. The aggregate stability values were retrieved from the literature by referring to the soil texture (Wischmeier & Smith, 1981). The cohesion parameter is used in the model to influence the flow detachment. The values of the cohesion were obtained from the field observation using a vane taster. The values of both parameters were converted into PcRaster table format, which was later used in PcRaster commands to generate aggregate stability and cohesion maps respectively. The D50 map is the median of the soil texture and is used to simulate the transport capacity and flow erosion. The D50 map was obtained by using the PcRaster commands as demonstrated in the Appendix. The values used to generate cohesion map and aggregate stability map are given in the Table 9.

Table 9 Cohesion and aggregate stability values

Soil types	Cohesion	Aggregate stability
Lixisols	4	0.36
Acrisols	3.5	0.32
Regosols	5	0.30
Cambisols	3	0.38
Gleyslos	4.5	0.27
Alisols	2.5	0.31

Channels

The channels are manmade ditches connected to the outlet of a catchment. The model considers channels to be impermeable as water that enters the channel network does not overflow.
The channel mask was created from the local drainage direction in PcRaster using the Accuflux operation and was used to create channel input maps.

Rainfall data

OpenLisem model is a rainfall event based model, therefore it involves the use of detailed rainfall event data for the simulation of the soil erosion. Baartman et al. (2012) suggested that a rainfall event with a total amount of 5 mm and which last for more than 30 minutes can be used in the simulation.

The rainfall event data collected from the field had errors and gaps which prevent the user to consider the data for further analysis in this study. Therefore, remote sensing rainfall data were considered in this research. Remote sensing data contains a useful source for data acquisition by giving temporal and spatial coverages that can be used in erosion modelling. Remote sensing can provide various data on meteorological variables such as rainfall data.

The downloaded rainfall data were in millimetre per hour and had a temporal resolution of 15 minutes and a spatial resolution of 3 kilometre. The event based rainfall data were georeferenced to the same coordinates system of the catchment and afterwards, resampled using the nearest neighbourhood algorithm through ILWIS 3.7.2 software. Furthermore, the rainfall event based value were extracted as table for additional rainfall analysis.

The remote sensing data contain uncertainties and should be validated before being used in the modelling process (Thiemig et al., 2012). The validation can be done by comparing satellite data to ground based recorded data (Collischonn & Pante, 2011). Therefore, the downloaded rainfall data were validated by comparing them to daily rainfall data.

Rainfall intensity have been reported to contribute to soil erosion especially high rainfall intensities (Baartman et al., 2012). To assess the impacts of different magnitude rainfall events on soil loss and sedimentation in the sub-catchment of Byabagabo-Jabana, two other rainfall events had been generated from the downloaded satellite rainfall event. This was done by increasing and decreasing the rainfall intensity using the Intensity Duration Frequency (Elsebaie, 2012). The IDF helps to find the probability that best fits the observed records and use the fitted probability to produce rainfall intensities for different duration (De Paola et al., 2014). To produce the rainfall events scenarios, the Rwandan's Intensity Duration Frequency (IDF) for precipitation was used. The formula below was used for this case which was developed by Demarée & Van de Vyver (2013).

$$i = \frac{c}{(T_d)^e + f} = \frac{96.6}{(T_d)^{0.97} + 13.90}$$

Where **i** = precipitation intensity
Td = duration
c,e,f = coefficients that vary for locations and return periods

Run of OpenLISEM model

All the produced input maps were resampled in ArcGIS by using the Nearest Neighbour algorithm. As OpenLISEM is a grid based, grid size of 10 meters was used in this model as suggested by Hessel (2005) to get realistic results, a grid cell should be less than 15m. OpenLISEM assumes that the width of the stream should be less than the gridsize (Hessel, 2005), the width of the stream was 9m.

The final input maps used in the model had a resolution 10 meter. Those maps were then converted into asci files and exported into PcRaster. Furthermore, all the input maps were extracted by the mask map. For the maps that were not available for the study area such as stoniness, hard surfaces, a mask of zero values were generated and assigned to them. The mask map area was 804 ha.

In the run file in OpenLISEM, the directory of the input data were set as well as the infiltration model to be used, which was the Green Ampt Layer 1. The selection of the storage equation for the interception was also completed. OpenLISEM outputs rely on both time step length and cell size. According to (Hessel, 2005), when using a kinematic wave equation, a time step should not be larger than the cell size. In this study, a time step of 10 seconds was selected as the cell size was of 10m. Three rainfall events considered as high, medium and low were used to assess the effects of rainfall intensities within the catchment of Byabagabo-jabana.

Software

The following software were used to create and analyse the data and image and to create the input data of OpenLISEM:

1. ArcGIS was used for image processing and visualization
2. ERDAS imagine was used for image processing
3. PcRaster was used to generate input maps for OpenLISEM model
4. OpenLISEM was used to predict the soil loss and sedimentation
5. ILWIS version 3.3 for rainfall data processing

Calibration of OpenLISEM

There was no discharge data for the Byabagabo-Jabana sub-catchment which could have helped to calibrate OpenLisem model. Therefore, the discharge data from a neighbour catchment has been used to calibrate OpenLISEM. This was done by a visual comparison of the simulated sedigraph with the discharge data, afterwards, some parameters were improved. This process were done till the time further simulation was not possible.

Validation of OpenLISEM

The validation of the model requires both comparing the simulated output with field measurements and also a mathematical model validation (De Roo, 1996). OpenLISEM uses empirical model in the process, therefore some of the input data used were obtained from field observation to increase the accuracy of the result. However, there was no historical data on soil loss and sedimentation of the Byabagabo_Jabana catchment which could have helped for validation, therefore the general reliability of OpenLISEM in this study was based on the comparison of the model with the evidence of small gullies recorded from the field observation.

5. RESULTS AND DISCUSSION

5.1. Predicting the current soil loss and sedimentation

Rainfall events

Three rainfall events were used to determine the effects of rainfall intensities on soil loss and sedimentation within the catchment. One rainfall events for which the rainfall data were available, was selected and represents an event of 23/10/2013. The selected rainfall events were classified as high rainfall event, medium rainfall event and low rainfall event based on the total rainfall intensity. It is noted that some other rainfall could have been higher than the selected events, but due to limited data, the events used in this research are assumed to represent the reality. The medium rainfall event represent the real rainfall event while other rainfall events were obtained by decreasing and increasing the rainfall intensity, method adapted using an IDF of Rwanda developed by (Demarée & Van de Vyver, 2013). The rainfall events used in this study are given in (Table 10) and the corresponding return period are provided in (Table 10, Appendices 7).

Table 10 Values for the three rainfall events scenarios

Time (minutes)	Low rainfall event (mm/hour)	Medium rainfall event (mm/hour)	High rainfall event (mm/hour)
0	0	0	0
15	1.6	0.4	5.1
30	1.9	2.3	5.8
45	2.2	5.1	6.8
60	2.6	5.1	8.1
75	3.3	6.4	10.1
90	4.3	6.9	13.4
105	6.6	19	20.2
120	14.1	26.6	43.1
135	8.9	23.4	27.4
150	5.2	9.5	16.1
165	3.7	6.4	11.5
180	2.9	6.4	9
195	2.4	5.1	7
210	2.1	5.1	6.3
225	1.7	3.6	5.5
240	0	0	0

Table 11 Total amount, intensity and return period of the three rainfall events

Scenarios	Total amount	Total intensity	Return period per year
Rainfall event 1	16 mm	64 mm / hr	1
Rainfall event 2	33 mm	132 mm /hr	1
Rainfall event 3	49 mm	196 mm / hr	1

Driving factors of soil loss and sedimentation in the catchment

OpenLISEM considers both soil loss and sedimentation which reflects the actual amount of soil detached and actual amount transported to the outlet by the runoff. Also it shows the amount of sediments transported outside the catchment. The deposition reflects the amount of sediments that could not be carried while suspended sediments are the sediments that are carried by the stream power. The total soil loss is the amount of soil loss at the catchment level. The average soil loss is normally calculated per unit area e.g. hectare.

The simulation of soil erosion by OpenLISEM model using event based rainfall data produced a magnitude of soil erosion and deposition rates. The result showed the spatial variability of soil loss and sedimentation in the Byabagabo-Jabana sub-catchment.

The output of the map shows traces of erosion in the middle of the slope which can be defined as gullies. Similar results were observed during the field as some gullies were recorded in banana plantations in the middle of the slope. The sedimentation are observed in the flood plain areas and at the outlet of the catchment which confirms the observation from the field.

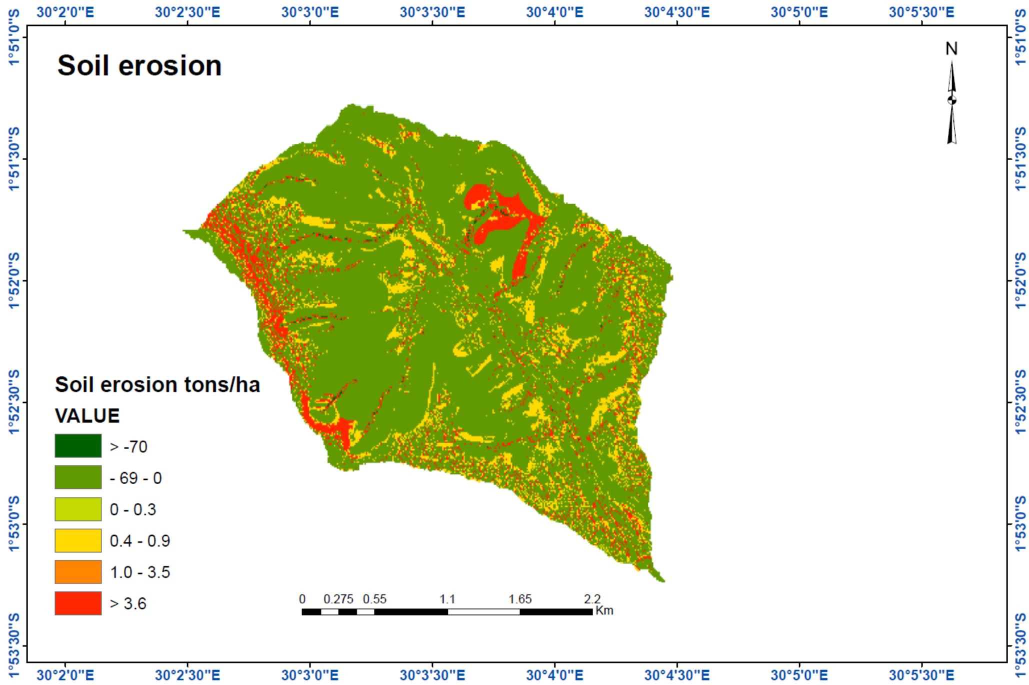


Figure 13 Soil erosion map

The results of the model are different from other investigation conducted in East African highlands (Hessel et al., 2006) using OpenLISEM. Comparing the results of Byabagabo-jabana sub-catchment with one of the catchment assessed, there is underestimation of the total soil loss in Byabagabo-Jabana sub-catchment, while there is over prediction of total soil loss as compared to the second catchment. This could be explained by the differences in the rate of infiltration and the total rainfall intensities considered in the studies. This confirms other research study where differences in rain intensities has seen to lead to high or low rate of erosion (Mohamadi & Kavian, 2015).

Effects of rainfall intensities on soil loss and sedimentation

Overall, the soil loss and sedimentation in the catchment were in the following increasing order: Low rainfall event < Medium rainfall event < High rainfall event. This shows that the increase of intensity has increased both the rate of soil loss and deposition. This can be explain by the rainfall intensity which exceeds the rate of infiltration and leads to water flow. The total soil loss and sedimentation in selected rainfall events scenarios are summarized in Table 12 .

Table 12 Total amount of soil loss and sedimentation for the Byabagabo-Jabana sub-catchment

OpenLISEM result	Rain event 1	Rain event 2	Rain event 3
Deposited (tons/ha)	40	59	74
Total soil loss tons	2	30	44
Average soil loss tons/ha	0.003	0.037	0.047

The Rainfall event three has a low return period, but its rainfall intensity was high. The soil loss and sedimentation under high rainfall event was higher than the other rainfall events, meaning that the rainfall event three was the most damaging type of rainfall events Table 13. An analysis of the result on the different intensity sequence showed that the rate of sedimentation and soil loss increased gradually for the rainfall event two and sharply for the rainfall event three.
The increase of soil loss under high rainfall intensity could be attributed to the rate of infiltration. At the beginning, the rain is infiltrated into the soil and there is low rate of soil loss; when the intensity becomes higher than the infiltration rate then the soil erosion becomes high.

This is in line concept of soil loss with Niehoff et al. (2002), who stated that when the magnitude of infiltration is lower than the magnitude of rainfall intensity, then there is an increase of soil loss. This shows that rainfall characteristics are involved in the soil loss generation processes (Fang et al., 2012).
In addition, the increase of the rate of soil loss and sedimentation could be explained by the rills that are formed in the soil bed following the breakdown of the surface seal (Römkens et al., 1997). Similarly, a study conducted on hilly slope of China showed that the increase of rainfall intensity yield on the increase of soil erosion and sediment transport (Wei et al., 2007). The rainfall event one has a low intensity, reason why it resulted into a low rate of sedimentation and soil loss. Similar result have been found by Römkens et al., (2002) who stated that the decrease of rainfall intensity yield to stable erodible surface condition. Therefore, it can be concluded that high rainfall intensity can lead to great soil loss and sedimentation.

Response of soil loss and sedimentation to the rainfall events scenarios and land use types

The model also shows the rate of soil loss and sedimentation in different land use classes (Figure 14). Based on the result, only soil loss is found in banana plantation and the highest sedimentation is found in bare land. The rate of sedimentation in the sugarcane is almost two times lower than the rate of sedimentation in bare land. This could be related to the presence of vegetation cover in both forest and sugarcane which decreases the splash detachment of the soil and enhance the resist of the soil to transportation.

Forest and banana plantation are located in the upper lying areas but soil loss is only found in banana plantation in all rainfall events scenarios. The rate of soil loss in banana plantation is caused by the presence of bare surface found between the banana trees. Bare surface is exposed to the effects of raindrops which lead to the detachment and transportation of the soil. Normally, when it rains the leaves of banana plantation intercept a certain proportion of the rain and the remaining rain reaches the ground, where infiltration takes place and the rest of the rain is washed out due to lack of vegetation cover to retain the water.

Figure 14 shows variation of total soil loss and sedimentation in different land use types based on different rainfall scenarios. The negative values are referred to net sedimentation while positive value are referred to net soil loss.

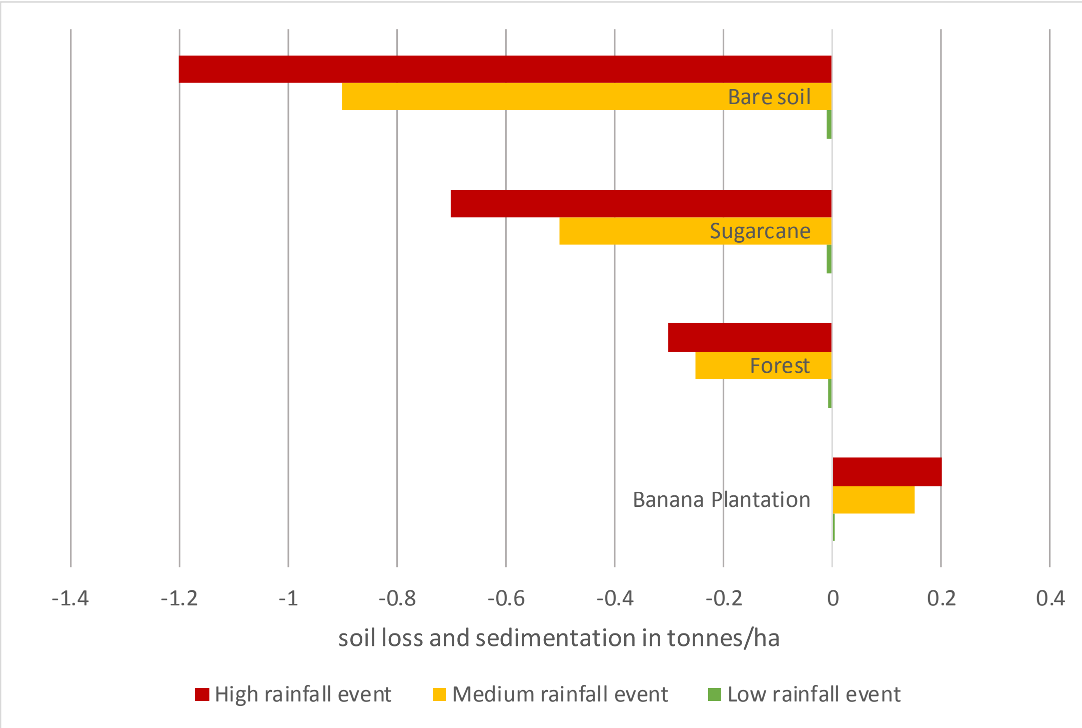


Figure 14 soil loss and sedimentation in different land use types

The amount of rainfall and its intensity are important explanatory factors of soil loss and sedimentation. High rainfall intensity can lead to erosion especially in areas with steep slope, fragile soil types and poor or degraded land cover.

Forested areas did not have net soil loss because the vegetation cover plays an important role in soil erosion reduction, Wischmeier & Smith, (1958), by increasing infiltration and reducing the water flow (Cerdà, 2002; Peng & Wang, 2012a). However, the rate of sedimentation can be explain by the presence of bare surface in the forest. Banana plantations can play a role in intercepting the raindrops but the interception alone might not prevent the effects of rain that reaches the ground (Savenije, 2004).
Bare land and sugarcane both had sedimentation, but the high rate of sedimentation was found in the bare land. Bare land are located in the floodplain area where sedimentation takes place and the bare land was not covered by any type of vegetation to reduce the amount of sediments. Another explanation could be that the same sediments can be eroded and deposited several times during the simulation. This confirms what other research have found e.g. (Cerdà, 2002; Labrière et al. 2015; Zhang et al., 2004) concluded that bare

soils have a dramatic impact on soil loss. Therefore, banana plantation and bare soil have contributed to the soil erosion in the Byabagabo-Jabana sub-catchment.

Furthermore, Figure 14 shows that there is variation in the rate of soil loss and sedimentation in different land use types. This indicates that the soil erosion is not only related to the high intensity of rainfall but other factors such as slope and soil erodibility are involved (Arnaez et al., 2007; Shrestha et al., 2014; Spanu et al., 2006).
Although not tested in the model, the soil texture of the Byabagabo-Jabana sub-catchment might have contributed to the increase of soil erosion. The laboratory analysis of soil samples collected from the field (Appendices 4) shows that the soil type of the area has an average of 39% of silt in the upper lying areas and an average of 10% in the low lying areas. Sand have an average of 35 % in the upper lying areas and an average of almost 80% in the low lying areas. The clay content in the upper lying areas is about 20% while in the low lying areas the average is about 10%. The organic matter ranges between 1.5 to 2% within the whole catchment. The presence of silt increases the rate of soil erosion in the catchment (Rhoton et al., 2002). In the low lying areas where sedimentation takes place there was almost 80% of sand which explain the rate of sedimentation in the flood plain areas.

Validation of the model

The validation of the model is very important because it helps to test the accuracy of the model output. In this study, there was no validation due to lack of data. During the field work, it was hard to find soil erosion features in the field, only two gullies were recorded. A qualitative validation could have been an alternative method of validation. However, overlaying two points with the erosion map could not realistic as those sample points were few. Therefore, no validation of the model was performed.

5.2. The best conservation measures between ecosystem based approaches and engineering measures

Identification of high risks areas

Figure 3 shows the identified high risk areas within the land cover map which occupy a surface area of 25 hectares. The area were selected based on the soil rate tolerance using a threshold of greater than 5 tonnes of soil loss per hectare per year. The mean of the slope of the identified high risks areas was 1580 m which is mostly found in the upper lying areas of the catchment. The selected areas “Erosion” (Figure 15) show the location where the effects of reduced soil loss and sedimentation after reforestation and bench terracing measures will be simulated. The three rainfall events were considered to simulate the effect reduced soil loss and sedimentation after bench terraces and reforestation measures

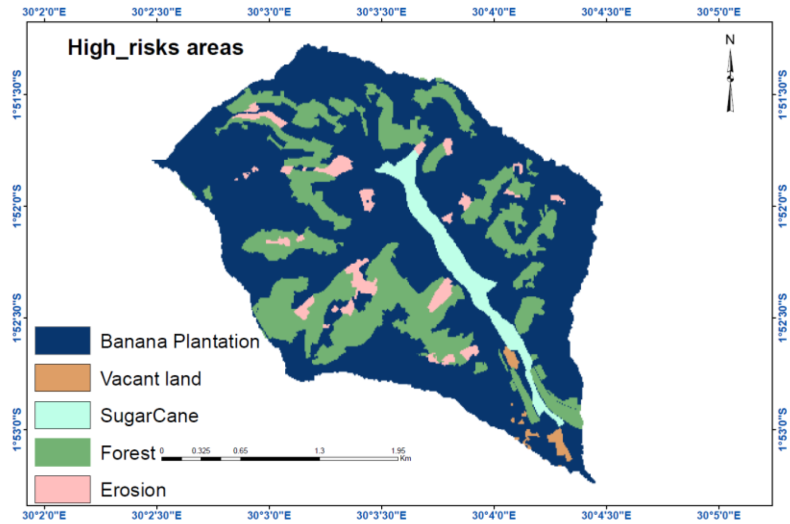


Figure 15 Land use with high risks area

The high risk areas are found in the upper lying areas of the sub-catchment. Those are location in sloping terrain where erosion takes place, which is in alignment with the findings from the field. After identifying high risks areas, reforestation and bench terracing measures effects on soil loss and sedimentation reduction were simulated.

Effect of reforestation and bench terraces measures to different rainfall events

In all rainfall scenarios, the total soil loss and sedimentation has reduced in both reforestation and bench terraces measures as compared to the current situation.
A comparison of reforestation measures with the current situation shows that, under low rainfall event there is very slight change. Only 0.1% (not shown) of soil loss and sedimentation was reduced. This is mainly because there was no sediment and soil loss under low rainfall event, consequently, reforestation measures and bench terraces measures had less effects though the cover factor was increased in reforestation measure and the slope length decreased under bench terraces measures. A major difference in soil loss and sedimentation is observed under medium and high rainfall event where reforestation measures reduced about 12% of the total soil loss and about 18% of the total sediments; while for bench terraces the reduction was about 25% of the total soil loss and 30% of total sediments as compared to current situation Table 13. The medium rainfall served as an example to show the differences in reduced soil erosion. The high rainfall event three showed almost similar result with the medium rainfall event.

It is noted that, the result discussed in this section are based on three rainfall events. The result shows the amount of soil loss and sedimentation that can be reduced after simulating the effects of reforestation and bench terracing measures based on those three particular rainfall events.

Table 13 Soil loss and sedimentation in current situation, reforestation and bench terraces measures

OpenLISEM result	Current situation	Reforestation measures	Bench terraces measure
Deposition (tons/ha)	59	50	44
Total soil loss (tons)	30	26	22.5
Average soil loss (tons/ha)	0.037	0.033	0.027

The reduction of soil loss and sedimentation in reforestation could be explained by the increase of the cover in reforestation measure which increases the infiltration rate and decreases the effects of raindrops, and hence reduce the detachment and transport of the soil. This is in agreement with Bulcock & Jewitt (2009); Siepel et al., (2002) who assessed the role of vegetation on a hillslope and found that, vegetation increases interception and reduces the stream power of overland flow. The reduced soil loss after reforestation has an average of about 12 % in the high risks areas which covers an area of 25ha in the current situation. This can be considered as low compared to other studies where reforestation was found to protect and restore degraded soil (Boojh, 2012). This can be explained by simulated reforested took place in a small area with an identified high risk areas. Therefore, reforestation measures can be an option to reduce soil erosion but to reduce more the rate of soil erosion, the intervention should not only covers the high risk areas but also other areas affected by soil erosion.

For the terraces measures, the reduction of soil loss and sedimentation can be explain by the decrease of the slope and the presence of the effect of grass around the bench which retain the water from the rain and prevent the water flow movement. This is in alignment with Prosser et al. (1995) who found that grass prevent erosion by overland flow due to the increase of infiltration rate. The bench terracing measures in this study has reduced about 25 percent of the total soil loss in the current situation occupying an area of 25 hectares. Similar result have been obtained by Z. Zhang et al. (2015) who showed that in some areas a slope of 15 percent might not be effective for soil erosion reduction especially in agricultural field. Therefore, a slope of 16 percent in this study might not be sufficient to reduce soil erosion.

Effect of reforestation and bench terraces measures under different land use types

Overall, under reforestation and bench terracing measures, the soil loss and sedimentation reduced in all land use types. The soil loss reduced by 15% in banana plantation under reforestation measures while the sedimentation of bare soil reduces by 10%. The soil loss reduced by 20% in banana plantation under bench terraces measures while the sedimentation of bare soil reduces by 10%.

Figure 16 shows the variation of the conservation measures in relation with the current situation. The negative values refers to sedimentation while the positive values refers to soil loss.

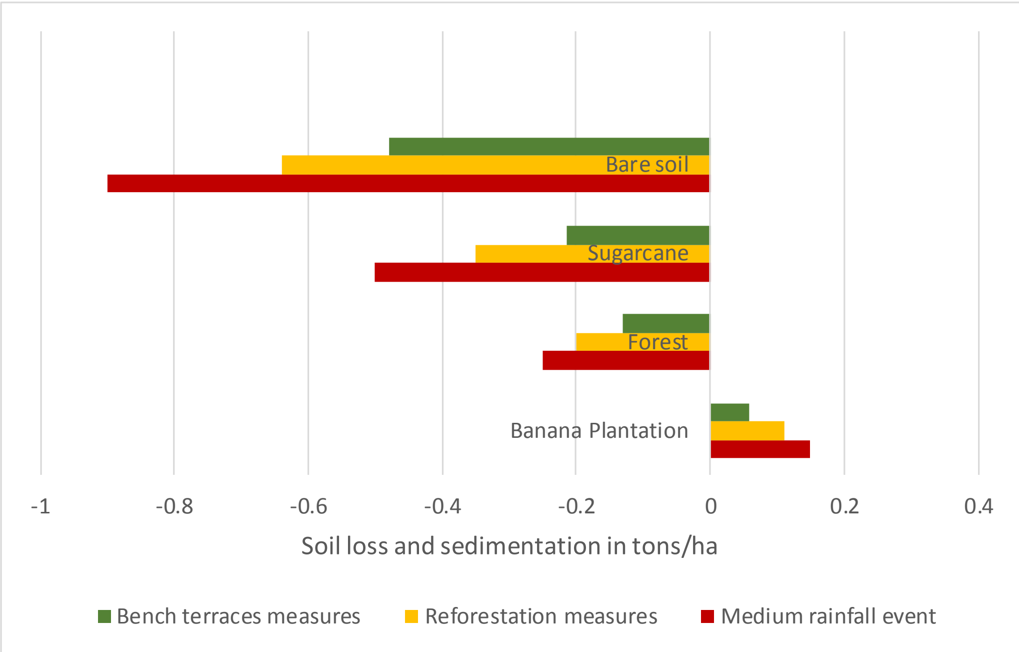


Figure 16 Soil loss and sedimentation in different land use types after implementation of both measures

The reduction of soil loss and sedimentation in land use types after reforestation measure can be explain by the conversion of high risks areas into reforestation which increases the soil cover, the hydraulic conductivity and the soil roughness and reduces the effects of the rain.

As a result, the energy, size and velocity of the raindrops are reduced to almost zero when the raindrops reaches the soil (Binkley & Brown, 1993). In addition, the root system of the forest increase its resistance to erosion Fang et al., (2012); Hudek et al.,(2014), which decreases the rate of sedimentation especially in low lying areas. This confirms results from other investigation where forest cover has seen to reduce soil erosion (Fernández-Moya et al., 2014; Peng & Wang, 2012a; Sun et al., 2014).

The reduction of soil loss and sedimentation in land use classes after bench terraces measures are related to the decrease of the slope in high risks areas. This is explained by the rain water which is retained in the bench and as the time pass, the water is infiltrated in the ground. Therefore, there is reduction of water flow and sedimentation in the low lying areas. In addition, the grass also played a role as it improved the resistant of the soil to movement.

This is in the agreement with another investigation conducted in Canada by Chow et al., (1999) where grasses planted along the terraces has seen to play an important role in minimizing soil erosion. Furthermore, other researchers e.g. Sun et al. (2014); Z. Zhang et al. (2015) found that the rate of soil erosion can be influenced by the slope factors.

One way analysis of variance (ANOVA) approach (Table 14) was used to determine if there is a significant difference between the reduced soil loss and sedimentation in bench terraces measures and the reduced soil loss and sedimentation in reforestation measures. In addition, we tested if there is significant difference between current situation and each one of the measure. The result from the medium rainfall event (which is the real event) was considered as current situation to do the ANOVA.

Table 14 Result and conclusion from ANOVA

	Group	Results (P>0.05)	Conclusion
Current situation	Reforestation measure	0.41	No difference
Current situation	Bench terraces	0.35	No difference
Bench terracing	Reforestation measure	0.04	Difference

5.3. Cost benefit analysis of reforestation and bench terracing measures

Implementation and maintenance costs of reforestation and bench terracing measures

The implementation and maintenance cost of the high risk areas was computed by multiplying the total area covered by the high soil erosion risks with the cost per hectare of each measure. The total area with high soil erosion risks was 25ha.

The result shows that the high cost of investment is observed in the first year followed by a low rate of investment from the second year till the twentieth for both measures. The investment cost of implementation in both measures takes place only in the first year while the investment of maintenance cost starts from the second till the twentieth year as shown in Figure 17.

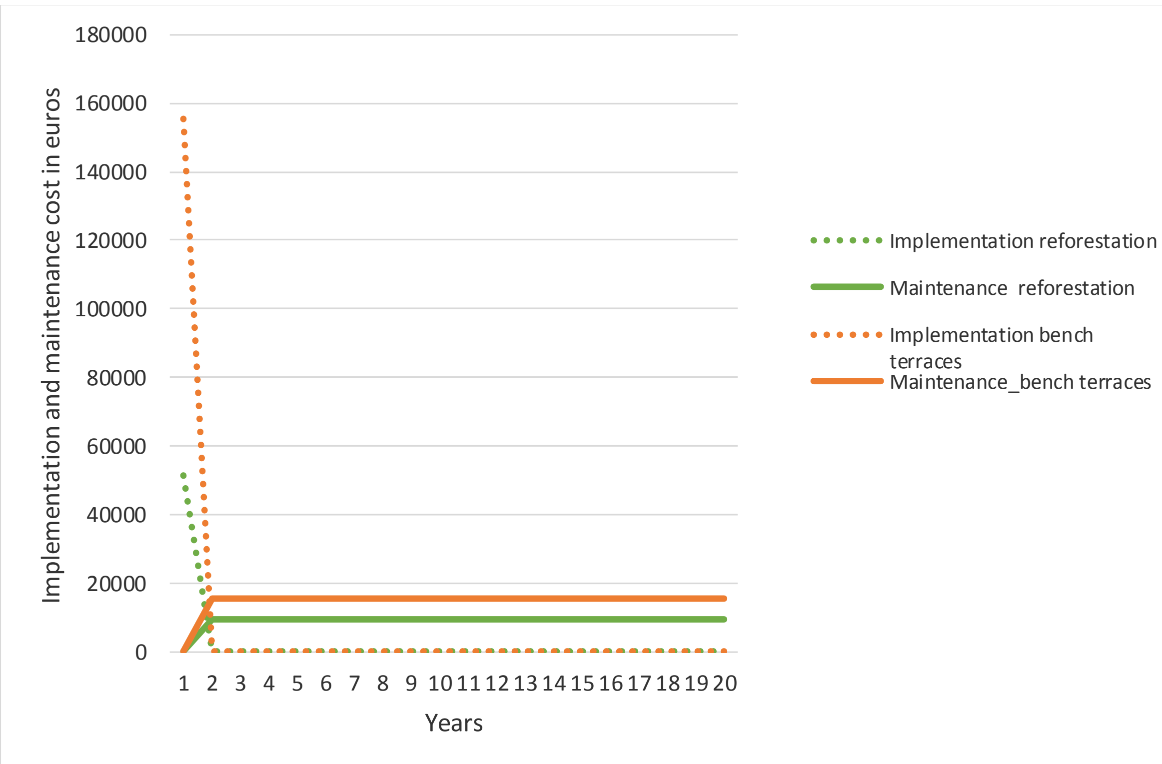


Figure 17 Implementation and maintenance cost in high risks areas for bench terraces and reforestation measures

The total cost of implementation and maintenance for reforestation measures after twenty years is around 451 thousands euro, while the total cost of implementation and maintenance for reforestation measures after twenty years is around 229 thousands euro. Overall, the implementation cost of bench terraces measures in high soil erosion risks areas is higher than the implementation cost of reforestation. This implies that to implement and maintain bench terraces measures in high soil erosion risk areas for a period of twenty years will create an extra total amount of about 50% the total cost of the reforested areas.

Bench terraces measures have reduced soil erosion as compared to reforestation measures but their costs for both implementation and maintenance are high and a failure to maintain can lead to their destruction and increase soil erosion (Bizoza & de Graaff, 2012). In some areas e.g. Kenya, studies showed that farmers refuse to implement bench terraces unless they get sponsor for the maintenance of bench terraces (Atampugre, 2014). Therefore, the participatory of stakeholders is required for a sustainable soil conservation measures (FAO, 2000).

Benefits of reforestation and bench terracing measures

Reduced soil loss and sedimentation

The assessment of the reduced soil loss and sedimentation in bench terracing and reforestation measures was converted into percentage based on the findings from the field. As shown in Figure 18, both measures reduced soil loss and sedimentation but the rate of reduction increases overtime. The trend of reforestation can be explained by the growth rate of the planted trees which reduces more soil erosion when the trees are mature. Therefore in the first year the rate is low and increase as the trees grow. The bench terraces measure reduces soil erosion in the first two years. This can be related to the decrease of the slope factor which reveals a quick effect on slowing down the flow of water.

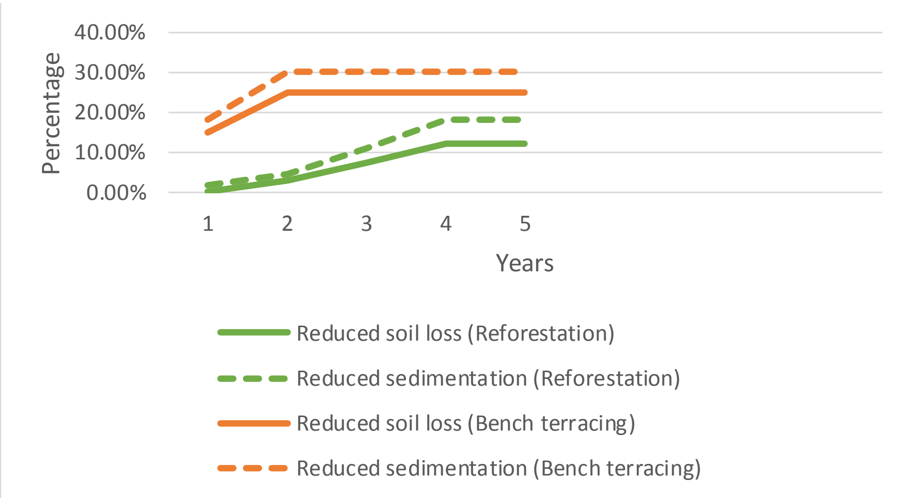


Figure 18 Soil loss and sedimentation risk reduction

Based on the result, both measures reduces soil erosion but the rate of reduction occurs over time depending on the measure. Bench terraces shows a quick soil erosion reduction as compared to reforestation measures. However, based on the findings from the field, bench terraces if well maintained could have a lifetime of twenty years while reforestation measures can stay longer.

According to FAO (2002), people emphasis on the actual benefits they can get after adopting a measure in the short term instead of considering the long term financial rationalisation of the investment. Promoters should then be aware of the time by which the technologies start to provide benefits (Bizoza & de Graaff, 2012). Therefore, reforestation measures might be considered for a long run while bench terraces measures could be considered for quick interventions.

Benefits of reforestation measures

Reforestation measures not only reduces soil erosion and sedimentation, but also provide a large number of benefits that are very important to the wellbeing. In this study, only 3 ecosystem services provided by tree were assessed as they were the most valued in the sub-catchment of Byabagabo-Jabana based on the field interviews. The total benefits of reforestation were assessed in high risks areas of the catchment as shown in Figure 19. To estimate the monetary values of provisioning services in high risk areas, the total values of each provisioning services was multiplied by the total area of the identified high risk areas. The benefits from the timber was 70% of the total benefits of reforestation, while 23% was assigned to fuelwood and the remaining 13% assigned to carbon sequestration. The highest value of timber services can be attributed to the high market value assigned to timber as compared to other services.

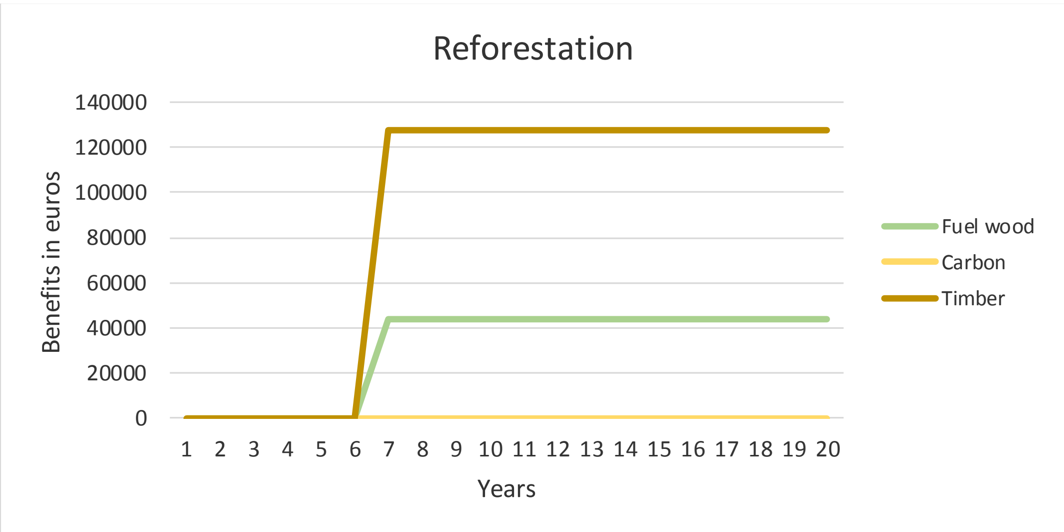


Figure 19 Benefits of reforestation measures in twenty years

Reforestation provides benefits that are useful to the community as one harvested tree can provide both fuelwood and timber in the Byabagabo-Jabana sub-catchment. However, compared to other studies (Häyhä et al. (2015); Thorsen et al. (2014), their values are low. This can be attributed to the market price assigned to the key services. In addition, only 1/3 of timber and fuelwood are harvested after seven years of planting which reduces the benefits of reforestation.

Reforestation can provide multiple services that benefits the society (Willemen et al., 2012); at different scale (De Groot et al., 2010). However, only valuing few services and assuming that the obtained value is for the whole ecosystem might be a source of errors especially in economic valuation (Barbier, 1997).

Bench terraces measures also provide other services as shown in Figure 20. Based on the result, 97% of the total benefits were assigned to food services while the remaining 3% were attributed to both forage and carbon sequestration. The high values of food provision could be attributed to the high demand and high monetary value in the market place.

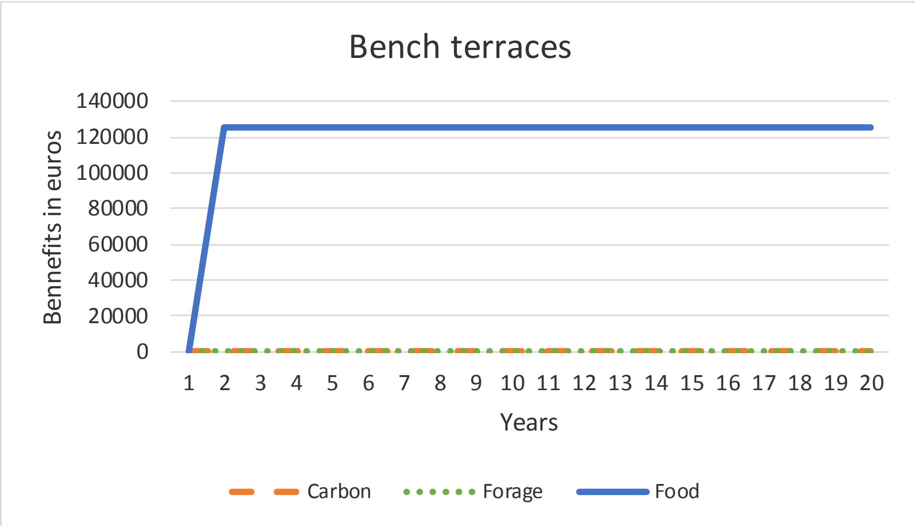


Figure 20 Benefits of bench terraces measures after 20 years

The benefits from bench terraces start to occur after one year and remain profitable. However, due to lack of data on the economic value of banana plantation in the catchment, the values considered in this study was from a study conducted by One Acre Fund during the evaluation of the profit of one particular type of the banana plantation. This could have been a source of error as that particular type of banana plantation might not occur within the catchment. The benefits of grass are low compared to other study conducted in Ethiopia (Balana et al., 2012; USDA Natural Resource Conservation Service, 2010).

Incremental benefits analysis of reforestation measures and bench terracing measures at 20 years

The reforestation and bench terraces measures have revealed benefits that are associated in case a stakeholder might want to choose to implement the measures, and also the cost related to the implementation measures were discussed. However, there is a need to show whether the benefits are enough to justify the costs. Table 15 shows the onsite and offsite total benefits for both reforestation and bench terracing measures.

Table 15 Onsite and Offsite benefits of reforestation and bench terraces measures

Measures	Onsite benefits					Offsite benefits	
	Timber (€)	Fuelwood (€)	Food (€)	Fodder (€)	Reduced soil loss (%)	Carbon sequestration (€)	Reduced sedimentation (%)
Bench terraces	n.a	n.a	2 375 000	57	25	2	30
Reforestation	609 000	1 789 000	n.a	n.a	12	428	18

Table 15 shows that the provisioning services of both bench terraces and reforestation that accumulate in high risks soil erosion areas within the catchment are higher than the key regulation services.

This is different from other research as carbon storage was found to exceeds the monetary values of other services (Naidoo & Ricketts, 2006). This underestimation could be linked to the assumption made while estimating the benefits of carbon sequestration, as the values attributed to carbon sequestration were retrieved from the literature. In addition, as the rain event used in this study was extreme, the benefits of all the carbon sequestrated by trees in that particular moment was not taken into consideration.

Overall, reforestation and bench terraces measures revealed multiple benefits in terms of regulation and provisioning services. The benefits for each measures have been deducted from the costs for a period of 20 years to see if the measures are cost effective as shown in Figure 21.

Figure 21 shows the net benefits and the percentage of reduced soil loss and sedimentation over a period of 20 years for bench terraces and reforestation measures.

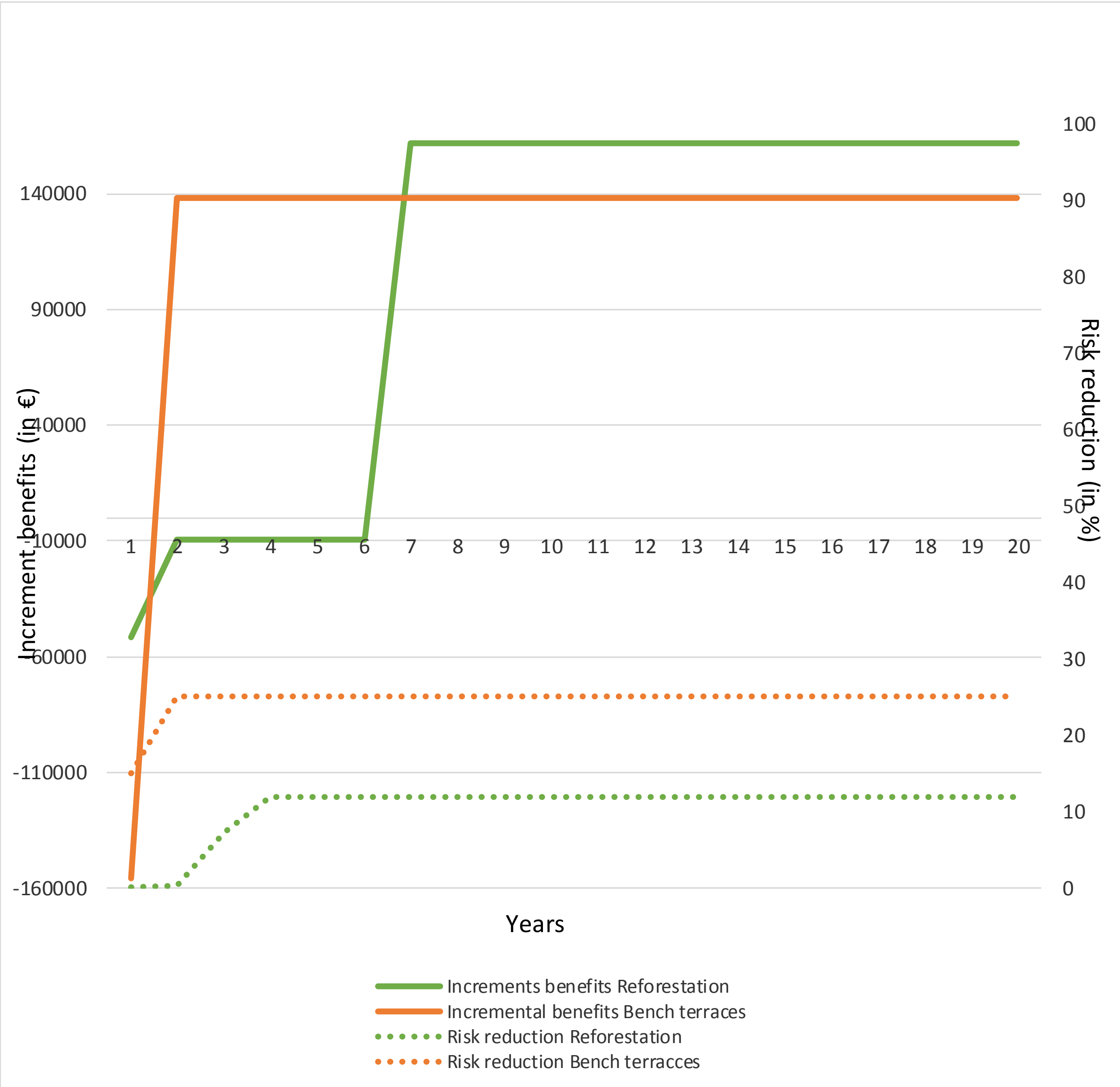


Figure 21 Incremental benefits of reforestation and bench terraces measures

Reforestation and bench terraces measures are of values as they provide both economic and environmental benefits which confirm the findings by Prabuddh & Suresh, (2013).
The trend in reforestation measures is explained by a high initial investment cost without any benefit from timber and fuelwood as the trees are still young to be harvested at the beginning. In addition, the benefits from the carbon sequestration start to occur early but their income is still low which gives a negative value. However, net benefit are realized in the seventh year as timber and fuelwood are only harvested seven years after implantation of the reforestation measures. In this regards, due to the rate of soil erosion reduction which is low in the first year, taking into consideration of the low implementation and maintenance cost and also to the benefits obtained, reforestation could be considered as a solution towards resilient soil erosion reduction measures.

The trend of bench terraces measures could be explained by a very high investment in the first year without any benefits. However, in the second year, the benefits from the provision of food, forage and carbon sequestration start to occur. This is mainly because banana plantation are harvested on a yearly basis, starting one year after plantation. In addition, the benefits from fodder and carbon sequestration start to occur in the second year which add value to the net benefits. Based on the results, bench terraces measures reduces fast the soil erosion risks and require a high cost of implementation and maintenance. However, the total cost of implementation and maintenance can be compensated by the benefits provided by the key services. Therefore, the bench terraces measures could be implemented in areas where soil erosion risks are relatively severe.

The valuation method used in this research might not be reflected as the most precise method to value the benefits of reforestation. As they provide multiple services which were not captured in this study. An assumption that timber, fuelwood and carbon sequestration represent the total benefits of reforestation does not apply in real world. This can introduce errors while analysing the benefits (Barbier, 1997; Mishra & Rai, 2014). Another approach in which reforestation are valued as a whole could be explored to assess the effects in terms of reducing the source of errors.

The result shows that both costs and benefits of reforestation and bench terraces measures varied significantly within the catchment. The benefits of reforestation and bench terraces measures are large, based on the services considered, and in some services there is overestimation or underestimation. In order to be consistent in the analysis a discount rate of 13 % was used during the computation for each benefits.

Internal rate of return (IRR) and Net Present Value (NPV)

The NPV was used as one of decision criteria in comparing the net benefits engineering and ecosystem based measures. In this research, the Net Present Value (NPV) shows the total amount of money that a stakeholder can get while implementing a measure over a period of twenty years.

The NPV is obtained after deducting the total cost from the benefits for each measure and multiplying the discount rate, this means that the NPV should be positive to be cost effective. It is a preferred criteria to choose between two exclusive measures (Faisalabad & Arshad, 2012; Gittinger, 1984).

In this research, the Net Present Value (NPV) shows the total amount of money that a stakeholder can get if he decides to implement a measure over a period of twenty years. The twenty years were selected based on the findings from the field. The IRR helps to know at which rate of return the NPV would be zero, which means that if the rate of return obtained for each measure is equal or lower than the discount rate (13% in this study) then there won't be any profit.

After computing the IRR and NPV of bench terracing measures and bench terraces measures over a period of twenty years, the results reveal that for bench terraces measures the NPV is € 629 thousands and the IRR is 82% while for reforestation measures the NPV is € 416 thousand and IRR is 41% (Appendices 5, Appendices 6).

A possible explanation of a very high NPV in bench terracing measures is the influence of the benefits from food provided measures which makes it more profitable than reforestation measures. Similar investigation conducted in south India have found same result (Sudha & Sekar, 2015).

The reforestation measures also have a positive NPV have different ecosystem services but their NPV is low compared to bench terraces measures and other studies (Thorsen et al., 2014). Two explanations could be provided. First, this could be attributed to the market price between countries. Second, in this study only 1/3 of provisioning services is harvested which make the total provisioning benefits of reforestation low.

Normally, in cost benefit analysis, a sensitivity analysis is required as changes in some parameters may occur over time (Gittinger, 1984; S. Liu, Costanza et al., 2010; Newton et al., 2012). However, in this study no sensitivity analysis was done, the considered discount rate (13%) was assumed to be constant over time.

The IRR for both measures is greater than the rate of return but the bench terraces measures has a high rate of value as compared to bench terraces measures. When IRR is greater than the discount rate, it means that people who select that project could recover the money spent for the implementation and maintenance cost (Gittinger, 1984). However, when choosing between two project, the one that has a high IRR a high chance than over the one with a low IRR (Faisalabad & Arshad, 2012).

Both reforestation and bench terraces measures showed profits which means that they are profitable. However, bench terraces measures revealed a high profits as compared to reforestation measures. Linking the results to the main objective of the study, could be a cost effective measures considering the soil erosion risks reduction and the net benefits.

5.4. Limitations and recommendation

5.4.1. Limitations

Soil erosion assessment

The main limitation of this research for assessing erosion was lack of some data in the study area:

- OpenLISEM model requires input data on high resolution which are very hard to find in a developing country. For this study, some of the input data used were retrieved from the literature which could have been a source of the error.
- It is very hard to find all necessary input parameters of the OpenLISEM model due to limited resources and time, especially in developing country. Therefore, some values of the parameters used in the model were retrieved from literature by referring to information on land cover and soil

characteristics of the catchment. This could have introduced some errors as for the manning's n, random roughness the country considered as reference was not similar to the Byabagabo-Jabana sub-catchment.

- Rainfall data plays an important role in OpenLISEM model. The satellite rainfall data used in this study did not cover did not cover the complete study area, an assumption by which we regionalized satellite data would not be realistic to the real worlds. As there is spatio-temporal variability in rainfall intensities, the selected one might have been different in the Byabagabo-jabana sub-catchment.

- There was no validation data, only a calibration was done using discharge data from another catchment which might have over/underestimated the output of the model. Validating the model using field data especially for the hydraulic conductivity could improve the knowledge on the soil erosion of the Byabagabo-jabana sub-catchment.

- The model used in this study is based on a single high rain event scenario to assess the effects of bench terraces and reforestation measures, the use of yearly based model will help to improve knowledge on the efficiency of the measures as there is temporal variability in the rain.

Cost-benefit analysis

The main limitation for the cost benefit analysis of the two measures were:

- For food services, the profit were based on one particular type of banana plantation which was assumed to be constant within the whole catchment. This can lead to over/underestimation of the food benefits.

- For fodder services, due to uncertainty in spatial distribution and few studies have assessed the profits of grass, it was difficult to assign values which is also another source of error in analysing the benefits of bench terraces.

5.4.2. Recommendation

To improve the accuracy of the results, some recommendation are provided,

- OpenLisem model requires a lot of data which are unavailable especially in a developing country. Some data used were retrieved from the literature which could have yield to inaccurate result. Therefore, further study with field data especially on sensitive parameters would improve the result.

- The selection of the best conservation measure was based on a single events while there is temporal variability of the rain throughout the year, therefore a yearly rainfall based model will improve the knowledge on the performance of both measures.

- The ecosystem services assessed in the model were only five while there is a large number of ecosystem services. In addition, there was limited data and some data used were from the literature. Therefore, further study with more detail data will improve the result.

6. SYNTHESIS

Soil erosion is a worldwide environmental problem. Ecosystem-based measure can reduce both onsite and offsite risks of soil erosion but their effects are still less assessed. In addition, engineering measures that are mostly applied to reduce soil erosion require a high cost of implementation and maintenance. The aim of the study was: (1) To assess the soil erosion for both onsite and offsite effects (2) analyse the effects of engineering and ecosystem based approaches (3) cost-benefit analysis of both measures followed by a comparison of the measure to select the cost effective measure.

This method is implemented to a study area of Rwanda in the sub-catchment of Byabagabo-Jabana. The OpenLISEM was used for soil erosion assessment and in the selection of best soil conservation measures between engineering and ecosystem based approaches measures. Furthermore, the cost-benefit analysis was considered to select the cost effective measure using Internal Rate of Return and Net Present Value as criteria for the assessment.

The results reveal that there is high rate of soil loss and sedimentation within the highest rainfall event scenario. The results also showed that the highest soil loss was found in banana plantation which are located on the slope of the study area, while the highest rate of sedimentation was found in bare soil located at the outlet of the study area. Soil loss and sedimentation and its driving factors have been assessed earlier by various authors. Though various examples have linked the increase of soil loss and sedimentation to high rainfall intensity; other investigators showed that land use types is one of the most important factor that affect soil erosion. The study showed that different factors contributed to soil loss and sedimentation in the area such as rainfall intensities and land use types. This is explained by the fact that increasing the rainfall intensity has led to the increase of soil loss and sedimentation, while at the same time there was spatial variability on the rate of soil loss and sedimentation in different land use types.

The simulation of the effects of reforestation and bench terraces measures in high risks areas helped to reduce both soil loss and sedimentation. In the study area, under a high rainfall event, the current situation had the highest soil loss and sedimentation (average of 0.037 tonnes per hectare) followed by reforestation measures (average of 0.033 tonnes per hectare) and bench terraces measures (average of 0.027 tonnes per hectare). Analysis of variance (ANOVA) on 30 sample points showed that though both measures contributed to the decrease of soil loss and sedimentation, there is a significant difference between the reduced soil loss and sedimentation in bench terraces measures and also in reforestation measures. In addition, analysis of variance (ANOVA) on 30 sample points showed that there is no significant difference between current situation and both measures. Based on the findings, bench terraces measures have reduced more soil loss and sedimentation as compared to reforestation measures.

Furthermore, the cost benefits analysis of reforestation and bench terraces measures helped to know which measures will be cost effective over a long period of time. To achieve this, a time period of twenty years was selected in which the spatial and temporal aspects were analysed. The result showed that the costs of implementation and maintenance of bench terraces are double the cost of reforestation. To assess if the benefits justify the cost, an incremental benefit was computed. Both measures revealed to be profitable. Furthermore, the result from the field also showed that it takes about two years for bench terraces to control erosion whilst for reforestation it takes seven years. However, from the first year there is a certain percentage that is reduced.

To assess if the net incremental benefits are justifiable in the future, the NPV and IRR for a period of twenty years have been assessed using a discount rate of 13%. The Net Present Value of reforestation measures was € 414 thousands with an Internal Rate of Return of 41% while the Net Present Value of reforestation measures was € 628 thousands with a an Internal Rate of Return of 82 %. The results reveal that implementing both measures will recover the cost but, if a stakeholder chooses to implement bench terraces measures there would be more cost effective.

In reference to the scope of the research, the cost effective measure could be bench terraces. However, both measures showed capacity to reduce soil erosion and provide net benefits though there are some differences. Therefore, the bench terraces measures could be used as a measure to reduce soil erosion in areas highly affected by erosion while reforestation measures could be used as a measure towards resilient soil erosion reduction.

The results of the study will support in soil conservation planning and most importantly in acknowledging the benefits provided by the ecosystem especially in Rwanda. Nonetheless, the lack of all required input data and validation data for OpenLISEM model and also due to limited data to assess the cost benefit analysis of both measures, the result might contain errors. Therefore, further study using very detailed data would lead to more accurate result. In addition, a combination of the two measures could be explored to see the effects in terms of spatial and temporal aspects.

7. CONCLUSION

The main objective of this research was to assess the cost-effectiveness of reforestation measures in comparison with bench terraces measures for soil erosion risk reduction. To achieve this, three sub-objectives were set and three research questions along way.

1. **Soil erosion assessment for both onsite and offsite effects**

   Three rainfall events considered as high (196 mm per hour), medium (136 mm per hour) and low intensities (64 mm per hour) were selected to assess the effects of high, medium and low rainfall intensities on soil loss and sedimentation and also on different land use types. Based on the findings the increase of rainfall intensity has contributed to the increase of soil loss and sedimentation in the catchment which can be attributed to the rainfall intensity which exceeds the rate of infiltration.
   In addition, the response of land use types to different rainfall events scenarios was evaluated. In all rainfall events scenarios, soil loss was only found in banana plantation. This could be explained by the presence of bare surface found between banana plantations and also the banana plantation were mostly located in the upper lying areas which are more prone to erosion. The highest sedimentation was found in bare soils as they were located in the low lying areas where sedimentation takes place. In addition, the absence of vegetation cover within the bare land increased the rate of sedimentation. Therefore, land use and rainfall factors are one of the most contributing factors in the catchment.

2. **The effects of ecosystem based approaches and bench terraces measures for soil loss and sedimentation reduction**

   The three rainfall events were used to simulate the effects of soil loss and sedimentation under the two measures. The result indicates that both reforestation and bench terraces have contributed to the reduction of soil loss and sedimentation under all rainfall events. The medium rainfall events was used as a current situation with no measure to test the effects of reduced soil loss and sedimentation under reforestation and bench terraces measures.

   The reduction of soil loss and sedimentation in reforestation measures was explained by the increase of vegetation cover which increases the interception of the raindrops, infiltration rate and the increase of soil roughness and therefore reduces the soil erosion. However, as the effects were only simulated under a small area only 25 hectares, only 12% of total soil loss and 18% of total sedimentation were reduced.
   The reduction of soil loss and sedimentation in bench terracing measures is explained by the decrease of the slope length and the presence of grasses along the bench which slow down the stream power of the flow and reduces the erosion. However, the effects were low only 25% of the total soil loss and 30% of the total sedimentation were reduced. This was attributed to the slope factor (16%) used to reduce the bench terraces which might not be effective in the banana plantation.

   To analyse if there is a significant difference between 30 samples of the predicted reduced soil loss and sedimentation in reforestation and in bench terraces measures, ANOVA was used. At (P >0.05), there was significant difference between the two measures in terms of soil and sedimentation reduction. Furthermore, ANOVA was also considered to test if there is significant difference between no measure and bench terraces and no measure and reforestation, the result for the two scenarios revealed that there is no significant difference between each measure and the no measure.

3. **Cost benefit analysis of the two measures**

   The result of the implementation and maintenance costs of the two measures revealed that bench terracing measures cost of implementation and maintenance are double the cost of implementation of reforestation measures. An analysis of the benefits of the two measures was done to see if the costs related to the implementation and maintenance can be justified. The result showed that reforestation measures have multiple services which are benefits to the wellbeing. However, only 1/3 of the key provisioning services of reforestation is harvested and sold at a low market price. Which decreases the benefits of reforestation. Food services from bench terraces were higher due to their market price. Although the benefits of reforestation were low as compared to other studies and the costs of bench terraces was high, all the measures revealed a net benefits after deducting all the costs from the total benefits. In addition, all the measures, showed a capacity of reducing soil erosion but their rate of reduction increases over time.

   The NPV and IRR were used to analyse the profits in twenty years using a discount rate of 13%. The NPV of bench terraces measures was € 624 thousands while the NPV of reforestation measures was € 415 thousands. The IRR of bench terraces measures was 89% while the IRR of reforestation measures was 41%. This means that all the measures will recover the cost but the one who implement bench terraces measures have a high chance of recovery.

Based on the scope of the research, the cost effective measure could be bench terraces. However, both measures have shown capacity to reduce soil erosion and provide net benefits though there is some differences. Therefore, the bench terraces measures could be used as a measure to reduce soil erosion in areas highly affected by erosion while reforestation measures could be used as a measure towards resilient soil erosion reduction. In addition, though the bench terraces measures are strong in terms of soil erosion control, reforestation measures provide multiple services that are very useful to the society as compared to bench terraces measures.

LIST OF REFERENCES

Andrews, J. H., & Tommerup, I. C. (1995). *Advances in Plant Pathology, Volume 11*. Academic Press. Retrieved from https://books.google.com/books?id=SqHUOitkwssC&pgis=1

Arnaez, J., Lasanta, T., Ruiz-Flaño, P., & Ortigosa, L. (2007). Factors affecting runoff and erosion under simulated rainfall in Mediterranean vineyards. *Soil and Tillage Research*, *93*(2), 324–334. doi:10.1016/j.still.2006.05.013

Atampugre, G. (2014). Cost and Benefit Analysis of the adoption of Soil and Water Conservation methods , Kenya, *4*(8), 1–14. Retrieved from http://www.ijsrp.org/research-paper-0814/ijsrp-p3247.pdf

Baartman, J. E. M., Jetten, V. G., Ritsema, C. J., & Vente, J. (2012). Exploring effects of rainfall intensity and duration on soil erosion at the catchment scale using openLISEM: Prado catchment, SE Spain. *Hydrological Processes*, *26*(7), 1034–1049. doi:10.1002/hyp.8196

Baccelli, E., Jacquet, P., Mans, B., & Rodolakis, G. (2012). *Intermediate Financial Management*. *IEEE Transactions on Information Theory* (Vol. 58). Retrieved from http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6071007

Balana, B. B., Muys, B., Haregeweyn, N., Descheemaeker, K., Deckers, J., Poesen, J., … Mathijs, E. (2012). Cost-benefit analysis of soil and water conservation measure: The case of exclosures in northern Ethiopia. *Forest Policy and Economics*, *15*, 27–36. doi:10.1016/j.forpol.2011.09.008

Barbier, E. B. (1997). The economic determinants of land degradation in developing countries. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *352*(1356), 891–899. doi:10.1098/rstb.1997.0068

Berry, L., Olson, J., & Campbell, D. (2003). Assessing the Extent, Cost and Impact of Land Degradation at the National Level: Findings and Lessons Learned from Seven Pilot Case Studies. *A Case Study Prepared for the Food and Agriculture Organization of the United Nations Retrieved from Http://www.fao.org*, 28.

Binkley, D., & Brown, T. C. (1993). Forest Practices As Nonpoint Sources of Pollution in North America. *Water Resources Bulletin*. doi:10.1111/j.1752-1688.1993.tb03233.x

Bizoza, a. R., & de Graaff, J. (2012). Financial cost-benefit analysis of bench terraces in Rwanda. *Land Degradation and Development*, *23*(2), 103–115. doi:10.1002/ldr.1051

Boojh, R. (2012). Ecosystem approach to disaster risk reduction. *Ecosystem Approach to Disaster Risk Reduction*, 187. Retrieved from http://nidm.gov.in/PDF/pubs/Ecosystem Approach.pdf

Bulcock, H. H., & Jewitt, G. P. W. (2009). Improved spatial mapping of leaf area index using hyperspectral remote sensing for hydrological applications with a particular focus on canopy interception. *Hydrology and Earth System Sciences Discussions*, *6*(5), 5783–5809. doi:10.5194/hessd-6-5783-2009

Cerdà, A. (2002). The effect of season and parent material on water erosion on highly eroded soils in eastern Spain. *Journal of Arid Environments*, *52*, 319–337. doi:10.1006/jare.2002.1009

Chow, T. L., Rees, H. W., & Daigle, J. L. (1999). Effectiveness of terraces/grassed waterway systems for soil and water conservation: A field evaluation. *Journal of Soil and Water Conservation*, *54*(3), 577–583. Retrieved from http://www.jswconline.org/content/54/3/577.abstract

City of Kigali. (2013). *Kigali City master plan report*. Retrieved from http://www.masterplan2013.kigalicity.gov.rw/downloads/Docs/RWF1101_03_Kigali City_Master Plan Report_03062013-s.pdf

Collischonn, B., & Pante, A. R. (2011). TRMM-forced rainfall-runoff modeling for water management purposes in small ungauged basins, (July), 1. Retrieved from http://iahs.info/uploads/dms/16732.16-66-71-343-06-Collischonn.pdf

Crossman, N. D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., … Maes, J. (2013). A blueprint for mapping and modelling ecosystem services. *Ecosystem Services*, *4*, 4–14. doi:10.1016/j.ecoser.2013.02.001

De Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, *7*(3), 260–272. doi:10.1016/j.ecocom.2009.10.006

De Groot, R. S., Wilson, M. A., & Boumans, R. M. J. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services: Special Issue: The Dynamics and Value of Ecosystem Services: Integrating Economic and Ecological Perspectives. *Ecological Economics*, *2002*(41), 393–408. Retrieved from http://www.mendeley.com/research/typology-classification-description-valuation-ecosystem-functions-goods-services-special-issue-dynam/

De Paola, F., Giugni, M., Topa, M. E., & Bucchignani, E. (2014). Intensity-Duration-Frequency (IDF) rainfall curves, for data series and climate projection in African cities. *SpringerPlus*, *3*(1), 133. doi:10.1186/2193-1801-3-133

De Roo, A. P. J. (1996). The LISEM project: an introduction. *Hydrological Processes*, *10*(April 1995), 1021–1025. doi:10.1002/(SICI)1099-1085(199608)10:8<1021::AID-HYP407>3.0.CO;2-I

De Roo, A. P. J., & Jetten, V. G. (1999). Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa. *Catena*, *37*(3-4), 477–493. doi:10.1016/S0341-8162(99)00034-X

De Roo, A. P. J., & Offermans, R. (1995). LISEM: a physically-based hydrological and soil erosion model for basin-scale water and sediment management. *Modelling and Management of Sustainable Basin-Scale Water Resource Systems*, (231), 399–407. Retrieved from http://hydrologie.org/redbooks/a231/iahs_231_0399.pdf

De Roo, A. P. J., Offermans, R. J. E., & Cremers, N. H. D. T. (1996). LISEM: a single-event, physically based hydrological and soil erosion model for drainage basins. II: sensitivity analysis, validation and application. *Hydrological Processes*, *10*(April 1995), 1119–1126. doi:10.1002/(SICI)1099-1085(199608)10:8<1119::AID-HYP416>3.0.CO;2-V

Demarée, G. R., & Van de Vyver, H. (2013). Construction of intensity-duration-frequency (IDF) curves for precipitation with annual maxima data in Rwanda, Central Africa. *Advances in Geosciences*, *35*, 1–5. doi:10.5194/adgeo-35-1-2013

Dominati, E. J., Mackay, A., Lynch, B., Heath, N., & Millner, I. (2014). An ecosystem services approach to the quantification of shallow mass movement erosion and the value of soil conservation practices. *Ecosystem Services*, *9*, 204–215. doi:10.1016/j.ecoser.2014.06.006

Dooley, E. E. (2005). Millennium ecosystem assessment. *Environmental Health Perspectives*, *113*, A591–A591. doi:10.1007/BF02987493

Elsebaie, I. H. (2012). Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia. *Journal of King Saud University - Engineering Sciences*, *24*(2), 131–140. doi:10.1016/j.jksues.2011.06.001

F.Richards, A. (1988). *Vane Shear Strength Testing in Soils: Field and Laboratory Studies, Issue 1014*. ASTM International. Retrieved from https://books.google.com/books?id=G5ZZuwpJdLEC&pgis=1

Faisalabad, S. R., & Arshad, A. (2012). Net Present Value is better than Internal Rate of Return. *Interdisciplinary Journal of Contemporary Research In Business*, *4*(8), 211–219. Retrieved from http://search.proquest.com.library.capella.edu/docview/1282292585?accountid=27965\nhttp://wv9lq5ld3p.search.serialssolutions.com.library.capella.edu/?ctx_ver=Z39.88-2004&ctx_enc=info:ofi/enc:UTF-8&rfr_id=info:sid/ProQ:abiglobal&rft_val_fmt=info:ofi/fmt:ke

Fang, N. F., Shi, Z. H., Li, L., Guo, Z. L., Liu, Q. J., & Ai, L. (2012). The effects of rainfall regimes and land use changes on runoff and soil loss in a small mountainous watershed. *Catena*, *99*, 1–8. doi:10.1016/j.catena.2012.07.004

FAO. (2000). *Manual on Integrated Soil Management and Conservation Practices*. *FAO Land and Water Bulletin* (Vol. 8). Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Manual+on+Integrated+Soil+Management+and+Conservation+Practices#6

Fao. (2002). *Optimizing soil moisture for plant production - The significance of soil porosity*. *FAO Soils Bulletin* (Vol. 79). Retrieved from ftp://ftp.fao.org/agl/agll/docs/sb79.pdf

FAO SAFR. (2002). *Irrigation Manual* (Vol. IV). Retrieved from ftp://ftp.fao.org/docrep/fao/010/ai590e/ai590e00.pdf

Fernández-Moya, J., Alvarado, A., Forsythe, W., Ramírez, L., Algeet-Abarquero, N., & Marchamalo-Sacristán, M. (2014). Soil erosion under teak (Tectona grandis L.f.) plantations: General patterns, assumptions and controversies. *Catena*, *123*, 236–242. doi:10.1016/j.catena.2014.08.010

Gifford, C. (2005). *Weathering and Erosion*. Evans Brothers. Retrieved from https://books.google.com/books?id=S3T5qnnBKJgC&pgis=1

Gittinger, J. P. (1984). *Economic analysis of agricultural projects*. *Processing*. Retrieved from https://web.stanford.edu/group/FRI/indonesia/documents/gittinger/gittinger.pdf

Government, R. (2012). 2012 Population and Housing Census .Report on Provincial Results. *National Institute of Statistics of Rwanda*, (November), 1–50.

Grimm, M., Jones, R., & Montanarella, L. (2002). Soil Erosion Risk in Europe. *European Communities*, *2002*. Retrieved from http://www.env-edu.gr/Documents/Soil Erosion Risk in Europe.pdf

Häyhä, T., Franzese, P. P., Paletto, A., & Fath, B. D. (2015). Assessing, valuing, and mapping ecosystem services in Alpine forests. *Ecosystem Services*, *14*, 12–23. doi:10.1016/j.ecoser.2015.03.001

Hessel, R. (2005). Effects of grid cell size and time step length on simulation results of the Limburg soil erosion model (LISEM). *Hydrological Processes*, *19*(15), 3037–3049. doi:10.1002/hyp.5815

Hessel, R., van den Bosch, R., & Vigiak, O. (2006). Evaluation of the LISEM soil erosion model in two catchments in the East African Highlands. *Earth Surface Processes and Landforms*, *31*(4), 469–486. doi:10.1002/esp.1280

Hoyningen-Huene, J. von. (1983). Die Interzeption des Niederschlages in landwirtschaftlichen Pflanzenbeständen. *DVWK Schriften*, *57*, 3–53. Retrieved from http://www.mendeley.com/research/die-interzeption-des-niederschlages-landwirtschaftlichen-pflanzenbeständen/

Hudek, C., Sterk, G., van Beek, R. L. P. H., & de Jong, S. M. (2014). Modelling soil erosion reduction by Mahonia aquifolium on hillslopes in Hungary: The impact of soil stabilization by roots. *CATENA*, *122*, 159–169. doi:10.1016/j.catena.2014.06.017

Jetten, V., Govers, G., & Hessel, R. (2003). Erosion models: Quality of spatial predictions. *Hydrological Processes*, *17*(5), 887–900. doi:10.1002/hyp.1168

Jones, H., Clough, P., Höck, B., & Phillips, C. (2008). *Economic costs of hill country erosion and benefits of mitigation in New Zealand : Review and recommendation of approach Economic costs of hill country erosion and benefits of mitigation in New Zealand : Review and recommendation of approach* (Vol. 1).

Kagabo, D. M., Stroosnijder, L., Visser, S. M., & Moore, D. (2013). Soil erosion, soil fertility and crop yield on slow-forming terraces in the highlands of Buberuka, Rwanda. *Soil and Tillage Research*, *128*, 23–29. doi:10.1016/j.still.2012.11.002

Kareiva, P., Tallis, H., Ricketts, Tailor, H., Daily, Gretchen, C., & Polasky, S. (2011). Natural Capital: Theory and Practice of Mapping Ecosystem Services. Retrieved August 14, 2015, from http://www.amazon.com/Natural-Capital-Practice-Ecosystem-Services/dp/0199589003

Knijff, J. Van der, Jones, R. J. A., Montanarella, L., & Van der Knijff, J. M. (1999). Soil erosion risk assessment in Italy. *Luxembourg: Office for Official Publications of the European Communities*, *EUR 19022*(EN), 32 pp. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Soil+Erosion+Risk+Assessment+in+Italy#0

Krieger, D. J. (2001). Economic Value of Forest Ecosystem Services : A Review. *The Wilderness Society*, 1–31. Retrieved from http://www.truevaluemetrics.org/DBpdfs/EcoSystem/The-Wilderness-Society-Ecosystem-Services-Value.pdf

Kuhlman, T., Reinhard, S., & Gaaff, A. (2010). Estimating the costs and benefits of soil conservation in Europe. *Land Use Policy*, *27*(1), 22–32. doi:10.1016/j.landusepol.2008.08.002

Kumar, P., & Martinez-alier, J. (2011). The Economics of Ecosystem. *Economic and Political Weekly*, *xlvi*(24), 76–80. Retrieved from http://www.teebweb.org/wp-content/uploads/Study and Reports/Additional Reports/Manual for Cities/TEEB Manual for Cities_English.pdf

Labrière, N., Locatelli, B., Laumonier, Y., Freycon, V., & Bernoux, M. (2015). Soil erosion in the humid tropics: A systematic quantitative review. *Agriculture, Ecosystems & Environment*, *203*, 127–139. doi:10.1016/j.agee.2015.01.027

Liu, B., & Nearing, M. (2000). Slope length effects on soil loss for steep slopes. *Soil Science Society of …*, *1763*(July 1999), 1759–1763. Retrieved from https://dl.sciencesocieties.org/publications/sssaj/abstracts/64/5/1759

Liu, S., Costanza, R., Troy, A., D'Aagostino, J., & Mates, W. (2010). Valuing New Jersey's ecosystem services and natural capital: a spatially explicit benefit transfer approach. *Environmental Management*, *45*(6), 1271–85. doi:10.1007/s00267-010-9483-5

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Synthesis*. *Ecosystems* (Vol. 5). doi:10.1196/annals.1439.003

Mishra, P. K., & Rai, S. C. (2014). A Cost–Benefit Analysis of Indigenous Soil and Water Conservation Measures in Sikkim Himalaya, India. *Mountain Research and Development*, *34*(1), 27–35. doi:10.1659/MRD-JOURNAL-D-12-00013.1

Mohamadi, M. A., & Kavian, A. (2015). Effects of rainfall patterns on runoff and soil erosion in field plots. *International Soil and Water Conservation Research*, *3*(4), 273–281. doi:10.1016/j.iswcr.2015.10.001

Morgan, R. P. C. (2009). *Soil Erosion and Conservation*. John Wiley & Sons. Retrieved from https://books.google.com/books?id=j8C8fFiPNOkC&pgis=1

Morgan, R. P. C., & Duzant, J. H. (2008). Modified MMF (Morgan–Morgan–Finney) model for evaluating effects of crops and vegetation cover on soil erosion. *Earth Surface Processes and Landforms*, *33*(1), 90–106. doi:10.1002/esp.1530

Morgan, R. P. C., & Nearing, M. . (2011). *Handbook of Erosion Modelling*. John Wiley & Sons. Retrieved from https://books.google.com/books?id=pSO4X3XbhJIC&pgis=1

Naidoo, R., & Ricketts, T. H. (2006). Mapping the economic costs and benefits of conservation. *PLoS Biology*, *4*(11), 2153–2164. doi:10.1371/journal.pbio.0040360

Nelson, E. J., & Daily, G. C. (2010, July 22). Modelling ecosystem services in terrestrial systems. Retrieved May 25, 2015, from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2990460/?tool=pmcentrez&report=abstract.html

Newton, A. C., Hodder, K., Cantarello, E., Perrella, L., Birch, J. C., Robins, J., … Cordingley, J. (2012). Cost-benefit analysis of ecological networks assessed through spatial analysis of ecosystem services. *Journal of Applied Ecology*, *49*(3), 571–580. doi:10.1111/j.1365-2664.2012.02140.x

Niehoff, D., Fritsch, U., & Bronstert, A. (2002). Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology*, *267*(1-2), 80–93. doi:10.1016/S0022-1694(02)00142-7

Olson, J., & Berry, L. (2000). *The extent and importance of land degradation* (Vol. 000). Retrieved from www.fao.org/nr/lada/index.php

OneAcreFund. (2015). *Soybean — Long Rain Season , Kenya and Rwanda (2014) Soybean — Long Rain Season , Kenya and Rwanda (2014)*. Retrieved from https://www.oneacrefund.org/blogs/tag/bananas/175

Peng, T., & Wang, S. (2012a). Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. *CATENA*, *90*, 53–62. doi:10.1016/j.catena.2011.11.001

Peng, T., & Wang, S. (2012b). Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. *Catena*, *90*, 53–62. doi:10.1016/j.catena.2011.11.001

Prabuddh, K. M., & Suresh, C. R. (2013). A Cost – Benefit Analysis of Indigenous Soil and Water Conservation Measures in Sikkim Himalaya, India. *Mountain Research and Development*, *34*(1), 27–35. doi:10.1659/MRD-JOURNAL-D-12-00013.1

Prosser, I. P., Dietrich, W. E., & Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. *Geomorphology*, *13*(1-4), 71–86. doi:10.1016/0169-555X(95)00020-6

Raventós, J., Wiegand, T., Maestre, F. T., & de Luis, M. (2012). A resprouter herb reduces negative density-dependent effects among neighboring seeders after fire. *Acta Oecologica*, *38*, 17–23. doi:10.1016/j.actao.2011.08.004

Reeuwijk, L. P. va. (2002). pipette methode.pdf. Retrieved from http://www.isric.org/isric/webdocs/docs//ISRIC_TechPap09.pdf

Renard, K., Foster, G., Weesies, G. a., McCool, D. K., & Yoder, D. C. (1997). *Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE), Agricultural Handbook 703. Agriculture Handbook* …. Retrieved from http://www.cabdirect.org/abstracts/19971903652.html

Rhoton, F. E., Shipitalo, M. J., & Lindbo, D. L. (2002). Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. *Soil and Tillage Research*, *66*(1), 1–11. doi:10.1016/S0167-1987(02)00005-3

Römkens, M. J. M., Helming, K., & Prasad, S. N. (2002). Soil erosion under different rainfall intensities, surface roughness, and soil water regimes. *Catena*, *46*(2-3), 103–123. doi:10.1016/S0341-8162(01)00161-8

Römkens, M. J. M., Prasad, S. N., & Gerits, J. J. P. (1997). Soil erosion modes of sealing soils: a phenomenological study. *Soil Technology*, *11*(1), 31–41. doi:10.1016/S0933-3630(96)00113-4

Sadeghi, S. H. R., Sharifi Moghadam, E., & Khaledi Darvishan, A. (2016). Effects of subsequent rainfall events on runoff and soil erosion components from small plots treated by vinasse. *Catena*, *138*, 1–12. doi:10.1016/j.catena.2015.11.007

Savenije, H. H. G. (2004). The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes*, *18*(8), 1507–1511. doi:10.1002/hyp.5563

Saxton, K., & Rawls, W. (2006). Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science Society of America Journal*, *70*, 1569–1578. doi:10.2136/sssaj2005.0117

Schägner, J. P., Brander, L., Maes, J., & Hartje, V. (2013). Mapping ecosystem services' values: Current practice and future prospects. *Ecosystem Services*, *4*, 33–46. doi:10.1016/j.ecoser.2013.02.003

Schertz, D. L. (1983). The basis for soil loss tolerances. *Journal of Soil and Water Conservation*, *38*(1). Retrieved from http://www.jswconline.org/content/38/1/10.extract

Shi, Z. H., Cai, C. F., Ding, S. W., Wang, T. W., & Chow, T. L. (2004). Soil conservation planning at the small watershed level using RUSLE with GIS: a case study in the Three Gorge Area of China.

CATENA, *55*(1), 33–48. doi:10.1016/S0341-8162(03)00088-2

Shrestha, D. P. (1997). Assessment of soil erosion in the Nepalese Himalaya, a case study in Likhu Khola Valley, Middle Mountain region. *Land Husbandary*, *2*(1), 59–80.

Shrestha, D. P., Suriyaprasit, M., & Prachansri, S. (2014). Assessing soil erosion in inaccessible mountainous areas in the tropics: The use of land cover and topographic parameters in a case study in Thailand. *CATENA*, *121*, 40–52. doi:10.1016/j.catena.2014.04.016

Shrestha, D. P., Zinck, J. A., & Van Ranst, E. (2004). Modelling land degradation in the Nepalese Himalaya. *Catena*, *57*(2), 135–156. doi:10.1016/j.catena.2003.11.003

Siepel, A. C., Steenhuis, T. S., Rose, C. W., Parlange, J.-Y., & McIsaac, G. F. (2002). A simplified hillslope erosion model with vegetation elements for practical applications. *Journal of Hydrology*, *258*(1-4), 111–121. doi:10.1016/S0022-1694(01)00569-8

Soliman, M. M. (2011). *Engineering Hydrology of Arid and Semi-Arid Regions*. CRC Press. Retrieved from https://books.google.com/books?id=SUTwnO62bU8C&pgis=1

Spanu, V., Shrestha, D. P., & Sciences, N. (2006). Vegetation Cover As an Indicator for Effective Implementation of Land Use Regulations in Sardinia.

Sudha, R., & Sekar, C. (2015). Economics and Adoption Behaviour of Farmers in Soil Conservation Technologies in Hilly Zone of South India, *28*(i), 211–218. doi:10.5958/0974-0279.2015.00036.1

Sun, W., Shao, Q., Liu, J., & Zhai, J. (2014). Assessing the effects of land use and topography on soil erosion on the Loess Plateau in China. *CATENA*, *121*, 151–163. doi:10.1016/j.catena.2014.05.009

Tallis, H., & Polasky, S. (2009). Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Sciences*, *1162*, 265–83. doi:10.1111/j.1749-6632.2009.04152.x

TEEB. (2010). *The Economics of Ecosystems and Biodiversity: Mainstreaming the economics of Nature: A synthesis of the approach, conclusions and recommendations of TEEB. Environment*. Retrieved from http://www.iges.or.jp/jp/news/topic/pdf/1103teeb/teeb_synthesis_j.pdf

Tenge, a. J., De Graaff, J., & Hella, J. P. (2005). *Financial efficiency of major soil and water conservation measures in West Usambara highlands, Tanzania*. *Applied Geography* (Vol. 25). doi:10.1016/j.apgeog.2005.08.003

Tennakoon, K. (2004). *Parameterisation of 2D Hydrodynamic Models and Flood Hazard Mapping for Naga city, Philippines*. Retrieved from http://www.itc.nl/library/papers_2004/msc/upla/tennakoon.pDF

Thiemig, V., Rojas, R., Zambrano-Bigiarini, M., Levizzani, V., & De Roo, A. (2012). Validation of Satellite-Based Precipitation Products over Sparsely Gauged African River Basins. *Journal of Hydrometeorology*, *13*(6), 1760–1783. doi:10.1175/JHM-D-12-032.1

Thorsen, B. J., Mavsar, R., Tyrvainen, L., Prokofieva, I., & Stenger, A. (2014). *The Provision of Forest Ecosystem Services: Quantifying and valuing non-marketed ecosystem services* (Vol. I). Retrieved from http://www.efi.int/files/attachments/publications/efi_wsctu_5_vol-1_en_net.pdf

Twagiramungu, F. (2006). *Environmental Profile of Republic of Rwanda*. Retrieved from http://www.vub.ac.be/klimostoolkit/sites/default/files/documents/rwanda-environmental-profile.pdf

USDA Natural Resource Conservation Service. (2010). *Final Benefit-Cost Analysis for the Grassland Reserve Program (GRP)*. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_007508.pdf

USDA Natural Resources Conservation Service (NRCS). (2000). Erosion and Sedimentation on Construction Sites. Retrieved July 21, 2015, from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053285.pdf

Wei, W., Chen, L., Fu, B., Huang, Z., Wu, D., & Gui, L. (2007). The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. *Journal of Hydrology*, *335*(3-4), 247–258. doi:10.1016/j.jhydrol.2006.11.016

Willemen, L. (2010). *Mapping and modelling multifunctional landscapes*. Retrieved from http://library.wur.nl/WebQuery/wda/1935827

Willemen, L., Burkhard, B., Crossman, N., Drakoue, E. G., & Palomo, I. (2015). Editorial: Best practices for mapping ecosystem services. *Ecosystem Services*, *13*, 1–5. doi:10.1016/j.ecoser.2015.05.008

Willemen, L., Drakou, E. G., Dunbar, M. B., Mayaux, P., & Egoh, B. N. (2013). Safeguarding ecosystem services and livelihoods: Understanding the impact of conservation strategies on benefit flows to society. *Ecosystem Services*, *4*, 95–103. doi:10.1016/j.ecoser.2013.02.004

Willemen, L., Veldkamp, A., Verburg, P. H., Hein, L., & Leemans, R. (2012). A multi-scale modelling approach for analysing landscape service dynamics. *Journal of Environmental Management*, *100*, 86–95. doi:10.1016/j.jenvman.2012.01.022

Wischmeier, W. H., & Smith, D. D. (1958). Rainfall energy and its relation to soil loss. *Transactions of the American Geophysical Union*, (39), 285–291. doi:10.1029/TR039i002p00285

Wischmeier, W. H., & Smith, D. D. (1981). *Predicting rainfall erosion losses. Supersedes Agriculture Handbook 282* (Vol. 282). Retrieved from http://naldc.nal.usda.gov/download/CAT79706928/PDF

Zhang, B., Yang, Y., & Zepp, H. (2004). Effect of vegetation restoration on soil and water erosion and nutrient losses of a severely eroded clayey Plinthudult in southeastern China. *CATENA*, *57*(1), 77–90. doi:10.1016/j.catena.2003.07.001

Zhang, Z., Sheng, L., Yang, J., Chen, X., Kong, L., & Wagan, B. (2015). Effects of Land Use and Slope Gradient on Soil Erosion in a Red Soil Hilly Watershed of Southern China. *Sustainability*, *7*(10), 14309–14325. doi:10.3390/su71014309

Zuazo, V. H. D., Ruiz, J. A., Raya, A. M., & Tarifa, D. F. (2005). Impact of erosion in the taluses of subtropical orchard terraces. *Agriculture, Ecosystems & Environment*, *107*(2-3), 199–210. doi:10.1016/j.agee.2004.11.011

APPENDICES

Appendices 1 Script

```
##########################
## channel dimensions ##
##########################

culvert_fraction2 = scalar(0.7);
culvert_discharge2 = scalar(300);

#########################
### LAND COVER MAPS ###
#########################


unitmap  = unitmapbase;

veg_cover = veg_cover0;
veg_cover = if(grasswid gt 0, 0.95*grasswid/celllength(), veg_cover);

veg_cover = if(scenario eq 0, 1-baresoil,veg_cover);
report landuse = unitmap;

############################
### CHANNEL DIMENSIONS ###
############################
culvert_discharge = culvert_discharge2;
culvert_fraction_width = culvert_fraction2;

culverts = if(scenario eq 0,0,culverts);


##################
### BASE MAPS ###
##################

chanm = if(drains > 0,1,0)*mask;
barriersc = if(chanm > 0, 0, barriers);
report barriersc = if(scenario eq 0, 0, barriersc);
# no barrier when channel = culvert

report DEMm = DEM;
report Ldd = lddcreate (DEMm-out*10-chanm*2+barriersc,  1e20,1e20,1e20,1e20);
# runoff flow network based on dem, main outlet, channels and barriers
report accflow = accuflux(Ldd,100);
report chanmask  = scalar(if(accflow > 2000000,1.0));
report ups.map=accuflux(Ldd,1);
# reference map,  not used in lisem
report outlet = pit(Ldd);
# should be the same now as mainoutlet.map  !!!
report grad  = max(sin(atan(slope((DEMm+barriersc)*mask))),  0.0025);
# sine gradient  (-), make  sure slope > 0.001
```

```
###########################################
### MAPS WITH RAINFALL INFLUENCE ZONE ###
###########################################
report id = nominal(mask);
# rainfall zone. only one gage so homogeneous map
#########################
### VEGETATION MAPS ###
#########################
report coverc = veg_cover*mask;
# fraction plant soil cover, assumed grass

# LAI of plants inside gridcell (m2/m2)
coverc = min(coverc, 0.95);
lai = ln(1-coverc)/-0.4;
report lai = if(coverc gt 0, lai/coverc, 0);

###################
### HOUSE MAPS ###
###################

report housecov=housecover*mask;
# copy directly input
report roofstore = if(housecover gt 0,1,0)*mask;
# interception storage
report drumstore.map=if(housecover gt 0,raindrumsize,0)*mask;
# possible water rain drum at home in m3
###############################################################
### INFILTRATION MAPS for option one layer GREEN & AMPT ###
###############################################################
report ksat = lookupscalar(soiltbl, 1, soilunit) * mask;
report pore = lookupscalar(soiltbl, 2, soilunit) * mask;
report psi = lookupscalar(soiltbl, 3, soilunit) * mask;
report soildep = lookupscalar(soiltbl, 5, soilunit) * mask;
## report soildep = 1000*mask;
##lookupscalar(soiltbl, 7, soilunit) * mask;

report cohsoil = lookupscalar(soiltbl, 6, soilunit) * mask;
report aggrstab = lookupscalar(soiltbl, 7, soilunit) * mask;



##########################
### SOIL SURFACE MAPS ###
##########################
report rr = max(lookupscalar(LUtbl, 2, unitmap) * mask, 0.01);
# micro relief, random roughness (=std dev in cm)
report mann = lookupscalar(LUtbl, 1, unitmap) * mask;
report crust = mask*0;
# crust fraction assumed zero
report stone = mask*0;
# stone fraction assumed zero
report comp = 0*mask;
#fraction compacted = murrum roads
report hard = mask*hardsurf;
#hard surface cells, not used here, included in house cover
```

```
report roadwidth = scalar(if(road eq 1 or road eq 3, 3.75, if(road eq 2, 3, 0)))*mask;
# width tarred roads in m
####################
### CHANNEL MAPS ###
####################

### NOTE: primary channel is 3 and 4, wide and wider channel
### secondary channel is 2, assumed to increase slightly towards the primary
### tertiairy channel are the bigger drains along the main roads
report lddchan = lddcreate((DEMm-out*10)*chanmask,1e20,1e20,1e20,1e20);
# create a channel network
outpoint = cover(scalar(pit(lddchan)),0)*mask;
outpoint=if(outpoint == 1,2,if(outpoint == 2,1,0));
report outpoint = outpointuser;

report chanwidt = lookupscalar(chantbl, 1, chanmask);
# report chanwidth = chanmask * if(culverts gt 0, chanwidth*culvert_fraction_width, chanwidth);
report chandepth.map = chanmask * 0.3;
# report chanwidth.map = chanmask * 0.9;
#create a culvert of half the channel width
report chanmaxq = scalar(mask *0);
report chanksat = 0*mask;#ksatgras.map;#6.3*mask; #if(unitmap eq 5, 32.0, 0)*chanmask;
report chanlevees = 0*mask;

####################
### EROSION MAPS ###
####################
# default values NOT USED IN KAMPALA
report D50 = 40 * mask;
## report cohsoil = 4 * mask;
report cohplant = coverc * 4 * mask;
## report aggrstab = 4 * mask;
report chancoh = 100 * chanmask;
report cropheight = lookupscalar(LUtbl, 4, unitmap) * mask;
```

Appendices 2 Questionnaire for assessing the cost and benefits of reforestation measures

DATA SHEET FOR REFORESTATION MEASURES

Interviewee:

Interviewer:

Location:

Date:

Data	Indicators	Value
Reforestation	Seeds • Number of trees	……………………
	• Type of trees	……………………….
	Harvesting time	Starting year: …………..
	Erosion control starting time	Starting year: …………..
	Tree lifespan	Number of years: ………
• Planting cost	Labour • Number of people	……………………………...
	• Manpower/Year	Francs: ………………………..
	Mulching	Francs: …………………….
	Pruning	Francs: ……………………
• Reforestation maintenance	Labour • Number of people	………………………….
	• Manpower/Year	Francs: ……………………
	Annual pruning	Francs: ……………..
• Reforestation benefits	Timber	Yield: ……… Trees/ha/year

		Cost of tree: ……… Francs
	Fuel wood	Yield: ……….Trees/ha/year
		Cost of tree: ……….Francs
	Medicinal plants	Yield: ………… Kg/ha/year
		Cost of kg: ……….. Francs
	Fruits	Yield: …………. Kg/ha/year
		Cost of kg: …..…… Francs

Appendices 3 Questionnaire for assessing bench terraces measures

DATA SHEET FOR BENCH TERRACES MEASURES

Interviewee / Occupation:

Interviewer:

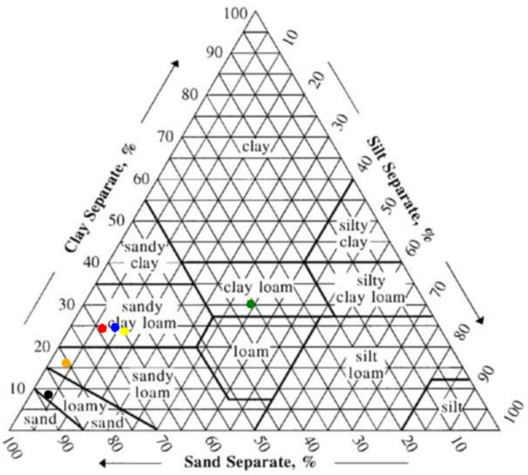
Organization:

Date:

Data	Indicators / Value		
Type of terraces constructed (Kigali)	Slope	Type Of terraces (Jabana case):	
	0-6%:		
	7-12%:		
	12-40%:		
	40-60%:		
	> 60%		
Time required to finish the construction	Slope (%)	No months:	Types of terraces (Jabana case)
	0-6%:		
	7-12%:		
	12-40%:		
	40-60%:		
	>60%		
Cost of terraces construction	Manpower: ha/terrace (Jabana case)	Days/francs:	
Cost of terraces maintenance	Manpower: ha/terrace (Jabana case)	Days/francs:	
Land area needed for terrace (Not available for cultivation anymore)	Slope (%)	Ha or sqm/terraces	Types of terraces (Jabana case)
	0-6%:		
	7-12%:		

	12-40%:		
	40-60%:		
	>60%		
Lifespan of terraces	No years:		

Appendices 4 Results from laboratory analysis of soil texture in the catchment



Appendices 5 The NPV and IRR of Reforestation measures

Year	Plantation cost-£	Maintenance cost-£	Total cost-£	Benefits_fuel wood-£	Benefits_timber-£	Benefits_carbon-£	Total_benefits-£	Increments-£	Discount	NPV	IRR
1	51632.375	0	51632.375	0	0	0	0	-51632.375	13%	£415,638.60	41%
2	0	9334.25	9334.25	0	0	22.55	22.55	-9311.7			
3	0	9334.25	9334.25	0	0	22.55	22.55	-9311.7			
4	0	9334.25	9334.25	0	0	22.55	22.55	-9311.7			
5	0	9334.25	9334.25	0	0	22.55	22.55	-9311.7			
6	0	9334.25	9334.25	0	0	22.55	22.55	-9311.7			
7	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
8	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
9	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
10	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
11	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
12	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
13	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
14	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
15	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
16	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
17	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
18	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
19	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			
20	0	9334.25	9334.25	43500	127781.25	22.55	171303.8	161969.55			

Appendices 6 the NPV and IRR of Bench terracing measures

Year	Construction cost (£)	Maintenance cost (£)	Total cost (£)	Benefits of carbon (£)	Benefits of forage (£)	Yield banana plantation	Total benefits (£)	Incremental benefits	Discount rate	NPV	IRR
1	155566.275	0	155566.275	0	0	0	0	-155566.275	13%	£628,952.34	82%
2	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
3	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
4	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
5	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
6	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
7	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
8	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
9	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
10	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
11	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
12	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
13	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
14	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
15	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
16	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
17	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
18	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			
19	0	15556.625	15556.625	0.125	3	125000	125003.125	109446.5			
20	0	15556.625	15556.625	0.125	3	125000	153700	138143.375			

Appendices 7 Return periods

Year	Day_rainfall	Rank	Left_prob.	Right_prob.	Return_period	PP
2005	27.4	1	0.02777778	0.972222222	1.028571429	-1.27635
1992	31	2	0.05555556	0.944444444	1.058823529	-1.06139
2008	31.3	3	0.08333333	0.916666667	1.090909091	-0.91024
1986	33.6	4	0.11111111	0.888888889	1.125	-0.7872
2011	36.9	5	0.13888889	0.861111111	1.161290323	-0.6801
2004	39.3	6	0.16666667	0.833333333	1.2	-0.5832
1991	42.3	7	0.19444444	0.805555556	1.24137931	-0.49324
2009	42.7	8	0.22222222	0.777777778	1.285714286	-0.40818
2006	43.2	9	0.25	0.75	1.333333333	-0.32663
1993	43.5	10	0.27777778	0.722222222	1.384615385	-0.24759
1997	45.2	11	0.30555556	0.694444444	1.44	-0.17027
1996	45.9	12	0.33333333	0.666666667	1.5	-0.09405
1995	48	13	0.36111111	0.638888889	1.565217391	-0.0184
2014	48.9	14	0.38888889	0.611111111	1.636363636	0.05714
2012	50.4	15	0.41666667	0.583333333	1.714285714	0.132996
1990	52.5	16	0.44444444	0.555555556	1.8	0.209573
2000	52.6	17	0.47222222	0.527777778	1.894736842	0.287275
2013	53.6	18	0.5	0.5	2	0.366513
1998	54.8	19	0.52777778	0.472222222	2.117647059	0.447726
1994	55.1	20	0.55555556	0.444444444	2.25	0.531391
2007	57	21	0.58333333	0.416666667	2.4	0.618046
1999	59.3	22	0.61111111	0.388888889	2.571428571	0.708309
1984	59.9	23	0.63888889	0.361111111	2.769230769	0.802907
1983	60.1	24	0.66666667	0.333333333	3	0.90272
1985	63.9	25	0.69444444	0.305555556	3.272727273	1.008836
2003	64.6	26	0.72222222	0.277777778	3.6	1.122631
1981	66.8	27	0.75	0.25	4	1.245899
1989	68.7	28	0.77777778	0.222222222	4.5	1.38105
1987	74.3	29	0.80555556	0.194444444	5.142857143	1.531444
1988	76.6	30	0.83333333	0.166666667	6	1.701983
2002	79.9	31	0.86111111	0.138888889	7.2	1.900247
2010	89.2	32	0.88888889	0.111111111	9	2.138911
1980	89.9	33	0.91666667	0.083333333	12	2.441716
1982	91.9	34	0.94444444	0.055555556	18	2.861929
2001	106	35	0.97222222	0.027777778	36	3.569467

Appendices 8 Rainfall events pattern