Assessing structural and ecosystem based measures to reduce surface runoff; A comparative study in Mpazi and Byababagabo Jabana sub-catchments, Kigali-Rwanda

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ABSTRACT

Many studies have been focused on the use of structural measures for mitigating surface runoff and flash flood in urban areas. The objective of this study was to assess the effects of structural and ecosystem based conservation measures on surface runoff in upstream areas and flash flood problem in downstream areas. Two sub catchments located within the City of Kigali in Rwanda were selected as the study areas. Mpazi sub catchment is highly urbanized and Byabagabo Jabana sub catchment is lightly populated. Moreover, Mpazi sub catchment was pointed out to be the main cause of flash flood in Nyabugogo commercial center in downstream areas in Kigali. OpenLISEM hydrological model was selected and used to examine the surface runoff behavior in both sub catchments. The land use/cover map of each sub catchments and other required data for running the model were acquired and processed. The surface runoff from each sub catchment was simulated, analyzed and a comparison was made to see which catchment generates more surface runoff. Furthermore, the impact of structural and ecosystem based measures on surface runoff reduction in Mpazi sub catchment was modelled. Also, the impact of ecosystem based measures on soil loss was assessed using OpenLISEM. The model calibration was done by comparing the model simulated results versus the field measured flood depth and flood volume. The sensitivity analysis shows that the model is very sensitive to Ksat. The main results were that simulation with the current land use/cover in both sub catchments showed high runoff generation (>112%) in Mpazi sub catchment than in Byabagabo Jabana sub catchment. The use of structural conservation measures in Mpazi sub catchment showed a decrease in surface runoff by 45% compared to baseline scenario as well as a considerable decrease in flash flood in Nyabugogo commercial center. However, much sediment was also generated. The ecosystem based measures decrease surface runoff by 22% and soil loss by 65% compared to the baseline scenario. The combination of structural and ecosystem based measures led to a noticeable decrease in surface runoff (62%) and flash flood in downstream areas. The combined scenario was found to be more effective than other applied conservation measures (scenarios). The main conclusion was that the ecosystem based measures can be used as alternative measures to reduce surface runoff and soil losses that cause flash floods in many downstream areas in Kigali City.

Keywords: Ecosystem based measures, surface runoff, land use/cover, OpenLISEM

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ASCII: American Standard Code for Information Interchange (Raster file format)
DEM: Digital Elevation Model
GPS: Global Positioning System
GIS: Geographical Information System
ILWIS: Integrated Land and Water Information System
MSGMPE: Meteosat Second Generation Multi-Sensor Precipitation Estimate
NDVI: Normalized Difference Vegetation Index
OpenLISEM: Limburg soil erosion model

1. INTRODUCTION

1.1. Research backgroung and justification

Ecosystem services are considered the benefits that can be gained from ecosystems (MA, 2005). Another definition of ecosystem services involves the capacity of ecosystems to provide goods and services that can support humans in their daily life (de Groot et al., 2010). de Groot et al. (2002) subdivide ecosystem services and goods into four categories: regulating functions (*e.g. flood prevention*), habitat functions (*e.g. gathering of fish*), production functions (*e.g. fuel wood*) and information functions (*e.g. eco-tourism*).

Ecosystem regulating services can play an important role in mitigating and preventing natural hazards, reducing climate change impact, water regulation and protection of soil erosion among others (de Groot et al., 2010). Well-managed wetlands and forests, for example, may act as a buffer to natural hazards. In addition, they can reduce the impact of hazards like cyclones, flooding, avalanches, etc (Munang et al., 2013).

The increase in runoff coming from the upper urban watershed is the main cause of extreme flash floods affecting low laying areas. These high flood magnitudes are causing substantial damages to properties and human lives (Špitalar et al., 2014). They destroy bridges, houses and interrupt transport, water and electricity supply (Wolski et al., 2014). In addition to that, the increased volume of runoff contributes to the transport of sediments and pollutants (e.g. human waste, pesticides) that may affect water bodies in downstream areas (Hrdinka et al., 2012).

Vegetation cover, such as forests, grasslands and shrublands play a crucial role in the reduction of water runoff in an upper watershed (Qin et al., 2013). Tree leafs intercept rainfall while grasslands store runoff by increasing soil infiltration (Fu et al., 2013). The water flow regulating services of a forest cover can contribute to the reduction of runoff of surface water (de Groot et al., 2002). Huang et al. (2003) demonstrated how afforestation in upper watersheds affects runoff of surface water. As trees become older, there is a significant reduction in the generation of runoff. The protective role of vegetation cover is also relevant in urban areas. Yang et al. (2015) used the modified Soil Conservation Service model (SCS) to study the role of green spaces in urban areas. They found a considerable reduction in the runoff of surface rainfall which is the main factor for flood generation in downstream areas.

Water flow regulation services of downstream floodplains may play a significant role to store runoff water coming from upstream areas. Due to the high infiltration rate, the floodplains retain the runoff water and serve as a water reservoir (Dessie et al., 2014). This helps to reduce the risk of flooding in downstream areas (Schober et al., 2013). In addition, De Martino et al. (2012) highlighted the importance of a vegetated floodplain in holding floods volumes. Javaheri & Babbar-Sebens (2014) studied the benefit of wetland restoration for peak flow reduction. The peak flow was reduced considerably with different simulated wetland depth.

Population growth, urbanization and other human activities are causing significant changes to land cover; forests have been cleared and replaced by built-up areas and water bodies have decreased (Qi et al., 2013). In addition, vegetation-covered land and wetlands are increasingly converted to urban areas (Qiu et al., 2015), green spaces in already built-up areas are sacrificed for further urbanization (Haas et al., 2015), and wetlands are being degraded and reduced due to population occupation and other economic activities

(Xianzhao & Shanzhong, 2011). Traditional urban drainage systems in the form of canals are still used to replace natural drainage systems for flood management (Meierdiercks et al., 2010). Jennings & Jarnagin (2002) used different multi-temporal aerial photography to map changes in surface permeability in urban areas. The results showed a considerable decrease in soil surface permeability with urban development.

Rapid urban growth and decrease in farmland (e.g. grassland) in upper watersheds increase surface runoff and might be the cause of flash floods (Shi et al., 2007). Fu et al. (2013) warned that the destruction of upstream forest and grasslands increases runoff and may cause the risk of flooding in downstream areas. On the study of runoff response to different land cover change (e.g. urbanization, deforestation) in upstream small watersheds, Solín et al. (2010) found a linear correlation between increasing soil compaction and surface runoff. The change in land use (urbanization) in downstream floodplains reduces the natural soil permeability and may lead to flood risks to occupants (Suriya & Mudgal, 2012). Furthermore, urban development in a wetland affects the hydrological regime. It blocks the infiltration process of precipitation and surface runoff from upstream areas and increases water flow volumes. This increases flood risk in downstream urbanized areas (Lee et al., 2006).

Also, in Rwanda, there is a rapid growing of urban areas, together with an increase in (peri-) urban flooding. According to REMA, (2013) in the capital city Kigali, the rapid population growth and the migration of people coming from rural areas to the city have caused the degradation of the natural environment. Many houses have been built on steep slopes and flood prone zones in some watersheds. The former industrial zones are still in wetlands even though there is a plan to relocate them. Kigali city Council is planning to increase the capacity of the drainage channels and to use gabions wall to enhance channel roughness (SHER Ingénieurs-Conseils s.a., 2013) for floods mitigation.

In Kigali City, unplanned housing on fragile hill slopes and in other high-risk zones have replaced urban green spaces such as forest and grasslands. The rapid urban developments in different upper watersheds of the city have caused a reduction in soil surface permeability. This results in the generation of surface runoff in the upper watershed during a severe rainfall. Other human activities such as agriculture, sand quarries, settlements and transport activities (bus station) have been conducted in wetlands and floodplains zones. For example, some commercial centers (e.g. Nyabugogo business center) and industries (e.g. Inyange industry) are located in wetlands and floodplains zones. In addition to that, the Kigali city lacks adequate drainage and households rain-water collection systems which may contribute to the reduction of runoff generation. Furthermore, the Kigali city lacks secondary rainwater drainage channels in some upper watershed which contribute to the development of gullies.

In recent years, frequent flash floods have been observed in some areas of the Kigali city such as Nyabugogo commercial center, Gikondo industrial parks and in Nyabarongo-Akagera floodplain agricultures fields during the rainy season. This interrupt business, transport and other development activities for several hours and sometimes causes other damages (e.g. accidents). According to local authorities and people, the most severe recent flood events took place on 23 February 2013 and 26th November 2015 which caused a lot of damages and death of three people in Nyabugogo Commercial Center. In order to cope with this flooding problems, the Kigali City Council has constructed traditional drainage channels for runoff collection in some parts of the city and increased the culverts in downstream areas. The Kigali City Council requested the citizens to use rainwater harvesting system at household level but only a few houses adapted it. Also, terraced green walls to retain and control soil erosion and runoff have been established in few areas (REMA, 2013). Despite the use of those different flood control measures, the flooding problem persists in some areas of the City.

In this study, different conservation measures based on ecosystem regulation services (ex: reforestation, grassland) to reduce surface runoff will be applied. Little attention has been given to this type of flood mitigation measures in past years in Kigali City. This ecosystem based mitigation measures will be utilized in upper watersheds to reduce high amount of runoff coming from those areas which are the main causes of flooding in downstream areas.

1.2. Problem statement

The city of Kigali has recognized a rapid urban development in the last twenty years. In some urban watersheds, houses have been built on steep slopes and in floodplain areas. They replaced green spaces such as forest and grasslands. This lead to the reduction of surface permeability in upper areas as well as in floodplain zones. The amount of runoff generated in upper areas during rainfall has been increased due to low infiltration and are causing flash flood in downstream areas. This affect business and transport facilities (e.g. roads, bus stations) for several hours and sometimes causes other damages and accidents. In order to cope with the flooding problem, the Kigali City Council (KCC) has constructed traditional drainage channels for runoff collection in some parts of the city and increased culverts capacity in downstream areas. Despite this effort, the flash floods are still observed in some parts of the City. The figure 1.1 below shows the situation in case of flooding in Mpazi sub catchment (Nyabugogo center).

Flash flood in Nyabugogo Commercial Center in 2015 Flash flood in Nyabugogo Commercial Center in 2013

Figure 1.1: Flooding in Nyabugogo Commercial Center (study are)

Source: Touch Rwanda newspaper, (2015); Newtimes Rwanda newspaper, (2013)

In this study, different conservation measures based on ecosystem regulation services (ex: reforestation, grassland) to reduce surface runoff will be applied. The ecosystem based mitigation measures will be utilized in upper watersheds to reduce high amount of runoff coming from those areas which are the main causes of flooding in downstream areas. The use of ecosystem based measures for flood management in Kigali City has been given a little attention in past years. This research considered the use of ecosystem based measures (ex: reforestation, grassland) and compare them with structural measures (e.g retention pond). The study was conducted in two sub catchments which are located in Kigali City: (i) Mpazi sub catchment is highly urbanized and has been identified by SHER Ingénieurs-Conseils s.a. (2013) as the main cause of flash flood in Nyabugogo commercial center (downstream area), and (ii) Byabagabo Jabana sub catchment is lightly populated with a high rate of developments. A spatial event-based rainfall-runoff model was used to simulate the effect of land use/cover change on runoff generation and flash flood problem in the lowlands in order to assess different proposed measures for flood management.

1.3. Objectives and research questions

1.3.1. Main objective

The main objective of this study is to assess the effects of structural and ecosystem based measures to reduce surface runoff in upstream areas and flash flood problem in downstream areas. In particular the relevance and protective capacity of selected ecosystem-based risk reduction measures are considered.

1.3.2. Specific objectives

1. To assess the effect of the existing land use/cover types on surface runoff generation using a spatial runoff model in Mpazi and Byabagabo Jabana subcacthment;
2. To assess the impact of structural conservation measures for runoff reduction;
3. To assess the impact of ecosystem based conservation measure (reforestation, grass cover, water harvesting) for runoff and soil loss in Mpazi sub catchment;

1.3.3. Research questions

1. Which land use/cover type produces more surface runoff and why?
2. Which sub catchment generates more surface runoff and why?
3. Which structural conservation measures will help in reducing surface runoff?
4. Which upstream ecosystem based conservation measures reduce surface runoff and soil loss?

1.3.4. Hypothesis

Hydrological models are very useful to study surface runoff and flash flood hazards. Using OpenLisem hydrological model, this study will help to identify responsible factors that are causing high runoff and flash flood in Mpazi sub catchment. It will also provide other conservation measures for flood management typical based on ecosystem services. This will help decision makers and urban planners for the future plan of the Kigali City.

1.4. Thesis structure

This thesis report is composed of seven chapters represented as follows:

The first chapter comprises of the research background and justification, description of the problem statement and objectives and research question of the research. The second chapter provides the literature review which describes factors affecting surface runoff and some models in runoff studies. Chapter third describes the study areas. Chapter four present methodology and data used in this study. Chapter five provides information on data processing. Chapter six shows the results and their discussion. Chapter seven is the last one and provide the conclusion of this study, some recommendation and limitation of the study.

2. LITERATURE REVIEW

2.1. Ecosystem regulating services and natural hazards

The ecosystem regulating services can play an important role in natural hazard mitigation and prevention, water regulation and soil erosion control among others. For example, a well-managed wetlands and forests may act as a buffer to natural hazards. They can reduce the harmful impact of hazards like cyclones, flooding, landslides, etc. In addition to that, they help to reduce the negative impact of climate change to natural and human system. They purify air, reduce carbon emissions and prevent some diseases (de Groot et al., 2010; Munang et al., 2013). In modelling different type of natural hazards, Nel et al. (2014) demonstrated how restoring natural vegetation would be an adequate tool for reducing wildfire and drought hazards as the invasive alien trees contribute to the spread of drought and wildfires hazards in the forest.

2.2. Surface runoff generation in urban watersheds

According to Fu et al. (2013) the destruction of upstream forest and grasslands increases runoff and may cause the risk of flooding in downstream areas in watersheds. The presence of forest in upper areas help to intercepts rainfall and the ground cover absorbs overland flow. This reduces surface runoff as well as flooding in downstream areas. Rapid urban growth in watershed increases the loss in pervious areas which reduce the infiltration capacity of soil and leads to the generation of surface runoff during rainfall (Miller et al., 2014). By analysing different land use/cover maps of an urban catchment from the year 2000 to 2010, Abas & Hashim (2014) found a big correlation between urban expansion and surface runoff generation. Surface runoff increased significantly with urban expansion in the period of ten years. Furthermore, traditional urban drainage structures contribute to a surface runoff in urban areas. They reduce the soil infiltration and roughness and hence increase runoff and affect the water cycle (Meierdiercks et al., 2010).

Floodplains play a key role in restoring rainfall runoff coming from upper areas due to high infiltration. With the conversion of floodplain into urbanization in some parts of the world, pervious surface has been decreased in downstream areas (Suriya & Mudgal, 2012). Furthermore, the use of dykes and other structural measures in downstream areas for flood protection, separate rivers from their floodplains which consequently increases flooding in low lying areas (Schober et al., 2013a).

2.3. Factors affecting surface runoff and soil erosion

2.3.1. Vegetation

The presence of vegetation cover contributes to reduce the amount of runoff generated during a rainfall event. Canopies retain some rain water and other fall through them and reach the ground. The intercepted rainwater is evaporated and return to the atmosphere. Ground vegetation cover protects the soil from raindrop impact and hence reduces soil erosion. In addition to that, plant root system stabilizes soil and contributes to the formation of organic matter. This increases the soil porosity and positively affects water infiltration (Fattet et al., 2011; Shrestha et al., 2004; Y. Zhang & Shuster, 2014).

2.3.2. Soil

Soil porosity shows high correlation with infiltration. In the study on infiltration in different soil types (agriculture soil and bare soil) (Wang et al., 2015) found high infiltration rate in coarse soil used for agriculture purposes than in bare land. Also high runoff and sediments were observed in bare soil than in agriculture land. In addition to that surface runoff and erosion decrease with increasing soil aggregate stability and the latter increases with the presence of canopy cover (Holifield Collins et al., 2015).

2.3.3. Slope and size of the Catchment

El Kateb at al., 2013 used the plot size of seven square meters ($7m^2$) to study the effect of different slope gradient on surface runoff and soil erosion. The amount of surface runoff and soil erosion increased with higher steep slope plot than on a moderate steep slope. The size of the watershed affects the amount of runoff generated during a rainfall event. The runoff volume increases with the decreasing watershed size. For example in a small urban watershed, due to the presence of buildings and roads, the amount of runoff generated are much higher than in a larger catchment where the proportion of area affected by urban development activities is small (Klein, 1984).

2.3.4. Precipitation

The runoff generated during a rainfall event are strongly affected by the amount of precipitation. On the study of the relationship between precipitation and annual runoff in different years, Zhang et al. (2015) found the high correlation between the runoff produced and the quantity of precipitation fallen. The runoff decreased as the precipitation decreases. However, the evapotranspiration showed a big increase.

2.4. Structural and ecosystem based measures for runoff reduction

Recently, some countries have started to recognize the role of ecosystem regulating its services for flood reduction in urban areas. For example, the European Union is emphasizing on the restoration of river floodplains to its member states as a sustainable way of flood protection (Habersack et al., 2013). Zhang et al. (2012) emphasized on the establishment of urban forest and grassland as a way of reducing runoff in urban areas. The vegetated area stores more rainfall than the hard surface and hence reduce the risk of flooding in downstream areas. Plan have been made to rehabilitate degraded wetlands in different watersheds (Tong et al., 2007). Liu et al. (2014) highlighted the use of integrated green infrastructures as a way of reducing rainfall surface runoff in urban areas. The applied measures were to increase green concave spaces (trees and vegetation), use of porous pavement and the construction of runoff retention structures. Materials such as permeable bricks which allow infiltration during rainfall started to replace sealed surface in some urban areas. Furthermore, the use of green infrastructure (e.g. permeable pavement) reduces runoff velocity by increasing surface roughness and infiltration (Yang et al., 2015).

2.5. Hydrological models

Different types of hydrologic models have been useful to study the impact of land use/cover change on flooding using different scenarios. For example Ali et al. (2011) used the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) to study the effect of different land use change on runoff generation. They found a correlation in peak discharge and runoff volume and urban growth. The HEC-HMS model is designed to simulate hydrologic processes (e.g. runoff) at the watershed level. It allows all hydrologic analysis procedures such as infiltration and hydrologic rout (Halwatura & Najim, 2013; Knebl et al., 2005).

MISDc (Modello Idrologico Semi-Distribuito in continuo') is the type of hydrological model used in the flood simulation. The model was initially developed for flood forecasting and hydraulic hazard assessment. It was used successfully to study the flooding behaviour from small to larger catchments in Italy (Brocca et al., 2011). However the MISDc model has some limitations in simulating stream base flow (Ciabatta et al., 2015).

SOBEK 1D2D is a widely used hydrodynamic model in flood modelling. It has advantages compared to the other hydrological models as it integrates one-dimensional (1D) channel flow model with two-dimensional (2D) overland flow model. It has a variety of uses including simulation of flood inundation, water quality prediction and analysis of urban drainage system (Vanderkimpen & Flood, 2009). It has been used in different areas for floods simulation (Lammersen, Engel, Langemheen, & Buiteveld, 2002; Pistrika & Jonkman, 2010) (Lammersen et al, 2002; Pistrika & Jonkman, 2010). Although with dependence on the data resolution and data type, the model may require very long run time (Carrivick, 2006).

Several other studies on the effect of land use change on flooding and soil erosion using Limburg soil erosion model (LISEM) have been conducted. For example Baartman et al. 2012 used LISEM model to study soil erosion and runoff using rainfall event of different magnitude in a medium catchment in Spain. Erosion was found to increase with increase rainfall event magnitude and deposition was taking place before reaching the catchment outlet. The models results showed that the runoff was infiltrating before reaching the channels. Also it was found that the model need a separate calibration for each simulated rainfall event. OpenLISEM model was also used in other several studies related to flash flood, runoff and erosion (Nearing et al., 2005; Sanchez et al., 2014). In this study, OpenLISEM model was selected and used to assess the effect of ecosystem based and structural measures on surface runoff in two small catchments. Further details on the choice of the model are provided in section 4.2.

2.6. OpenLisem for runoff and soil erosion modelling

Lisem (Limburg soil erosion model) model is a physically based initial designed to simulate erosion and runoff at small catchment level. The model simulates soil erosion, runoff and shallow floods during a rainfall event. It is incorporated in raster format and expressed in term of Geographical Information System command (De Roo et al., 1996). OpenLisem includes hydrological processes such as interception and throughfall, surface storage in micro depression, infiltration (two-layer Green and Ampt), overland and channel flow and spatially distributed rainfall (Nearing et al., 2005). According to de Jong & Jetten (2007), the net precipitation are obtained by subtracting interception storage of leaves and branches. This precipitation reach the ground and generate surface runoff. The runoff is directed by the kinematic wave and in the case of channels, the latter is determined by its dimensions, roughness and slope bed. For the soil erosion, the sediment is caused by splash detachment due to rainfall kinetic energy and soil detachment by overland flow (Baartman et al., 2012).

2.7. Model calibration and validation

The model calibration and validation are usually performed to obtain acceptable results. The most method used is the comparison of the model simulated results and the field measured results (Hessel et al., 2003). If there is a difference in the results, some parameters of model input (e.g. Ksat) are changed until the results become similar. It is advisable to calibrate the model when acting at small to medium catchments where the simulation is influence by spatial variability. Furthermore, for a model to have good results, an event to be calibrated shall belong inside the range of calibration (Jetten et al., 1999).

3. STUDY AREA

3.1. Introduction

“Kigali, Rwanda”

The study area is located in Kigali, the capital city of Rwanda. It is selected for so many reasons, it is the most vulnerable area to flooding in the City, and there is a gap in knowledge on how to resolve this problem in a sustainable manner, the socio economic value of the area (commercial and transport center) and lack of data for flood studies.

Two sub catchments, Mpazi and Byabagabo Jabana, were selected for this research. Both the catchments are part of Nyabugogo basin which is located in Kigali City. They look similar in size and other physical characteristics but one is very much urbanized and the other is sparsely populated. The different in characteristics of the two sub catchments facilitated to assess the impact of urban development on runoff generation. Figure 3.1 shows the location of Mpazi and Byabagabo Jabana sub catchments.

Study area location

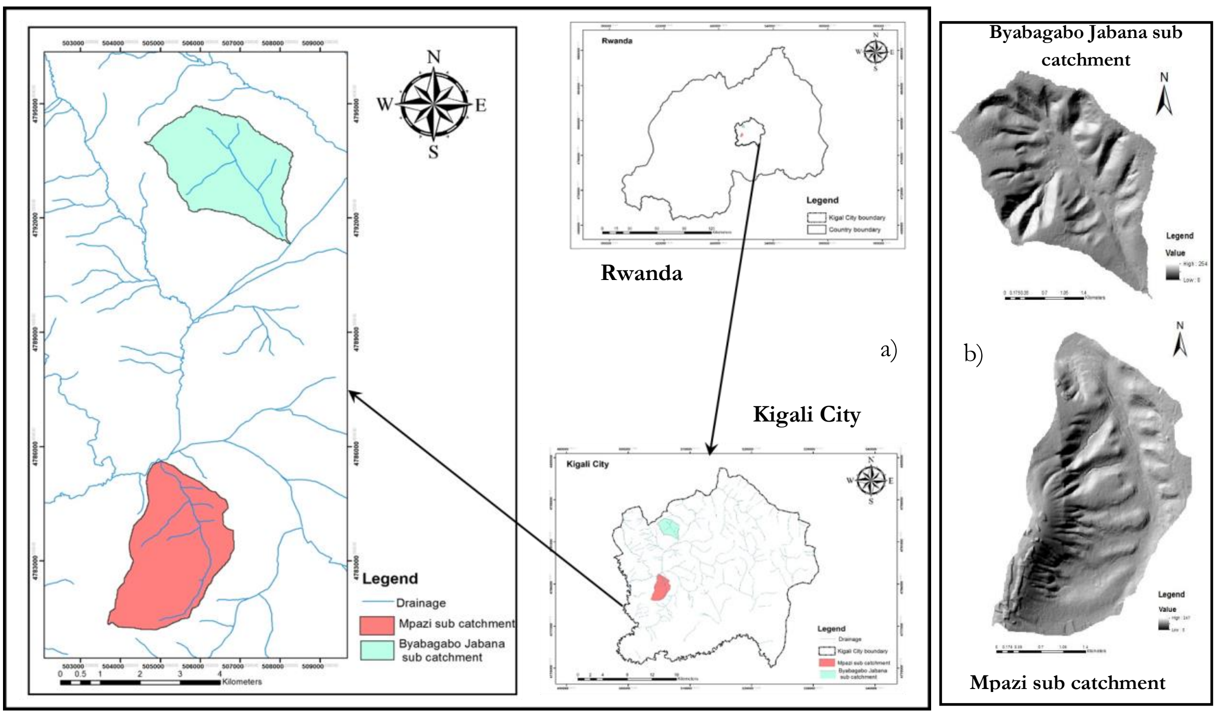


Figure 3.1: a) Location of Study areas in Kigali City, Rwanda; b) Shaded relief image of the two sub catchments.

3.1.1. Mpazi sub-catchment

Mpazi sub-catchment is very urbanized and is located in Nyarugenge districts (1°57'S, 30°3'E), Kigali City. It covers an area of 8.7 km^2. It has very steep topography (some > 30 degrees) with the elevations ranging from 1377 m to 1850 m a.s.l. Since most of the sub-catchment is heavily urbanized, this causes excessive runoff during rainfall. The sub-catchment has been identified as the root cause of flooding in Nyabugogo commercial center in the downstream area (SHER Ingénieurs-Conseils s.a., 2013). The figure 3.2b shows the urban area in this sub basin.

3.1.2. Byabagabo Jabana sub-catchment

Byabagabo Jabana sub-catchment is sparsely populated and is located in Gasabo districts (1°52'S, 30°3'E) in Kigali City. This sub basin has an area of 8.04 km^2. It has steep topography with the elevations ranging from 1400 m to 1750 m a.s.l. Land cover in Byabagabo Jabana sub catchment comprises few residential areas dispersed on steep hillslopes, small forests and agriculture fields occupy the major part of the sub catchment. The figure 3.2a presents low urbanization level in this sub catchment.

a) Byabagabo Jabana sub catchment b) Mpazi sub catchment

Figure 3.2: Lightly populated Byabagabo Jabana sub catchment (a); highly urbanized Mpazi sub-catchment (b).

Source: Kigali City Council, 2010

3.2. Land use

3.2.1. Mpazi sub catchment

The built up area dominate this urban sub catchment occupying 72 % of the total area. The main other land use are forest areas with 16% and agriculture areas with 11 %. The residential area is located in upper part of the catchment with some houses on the slope of more than 20 degrees and the Nyabugogo commercial center occupying the downstream (floodplain) area. The small forest plantation mainly consists of eucalyptus trees and is located in the upper part of the catchment. The slopes below 27% account for 35 % of the sub catchment while the area with a slope more than 20 % account for 20%.

3.2.2. Byabagabo Jabana sub catchment

The current land use in Bybagabo Jabana sub catchment consists of forest areas covering 24% of the total area, 68 % of agriculture fields, built up area only account for 3 % and other land use types occupying 5 %. Eucalyptus forests type are dominant in the sub catchment and located on a steep slope. The main types of agriculture in the area are sugarcane plantation in the floodplain and banana plantation. In this catchment, the slope value above 36% account for 33% of the total sub catchment area while the remaining area (<35%) account for 66% of the basin area.

3.3. Soil

The soils in both sub catchments have been derived from schistose, sandstones, quartzite, granite, gneissic, intrusive rocks and volcanic materials (SHER Ingénieurs-Conseils s.a., 2013). The dominating soil types in the study area are clay loam acrisols, sandy loam regosols and cambisols.

3.4. Climate

Both Byabagabo Jabana and Mpazi sub-catchments are located in the same big basin, they have the same tropical temperate climate. The average annual temperature ranges between 16 and 21 degree celsius. The average monthly temperature varies by 1.5 degree Celsius. The total annual precipitation is below 1,200 millimetres. The wettest month is April with an average precipitation of 183 mm while the driest month is July with 9 mm precipitation. They have two rainy seasons which are the long rains seasons from February to May and the short rains seasons from September to January. The rainiest time of the year is March through May in Kigali City. The Figure 3.3 below shows the average daily temperature and monthly rainfall of Kigali City of the year 2013.

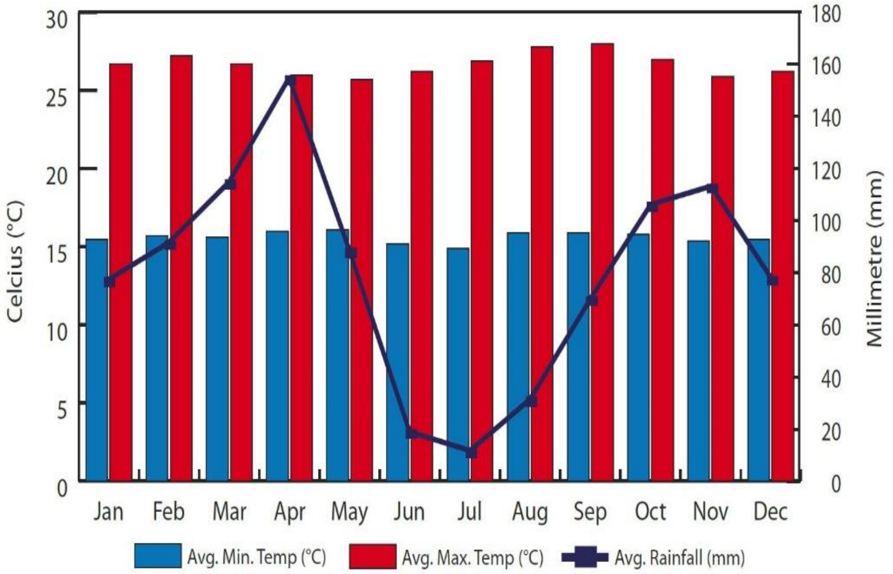


Figure 3.3: Kigali City average monthly rainfall and temperature of the year 2013

Source: REMA (Kigali State of environment), 2013.

4. RESEARCH METHODOLOGY AND MATERIALS

4.1. Introduction

The chapter explains the methods applied to answer the research questions. To study the behaviour of surface runoff at various land use/cover types as well as to study the effect of urbanization, two sub catchments located in Kigali-Rwanda were selected. They have different land use/cover characteristics. Mpazi sub catchment is very much urbanized with little vegetation cover in upper areas whereas Byabagabo Jabana sub catchment is sparsely populated with higher part covered by forest. The land use/cover maps of the sub catchments were acquired and analysed in details. The surface runoff from each sub catchment was simulated, analysed and a comparison was made to see which catchment generates more runoff. In order to analyse the surface runoff behaviour to different land use/cover at the catchment scale, a rainfall runoff flash flood model was selected. OpenLisem hydrological model was used for that purpose.

Mpazi sub catchment was pointed out to be the main cause of flash flood in Nyabugogo commercial center in downstream areas in Kigali (SHER Ingénieurs-Conseils s.a., 2013). In order to cope with this problem, structural measures (retention pond) and ecosystem based measures (reforestation) were proposed. Their impact on surface runoff generation was modelled using OpenLISEM.

The surface runoff also brings sediments that stay loaded along the main drainage channel and block the movement of rainwater. Also, sediments are deposited at the outlet culvert blocking the water flow and hence causing a flash flood in the commercial centre. To analyse this problem, the impact of proposed ecosystem based measures on soil loss were also modelled using OpenLISEM.

In addition, to the simulation of the impact of the current land use/cover on surface runoff generation in both the sub catchments, various conservation measures were applied in Mpazi sub catchment which resulted in different scenarios. All conducted scenarios are shown below:

- Simulation with the current situation without any conservation measures in both Mpazi and Byabagabo Jabana sub catchment (baseline scenario);
- Simulation with urban densification in Byabagabo Jabana sub catchment (scenario 1);
- Simulation with the use of structural measures in Mpazi sub catchment (scenario 2);
- Simulation with the use of ecosystem based measures in Mpazi sub catchment (scenario 3);
- Simulation with the combined measures (ecosystem based and structural) in Mpazi sub catchment (scenario 4).

The flowchart summarizing the steps followed in this study is shown on figure 4.1.

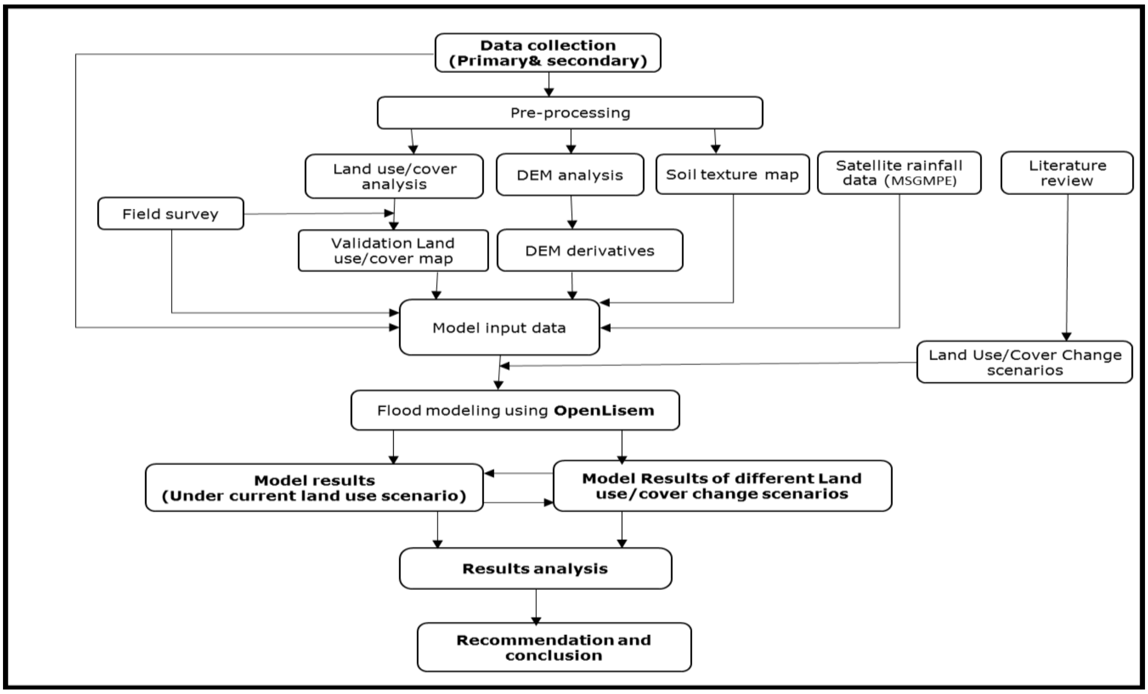


Figure 4.1: Methodological Flowchart

4.2. OpenLisem model description

OpenLISEM hydrological model was selected to simulate the hydrologic response in Byabagabo Jabana and Mpazi sub-catchments. This model was chosen because it is designed for small to medium (1ha-100km2) catchments (Sanchez-Moreno et al., 2014) and the model has been used in many countries including east Africa (this study area location) (Hessel et al., 2006). OpenLISEM is a spatially distributed physically based hydrologic and soil erosion model that operate at a catchment level. It has been used to simulate surface runoff and erosion for an individual rainfall event (De Roo et al., 1996). All the requirements for the model inputs and output are described in De Roo et al., (1996).

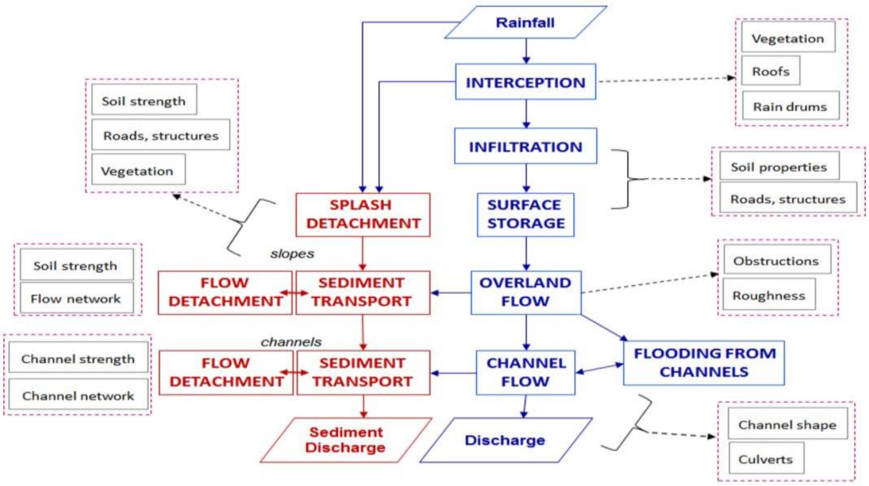


Figure 4.2: Flowchart summarizing the process of OpenLisem model

Source: V. Jetten, (2013), (http://blogs.itc.nl/lisem/basic-theory)

The model was run using grid cell size of 10x10 m. This size was determined because the maximum width of Mpazi sub catchment drainage channel is 7.5 m and the width of Byabagabo Jabana sub catchment drainage stream is 1m. Usually, OpenLISEM assumes that the channel (or stream) width is less than grid size (Hessel, 2005). The time step length used during simulation was ten second (10 sec). According to Hessel (2005), the choice of time step length to use depend on the grid cell size and the model results is good when the resolution is high. The simulation length time was set to 300 minutes taking into consideration the rainfall time and additional time for runoff water which was not infiltrated to reach the outlet of the sub catchments. For estimating discharge various processes e.g. interception, infiltration, overland flow, sediment detachment, transport and discharge need to be assessed as shown in the flowchart in figure 4.2.

4.2.1. Interception

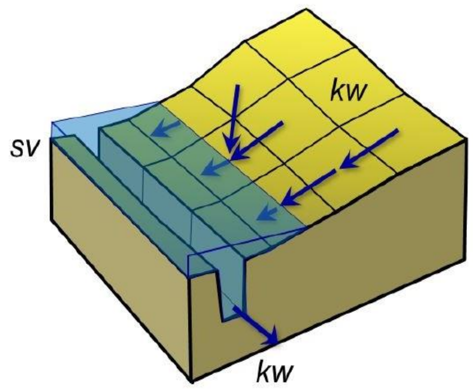
The interception by crops and vegetation influences the quantity of surface runoff generated during a rainfall event. The plant leaves intercept the raindrops and hence reduce the amount of water reaching the ground surface (V. G. Jetten, 1996). Depending on the type of vegetation cover, the amount of rainfall reaching the ground will be high or low. For example, dense vegetation cover will have high interception rate and reduce the amount rainfall reaching the ground to become runoff. For the simulation of interception in OpenLisem, the canopy is considered as the storage and is calculated based on the equation provided in V. Jetten (2002).

4.2.2. Infiltration

After the through fall hit the soil surface, the runoff are generated in two different ways. The first is saturation excess which takes place when the soil is full saturated. The second mechanism is infiltration excess which usually happens when the rainfall intensity is larger than the infiltration of water into soil (Yang et al, 2015). According to Jetten (2002), due to the availability of data, infiltration can be determined with different sub models. In this study, the first layer Green and Ampt is used. It has several parameters which are saturated hydraulic conductivity (Ksat1), saturated volumetric soil moisture content (Thetas1), initial volumetric soil moisture content (Thetai1), soil water tension at the wetting front (Psi1) and soil depth (SOILDEP1). Green and Ampt method applies the Darcy's equation to the vertical movement of water in soil. Several equations used to calculate infiltration are described in Jetten (2002).

4.2.3. Overland flow

The runoff water is transported in downstream towards the catchment outlet with a 2D kinematic wave function. Due to the effect of surface roughness on the flow movement, the manning's formula is also used to calculate the velocity. The runoff follow a predefined network called local drainage direction (ldd). Also the channel properties affect the runoff velocity routed towards the outlet. The runoff in the channel follow a 1D local drainage direction kinematic wave. The flood starts when the channels overflows due to the incoming overland flow.



SV: Saint Venant
KW: Kinematic Wave

Figure 4.3: Overland flow, channel flow and flooding from the channel.

Source: V. Jetten, (2016).

4.2.4. Discharge

The amount of runoff and sediment content from the catchment are usually collected at the catchment outlet by the discharge measurement. Also, the discharge measurements are used in the calibration and validation of the model (De Roo & Jetten, 1999). The discharge also contains suspended sediments which increase water volume and which has an effect on flooding. To estimate the amount of suspended sediments it is necessary to assess sediment detachment and transportation.

4.2.5. Erosion and deposition

The raindrops (with high energy) reaching the soil surface detaches soil and destroy the soil structure. The kinetic energy of the rainfall arises from throughfall and drainage from leaves. The splash detachment is calculated using the formula presented on equation 4.1 (V. Jetten, 2002).

$$Ds = (2.82/As\ Ke\ \exp(-1.48\ WH) + 2.96)\ P\ A\ /dt \qquad \textbf{4.1}$$

Where
Ds: splash detachment ($g.s^{-1}$),
As: the aggregate stability
Ke: rainfall or throughfall kinetic energy ($J.m^{-2}.mm^{-1}$),
WH: the depth of the surface water layer (mm),
P: rainfall or throughfall under the plant canopy in the timestep (mm),
A: surface over which the splash takes place (m^2)
dt: time step (s).

The detached soil particle are transported in downstream drainage channels based on the stream power of the runoff and concentration of suspended sediment. The runoff also detach soil particles on its way in downstream areas. The amount of materials carried by overland flow influences the detachment process. Thereafter some of the soil particles form the sediments along the way and other are transported out of the catchment. The equations used to calculate the deposition and soil detachment by overland flow are shown in equation 4.2 (V. Jetten, 2002).

$$D = Y\ (Tc-C)\ Vs\ w\ dx \qquad \textbf{4.2}$$

Where
D: Soil detachment by flow (Df) (kgs^{-1}) or deposition during flow (Dp) (kgs^{-1}),
Y: efficiency factor
Tc: Flow transport capacity ($kg.m^{-3}$),
C: sediment concentration in the flow ($kg.m^{-3}$),
Vs: settling velocity of the particles ($m\ s^{-1}$),
w: width of flow (m),
dx: cell width.

4.2.6. Data required to run OpenLISEM model

OpenLISEM requires a larger number of input variable and parameters. Those inputs maps range from catchments maps, vegetation maps, soil surface maps, infiltration related maps, and erosion related maps and channels maps. A table 4.1 below summarize the all inputs data required by OpenLISEM for erosion and surface runoff simulation.

Table 4.1: OpenLISEM input data for runoff and erosion modelling

Content	Map name	Range	Unit
Catchments maps			
Digital Elevation model	DEM.map		
Local drain direction	LDD.map	1-9	
Catchment boundaries	AREA.map	1	
Slope gradient	GRAD.map	> 0 and <= 1	
Location of outlet	OUTLET.map	0-3	
Vegetation maps			
Leaf area index	LAI.map	0-12	
Soil' fraction covered by vegetation	PER.map	0-1	
Vegetation height	CH.map	0-30	m
Soil surface maps			
Manning's n	N.map	0.001 – 0.5	
Random Roughness	RR.map	0.05 – 20	cm
width of impermeable roads	ROADWIDT.map	0-cellsize	m
Fraction cover with a crust		0 – 1	
Infiltration related maps (Green & Ampt., 1 layer)			
Saturated hydraulic conductivity	KSAT1.map	0-1000	mm/hr.
Saturated volumetric soil moisture content	THETAS1.map	0-1	
Initial volumetric soil moisture content	THETAI1.map	0-1	
Soil water tension at the wetting front	PSI1.map	0-1000	cm
Soil depth	SOILDEP1.map	0-1000	mm
Erosion related maps			
Aggregate stability	AGGRSTAB.map	0.00001-200	
Cohesion of bare soil	COH.map	>= 0.196	kPa
Additional cohesion by roots	COHADD.map	>= 0.196	kPa
D50 value of the soil	D50.map	25-300	μm
Channels			
Local drain direction of channel network	LDDCHAN.map	1-9	
Channel gradient	CHANGRAD.map	0.0001-10 6	
Manning's n for the channel	CHANMAN.map	0.001-0.6	
Cohesion of the channel bed	CHANCOH.map	> 0.196	kPa
Width of channel	CHANWIDT.map	0-cellwidth	
Channel cross section shape	CHANSIDE.map	0-10	m
Conservation maps (Rainwater harvesting maps, Retention pond maps)			
Rain drums locations	DRUMLOCA.map		
Drums volume	DRUMSTORE.map		m3
Buildings	HOUSECOVER.map		
Buffer ID (retention pond ID)	BUFFERID.map		
Buffer volume (retention pond volume)	BUFFERVOL.map		m3

Source: V. Jetten, (2014) (http://blogs.itc.nl/lisem/running-lisem/maps)

4.3. Data collection

Primary and secondary data were collected during a three week fieldwork period in October 2015. Secondary data were obtained from different public and privates institutions in Rwanda. Also primary data in both Mpazi and Byabagabo Jabana sub catchments were collected through fields' survey and observation, photographs and interviews for local people and key decision makers.

4.3.1. Secondary data

The table 4.2 below presents secondary data collected during fieldwork from different institutions.

Table 4.2: Secondary data of the study area

Data type	Data format	Method	Data source
Digital Elevation Model (DEM) Kigali (10m), 2010	Raster	From SRTM	Kigali City Council
Aerial photo (25 cm spatial resolution), 2010	Image	From High resolution quick bird satellite Image 2010	Kigali City Council
Land use/cover map (30 cm spatial resolution), 2012	Shapefile	From high resolution Orthophoto image 2012	Kigali City Council
Soil Map (1:50000), 2006	Shapefile	Laboratory & field measurements done by University of Ghent & MINAGRI	Ministry of Agriculture and Animal Resources (MINAGRI)
Roads, 2014	Shapefile	Digitized using high resolution orthophoto 2010	Rwanda Transport Development Agency
Daily rainfall data, 1980-2014	Table	Recorded by ground based weather station	Rwanda Meteorology Agency

4.3.2. Primary data

Stream cross section measurements

Byabagabo Jabana sub catchment

In this peri urban sub catchment, the cross section measurement of the primary stream was taken at three different location at certain points due to the inaccessibility of other parts of the area. Three measurements were taken in the middle of the river at five meters (5 m) interval and one measurement near the outlet. Also, their geographical locations were recorded using hand held GPS.

Mpazi sub catchment

The cross section measurement of primary and secondary drainage channels was taken at a different location along the channels. The top and bottom width, as well as the depth of the drainage channels were measured for determining information related to the channel capacity. In addition to that the width and the depth of the culverts at the catchment outlet were measured. Also, the geographical location of the measured points and that of bridges were recorded using hand held GPS. The measurements were taken using a meter tape (25 m) and BOSCH PLR 50 Laser Rangefinder. The figure 4.4b shows the location of the bridges on the main channel where measurements were taken.

Roads

The measurements of the roads width in both sub catchments were taken during fieldwork. The roads width are among the impermeable areas required as input to OpenLISEM model.

Field observation

Mpazi sub catchment

In this urbanized sub catchment, the upper forest is characterized by the poor ground cover (figure 4.4). This was mainly caused by cutting of tree for firewood and grazing in the past years. In addition to that, the people have been occupying and building houses in the upper forest. The absence of ground cover may have a negative impact on the infiltration (Ksat) and increases runoff velocity due the decrease in surface roughness. As Woo et al., (1997) warned that the absence of ground vegetation cover in the forest may contribute to soil erosion and runoff generation. Also in upper areas, the absence of secondary and tertiary channels led the formation of gullies in the neighbourhood which may increase the susceptibility to landslide and soil erosion during heavy rainfall.

Figure 4.4: Poor ground cover in upper forest in Mpazi sub catchment

4.3.3. Interview data

Interview with the decision makers

Semi structured interviews were conducted for nine key informants from various governmental institutions. The interviews were conducted using the questionnaire containing questions ranging from existing and future plans for flood and catchments management, experience with historical floods and specific plans for Mpazi (urban) sub catchment. The table showing the positions of the government officials interviewed and a questionnaire used are attached as Appendix 2.

Interview with local people

People living closer to the main drainage channel and in upper areas in Mpazi sub catchment were interviewed. People living closer to the main drainage channel have experienced flooding events in the recent past. On the other hand, people living in upper steep slope areas knows the cause of the existing forest degradation. Some of them have been affected by the runoff coming from the forest.

In total twenty (20) people were randomly selected for the interview. The aim of this interviews was to see their views on different causes of runoff and flooding, different adaptation and mitigation measures and what they think on the issue of relocation from high risk zones to a safer place. Also during interviews, people living closer to the main drainage channel indicated the maximum depth of runoff in case of a high rainfall event. Data was collected from interviews using the prepared questionnaire which lasted for an average of ten minutes per person. The geographical coordinate for the interviewed local people was recorded using hand held GPS. The figure 4.5a presents the location of interviewed people.

a) b)

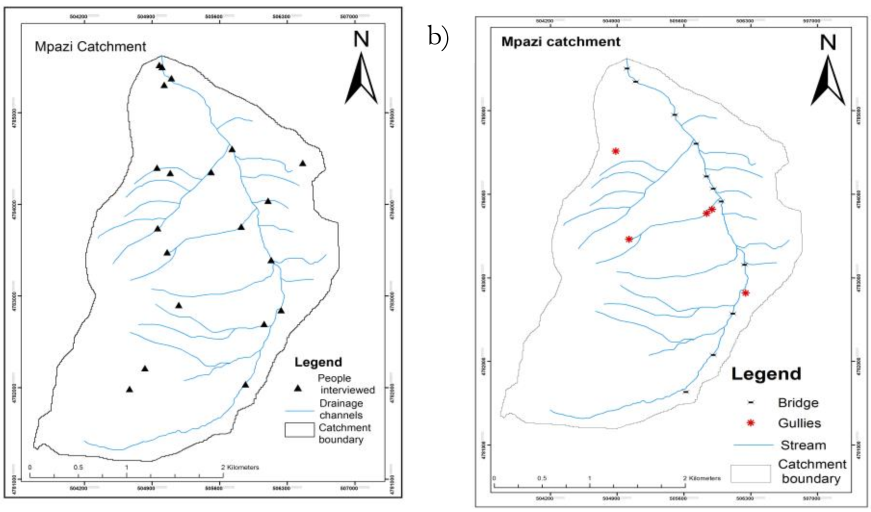


Figure 4.5: a) The location of interviewed people, b) Location of gullies and bridges

Analysis of interview data

Interview data from the questionnaires were analysed using Microsoft excel 2013. The outcome of the interviews was used as one of the inputs for designing land use/cover change scenarios and in the validation of the model results.

4.3.4. Soil samples collection and laboratory analysis

Six surfaces (disturb) soil samples for each sub watershed were collected using purposive sampling method during fieldwork. The topography of the watershed and other available soil data (e.g soil map) contributed to identify sampling site. Also, the geographical location was recorded using hand held GPS. The aim of soil sample collection was to determine the soil erodibility of the sub catchments. Information related to soil textures and organic matter content were obtained by analysing the soil samples in the laboratory. This method to retrieve soil physical properties for erodibility assessment were also applied in Bonilla & Johnson (2012).

The twelve soil samples for both sub catchments were analysed for soil texture (particle size) and organic matter content determinations. The soil particle size composition were determined using the pipette method as described by Reeuwijk (2002) while the organic matter content was determined using the ash method in the Geoscience Laboratory of ITC. The soil analysis was also done to validate the existing soil data. The figure 4.5 shows the photograph of soil sample analysis in the ITC Geoscience Laboratory.

Figure 4.6: Soil texture determination in ITC Geoscience Laboratory using the pipette method

5. DATA ANALYSIS

The size of the grid cell chosen was 10 x 10 m. This size was determined because the maximum width of Mpazi sub catchment drainage channel is 7.5 m and the width of Byabagabo Jabana sub catchment drainage stream is 1m. Usually, OpenLISEM assumes that the channel (or stream) width is less than grid size (Hessel, 2005). The time step length used during simulation was ten second (10 sec). According to Hessel (2005), the choice of time step length to use depend on the grid cell size and the model results is good when the resolution is high. The simulation length time was set to 300 minutes taking into consideration the rainfall time and additional time for runoff water which were not infiltrated to reach the outlet of the sub catchments. The OpenLISEM model version 2.03 was used in the modelling process.

For the rainfall-runoff model a database consisting of all the required parameters need to be first generated. For the highly urbanized Mpazi sub catchment a complete database containing all the necessary input maps was available which was prepared by Mureithi (2015). Only few data related to soil physical properties, channel properties, storage capacity of rainfall harvesting dumps and retention basin were generated while others were updated and included in the database.

For the peri-urban Byabagabo Jabana sub catchment a separate database had to be created. It is explained as follows:

5.1. Catchments maps

Digital elevation model (DEM) at 10 m resolution was used to delineated Byabagabo Jabana (peri-urban) sub catchment using Arc Hydro tools in ArcGIS 10.2.2. Also, the DEM was used to create sine of slope angle (grad.map) and local drain direction (Ldd) maps. The catchment outlet, channel local drain direction (Lddchan) showing the runoff direction and channel mask maps were created from local drain direction (Ldd) map. Furthermore, the channel slope maps were created using DEM and commands as described in PCRaster script attached in Appendix 1.

5.2. Land use/cover map

The current land use/cover map in both Mpazi and Jabana sub catchments were extracted from the land use/cover of Kigali City using analysis tools in ArcGIS 10.2.2. The land use/cover of the Kigali City was generated from the orthophoto image of 0.25 meters spatial resolution by Surbana, 2012. It was provided by mapping unit of Kigali City Council during fieldwork period. The land use/cover maps of both sub catchments are presented in figure 5.1.

As shown on figure 5.1a, the main land use/cover in Mpazi (urban) sub catchment is built up areas mostly on steep slope occupying more than 72% of the catchment total areas. Other land use/cover types are forest cover in upper catchment areas, agriculture land and bare land. The tree species in the forest are mostly eucalyptus with few native plants. The mixing farming (maize, beans) dominate the agriculture practices.

The main land use/cover in Byabagabo Jabana (peri urban) sub catchment is agricultures occupying more than 67% of the total catchment area (figure 4.1b). Banana plantation is the most important crops grown in the area. Also, the forests are covering most of the higher slope in this catchment. Eucalyptus are the dominants forest type with few shrubs and grass. The built up areas are less than 5% of the total area. The table 5.1 presents the land use/cover types per area and percentage.

Table 5.1: land use/cover types per area and percentage

Mpazi sub catchment

Land Use/Cover	Area (km2)	Percentage (%)
Agriculture	0.87	10.8
Bare land	0.08	1
Built up	5.80	72
Forest	1.27	15.8
Water body	0.03	0.4
Total	**8.05**	**100**

Byabagabo Jabana sub catchment

Land Use/Cover	Area (km^2)	Percentage (%)
Agriculture	6.03	67.8
Bare land	0.01	0.15
Built up	0.42	4.7
Forest	2.15	24.2
Wetland	0.28	3.15
Total	**8.9**	**100**

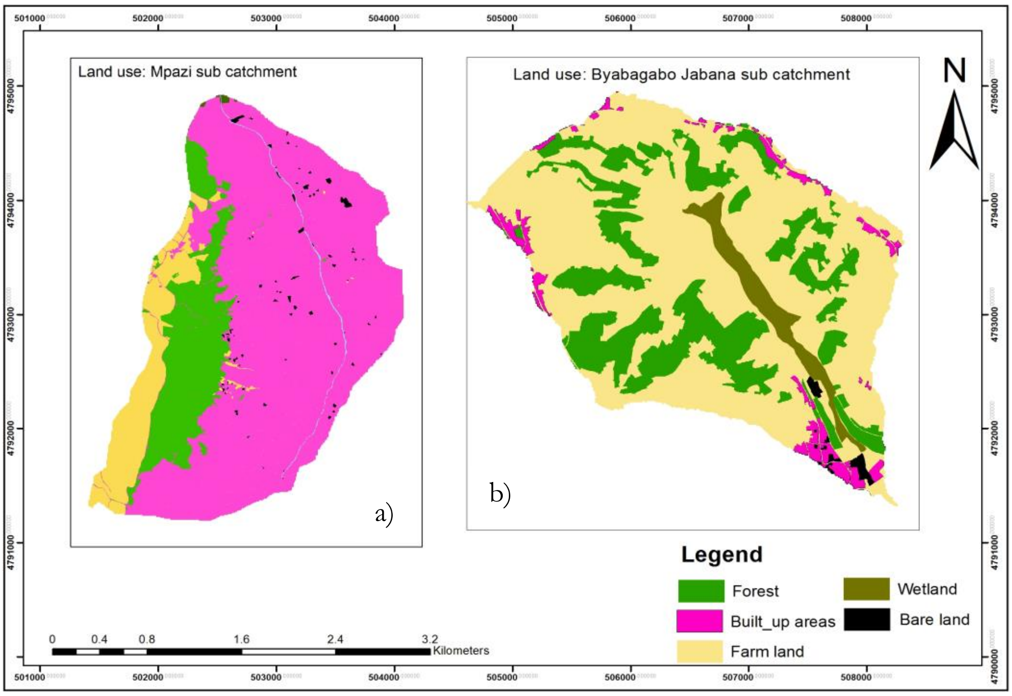


Figure 5.1: Land use/cover map a) Mpazi sub catchment; b) Bybagabo Jabana sub catchment

5.3. Soil map

The soil map was generated by the Rwandan Ministry of Agriculture and Animal Resources in collaboration with the University of Ghent in Belgium (Verdoodt & Van Ranst, 2006) at the scale of 1/50000. The soil map contains all information related to soil type, soil texture composition (silt, sand and clay), bulk density, organic matter content, soil depth and other information related to soil properties. Soil data was used to assess rain infiltration and soil erosion.

The available soil map was also used to determine **saturated hydraulic conductivity (Ksat), porosity (thetas) and initial volumetric soil moisture content (psi).** The Ksat, thetas and psi were obtained using the Soil Water Characteristics model (SPAW). The resulting soil moisture contents and saturated hydraulic conductivities served as the model input for assessing surface runoff and soil erosion.

5.4. Vegetation map

From the downloaded Landsat 8 image of June 2013, the Normalized Difference Vegetation Index (NDVI) was first calculated. Secondly, the vegetation cover map was generated from the NDVI image using the formula provided by van der Knijff et al. (2000). Later the vegetation cover map was used to determine the leaf area index (LAI). The LAI is related to the vegetation storage capacity and is used as an input in the Openlisem model to determine rainfall interception (de Jong & Jetten, 2007).

5.5. Plant height and ground cover estimation

The ground cover (surface) and plant height are used to calculate splash detachment caused by throughfall intensity and runoff velocity during rainfall events (De Roo et al., 1996). Forty three (43) points were selected in the field using stratified random sampling method by overlaying the available land use/cover map and high resolution aerial photo (25 cm). Those points were used as the ground truth for visual estimation of plant height and for ground cover (per) status following the method described by Hessel et al., (2003) and Schoeneberger et al., (2012). The figure 5.1 shows the location of sampling point per land use/cover in Byabagabo Jabana sub catchment.

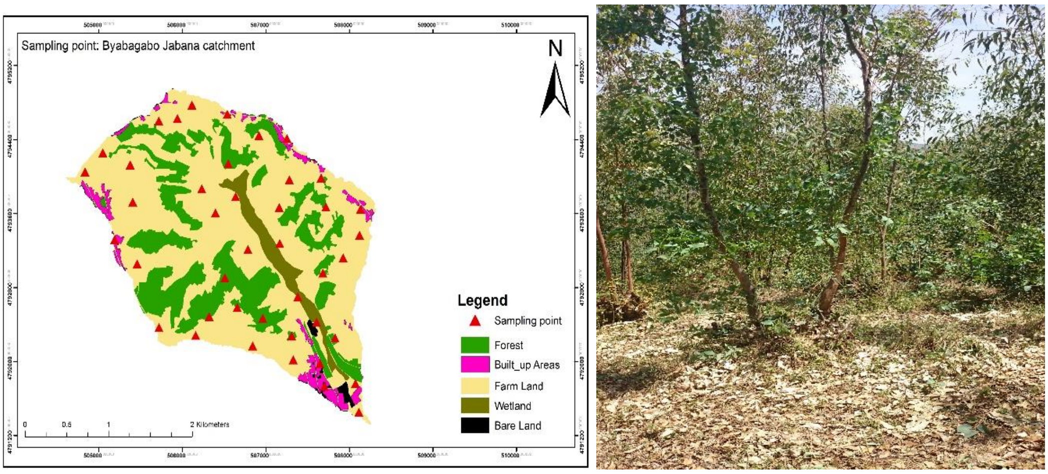


Figure 5.2: Distribution of sampling point for plant height estimation and soil sampling points

5.6. Surface roughness map

This initial land use/cover map with twelve classes was reclassified into five classes based on similar land use classes as verified in the field survey. Similar land use/cover classes were put in the same land use/cover classes as shown on table 5.2.

Table 5.2: Reclassified land use/cover of Byabagabo Jabana sub catchment

Current land use/cover map	Reclassified land use/cover map
Education institutions	Built up areas
Health facilities	
Low rise residential areas	
Utilities	
Warehouses	
Heavy industries	
Light industries	
Farm land	Farm land
Plantation	
Existing forest	Forest
Wetland	Wetland
Vacant land	Bare land

The land use/land cover map was used to determine random roughness (rr) and manning's coefficient (n) based on corresponding value retrieved from literature and observation made during fieldwork. Roughness parameters represent the flow resistance showed by land cover type to the overland flow during a rainfall event (Rai et al., 2010). It is one of the input maps required in runoff and erosion modelling by OpenLISEM. According to Alkema (2007), there is a good correlation between land use/cover and surface roughness and often the latter is generated from the available land use map. The type of land use/cover determines the speed of the flowing water as it resists to the surface runoff during a rainfall event. Table 5.3 presents the manning's values used in this study (Hessel et al, 2003; Jr. & Schneider, 1989; Li & Zhang, 2001; Pedzisai, 2010). As shown on the table, the manning's value in Mpazi sub catchment for the forest land use/cover type is different to the manning's value for forest cover in Byabagabo Jabana sub catchment. This is caused by the degradation (no ground cover) of eucalyptus forest in sub Mpazi catchment observed during fieldwork period.

Table 5.3: Manning's value for Mpazi and Byabagabo sub catchments.

Mpazi sub catchment

Land Use/Cover	Manning's value
Agriculture field	0.09
Bare land	0.03
Built-up areas	0.03
Forest	0.15
Roads	0.025

Byabagabo Jabana sub catchment

Land Use/Cover	Manning's value
Agriculture field	0.09
Bare land	0.03
Built-up areas	0.03
Forest	0.18
Roads	0.025
Wetlands	0.10

Source: Hessel et al, (2003); Jr. & Schneider, (1989); Li & Zhang, (2001); Pedzisai, (2010)

5.7. Soil erodibility map

Aggregate stability and cohesion properties determine soil erodibility of an area (Munkholm et al, 2016). OpenLISEM requires both cohesion and aggregate stability maps for soil erosion modelling. In this study the cohesion maps were obtained by measurement of soil cohesion using the pocket vane tester during fieldwork (Torri et al, 1987). Two measures were taken per each measuring site. The soil aggregate stability is decreased by the raindrops which may cause soil detachment and erosion. The aggregate value used to generate aggregate stability maps were adapted from literature referring to the available soil texture (Wischmeier & Smith, 1978).

5.8. Built up area map

The area occupied by buildings (building maps) are considered as hard surface in runoff modelling. In addition to that the roof of the buildings contribute to the interception of rainfall. The building footprint map for Byabagabo Jabana sub catchment was digitized from high resolution (0.25 cm) aerial photo 2012 provided by Kigali City Council during fieldwork. Also the number of buildings in the area can be used to estimate the amount of rainwater to be harvested.

5.9. Rainfall data

5.9.1. Available rainfall data

Daily rainfall data for 34 years (1980-2014) were collected from Rwanda Meteorology Agency. The rainfall data were recorded by two ground based weather stations which are Gitega and Kigali Kanombe Airport stations. Gitega weather station is located in the Mpazi sub_catchment and Kigali Kanombe Aiport weather station is located at 7 kilometres from Mpazi (urban) sub catchment and at 9 km from Byabagabo Jabana (peri-urban) sub catchment. The daily rainfall data from Gitega weather station has data gaps in 1994 due to war and genocide. Rainfall data from Kigali Kanombe Aiport weather station has no gaps and was thus selected to be used for further rainfall analysis.

Event based rainfall data at 10 minutes temporal resolution for the year 2014, recorded by automatic rain gauge installed at Kigali Kanombe Airport was also provided by Rwanda Meteorology Agency. However this rainfall data also contained some gaps in some months during the rainy season, this might be caused by interrupted electricity supply to the automatic rain gauge. For that reason, the rainfall data from these stations were not used for further analysis.

5.9.2. Satellite rainfall data

OpenLisem model uses detailed event based rainfall for runoff and erosion modelling (Baartman et al., 2012). Therefore, due to the gaps and errors found in the collected event based rainfall data, the available rainfall data were not considered in this study. The satellite (Meteosat Second Generation Multi-Sensor Precipitation Estimate (MSGMPE)) based rainfall data were used in this study. One rainfall event data of 29th October 2013 with total rainfall of 53.3 mm which has caused flash flood in Nyabugogo commercial center (study area) was used for the analysis. The Meteosat rainfall data were downloaded using a rainfall data receiver located at ITC. All the steps required for downloading the Meteosat 8 rainfall data are described in Maathuis et al., (2006).

The rainfall data in mmh^{-1} from MSGMPE have a temporal resolution of 15 minutes and a spatial resolution of three kilometre (3 km). They were georeferenced to the coordinate system of the study area and resampled using nearest neighbour interpolation in ILWIS 3.7.2. Afterwards, the average rainfall value in mmh^{-1} were extracted for further analysis. The rainfall event lasted for three hours (3 hours) and the total rain amount was 33.05 mm.

As suggested by Thiemig et al. (2012) the satellite derived rainfall data must be validated before use in research studies. The total daily MSGMPE rainfall data from the study area were compared to the daily rainfall data recorded by the ground based weather station. The total daily mpe rainfall was 36.11 mm whereas the daily rainfall from the ground based station was 53.6 mm. According to Collischonn et al. (2008), satellite derived rainfall data can be validated by comparison with ground based recorded rainfall data. In this study, a correction factor was created by dividing the total daily rainfall to the total mpe rainfall (ground based rainfall depth (mm)/mpe rainfall depth (mm)). Thereafter, the correction ratio was used to calibrate the event based mpe rainfall data.

Furthermore, the frequency analysis of the thirty years (1980-2014) daily rainfall data was carried out to determine the return period corresponding to the above rainfall event. The aim of this frequency analysis was to assess the magnitude and frequency of the rainfall event that took place on 29th October 2013. Usually, the Gumbel extreme method is used to determine the relationship between the magnitude, probability of occurrence and return period of the rainfall (Chow et al., 1988).
Furthermore, the event based rainfall data used in this study was assumed to be of the same intensities and duration in both Byabagabo Jabana and Mpazi sub catchments.

5.10. Land-use change scenarios for runoff and erosion assessment

To assess the effect of land use change on surface runoff and soil erosion in both Mpazi and Byabagabo Jabana sub catchments, different land use scenarios were developed. The effect of current land use/cover on runoff and discharge in both sub catchments were simulated using Openlisem. They were also used as baseline scenarios for comparison with other land use/cover change scenarios. Four other different land use/cover change scenarios were designed and simulated. The first land use change scenario was developed in Byabagabo Jabana (peri urban) sub catchment and three other scenarios were conducted in Mpazi (urban) sub catchment. Furthermore, each of the four different land use/cover change scenarios was compared to the baseline scenarios to assess any effect on runoff and soil erosion. The land use/cover change scenarios were developed based on the Kigali city master plan to 2025 and 2040 year, interviews data and observation made during fieldwork.

5.10.1. Scenario 1: Settlement densification

In this peri urban sub catchment (Byabagabo Jabana), the built-up areas were extended to agriculture fields. This scenario was designed based on the Kigali Master plan 2025 and 2040 where a part of this sub catchment will be occupied by an industrial area. Furthermore, field observation conducted by the researcher revealed a high trend in housing development. The built up areas were extended from the current 4.7% to 30%. Also, distance to the main roads and restriction on terrain slope angle (new buildings <36%) were taken into consideration. Other land use/cover types in the sub catchment were kept untouched. A set of pcraster commands were used to create this map. This scenario was done to assess the effect of future urban densification on surface runoff.

5.10.2. Scenario 2: Structural measures for reducing surface runoff

Structural measures are defined by Mohit & Sellu (2013) as engineering measures used to prevent floods and human properties. In this study, to reduce the quantity of surface runoff coming from upper areas in Mpazi (urbanized) sub watershed, two structural measures (detention reservoir, change channel characteristics) were proposed and combined in one scenario. Their effect was modelled using OpenLisem hydrological model.

5.10.3. Scenario 3: Ecosystem based measures for reduction of soil erosion and surface runoff

According to Mohit & Sellu (2013), ecosystem measures are based to the arrangement of a community or societies to mitigate floods damage. In this study, ecosystem based (non-structural) measures proposed in Mpazi sub catchment (urban) were grouped into four sub measures. The first measure was to relocate people living in high risk zone, the second was afforestation and grass planting in upper (steep slope) areas, third one was rainwater harvesting practices at household level and last was grass planting near the main drainage and secondary channels. All three ecosystems based measures for soil erosion and surface runoff regulation were combined and assessed in one scenario.

5.10.4. Scenario 4: Combination of structural measures and non-structural measures

This scenario integrate both engineering measures (scenario 2) and ecosystem based measures (scenario 3) for runoff and soil erosion reduction. This scenario was proposed to assess how effectives both scenarios are in comparison with each scenario.

5.11. Modelling surface runoff and erosion

All the necessary maps (land use/cover map, DEM, soil unit map, vegetation map and impermeable surface maps e.g. house cover map, road map and channel) were prepared in ArcGIS 10.2.2. All the maps were resampled using the nearest neighbour method to give them the same cell size. Afterwards, they were converted to ASCII format and exported to PCRaster. Also three additional tables of land cover, soil units and rainfall data were created. They show different properties related to land cover type, soil unit and rainfall data.

5.12. Scenarios development in PCRaster

Necessary attribute maps required to run the hydrological model for different scenarios were generated in PCRaster using appropriate scripts (Appendix 1). The database used for the baseline scenario (scenario 0) was created using the PCRaster script and by keeping the current land use/cover map in both catchments.
Input maps for other scenarios (scenario 1, 2, 3 & 4) were developed referring to the baseline scenario (scenario 0) by changing existing land use maps and house cover maps with a set of different commands in PCRaster script.

5.13. Criteria for comparing different land use scenarios

After simulation of different conservation measures (scenario 1, 2, 3 &4) using OpenLisem model, their outputs were assessed and compared. The results of baseline scenario (scenario 0) were compared with the simulated land use change results.
The modelling output (indicators) used in the assessment of both runoff and soil erosion were:

1) **Affected building (number)**

The number of buildings affected by flooding is important to identify which measures work better than others. Also buildings at risk of being impacted with such measures.

2) **Flooded area (m^2)**

The area affected by flood event is a good indicator for testing how good the applied conservation measure is.

3) **Total Flood (runoff) volume (m^3)**

The runoff volume is the total volume of the runoff water after a rainfall event. The decrease or increase in runoff volume shows the impact of applied measures.

4) **Total discharge (mm)**

The change in total discharge reflects the conservation measures applied.

5) **Total soil loss (kg)**

The total soil loss gives information about the amount of soil (or sediments) generated after a rainfall event. It is a good indicator to testing how good the applied conservation measure as it will decrease or increase.

6. RESULTS AND DISCUSSION

The results of the baseline scenario and the effect of different land use/cover scenarios on surface runoff and soil erosion are presented in this chapter. The chapter starts with the analysis of rainfall used in the simulation by OpenLisem model. Second, the results from each scenario (scenario 0, 1, 2, 3, 4) are presented and discussed. Comparison between developed land use/cover change scenarios and baseline scenario were done. All the results are presented following the criteria described in section 5.8.

6.1. Analysis of rainfall data

6.1.1. Monthly rainfall data

Daily and monthly rainfall data of the 30 years (1980-2014) are analyzed to understand the rainfall pattern in the study area (Byabagabo Jabana and Mpazi). Figure 6.1 shows the monthly average rainfall in the period of 30 years. On the figure it is clear that the rainfall pattern from January to May and from September to December correlates with the annual rainfall seasonality. The average yearly rainfall is 980mm. The proportion of the first rain season to the annual rain fall is 57% and for the second rain season is 43%. From the figure, it is clear that much of the rainfall amount are usually expected in March and April for the first main rain season and in October and November for the second season.

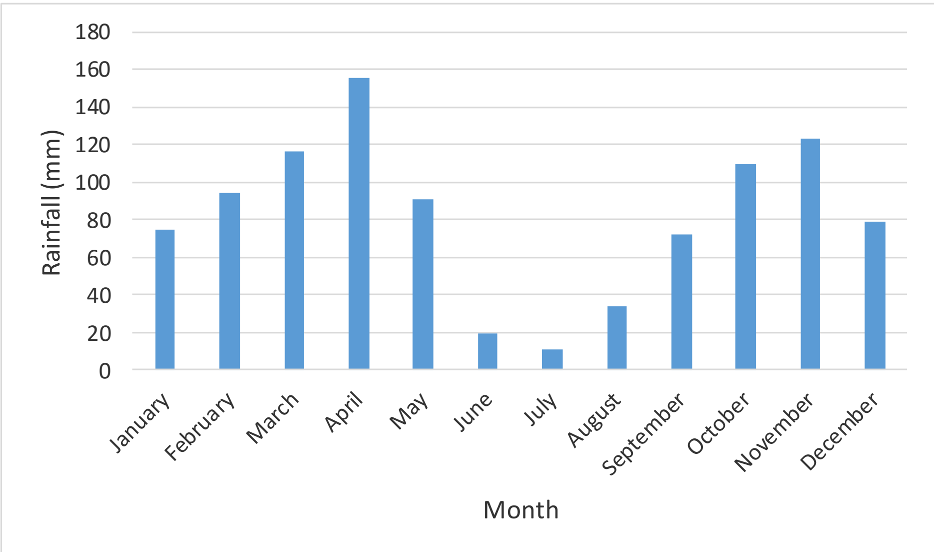


Figure 6.1: Average monthly rainfall from 1980 to 2014 for Kigali City

6.1.2. Satellite rainfall data

The rainfall event that hit the Mpazi (urban) sub catchment on 29th October 2013 were downloaded from MSGMPE and analyzed as described in section 5.5.2. This rainfall event caused flash flood in Nyabugogo commercial center and was only available from the MSGMPE rainfall database for this study area. This high rainfall event fell in the expected high rainfall season as can be seen on figure 6.1. The figure 6.2 shows how this rainfall event is well spatial distributed in both catchments of the study area.

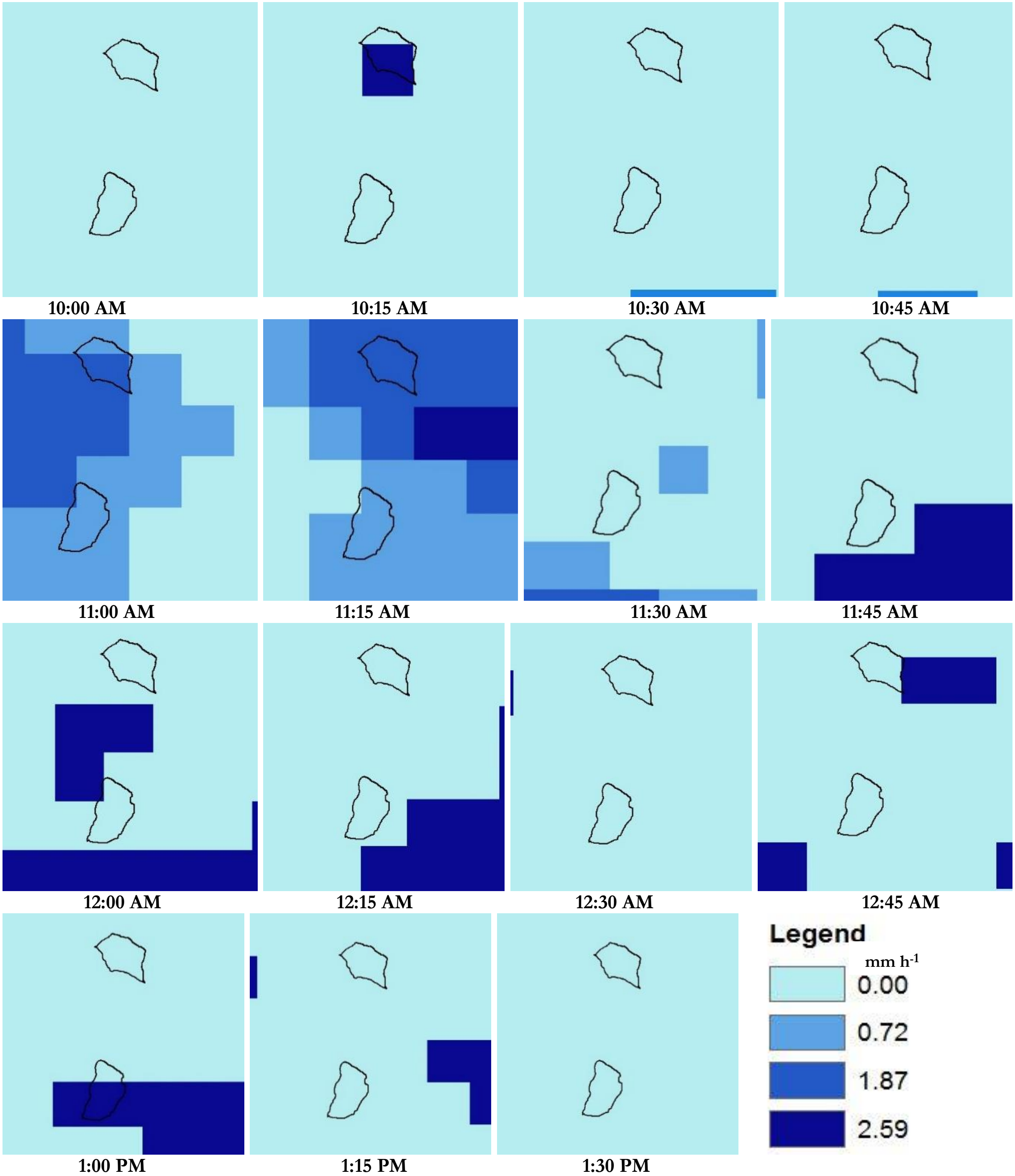


Figure 6.2: Distribution of event based rainfall in mm/hour of the 29 October 2013 over the study areas in Kigali, Rwanda.

6.1.3. Frequency analysis of rainfall data

Based on the available daily rainfall historical data (1980-2014) of the study area, a frequency analysis were done to calculate the rainfall return period corresponding to the rainfall event of 29 October 2013 as described in section 5.5.2. The figure 6.3 presents the Gumbel distribution of daily rainfall in the study area.

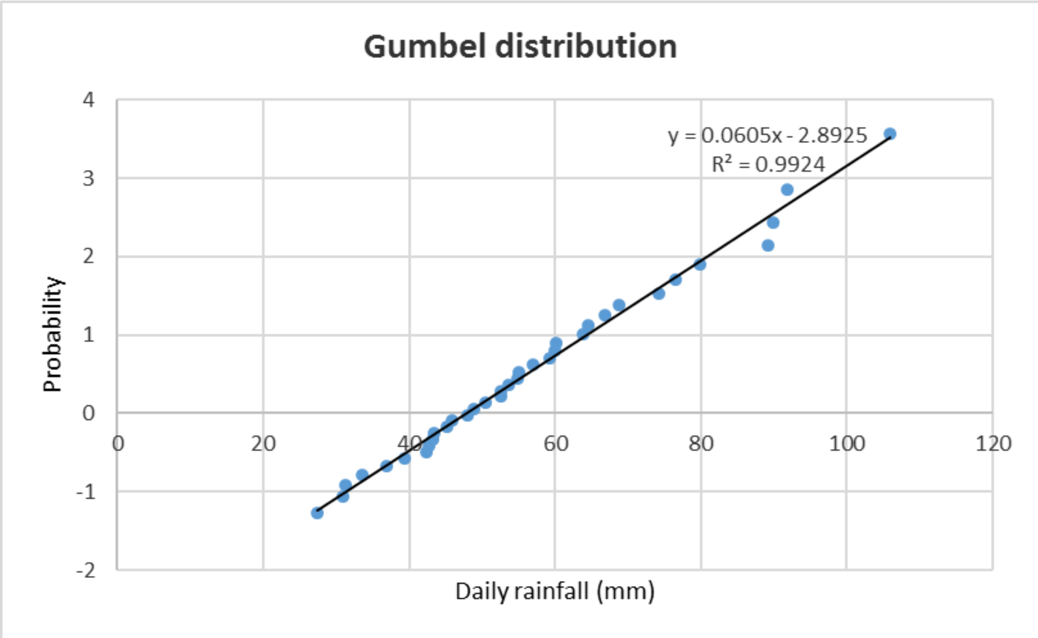


Figure 6.3: Gumbel plot for daily rainfall distribution in the study area

Y=-LN (-LN (left prob.));
Right prob. = 1-Left prob.; 6.1
Return period (T) =1/Right prob.

The formulas provided in equation 6.1 are used to calculate the return period corresponding to a rainfall event. From the record of the ground based meteorological station in the study area, the rainfall event of 29th October 2013 has the maximum of 53.6 mm total rainfall. As can be seen from the table 6.1, this rainfall corresponds to two year return period.

Table 6.1: Maximum daily rainfall and corresponding return period

Return period (years)	2	5
Maximum daily rainfall (mm)	53.6	70.88

In order to assess the effect of different conservation measures at different rainfall intensities, a once in five year rainfall was designed using extreme Gumbel method shown on figure 6.3. This rainfall (1:5 year) was the minimum chosen to be used in the simulation to test how effective are the proposed conservation measures. The researcher assumed that this type of rainfall is likely to occur. In addition to that they were time limitation for this study to conduct other simulations with different return periods. The event based rainfall correspond to the above event (1:5 year) was created by extrapolating the event based mpe rainfall data of the 29th October 2013. This was done using the Intensity Duration Frequency (IDF) curve for precipitation for Rwanda. The IDF curve helps to link the rainfall intensity, duration and a given return period using a mathematical expression. The equation and parameters used to extrapolate the two year mpe rainfall event to five year rainfall event are provided in Demarée & Van De Vyver (2013).

6.2. Model calibration and sensitivity analysis

Due to the lacking of historical discharge data in both sub catchments (study area), the OpenLISEM model was only calibrated based on the observed flood depth and flood volume recorded by a data logger in February 2013 (SHER Ingénieurs-Conseils s.a., 2013). The simulated flood depth in thee downstream area of Mpazi sub catchment was compared to the flood depth recorded by the field installed data logger. In order to improve simulated results, some parameters (Ksat) were reasonably adjusted.

According to De Roo & Jetten, (1999), the sensitivity analysis helps to identify model input parameters that has an impact on the model output and hence reduce uncertainty. In this study, the sensitivity analysis was done for Ksat and manning's in both Mpazi and Byabagabo Jabana sub catchment. As it is shown on table 6.2 and table 6.3 the sensitivity analysis was conducted by increasing (+20%) and decreasing (-20%) both the manning's value and Ksat value. All other model input parameters were kept unchanged. On the table, the response of other values from the sensitivity analysis of manning's and Ksat are presented.

Table 6.2: Sensitivity analysis results for Mpazi sub catchment

Mpazi sub catchment												
Parameters	Total discharge (% change)		Peak Discharge (% change)		Infiltration (% change)		Discharge/rainfall (% change)		Flooded area (% change)		Flood volume (% change)	
	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%
Ksat	3.9	-3.9	0.9	-1.3	-17.6	11.8	9.7	-4.2	0.2	-16.2	3	-6.4
Manning's n	0	-2	0.3	-0.7	-5.9	0	0	-1.4	0.2	-12	1.8	-6.8

Table 6.3: Sensitivity analysis results for Byabagabo Jabana sub catchment

Byabagabo Jabana sub catchment												
Parameters	Total discharge (% change)		Peak Discharge (% change)		Infiltration (% change)		Discharge/rainfall (% change)		Flooded area (% change)		Flood volume (% change)	
	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%
Ksat	30	-30	8.4	-7.4	-12.2	10.2	35.7	-28.6	1.1	-0.7	13.6	-12.3
Manning's n	10	-40	0.2	-7.6	0	12.2	14.3	-35.7	0.5	-5.1	2.9	-13.9

From the tables, it is clear that the increase in (+20%) Ksat resulted in decreases all the model outputs parameters except for the infiltration. This is caused by the positive correlation between Ksat and infiltration. As the Ksat increase, the infiltration increase and the surface runoff decrease which reduce the model output (total discharge, peak discharge, ratio discharge rainfall, flooded area and flood volume) as well. On the other hand the decrease of Ksat (-20%) increases the model output values except for the infiltration which show the positive correlation. This is caused by the increase in surface runoff due to low infiltration.

The change in manning's value by increasing or reducing 20% its original value shows the same trend as the change in Ksat on the model output. There is an inverse relationship between the manning's and the total discharge, peak discharge, ratio discharge rainfall, flooded area and flood volume. An increase in manning's value affects the runoff by reducing the flow velocity and hence increase the time for infiltration. The same observation was made by Hessel et al., (2003) where the change in land cover affected the flow velocity of runoff.

6.3. Assessment of surface runoff and soil erosion

6.3.1. Scenario 0: Current Land Use/Cover

Based on the current land use/cover map in both Mpazi and Byabagabo Jabana sub catchments, the simulation to estimate surface runoff and soil erosion was done using OpenLisem. Also, this scenario served as a baseline for comparison with other designed land use/cover change scenarios to assess their effect on surface runoff and soil erosion. The simulation of the current land use/cover were conducted using the two year return period and 5 year return period rainfall event. The results are explained for the 2 studied catchments as follows:

1. Mpazi sub catchment

The figure 6.4 shows the results of the simulation of current situation (scenario 0) for Mpazi (urban) sub catchment. The simulation was done using a once in 5 year (70.88 mm) rainstorm event. As can be seen in the figure, part of the downstream area are flooded where the maximum flood depth is 2 meters. These floods are mainly caused by runoff coming from high densely populated upper areas. The commercial buildings, bus station and important roads connecting the capital city to other provinces are all affected by the flash flood for several hours. In total, 71 buildings were affected by this flash flood. The number of buildings affected by this floods was calculated from an average area of 100 m² (10*10) per building noted by the researcher during fieldwork survey.

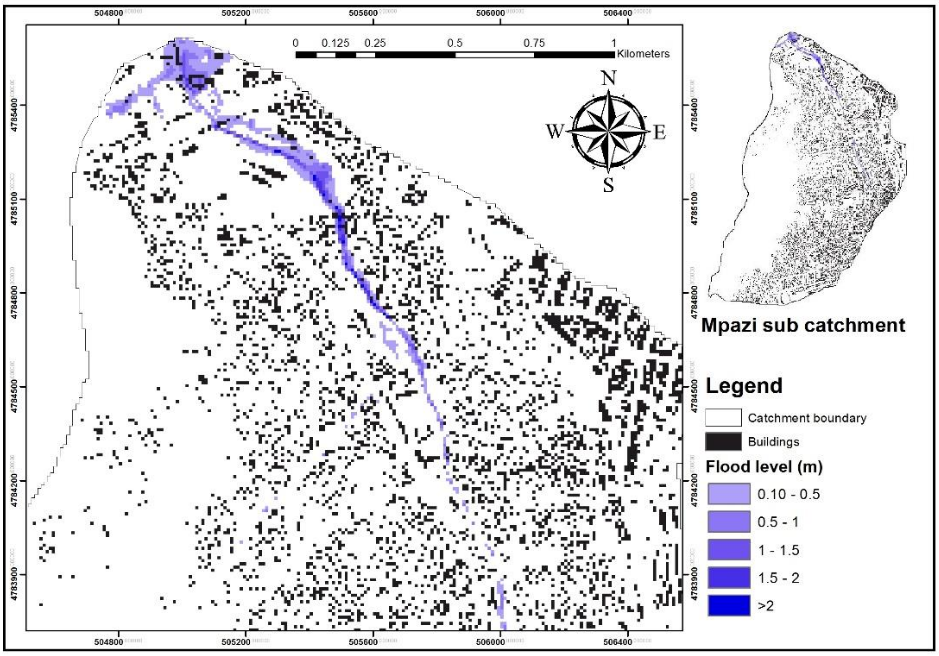


Figure 6.4: Baseline scenario results for Mpazi sub catchment, flood depth (m) using a 1:5 year rainstorm event (70.88 mm). The map also shows buildings affected by this floods.

The business center stays inundated for almost three to four hours as can be seen on figure 6.5. For the two year rainfall event, the model results shows no flash floods in this urban catchment

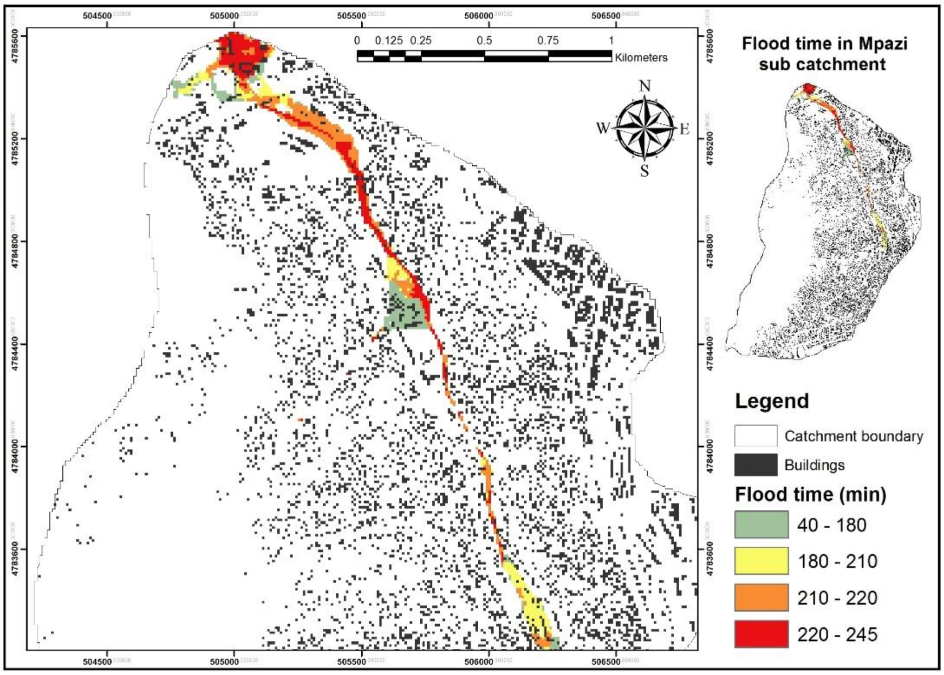


Figure 6.5: Baseline scenario results for Mpazi sub catchment, flood time (min) using a 1:5 year rainstorm event (70.88 mm). The map also shows buildings affected by this floods.

2. Byabagabo Jabana sub catchment

The results of the simulation of the current land use in Byabagabo Jabana (peri-urban) sub catchment are presented on figure 6.6. The simulation were done using a once in 5 year (70.88 mm) rainstorm event. As presented on the figure, the floods are occupying all floodplain (valley) where the maximum depth is 1.5 meters.

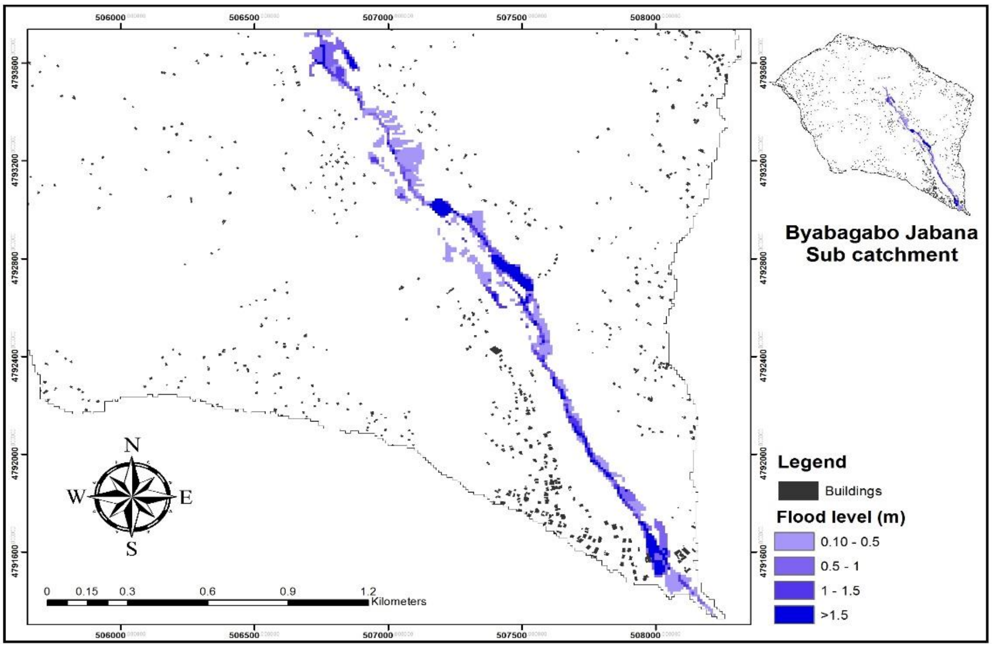


Figure 6.6: Baseline scenario results for Byabagabo Jabana sub catchment, flood depth (m) using a 1:5 year rainstorm event (70.88 mm). The map also shows buildings affected by this floods

Only 4 buildings are affected, this is caused by the low number of buildings located in the floodplain. The number of building are obtained from an average area of 72 m2 (9*8) per building estimated during fieldwork. Currently this floods is not a big problems in the area as it affects only few buildings located in near the valley which are used only few time by brick makers. The flooded area is the sugarcane plantation occupying almost all floodplain.

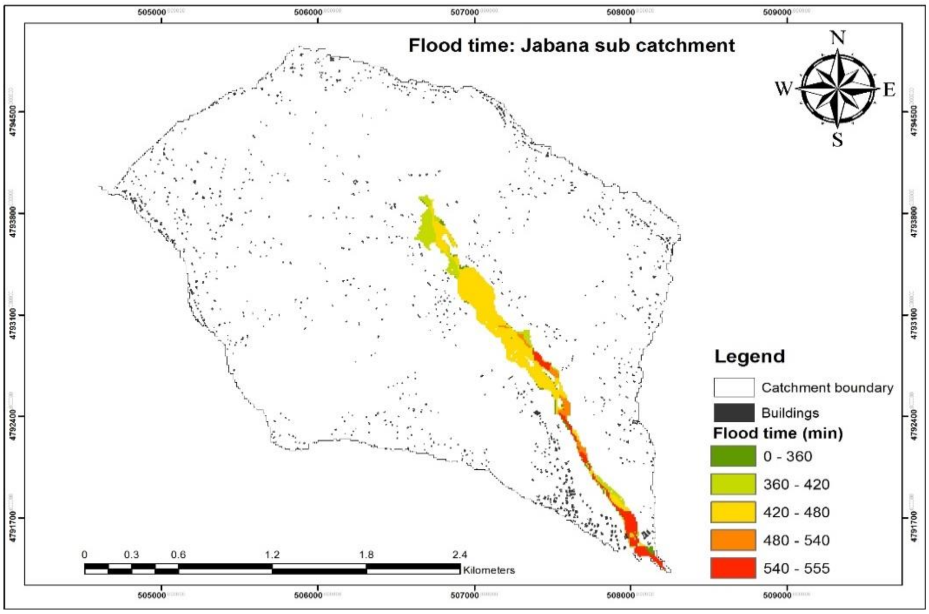


Figure 6.7: Baseline scenario results for Byabagabo Jabana sub catchment, flood time (min) using a 1:5 year rainstorm event (70.88 mm). The map also show buildings affected by this floods.

Figure 6.7 shows the maximum inundation time of seven hours near the catchment outlet and of five to six hours affecting the floodplains. The high inundation time is mainly caused by the topography of this catchment. For a once in two year's rainfall event, no floods were observed in this peri-urban catchment.

3. Discussion

For the highly urbanized sub catchment (Mpazi), the simulation of the current land use using a once in two year rainstorm event did not cause any floods in Nyabugogo center. This is mainly caused by the improvement made by Kigali city in 2015 where the size of the culverts in downstream area were increased. Also the local people were involved in removing the sediments from the canals. The simulation with a once in five year rainstorm (figure 6.4) leads to high amount of flash floods in Nyabugogo commercial center (downstream areas). This floods affect both business and transport activities. The maximum flood depth observed were 2 meters. Usually the flood depth increases the severity of the flood hazards as many properties (e.g. buildings) are negatively affected at different depth (Ootegem et al., 2015). This flash flood in downstream areas was caused by the runoff being collected from upper residential and forest areas and transported via the available drainage channels. In upper areas, the infiltration rate is very low due to the presence of impervious areas (built up) and the lack of ground cover in upper forest. In addition to that the absence of rainwater harvesting system at household level contribute to the amount of runoff generated from those areas. The high amount of runoff are shown also by the high level of discharge noted at the catchment outlet. This sub catchment is also characterized by steep slope which may have contributed to the high velocity of the runoff water coming from upper areas. The same observation were made by Zhou et al. (2013) where they found a big correlation between the amount of runoff generated and the rate of urbanization.

In contrast to Mpazi sub catchment, the total discharge in Byabagabo Jabana sub catchment is very low. This is mainly caused by the low amount of runoff coming from lightly urbanized upper areas. In this catchment the upper forests areas have ground cover and most of the agricultures fields are constituted by banana plantation with banana leaves at the ground. This increase in pervious surface has a big impact on runoff generated as they reduce the runoff speed and increase infiltration time (Descheemaeker et al., 2006). In addition to that, Byabagabo Jabana sub catchment has a natural drainage system and the existing floodplain are occupied by sugarcane plantation which may contribute to the infiltration of runoff before reaching the outlet (Schober et al., 2013b). However the flooded area and the flood volume in Byabagabo Jabana sub catchment are much higher than in Mpazi catchment. This is probably caused by topography of this peri urban catchment which is characterized by a long flat central valley. The simulation with 1:5 year rainfall event did not generate floods, this is probably caused by low inhabitant level in this catchment.

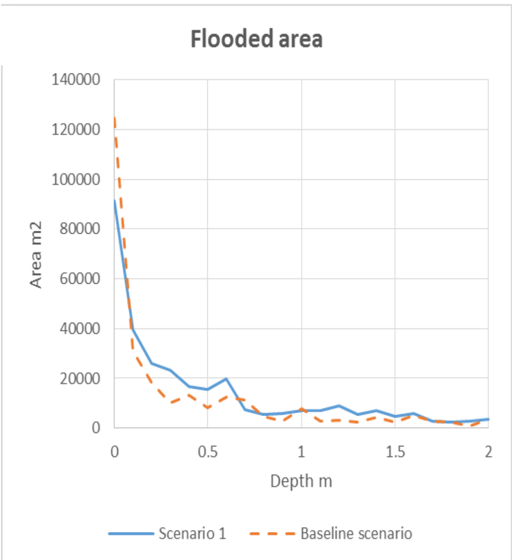
6.3.2. Scenario 1: Effect of Settlement Densification

Byabagabo Jabana sub catchment

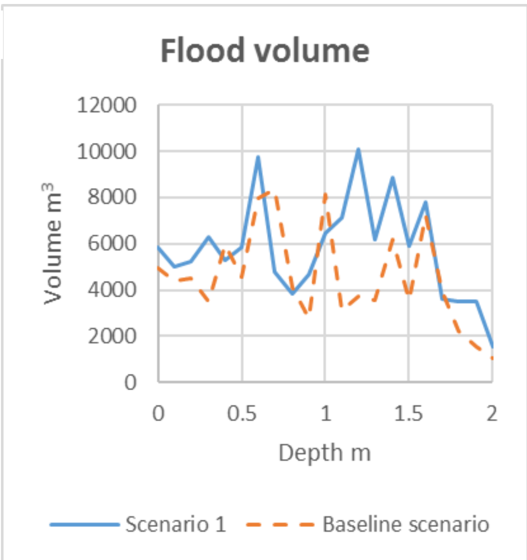
The residential area in this peri urban sub catchment occupy only 4.7% of the total catchment on current land use/cover. This scenario forecast on an increase in built up areas by the year 2040. The scenario was designed based on the Kigali Master plan 2025 and 2040. There is a plan to establish an industrial area in one part of this sub catchment. Furthermore, field observation conducted by the researcher revealed an increase of housing development. In this scenario, the built up areas were extended on an area currently used as mixed farming (agriculture area). They were extended from 4.7% to 30% of the total catchment size. Distance to the main roads and restriction on terrain slope angle (new buildings <36%) were taken into consideration in the development of this scenario. Other land use/cover types in the sub catchment were kept untouched. The rainfall-runoff simulation was carried out to assess the impact of urban densification on surface runoff.

The results show how flood volume, flooded area and the number of affected structures change at different depth under this urban densification scenario (Figure 6.8). Both flooded area and flood volume vary at different depth from 0 to 2m. There is an increase of 18% in flooded area and of 35% in flood volume compared to the baseline scenario. With this scenario there is a very high number of structures affected e.g. from 4 buildings in the baseline scenario to 305 buildings in this urban densification scenario. An increase of 30% in runoff volume were observed. Such big increase were caused by high amount of runoff coming from new buildings in this scenario. In general, the increase of built up areas from 4% to 30% to areas currently used as agricultures fields would increase the runoff volume and the number of structures affected. The table 6.4 provides summary of the flooded area, flood volume, total discharge and the structures affected by this scenario as compared to baseline scenario.

a)



b)



c)

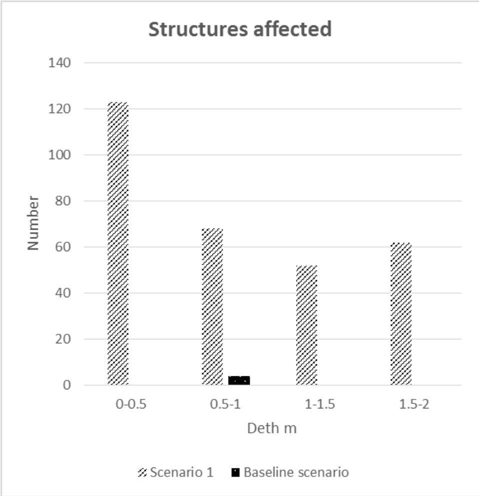


Table 6.4: Summary of model output for scenario 1

Criteria for evaluation	Baseline scenario	Scenario 1
Flooded volume (m3)	134787	182068
Flooded area (m2)	282600	339500
Total Discharge (mm)	14	18
Properties affected (number)	4	305

Figure 6.8: a) Flooded area (m^2); b) Flood volume (m^3); c) Number of buildings affected per flood depth for scenario 1 in Byabagabo Jabana (peri urban) sub catchment. Simulation for a 1:5 year rainfall event.

Discussion

The increase of urban areas in this lightly inhabited catchment leads to the generation of high amount of runoff (up to 30% increase as compared to the baseline scenario). This was caused by the increase in impervious cover due to the establishment of new buildings and hence the reduction in infiltration in upper areas. In addition, the reduction in surface roughness due to land cover change (reduction of agriculture areas) may have contributed to the increase in runoff velocity and consequently increase the peak discharge. Similar results were reported in Verbeiren et al. (2013) where the increase in built up areas from 1988 to 2006 has led to a considerable increase in surface runoff up to 40%.

6.3.3. Scenario 2: Effect of Structural measures in the Mpazi sub catchment

1. Detention Reservoir

Construction of a detention reservoir was proposed in downstream areas at two hundred meters (200m) from the main outlet. The location site of the detention reservoir was selected based on the report done by SHER Ingénieurs-Conseils s.a. (2013) and the field survey conducted by the researcher. The site is free for any development activities and is located near the main drainage channel. A retention pond was designed so that a small part was extended in the main drainage channel to ensure the collection of all runoff coming from upper areas. The depth of the drainage channel was kept higher than that of the reservoir to allow the continuation of runoff while other water are retained by the reservoir. It was designed considering the topography of the sub catchment to avoid deep excavation. It has the length of 350 meters, the width of 40 meters and the depth of 2.5 meters which make the total storage capacity of 30000 m^3. The size and capacity of the retention pond were based on the estimation of flood volume of the flooding event that took place in February 2013 which was 50000 m^3 (SHER Ingénieurs-Conseils s.a., 2013). The Figure 6.9a shows the map of the location of the proposed retention basin.

2. Channel roughness characteristics

The roughness of the channels is the resistance to the flowing movement of water caused by the materials constituting the drainage channels (Harun-ur-Rashid, 1990). In Mpazi sub catchment, the current primary and secondary drainage channels are made of stones, cement and concrete which render faster the movement of runoff during any rainfall event and cause flooding in downstream areas. This kind of drainage channel with low resistance to surface runoff may contribute to the nature of flooding in low laying areas (downstream). In order to increase the channel roughness, an engineering measures were proposed to increase the channel base resistance to the water flow (manning's). This is done by adding small gabions wall in the side of main drainage channel. Also, the materials constituent of the current smooth bottom were changed by using cobble (solid rock) materials to reduce the velocity of surface runoff coming from upper areas. In the modelling of this measures in openLISEM, the values of channels manning's were increased. The parameters of the drainage channels with high roughness characteristics provided by Arcement et al., (1989) were used.

Furthermore, the gullies located in the secondary channels contribute to sediment enrichment in the runoff water and making the slope susceptible to land sliding. The conservation measures proposed to stabilize those gullies are using earth plugs, loose-stone check dams and gabion walls. Figure 6.9 presents the map with the location of detention reservoir (a) and photos showing the current situation of the drainage channel (b) and a gully in upper catchment taken during fieldwork.

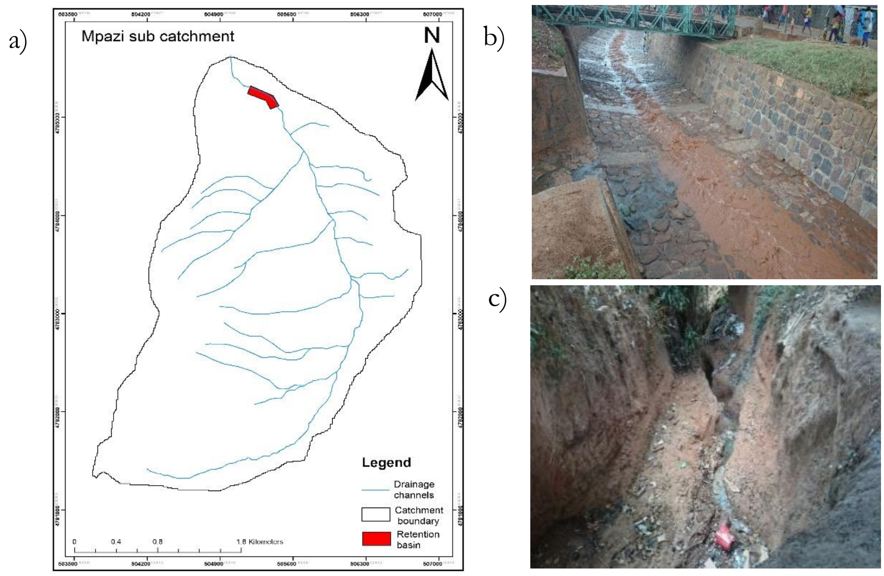
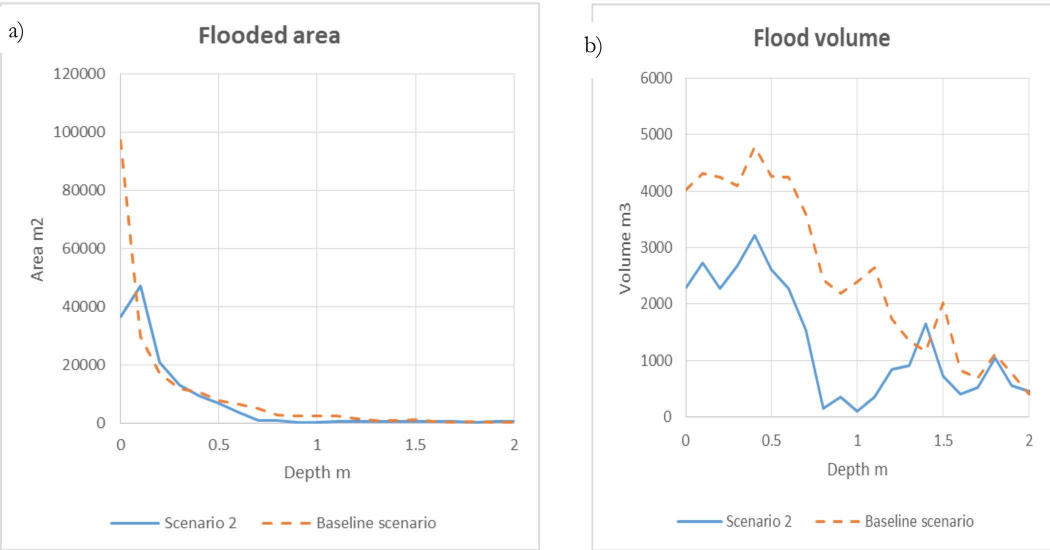


Figure 6.9: Location of detention reservoir (a); current situation of drainage channel (b); gully located in one of the secondary channels (c).

3. Modelling results

Figure 6.10 presents the results of the effect of structural measures on surface runoff in this urbanized catchment. The simulation was conducted using a once in five year rainfall event. According to the figure, there is a decrease in flood volume (up to 44%) and a decrease in flooded area (up to 27%) as compared to the baseline scenario. In terms of flooded area and flood volume with different depth (0-2m), a slight decrease in flooded area were observed while high decrease is clear in the flood volume. The number of structures affected decreases considerably (between 0 and 0.5 m depth) and in general the decrease of 25% in structure affected were observed. In addition, the decrease of total discharge by 45% in comparison to the baseline scenario was observed. The table 6.5 summarizes the total results of this scenario in terms of flooded area, flood volume, total discharge and affected buildings in comparison to the baseline scenario. The use of structures measures (retention pond) shows an improvement in terms of flooding reduction in downstream areas as it collects most of the runoff coming from highly urbanized upper areas.

From the point of view of Government officials in charge of planning and flood management interviewed, 22.2 % confirmed that the construction of retention pond and removing gullies are among the long-term planned engineering measures for flood reduction in Kigali City.



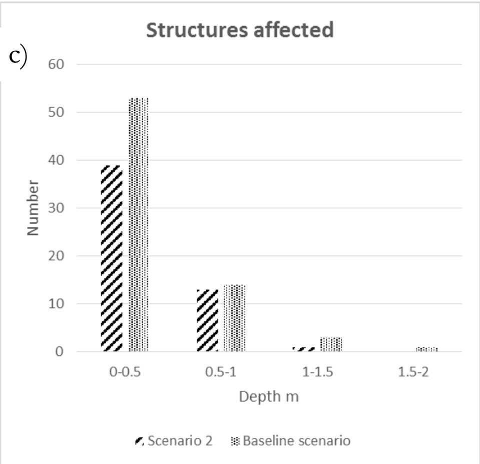


Table 6.5: Summary of model output for scenario 2

Criteria for evaluation	Baseline scenario	Scenario 2
Flooded volume (m3)	57116	35179
Flooded area (m2)	203300	149100
Total Discharge (mm)	51	28
Properties affected (number)	71	53

Figure 6.10: a) Flooded area (m²); b) Flood volume (m³); c) Number of buildings affected per flood depth, for scenario 2 in Mpazi (urban) sub catchment. Simulation for a 1:5 year rainfall event.

Discussion

The use of structure measures (retention pond and increase of channels manning's) has highly decreased the amount of runoff reaching Nyabugogo commercial center. They also reduced the velocity of runoff in channels. This reduced the flash flood affecting the center and the flooded areas as well. The use of retention pond decreases the total discharge significantly (section 5.2.3) due to the collection of the high amount of runoff coming from upper areas. The use of structural measures such river diversion work and detention pond were proposed by Hsieh et al. (2006) as another solution for flood management.

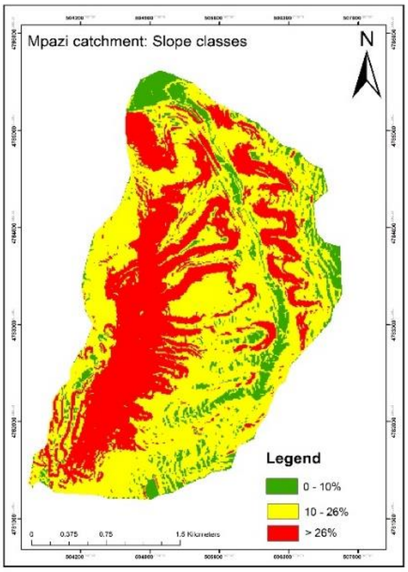
However the use of retention pond requires high maintenance cost as after every rainfall event there is a lot of sediment at the base of the pond. This may affect the capacity of the retention pond if no proper cleaning is done. The retention pond is also advantageous in terms of storing water that can be used for other purposes (e.g. cleaning, irrigation).

6.3.4. Scenario 3: Effect of Ecosystem based measures in the Mpazi sub catchment

1. Relocation of people

In Mpazi (urban) sub catchment, some buildings (household) are located on steep slope (>36%) and other few buildings are located in upper eucalyptus forest. In this catchment, slope ranging from 8%-26% dominate in 55 % of the total catchment area, while the slope of more than 26% accounts for 34% of the catchment area. The people living on steep slopes (>36%) were relocated and those areas were replaced by vegetation covers (grass and trees). The vegetation cover has a great impact both on runoff and soil properties. They increase ground roughness and hence has an impact on infiltration (Neris et al., 2013). According to the interviews conducted during fieldwork, this measure is one of the conservation measures in the future plan of the Kigali City Council to reduce flood related disaster in the city area. The Rwanda urbanization policy and Rwandan building make a restriction to build on the steep slopes (>26 %). The figure 6.11 present different slope classes and forest with no ground cover.

a)



b)

Figure 6.11: Map with slope classes (a); Current situation of ground cover in upper forest Mpazi sub catchment (b).

2. Afforestation in upper catchment

The existing eucalyptus forest has been degraded since there is no ground cover (grasses), this leads to the generation of high surface runoff during rainfall. According to the people living closer to the forest area, a lot of runoff water come from the forest during a rainfall event. They dig trenches in the forest to reduce runoff velocity. In this measure, the existing forestas upgraded by introducing new type of eucalyptus forest (e.g. Eucalyptus Globulus) which is tolerant to native plants. Also afforestation was extended on the steep slopes (>36%) after the relocation of people. The eucalyptus trees have more economic value because of their use for firewood and timber production. The forest serves as one of the source of income to the people living close to the forest. This measure will have a great impact on infiltration and the movement of runoff water as it will increase the surface roughness and reduce the speed of the runoff (Neris et al., 2013). The similar method has been applied successfully in Ethiopia as described in Yirdaw & Luukkanen (2003). Also, this conservation measure was thought to contribute to the reduction of soil erosion coming from upper forested areas. This type of measures has been incorporated in the model by changing Manning's roughness values (Hessel et al., 2003; Li & Zhang, 2001).

3. Rainwater harvesting

Mpazi sub catchment is highly urbanized where residential and commercial areas occupy more than 60% of the total watershed area. On average only 10% of the buildings have tanks for collecting rainwater. A rainwater harvesting system at household level was proposed to capture rainwater coming from rooftop of the buildings. Most of the buildings in the areas occupy a surface area of 56 m^2 (7m*8m). From fieldwork survey observation, the mostly used water tanks in this urbanized catchments have the capacity ranging from 200 litres to 400 litres. In this scenario a tank with the storage capacity of 350 litres was chosen and used in the modelling.

4. Modelling results

Figure 6.12 presents the results of the effect of the use of ecosystem based conservation measures on the flooded area, flood volume, total discharge and structures affected. According to the figure, a slight reduction both in flood volume and flooded area at different water depth were observed. Comparing to the baseline scenario, a decrease of 26% in flood volume and 23% in flooded area were seen from the model output. Considering the effect of this scenario on the number of building affected at different flood depth, there is only a slight decrease. The number of structures affected reduced from 71 to 62 buildings (13 % reduction). Also a decrease of 22% in total discharge comparing to the baseline scenario were observed. The ecosystem based conservation measures seem to slightly reduce runoff coming from upper areas and decrease flooding in downstream areas. The table 6.6 summarizes the total outcome of the model.

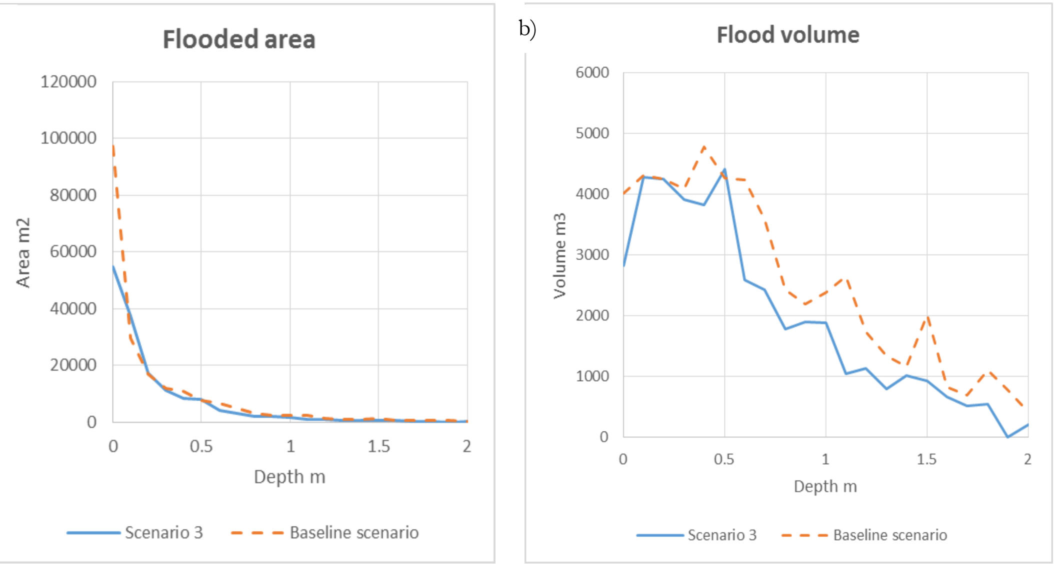
The ecosystem based measures were among the favoured plan by both local population and government officials. 40% of all the interviewed residents (Mpazi catchment) proposed the reforestation in upper forest while 60% of the respondents proposed rainwater harvesting techniques at household level as a measures for runoff and soil erosion reduction. 80% of the population living in high risk zone agreed to relocate from those zones if they are refunded. On the other hand among the government officials in charge of planning and flood management interviewed, 78% of the them confirmed the existence of plan to relocate people living in high risk zones, 67 % of them proposed the reforestation of degraded upper forest and 33% saw a solution in rainwater harvesting among other proposed plans.

Discussion

The output of the model on the use of ecosystem based measures showed a decrease of 22% in the amount of runoff generated and flash floods as well. This decrease in runoff can be attributed to the expansion of vegetation (e.g. forest) cover in upper areas and the use of rainwater harvesting system for capturing rainwater from houses roof. The same decreasing pattern in surface runoff was observed by Neris et al. (2013) where the forest type with ground cover increased the infiltration rate and hence reduced the overland flow. Also the use of rainwater harvesting system in some part showed a decrease in the amount of runoff generated during a rainfall event (Sample & Liu, 2014).

a)

b)



c)

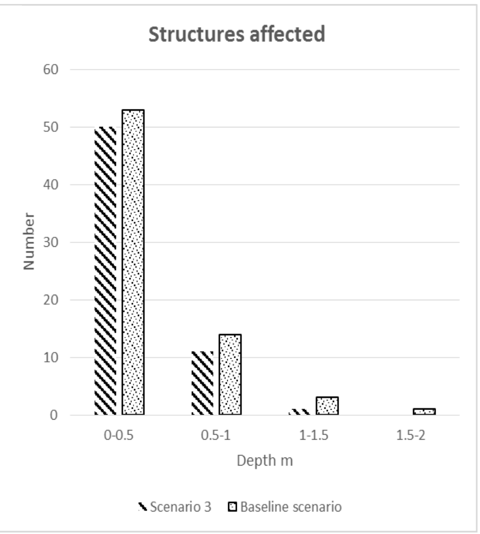


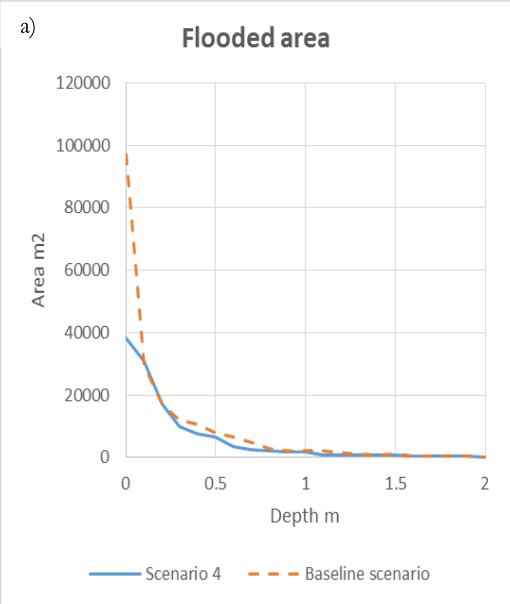
Table 6.6: Summary of model output for scenario 3

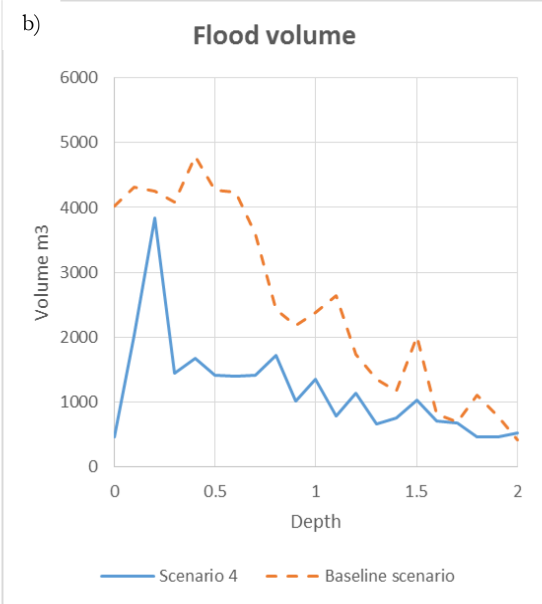
Criteria for evaluation	Baseline scenario	Scenario 3
Flooded volume (m3)	57116	42452
Flooded area (m2)	203300	155200
Total Discharge (mm)	51	40
Properties affected (number)	71	62

Figure 6.12: a) Flooded area (m²); b) Flood volume (m³); c) Number of buildings affected per flood depth for scenario 3 in Mpazi (urban) sub catchment. Simulation for a 1:5 year rainfall event.

6.3.5. Scenario 4: Combined effect of structural and Ecosystem based measures

Figure 6.13 shows the results of the effect of the combination of both structural and ecosystem based measures on the reduction of surface runoff and flooding. The result shows a considerable decrease in flood volume (decrease of 47%) and flooded areas (a decrease of 36%). In term of the number of buildings affected, this scenario is more effective than other individual scenarios. The buildings affected reduced from 71 to 46 (reduction of 35%). Considering a total discharge, a significant decrease of 63% was observed. In general, the combine scenario (structural and ecosystem based) is more effective in the reduction of flood and the number of properties affected. The table 6.7 summarizes the model output of the scenario 4.





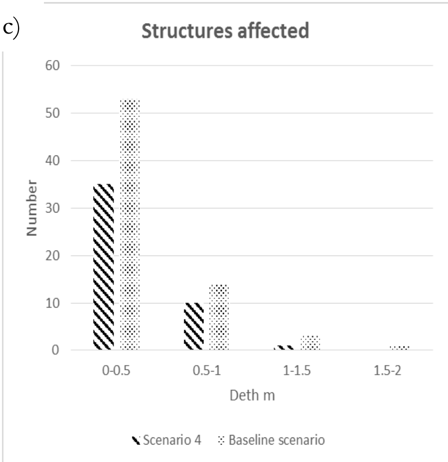


Table 6.7: Summary of model output for scenario 4

Criteria for evaluation	Baseline scenario	Scenario 4
Flooded volume (m3)	57116	30320
Flooded area (m2)	203300	131100
Total Discharge (mm)	51	19
Properties affected (number)	71	46

Figure 6.13: a) Flooded area (m²); b) Flood volume (m³); c) Number of buildings affected per flood depth, for scenario 4 in Mpazi (urban) sub catchment. Simulation for a 1:5 year rainfall event.

Discussion

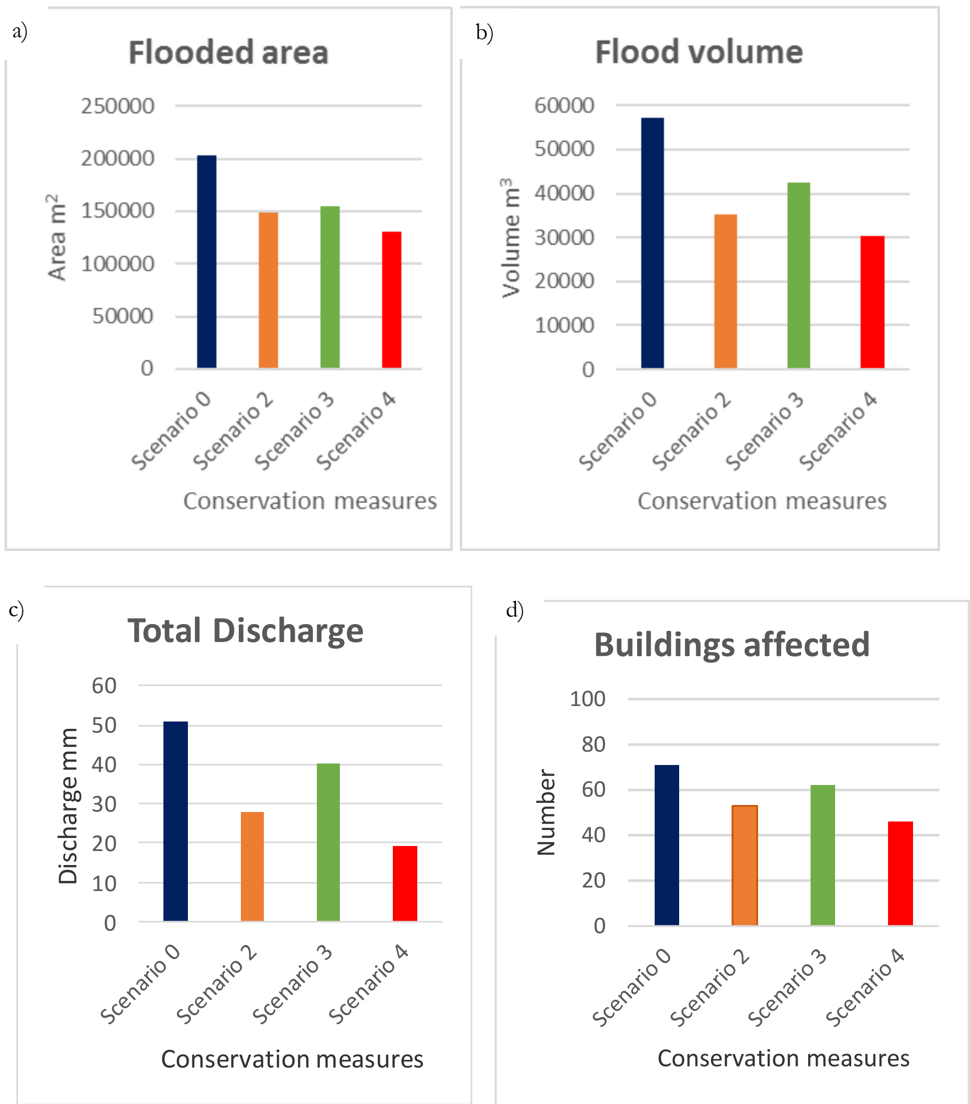
The combined effect of structural and ecosystem based measures showed a considerable decrease in both runoff and soil loss. In fact, the increased surface covered by vegetation contributed to the reduction of runoff coming from upper areas. This resulted in the decrease in the amount of runoff reaching the retention basin and the reduction of flash flood in downstream areas. Also, the combined effect of structural and non-structural measures was emphasized by Hsieh et al. (2006) as an effective measure for flood management.

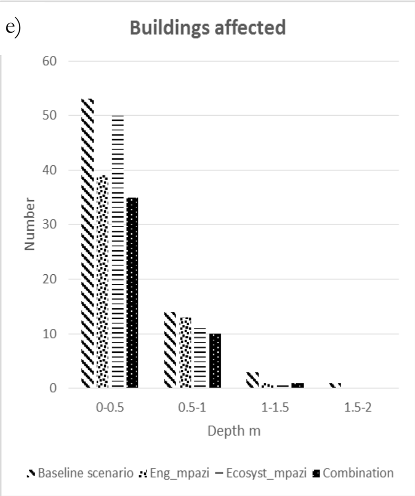
6.3.6. Comparison of different conservation scenarios in Mpazi sub catchment

Figure 6.14 shows the comparison of the effect of different conservation measures (scenario 2, 3, 4) on flood volume, flooded area, structures affected, total discharge and the number of properties affected in this urban catchment. As can be seen from the figure below, the combined effect of ecosystem based measures and structural conservation measures (scenario 4) have a strong effect in terms of reducing flood and the number of properties affected in comparing to other scenarios (2, 3). The structures measures also follow scenario 4 in terms of effectivity for flood reduction. Table 6.8 summarizes results of all scenarios (2, 3 &4). Also table 6.9 presents the buildings affected per different depth and per scenario.

Table 6.8: Results of model output for scenario 4

Criteria for evaluation	Baseline scenario	Scenario 2	Scenario 3	Scenario 4
Flooded volume (m3)	57116	35179	42452	30320
Flooded area (m2)	203300	149100	155200	131100
Total Discharge (mm)	51	28	40	19
Buildings affected (number)	71	53	62	46





Scenario 2: Structural conservation measures (Eng._mpazi)
Scenario 3: Ecosystem based conservation measures (Ecosyst._mpazi)
Scenario 4: Combined measures (scenario 2&Scenario 3)

Table 6.9: Buildings affected by floods per scenario

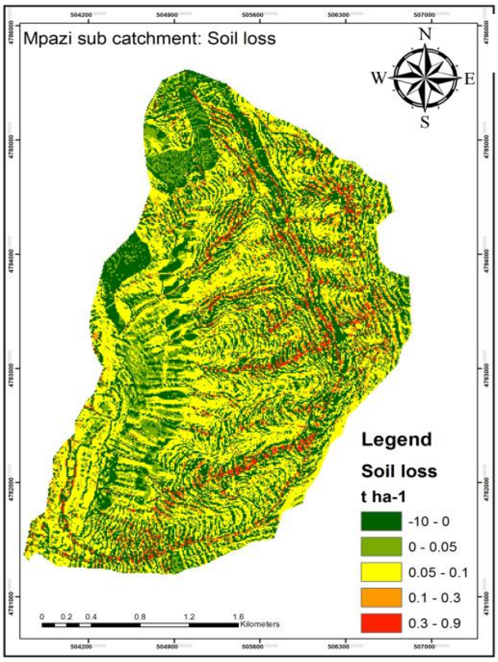
Flood depth (m)	Buildings affected			
	Baseline	Scenario 2	Scenario 3	Scenario 4
0-0.5	53	39	50	35
0.5-1	14	13	11	10
1-1.5	3	1	1	1
1.5-2	1	0	0	0
Total	**71**	**53**	**62**	**46**

Figure 6.14: a) Flooded area (m²); b) Flood volume (m³); c) Total discharge (mm); d) Number of buildings affected per scenario; e)Number of buildings affected per floods depth in all scenarios (0, 2, 3&4) in Mpazi (urban) sub catchment. Simulation for a 1:5 year rainfall event.

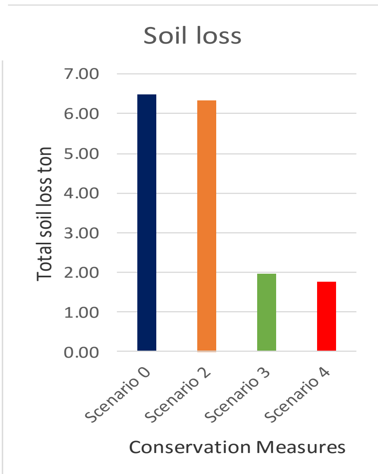
Mpazi sub catchment

Figure 6.15a shows the model results of soil loss of the current situation. The simulation of soil erosion was done using the maximum yearly rainstorm event (32.7 mm). As can be seen from the figure, the maximum soil loss is 0.9 ton per ha per rainstorm event. Most of the sediment loss are observed in upper secondary channels and gullies probably coming from the degraded upper forest. On the other hand, the application of ecosystem based measures reduced the soil loss up to 0.3 ton per ha for the rainfall event with 32.7 mm rain. The figure 6.15b presents the effect of different conservation measures (scenario 2, 3, 4) on total sediment loss in Mpazi (urban) catchment.

a)



b)



Scenario 2: Structural conservation measures
Scenario 3: Ecosystem based conservation measures
Scenario 4: Combined measures (scenario 2&scenario 3)

Figure 6.15: Soil loss with the current land use/cover in Mpazi sub catchment (a); Total soil loss per conservation (scenario 2, 3&4).

According to the figure (figure 6.15b), the ecosystem based measure (scenario 3) seems to be more effective than other conservation measures where the total sediment loss decreases by 65% comparing by the baseline scenario. The combined measures (scenario 4) also shows a similar trend in terms of sediment loss reduction, a reduction of 68% was noted. The structural based measures (scenario 2) only shows a little change in sediment reduction (reduction of 15%) compared to the baseline scenario probably caused by a change in flow velocity (manning's). The high decrease in soil loss observed in scenario 3 is mainly caused by the increase of vegetation cover in upper areas which affected negatively the amount of runoff generated and soil detachment.

Discussion

The sediments loss (6.15a) observed in the simulation with the current land use in Mpazi sub catchment are mainly caused by the absence of ground cover in upper forest. This facilitate the soil detachment by raindrops in the case of a rainfall event and sediments being transported by runoff. The maximum soil loss per event rainfall (0.9 ton/ha) was found to be in range with the results of other studies where the maximum soil loss was 4.16 t ha^{-1} per year (Teng et al., 2016).

In Mpazi sub catchment, the laboratory analysis of soil samples revealed that sand content were 40% to 72%. The soils have silt content of 4% to 70% and from 7% to 27% of clay content. Those results of soil texture distribution were in range with that of the current soil map of the study area. It has the sand content of 33% to 65%, 4% to 40% silt and 7 to 42 clay. The high composition of silt and sand in the collected samples also indicate the high erodibility in this sub catchment (Perez-Rodriguez et al., 2007).

The soil analysis also showed that the organic matter content were below 6% in upper areas (forest). This low organic content shows how the soil can easily be detached in case of a rainfall event. As Su et al., (2014) observed that there is a negative correlation between soil detachment and organic matter content.

A decrease (40%) in soil loss under ecosystem based measures and the combined impact of both ecosystem and structural measures (6.15b) was associated with the increase in forest ground floor (vegetation cover) in upper forest. The presence of vegetation cover may have increased the infiltration during a rainfall event. This reduces the speed of overland flow and decrease the soil detachment in the upper forest (Woo et al., 1997). Similar results were by Yuan et al. (2015) on the study at the effect of different slope land cover on sediments loss, the forest cover mixed with shrubs and grass showed a considerable decrease in sediments loss up to 29% compared to other forests areas without ground cover.

6.3.7. Ranking different conservation scenarios using multi criteria analysis

Different conservation measures (scenario 0, 1, 2, 3, 4) were ranked using decisions on a finite set of alternatives (DEFINITE). According to Janssen & Herwijnen. (2011) DEFINITE is a decision support software that can be used to select the best alternative from a set of alternative solutions for an identified problem. In this study, the proposed conservation measures (scenarios) were ranked according to their impact on various criteria set (number of buildings affected, flood volume, flooded area, total discharge and soil loss). Four different vision were used in giving weight to the criteria. Those visions (appendix 3) were social economic impact focusing on properties (buildings) affected, soil erosion focusing on soil loss reduction, flood disaster focusing on flood reduction and last one was the equal impact giving all criteria's the same weight. Except for the last vision (equal impact), other three visions were given weight referring to their focus.

The concave standardization was selected because all the criteria are the costs which mean the higher the value the worse the impact. Although the convex and linear standardization were also used to see if they may have any impact in the ranking of alternatives. Thereafter the sensitivity analysis for each criteria were done. The results of the ranking different conservation measures using DEFINITE were as follow:

- The combine measures (ecosystem and structural measures) was ranked the best in all cases.
- The ecosystem based measures was ranked the second in combining all the four visions together. They were ranked the second on "equal impact vision" and "soil erosion vision" and ranked the third in the two remaining vision.
- The structural measures were ranked the third in most cases except for social economic impact and flood disaster vision where they come as the seconds.

The sensitivity analysis between ecosystem based measures and structural measures using different standardization showed that ecosystem measures scored better in all criteria and was ranked the second after combined measures in most cases. Only a few times, structural measures were ranked the second. The figure 6.16 shows an example of sensitivity analysis and ranking of different conservation measures.

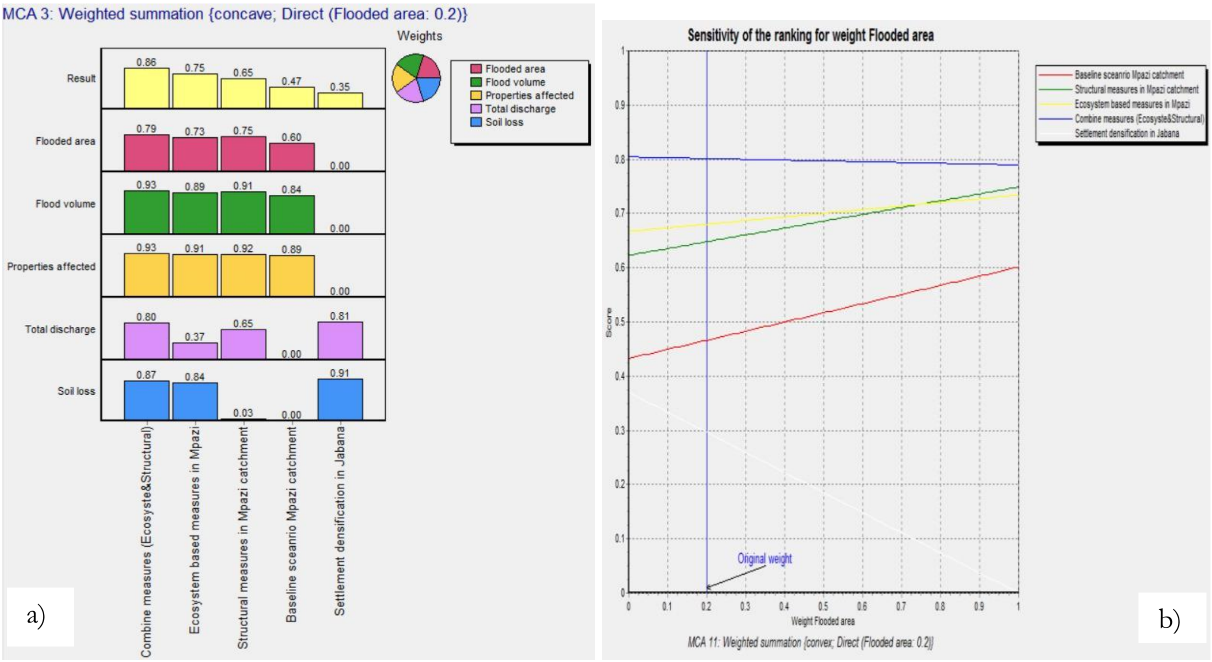


Figure 6.16: a) Ranking of different conservation measures; b) Sensitivity analysis in DEFINITE

From the above analysis, it can be concluded that the combine measures (ecosystem and structural) were the best conservation scenario (scenario) followed by ecosystem based measures scenario and finally the structural measures scenario.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

In the present study, OpenLISEM hydrological model was successful applied to assess the effects of structural and ecosystem based measures to reduce surface runoff in upstream areas and flash flood problem in the study area. On the behavior of surface runoff at various land use/cover, the model results showed that much runoff were generated in urban areas than in non-urban (peri urban) areas. The findings of simulation with the current land use/cover in the two sub catchments presented much higher runoff (>112%) in mpazi sub catchment than in Byabagabo Jabana sub catchment. This was caused by high urbanization rate in Mpazi catchment (>72%) than in Byabagabo Jabana sub catchment (5%). The settlement densification scenario in Byabagabo Jabana sub catchment (peri urban) increased the surface runoff by 30% compared to the baseline scenario. This was found to be caused by a reduction in pervious surface in this catchment due to the development of new buildings. It can be concluded that high urban development in Mpazi sub catchment increased impervious cover and has caused high runoff generation. This led to the increase of flash floods in Nyabugogo commercial center located in downstream floodplain areas.

The use of structural measures (scenario 2) in Mpazi sub catchment to reduce surface runoff led to a considerable decrease in runoff (45%) and flash floods in Nyabugogo commercial center. The retention pond retains most of the runoff water coming from upper areas. Only few runoff leaves the ponds at low velocity and reach the downstream areas with no big effect. However much sediments were found at the bottom of the reservoir ponds. This requires the maintenance of the pond after each rainfall event.

The model output results showed that the application of ecosystem based measures (reforestation, rainwater harvesting) in Mpazi sub catchment can decrease both soil loss up to 65% and surface runoff up to 22%. The increase in forest areas and the rehabilitation of the existing forest in combination with rainwater harvesting at household level (scenario 3) in upper areas are found to be major drivers of runoff reduction. Although the decrease in surface runoff caused by this measures was less compared to the application of structural measures.

Finally, the combined impact of both structural and ecosystem based measures in Mpazi sub catchment was more accurate than other conservation measures (scenario 2& 3). High decrease in both runoff (62%) and soil loss (68%) reduction were noted. Also the amount of sediments load at the bottom of retention pond reduced considerably.

The results of the ranking of all different conservation measures (scenarios) using DEFINITE in Mpazi sub catchment showed that the combined measures (structural and ecosystem) were the best conservation measures followed by ecosystem based measures and structural measures become the last.

These findings showed that the ecosystem based measures can be used as alternative measures to reduce surface runoff and soil losses that cause flash floods in many areas in Kigali City. This study also provides useful information that can be used by the city planner and other decision makers to mitigate floods.

7.2. Recommendations

- This study was intended to look only at the effect of applied different conservation measures on surface runoff. Further studies should be done on the cost effective analysis and environmental impact assessment for each proposed conservation measures.
- This study did not focus on the use of structural and non-structural measures for flood mitigation in Nyabugogo commercial center. More studies shall be done on structural methods such as the use of protection levee to the commercial center. Also non-structural measures such as flood forecasting and early warning system shall be promoted.
- More studies on the specific type of eucalyptus forest and native plants to be reintroduced in upper forest in Mpazi sub catchment shall be done for future better forest management.
- Due to time constraints, the simulations of the effect of different conservation measures on surface runoff were limited to the use of two different rainfall event (1:2 and 1:5 year) only. Simulation using different return period are recommended for further studies.

7.3. Limitations of study

The study was conducted in a data scarcity environment. Some of the limitation were:

- Lack of historical discharge and flood data in both Mpazi and Byabagabo Jabana sub catchments.
- Lack of accurate event based rainfall data recorded by ground based meteorological station.

LIST OF REFERENCES

Abas, A. A., & Hashim, M. (2014). Change detection of runoff-urban growth relationship in urbanised watershed. *IOP Conference Series: Earth and Environmental Science*, *18*(1), 012040. doi:10.1088/1755-1315/18/1/012040

Ali, M., Khan, S. J., Aslam, I., & Khan, Z. (2011). Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan. *Landscape and Urban Planning*, *102*(4), 271–279. doi:10.1016/j.landurbplan.2011.05.006

Alkema, D. (2007). Simulating floods. *ITC Dissertation*.

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

Bonilla, C. A., & Johnson, O. I. (2012). Soil erodibility mapping and its correlation with soil properties in Central Chile. *Geoderma*, *189-190*, 116–123. doi:10.1016/j.geoderma.2012.05.005

Brocca, L., Melone, F., & Moramarco, T. (2011). Distributed rainfall-runoff modelling for flood frequency estimation and flood forecasting. *Hydrological Processes*, *25*(18), 2801–2813. doi:10.1002/hyp.8042

Carrivick, J. L. (2006). Application of 2D hydrodynamic modelling to high-magnitude outburst floods: An example from Kverkfjöll, Iceland. *Journal of Hydrology*, *321*(1-4), 187–199. doi:10.1016/j.jhydrol.2005.07.042

Chow;, V. Te, Maidment;, D. R., & Mays, L. W. (1988). *Applied Hydrology*. New York : McGraw-Hill.

Ciabatta, L., Brocca, L., Massari, C., Moramarco, T., Gabellani, S., Puca, S., & Wagner, W. (2015). state-of-the-art satellite rainfall products over Italy.

Collischonn, B., Collischonn, W., & Tucci, C. E. M. (2008). Daily hydrological modeling in the Amazon basin using TRMM rainfall estimates. *Journal of Hydrology*, *360*(1-4), 207–216. doi:10.1016/j.jhydrol.2008.07.032

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. . (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*, *41*(3), 393–408. doi:10.1016/S0921-8009(02)00089-7

de Jong, S. M., & Jetten, V. G. (2007). Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis. *International Journal of Geographical Information Science*, *21*(5), 529–545. doi:10.1080/13658810601064884

De Martino, G., De Paola, F., Fontana, N., Marini, G., & Ranucci, A. (2012). Experimental assessment of level pool routing in preliminary design of floodplain storage. *The Science of the Total Environment*, *416*, 142–7. doi:10.1016/j.scitotenv.2011.11.032

De Roo, A. P. ., & Jetten, V. . (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., Wesseling, C. G., & Ritsema, C. J. (1996a). LISEM: A SINGLE-EVENT PHYSICALLY BASED HYDROLOGICAL AND SOIL EROSION MODEL FOR DRAINAGE BASINS. I: THEORY, INPUT AND OUTPUT. *Hydrological Processes*, *10*(8), 1107–1117. doi:10.1002/(SICI)1099-1085(199608)10:8<1107::AID-HYP415>3.0.CO;2-4

De Roo, A. P. J., Wesseling, C. G., & Ritsema, C. J. (1996b). Lisem: A Single-Event Physically Based Hydrological and Soil Erosion Model for Drainage Basins. I: Theory, Input and Output. *Hydrological Processes*, *10*(8), 1107–1117. doi:10.1002/(SICI)1099-1085(199608)10:8<1107::AID-HYP415>3.0.CO;2-4

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

Descheemaeker, K., Nyssen, J., Poesen, J., Raes, D., Haile, M., Muys, B., & Deckers, S. (2006). Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. *Journal of Hydrology*, *331*(1-2), 219–241. doi:10.1016/j.jhydrol.2006.05.015

Dessie, M., Verhoest, N. E. C., Admasu, T., Pauwels, V. R. N., Poesen, J., Adgo, E., … Nyssen, J. (2014). Effects of the floodplain on river discharge into Lake Tana (Ethiopia). *Journal of Hydrology*, *519*, 699–

710. doi:10.1016/j.jhydrol.2014.08.007
El Kateb, H., Zhang, H., Zhang, P., & Mosandl, R. (2013). Soil erosion and surface runoff on different vegetation covers and slope gradients: A field experiment in Southern Shaanxi Province, China. *Catena*, *105*, 1–10. doi:10.1016/j.catena.2012.12.012
Fattet, M., Fu, Y., Ghestem, M., Ma, W., Foulonneau, M., Nespoulous, J., … Stokes, A. (2011). Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength. *Catena*, *87*(1), 60–69. doi:10.1016/j.catena.2011.05.006
Fu, B., Wang, Y. K., Xu, P., & Yan, K. (2013). Mapping the flood mitigation services of ecosystems - A case study in the Upper Yangtze River Basin. *Ecological Engineering*, *52*, 238–246. doi:10.1016/j.ecoleng.2012.11.008
Haas, J., Furberg, D., & Ban, Y. (2015). Satellite monitoring of urbanization and environmental impacts—A comparison of Stockholm and Shanghai. *International Journal of Applied Earth Observation and Geoinformation*, *38*, 138–149. doi:10.1016/j.jag.2014.12.008
Habersack, H., Schober, B., & Hauer, C. (2013). Floodplain evaluation matrix (FEM): An interdisciplinary method for evaluating river floodplains in the context of integrated flood risk management. *Natural Hazards*, *75*(S1), 5–32. doi:10.1007/s11069-013-0842-4
Halwatura, D., & Najim, M. M. M. (2013). Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environmental Modelling and Software*, *46*, 155–162. doi:10.1016/j.envsoft.2013.03.006
Harun-ur-Rashid, M. (1990). Estimation of Manning's roughness coefficient for basin and border irrigation. *Agricultural Water Management*, *18*(1), 29–33. doi:10.1016/0378-3774(90)90033-U
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., Jetten, V., Baoyuan, L., Yan, Z., & Stolte, J. (2003). Calibration of the LISEM model for a small Loess Plateau catchment. *Catena*, *54*, 235–254. doi:10.1016/S0341-8162(03)00067-5
Hessel, R., Jetten, V., & Guanghui, Z. (2003). Estimating Manning's n for steep slopes. *Catena*, *54*(1-2), 77–91. doi:10.1016/S0341-8162(03)00058-4
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
Holifield Collins, C. D., Stone, J. J., & Cratic, L. (2015). Runoff and sediment yield relationships with soil aggregate stability for a state-and-transition model in southeastern Arizona. *Journal of Arid Environments*, *117*, 96–103. doi:10.1016/j.jaridenv.2015.02.016
Hrdinka, T., Novický, O., Hanslík, E., & Rieder, M. (2012). Possible impacts of floods and droughts on water quality. *Journal of Hydro-Environment Research*, *6*(2), 145–150. doi:10.1016/j.jher.2012.01.008
Hsieh, L. S., Hsu, M. H., & Li, M. H. (2006). An assessment of structural measures for flood-prone lowlands with high population density along the Keelung River in Taiwan. *Natural Hazards*, *37*(1-2), 133–152. doi:10.1007/s11069-005-4660-1
Huang, M., Zhang, L., & Gallichand, J. (2003). Runoff responses to afforestation in a watershed of the Loess Plateau, China. *Hydrological Processes*, *17*(13), 2599–2609. doi:10.1002/hyp.1281
Javaheri, A., & Babbar-Sebens, M. (2014). On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding. *Ecological Engineering*, *73*, 132–145. doi:10.1016/j.ecoleng.2014.09.021
Jennings, D. B., & Jarnagin, S. T. (n.d.). Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed. *Landscape Ecology*, *17*(5), 471–489. doi:10.1023/A:1021211114125
Jetten, V. (2002). LISEM, 1–64.
Jetten, V. (2016). LISEM - Limburg Soil Erosion Model - User manual, 1–64. Retrieved from http://www.itc.nl/lisem/download/lisemmanualv2x.pdf
Jetten, V. . (2013). Basic theory | openLISEM – a spatial model for runoff, floods and erosion. Retrieved February 14, 2016, from http://blogs.itc.nl/lisem/basic-theory/
Jetten, V. . (2014). Maps | openLISEM – a spatial model for runoff, floods and erosion. Retrieved February 14, 2016, from http://blogs.itc.nl/lisem/running-lisem/maps/
Jetten, V., De Roo, A., & Favis-Mortlock, D. (1999). Evaluation of field-scale and catchment-scale soil erosion models. *Catena*, *37*, 521–541. doi:10.1016/S0341-8162(99)00037-5
Jetten, V. G. (1996). Inception of tropical rain forest: Performance of a canopy water balance model. *Hydrological Processes*, *10*(October 1993), 671–685.

Jr., G. J. A., & Schneider, V. R. (1989). Guide for Selecting Manning ' s Roughness Coefficients for Natural Channels and Flood Plains United States Geological Survey Water-supply Paper 2339. *Area*, *2339*(2339), 39. doi:Report No. FHWA-TS-84-204

Klein, M. (1984). Effect of catchment size on runoff relationships — A comment. *Journal of Hydrology*, *71*(1-2), 191–195. doi:10.1016/0022-1694(84)90078-7

Knebl, M. R., Yang, Z.-L., Hutchison, K., & Maidment, D. R. (2005). Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event. *Journal of Environmental Management*, *75*(4), 325–36. doi:10.1016/j.jenvman.2004.11.024

Lammersen, R., Engel, H., Langemheen, W. Van De, & Buiteveld, H. (2002). Impact of river training and retention measures on flood peaks along the Rhine, *267*, 115–124.

LEE, S. Y., DUNN, R. J. K., YOUNG, R. A., CONNOLLY, R. M., DALE, P. E. R., DEHAYR, R., … WELSH, D. T. (2006). Impact of urbanization on coastal wetland structure and function. *Austral Ecology*, *31*(2), 149–163. doi:10.1111/j.1442-9993.2006.01581.x

Li, Z., & Zhang, J. (2001). Calculation of Field Manning's Roughness Coefficient. *Agricultural Water Management*, *49*(2), 153–161. doi:10.1016/S0378-3774(00)00139-6

Liu, S., Costanza, R., Farber, S., & Troy, A. (2010). Valuing ecosystem services Theory, practice, and the need for a transdisciplinary synthesis, Annals of the New York Academy of Sciences Volume 1185, Issue 1. *Annals of the New York Academy of Sciences*, *1185*(1), 54–78. Retrieved from http://onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2009.05167.x/abstract

Liu, W., Chen, W., & Peng, C. (2014). Influences of setting sizes and combination of green infrastructures on community's stormwater runoff reduction. *Ecological Modelling*. doi:10.1016/j.ecolmodel.2014.11.007

Meierdiercks, K. L., Smith, J. A., Baeck, M. L., & Miller, A. J. (2010). Analyses of Urban Drainage Network Structure and its Impact on Hydrologic Response1. *JAWRA Journal of the American Water Resources Association*, *46*(5), 932–943. doi:10.1111/j.1752-1688.2010.00465.x

Miller, J. D., Kim, H., Kjeldsen, T. R., Packman, J., Grebby, S., & Dearden, R. (2014). Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology*, *515*, 59–70. doi:10.1016/j.jhydrol.2014.04.011

Mohit, M. A., & Sellu, G. M. (2013). Mitigation of Climate Change Effects through Non-structural Flood Disaster Management in Pekan Town, Malaysia. *Procedia - Social and Behavioral Sciences*, *85*, 564–573. doi:10.1016/j.sbspro.2013.08.385

Munang, R., Thiaw, I., Alverson, K., Liu, J., & Han, Z. (2013). The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability*, *5*(1), 47–52. doi:10.1016/j.cosust.2013.02.002

Munkholm, L. J., Heck, R. J., Deen, B., & Zidar, T. (2016). Geoderma Relationship between soil aggregate strength , shape and porosity for soils under different long-term management, *268*, 52–59.

Mureithi, I. N. (2015). Flash Flood Hazard and Coping Strategies in Urban Areas : Case Study in Mpazi Catchment , Kigali, Rwanda., 1–8.

Nearing, M. A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., … van Oost, K. (2005). Modeling response of soil erosion and runoff to changes in precipitation and cover. *CATENA*, *61*(2-3), 131–154. doi:10.1016/j.catena.2005.03.007

Nel, J. L., Le Maitre, D. C., Nel, D. C., Reyers, B., Archibald, S., van Wilgen, B. W., … Barwell, L. (2014). Natural hazards in a changing world: a case for ecosystem-based management. *PloS One*, *9*(5), e95942. doi:10.1371/journal.pone.0095942

Neris, J., Tejedor, M., Rodríguez, M., Fuentes, J., & Jiménez, C. (2013). Effect of forest floor characteristics on water repellency, infiltration, runoff and soil loss in Andisols of Tenerife (Canary Islands, Spain). *CATENA*, *108*, 50–57. doi:10.1016/j.catena.2012.04.011

Newspaper, T. R. (2015). Nyabugogo: Imvura yateje umwuzure abantu n' imodoka babura uko batambuka - Touch Rwanda. Retrieved January 16, 2016, from http://www.touchrwanda.com/nyabugogo-imvura-yateje-umwuzure-abantu-n-imodoka-babura-uko-batambuka/

Ootegem, L. Van, Verhofstadt, E., Herck, K. Van, & Creten, T. (2015). Multivariate pluvial fl ood damage models ☆, *54*, 91–100.

Pedzisai, E. (2010). Rainfall - runoff modelling for flash floods in Cuong Thinh catchment, Yen Bai Province, Vietnam, 81. Retrieved from http://www.itc.nl/library/papers_2010/msc/aes/pedzisai.pdf

Perez-Rodriguez, R., Marques, M. J., & Bienes, R. (2007). Spatial variability of the soil erodibility

parameters and their relation with the soil map at subgroup level. *Science of the Total Environment*, *378*(1-2), 166–173. doi:10.1016/j.scitotenv.2007.01.044
Pistrika, A. K., & Jonkman, S. N. (2010). Damage to residential buildings due to flooding of New Orleans after hurricane Katrina. *Natural Hazards*, *54*(2), 413–434. doi:10.1007/s11069-009-9476-y
Qi, Z.-F., Ye, X.-Y., Zhang, H., & Yu, Z.-L. (2013). Land fragmentation and variation of ecosystem services in the context of rapid urbanization: the case of Taizhou city, China. *Stochastic Environmental Research and Risk Assessment*, *28*(4), 843–855. doi:10.1007/s00477-013-0721-2
Qin, J., Ding, Y., Wu, J., Gao, M., Yi, S., Zhao, C., … Wang, S. (2013). Understanding the impact of mountain landscapes on water balance in the upper Heihe River watershed in northwestern China. *Journal of Arid Land*, *5*(3), 366–383. doi:10.1007/s40333-013-0162-2
Qiu, B., Li, H., Zhou, M., & Zhang, L. (2015). Vulnerability of ecosystem services provisioning to urbanization: A case of China. *Ecological Indicators*, *57*, 505–513. doi:10.1016/j.ecolind.2015.04.025
Rai, R. K., Upadhyay, A., & Singh, V. P. (2010). Effect of variable roughness on runoff. *Journal of Hydrology*, *382*(1-4), 115–127. doi:10.1016/j.jhydrol.2009.12.022
Reeuwijk, L. P. van. (2002). ISRIC_TechPap09_2002.pdf.
REMA. (2013). Kigali State of Environment, *1*. doi:10.1017/CBO9781107415324.004
Rwanda, N. (2013). Heavy storms leave city Nyabugogo traders in tears.
Sample, D. J., & Liu, J. (2014). Optimizing rainwater harvesting systems for the dual purposes of water supply and runoff capture. *Journal of Cleaner Production*, *75*, 174–194. doi:10.1016/j.jclepro.2014.03.075
Sanchez-Moreno, J. F., Jetten, V., Mannaerts, C. M., & de Pina Tavares, J. (2014). Selecting best mapping strategies for storm runoff modeling in a mountainous semi-arid area. *Earth Surface Processes and Landforms*, *39*(8), 1030–1048. doi:10.1002/esp.3501
Schober, B., Hauer, C., & Habersack, H. (2013a). A novel assessment of the role of Danube floodplains in flood hazard reduction (FEM method). *Natural Hazards*, *75*(S1), 33–50. doi:10.1007/s11069-013-0880-y
Schober, B., Hauer, C., & Habersack, H. (2013b). A novel assessment of the role of Danube floodplains in flood hazard reduction (FEM method). *Natural Hazards*, *75*(S1), 33–50. doi:10.1007/s11069-013-0880-y
SHER Ingénieurs-Conseils s.a. (2013). Consultancy Services for Development of Rwanda National Water Resources Master Plan - Exploratory Phase Report, (021). Retrieved from http://41.215.250.87:8083/rwandawater/sites/default/files/NWRMP ExPhR_main_prnt.pdf
Shi, P.-J., Yuan, Y., Zheng, J., Wang, J.-A., Ge, Y., & Qiu, G.-Y. (2007). The effect of land use/cover change on surface runoff in Shenzhen region, China. *CATENA*, *69*(1), 31–35. doi:10.1016/j.catena.2006.04.015
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
Solín, Ľ., Feranec, J., & Nováček, J. (2010). Land cover changes in small catchments in Slovakia during 1990–2006 and their effects on frequency of flood events. *Natural Hazards*, *56*(1), 195–214. doi:10.1007/s11069-010-9562-1
Špitalar, M., Gourley, J. J., Lutoff, C., Kirstetter, P.-E., Brilly, M., & Carr, N. (2014). Analysis of flash flood parameters and human impacts in the {US} from 2006-2012. *Journal of Hydrology*, *519*(0), -. doi:http://dx.doi.org/10.1016/j.jhydrol.2014.07.004
Su, Z., Zhang, G., Yi, T., & Liu, F. (2014). Soil {Detachment} {Capacity} by {Overland} {Flow} for {Soils} of the {Beijing} {Region}. *Soil Science*, *179*(Copyright (C) 2015 American Chemical Society (ACS). All Rights Reserved.), 446–453. doi:10.1097/SS.0000000000000089
Suriya, S., & Mudgal, B. V. (2012). Impact of urbanization on flooding: The Thirusoolam sub watershed – A case study. *Journal of Hydrology*, *412-413*, 210–219. doi:10.1016/j.jhydrol.2011.05.008
Teng, H., Viscarra, R. A., Shi, Z., Behrens, T., Chappell, A., & Bui, E. (2016). Environmental Modelling & Software Assimilating satellite imagery and visible e near infrared spectroscopy to model and map soil loss by water erosion in Australia, *77*, 156–167.
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
Tong, C., Feagin, R. A., Lu, J., Zhang, X., Zhu, X., Wang, W., & He, W. (2007). Ecosystem service values and restoration in the urban Sanyang wetland of Wenzhou, China. *Ecological Engineering*, *29*(3), 249–258. doi:10.1016/j.ecoleng.2006.03.002
Torri, D., Sfalanga, M., & Del Sette, M. (1987). Splash detachment: Runoff depth and soil cohesion.

Catena, *14*(1-3), 149–155. doi:10.1016/S0341-8162(87)80013-9
V., J. R. & H. M. (2011). SPINlab | VU University Amsterdam. Retrieved February 5, 2016, from https://www.feweb.vu.nl/gis/research/?ResearchID=301&MenuStat=
van der Knijff, J. M., Jones, R. J. ., & Montanarella, L. (2000). Soil Erosion Risk Assessment in Europe. *European Soil Bureau*. Retrieved from http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_cd/pdf/ereurnew2.pdf
Vanderkimpen, P., & Flood, M. (2009). Flood modeling for risk evaluation – a MIKE FLOOD vs . SOBEK 1D2D benchmark study, 77–84.
Verbeiren, B., Van De Voorde, T., Canters, F., Binard, M., Cornet, Y., & Batelaan, O. (2013). Assessing urbanisation effects on rainfall-runoff using a remote sensing supported modelling strategy. *International Journal of Applied Earth Observation and Geoinformation*, *21*, 92–102. doi:10.1016/j.jag.2012.08.011
Verdoodt, A., & Van Ranst, E. (2006). The soil information system of Rwanda: a useful tool to identify guidelines towards sustainable land management. *Afrika Focus*, *19*(1), 69–92.
Wang, G., Fang, Q., Wu, B., Yang, H., & Xu, Z. (2015). Relationship between soil erodibility and modeled infiltration rate in different soils. *Journal of Hydrology*, *528*, 408–418. doi:10.1016/j.jhydrol.2015.06.044
Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses. *Agriculture Handbook No. 537*, (537), 285–291. doi:10.1029/TR039i002p00285
Wolski, P., Stone, D., Tadross, M., Wehner, M., & Hewitson, B. (2014). Attribution of floods in the Okavango basin, Southern Africa. *Journal of Hydrology*, *511*, 350–358. doi:10.1016/j.jhydrol.2014.01.055
Woo, M., Fang, G., & diCenzo, P. D. (1997). The role of vegetation in the retardation of rill erosion. *Catena*, *29*(2), 145–159. doi:10.1016/S0341-8162(96)00052-5
Xianzhao, L., & Shanzhong, Q. (2011). Wetlands environmental degradation in the Yellow River Delta, Shandong Province of China. *Procedia Environmental Sciences*, *11*, 701–705. doi:10.1016/j.proenv.2011.12.109
Yang, L., Zhang, L., Li, Y., & Wu, S. (2015). Water-related ecosystem services provided by urban green space: A case study in Yixing City (China). *Landscape and Urban Planning*, *136*, 40–51. doi:10.1016/j.landurbplan.2014.11.016
Yang, W. Y., Li, D., Sun, T., & Ni, G. H. (2015). Saturation-excess and infiltration-excess runoff on green roofs. *Ecological Engineering*, *74*, 327–336. doi:10.1016/j.ecoleng.2014.10.023
Yang, Y., Endreny, T. A., & Nowak, D. J. (2015). Simulating the effect of flow path roughness to examine how green infrastructure restores urban runoff timing and magnitude. *Urban Forestry & Urban Greening*, *14*(2), 361–367. doi:10.1016/j.ufug.2015.03.004
Yirdaw, E., & Luukkanen, O. (n.d.). Indigenous woody species diversity in Eucalyptus globulus Labill. ssp. globulus plantations in the Ethiopian highlands. *Biodiversity & Conservation*, *12*(3), 567–582. doi:10.1023/A:1022483700992
Yuan, Z., Chu, Y., & Shen, Y. (2015). Simulation of surface runoff and sediment yield under different land-use in a Taihang Mountains watershed, North China. *Soil and Tillage Research*, *153*, 7–19. doi:10.1016/j.still.2015.04.006
Zhang, B., Xie, G., Zhang, C., & Zhang, J. (2012). The economic benefits of rainwater-runoff reduction by urban green spaces: a case study in Beijing, China. *Journal of Environmental Management*, *100*, 65–71. doi:10.1016/j.jenvman.2012.01.015
Zhang, L., Podlasly, C., Feger, K.-H., Wang, Y., & Schwärzel, K. (2015). Different land management measures and climate change impacts on the runoff – A simple empirical method derived in a mesoscale catchment on the Loess Plateau. *Journal of Arid Environments*, *120*, 42–50. doi:10.1016/j.jaridenv.2015.04.005
Zhang, Y., & Shuster, W. (2014). Impacts of Spatial Distribution of Impervious Areas on Runoff Response of Hillslope Catchments: Simulation Study. *Journal of Hydrologic Engineering*, *19*(6), 1089–1100. doi:10.1061/(ASCE)HE.1943-5584.0000905
Zhou, F., Xu, Y., Chen, Y., Xu, C.-Y., Gao, Y., & Du, J. (2013). Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. *Journal of Hydrology*, *485*, 113–125. doi:10.1016/j.jhydrol.2012.12.040

APPENDICES

Appendix 1: PCRaster script for OpenLISEM input database (Adapted from V. Jetten, 2014)

```
binding
 scenario = scalar(1);
  ##################
  ### input maps ###
  ##################
  mask = mask.map;
  DEM = demf.map;
  # digital elevation model, area must be <= mask
  unitmapbase = landuse.map;
   soilunit = soil.map;
  # unitmapbase = soils.map;
  # if there is a hydrological unit maps that is better
  barriers = barriers20m.map;
  # in m, anything that obstructs flooding: northern bypass, roads, NOT houses
  # added to the DEM
  road = road.map;
  # road map, 0-1 for road fraction cover, contains all tarred roads
  drains = drain.map;
  #primary and secondary drains
  #levees = chanlevee20m.map;
  # height (m) small levees on both sides of the channel, subpixel
  culverts = culvertsNEW.map;
  # location with main culverts in primary drain
  out = mainoutlet20m.map;
  # main outflowpoint, needed for a correct flow network
  outpointuser = outpoint20m.map;
  house_cover0 = housecov.map;
  # housing density fraction current and future
  hard_surf0 = hardsurf2020.map;
  # other hard surfaces (0-1)
  # murrumroad = murrumNEW.map;
  # fraction murrum road in pixe, from sat img
  veg_cover0 = vegetatn.map;
  grasswid0 = grassbuf.map;
  # fraction veg cover from sat img

  ######################################
  ### hydrological data input table ###
  ######################################
  chantbl = chandim.tbl;
  #channel measurements
  soiltbl = soilun.tbl;
  # this table is linked to the soil hydro properties
 LUtbl = landuse.tbl;
 # land use surface properties

  ##########################################
  ### output LISEM database, default names ###
  ##########################################
 # basic topography related maps
  DEMm = dem.map;          # adjusted dem
  barriersc = barriers.map;
```

```
 Ldd = ldd.map;             # Local Drain Direction surface runoff
 grad = grad.map;           # slope, sine!
 id = id.map;               # pluviograph influence zones
 outlet = outlet.map;       # location outlets and checkpoints
 landuse = landunit.map;    # land units combined soil and vegetation
 outpoint=outpoint.map;     # points where hydrograph output is generated
# impermeable roads
 roadwidth = roadwidt.map;  # rad width (m)
# vegetation maps
 coverc= per.map;           # cover fraction (-)
 lai= lai.map;              # leaf area index (m2/m2) for interception storage
 cropheight= ch.map;        # plant height in m, for erosion, not used
 grasswid = grasswid0.map;       # width of grass strips for infiltration
# Green and AMpt infiltration maps
 ksat = ksat1.map;          # sat hydraulic conductivity (mm/h)
 pore = thetas1.map;        # porosity (-)
 thetai = thetai1.map;      # initial moisture content (-)
 psi = psi1.map;            # suction unsat zone (cm)
 soildep = soildep1.map;    # soil depth (mm), assumed constant
 ksat2 = ksat2.map;         # sat hydraulic conductivity (mm/h)
 pore2 = thetas2.map;       # porosity (-)
 thetai2 = thetai2.map;     # initial moisture content (-)
 psi2 = psi2.map;           # suction unsat zone (cm)
 soildep2 = soildep2.map;   # soil depth (mm), assumed constant
# surface maps
 rr = rr.map;               # surface roughness (cm)
 mann = n.map;              # mannings n ()
 stone = stonefrc.map;      # stone fraction on surface (-)
 crust = crustfrc.map;      # crusted soil (-), not present
 comp = compfrc.map;        # compacted soil (-), murrum roads
 hard = hardsurf.map;       # impermeable surfaces (0 or 1)
# erosion maps , not used
 cohsoil = coh.map;         # cohesion (kPa)
 cohplant = cohadd.map;     # added root cohesion (kPa)
 D50 = d50.map;             # median of texture (mu)
 aggrstab = aggrstab.map;   # aggregate stability number (-)
 chancoh = chancoh.map;     # channel cohesion (kPa)
 D90 = d90.map;             # median of texture of suspended (mu)
# channel maps
 lddchan = lddchan.map;     # channel 1D network
 chanwidt = chanwidt.map;  # channel width (m)
 changrad = changrad.map;   # channel gradient, sine
 chanman = chanman.map;     # channel manning (-)
 chanside = chanside.map;   # angle channel side walls, 0 = rectangular
# channel flooding maps: channels that have a depth > 0 can flood
# channels with a depth 0 will never flood but are infinitely deep!
 chandepth = chandepth.map; # channel depth (m)
 chanmaxq = chanmaxq.map;   # maximum discharge (m3/s) in culvert locations in channel
 chanlevees = chanlevee.map;
 chanksat = chanksat.map;
# houses
 housecov = housecover.map; # house cover fraction
 roofstore = roofstore.map; # roof interception (mm) \
 raindrumsize = scalar(0);  # raindrum size (m3)
 drumstore = drumstore.map; # locations of rainwater harvesting in drums (0/1)
 baresoil = baresoil.map;   # not used in lisem, for reference
```

```
########################
### LAND COVER MAPS ###
########################
# checck and adapt different land cover according to scenarios
unitmap = unitmapbase;
report grasswid =  0*mask;
# grass trips along channels or houses
housecover = scalar(house_cover0);
 veg_cover = veg_cover0;
 veg_cover = if(grasswid gt 0, 0.95*grasswid/celllength(), veg_cover);
 # assumed max cover in grassed water ways
hardsurf = hard_surf0;
hardsurf = if (grasswid gt 0, 0, hardsurf);
veg_cover = if(scenario eq 0, 1-baresoil,veg_cover);
# not used in lisem, for reference
report landuse = unitmap;
## report grasswid = grasswid0;
###########################
### 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
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));
## 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, 4, soilunit) * mask;
#report soildep = 1000*mask;
#lookupscalar(soiltbl, 7, soilunit) * mask;
thetai = 0.9*pore;#lookupscalar(soiltbl, 4, unitmap) * mask;
report thetai = thetai * (1-0.2*coverc);
#GRASS PROMOTES EVEAPORATION AND CAUSES A DRIER SOIL

##########################
### 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, 4, if(road eq 2, 3, 0)))*mask;
# width tarred roads in m

#####################
### CHANNEL MAPS ###
#####################
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 changrad = max(0.0025,sin(atan(slope(chanmask*DEMm))));
report changrad.map = max(0.01,sin(atan(slope(chanmask*DEMm))));
# channel slope
report chanman = lookupscalar(chantbl, 3, chanmask);
report chanside.map = chanmask*scalar(0);
```

```
  # rectangular channel
  report chandepth = lookupscalar(chantbl, 2, chanmask);
  # chanwidth is 1m for primary
  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
  report D50 = 40 * mask;
  report cohsoil = 4 * mask;
  report cohplant = coverc * 4 * mask;
  report aggrstab = 4 * mask;
  report chancoh = 100 * chanmask;
  report D90 = 40 * mask;
  report cropheight = lookupscalar(LUtbl, 4, unitmap) * mask;
```

Appendix 2: Interviews

2.1. Used fieldwork questionnaire

ITC-University of Twente

Researcher: Crispin KABEJA
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Research Title: Assessing structural and ecosystem based measures to reduce surface runoff; A case study in Mpazi and Byabagabo Jabana sub-catchments, Kigali-Rwanda

Purpose of the questionnaire
This questionnaire is designed for collecting interview data on how authority plan to resolve the problems of flooding in Nyabugogo commercial center and how local people perceive this flooding problems.
The provided information will be used as input for this scientific research only.

Questionnaire Number: ………
Date: ……………………
Time of Interview: …………
Location: …………………
Section 1: General Information
This section asks for the contact details about the interviewee, the current position or activities and other relevant information.

- Contact name: ……………………………..
- Organization: ……………………….
- Position: ……………………………
- E-mail: ……………………………….
- Tel: ………………………………………….
- Home address: ………………………..

Section 2: Flash flood (or surface runoff) perception and its effect.
This section asks questions about flash floods in Nyabugogo business centre (downstream area) and surface runoff generation in upstream areas.

1) Do you know what flash floods/runoff are? **Yes**…… **No**…………..
2) Do you have any problems of floods in this area? **Yes**…… **No**…………..
3) According to you what do you think is the cause of this flash flood/ Runoff?
   a. Heavy rainfall
   b. Unplanned settlement in upstream areas
   c. Building in wetlands (floodplain)
   d. Deforestation in upper watersheds
   e. Poor cleaning or maintenance of the drainage channel?
   f. Other……………………………………
4) Do you remember the date of last flash floods? **a.** February 2013 **b.** December 2013 **c.** Other………………………………………
5) According to you how deep was the water of the above flash floods?
   1. In Nyabugogo business center? **a.** 0.2 m **b.** 0.5 m **c.** 1 m **d.** 1.5 m **e.** Other…………………
   2. On the bridges (m)? **a.** 0.2 m **b.** 0.5 m **c.** 1 m **d.** 1.5 m **e.** Other……………………
   3. In drainage channel…………………………….
6) Did this flash flood affect the people living or working in Nyabugogo business center or in Mpazi upper watershed?
   Yes……**No**……..
   If yes, How?
   a. Properties **b.** Workplace **c.** Physical Safety **d.** Other…………
7) How often this flooding problem occur within a month/year?
   a. One time **b.** Two time **c.** Three time **d.** Other……………….……….....

Section 3: Existing and planned mitigation measures
This sections asks about the currents and planned measures (structural or ecosystem based) to reduce surface runoff and flash flood.

3.1 Specific questions for Government official and other authority in charge of planning and environment management.

1) What is the role of your institution before and after a flood event in Nyabugogo commercial center?
a. Prevention **b.** Awareness raising **c.** Evacuation **d.** Reconstruction **e.** Other……………
2) Is there any measures (structural and non-structural) taken by your institution to reduce flash floods in Nyabugogo commercial center? **Yes**……....**No**………..
If yes, which measures?
a. Structural measures **1**…………………...**2**………………..………**3**………………......
b. Non-structural measures **1**………………**2**……………………….**3**………………….
3) Is there any measures based on ecosystem regulation services for flash flood reduction in Nyabugogo commercial center? **Yes**………..**No**……..
- If yes, which one?
a. Afforestation **b.** Grassed waterways **c.** Land use spatial planning **d.** Other……………………
4) Do you consider to relocate people living in Nyabugogo flood prone hazards zone and in Mpazi upstream areas (high risk zones) to safer place? **Yes**…………**No**………..
5) Do you collaborate with people living or working in Nyabugogo business center before and after floods events? **Yes**…………**No**……….. If yes, How?
a. Cleaning drainage channel **b.** Reconstruction **c.** Awareness raising **d.** Other…………………
6) How do you planning to remove gullies in some upper stream areas of Mpazi sub catchment?
a. Use of broken stones **b.** Use of concrete rubble **c.** Earth plugs **d.** Soil filling and tree planting **e.** Other…………………
7) What is your future plans to reduce or prevent flash flood that may affect other catchments in Kigali city? (e.g Byabagabo Jabana sub-catchment)
a. Relocate people living in steep slope **b.** Afforestation **c.** Increasing drainage channels **d.** Create recreational park **e.** Land use spatial planning **f.** Other………………………………

3.2 Local people consideration for floods prevention and management in Mpazi sub catchment

1) What do you think shall be the solution to this flash floods (runoff) problems?
   - **a.** Increasing the drainage channel capacity?
   - **b.** Relocate the business centre and people living here to safer place?
   - **c.** Increases the forest cover (vegetation) in upper areas?
   - **d.** Rainwater harvesting at household level in upper areas?
   - **e.** Other …..…………………...
2) Do play any role before or after a flash flood event? **Yes**……**No**…………………..
If yes, which one? **a.** Cleaning drainage channels **b.** Reconstruction **c.** Other…………….
3) Would you agree to relocate and continue with your activities in a safer place? **Yes** …..**No**……..
If no, why? …………………

Any other advice that you consider useful to this research? …………………..

Would you like to receive the feedback from this research? **Yes**……..**No**……………

THANK YOU!

2.1. Position of Government official interviewed

No	Names	Position	Institution
1	G1	Flood and Drought Monitoring Officer	RNRA
2	G2	Watershed Management Officer	RNRA
3	G3	Climate Change Program Manager	REMA
4	G4	GIS Expert	RHA
5	G5	Green Village and M&E Officer	RHA
6	G6	Ag. Director One Stop center	Kigali City Council
7	G7	Director of Infrastructure	Kigali City Council
8	G8	Flood Risk Management Officer	MIDIMAR
9	G9	District Urban Planner	Nyarugenge District

Appendix 3: Vision and weight given used in MCA

	Equal	Socio-economic	Flood focused	Soil loss focused
Properties affected	0.2	1	4	5
Flood volume	0.2	2	1	2
Flood area	0.2	3	2	3
Soil loss	0.2	4	5	1
Total discharge	0.2	5	3	4