Evaluating Flash Flood Risk Reduction Strategies in Built-up Environment in Kampala

AIDAN MHONDA
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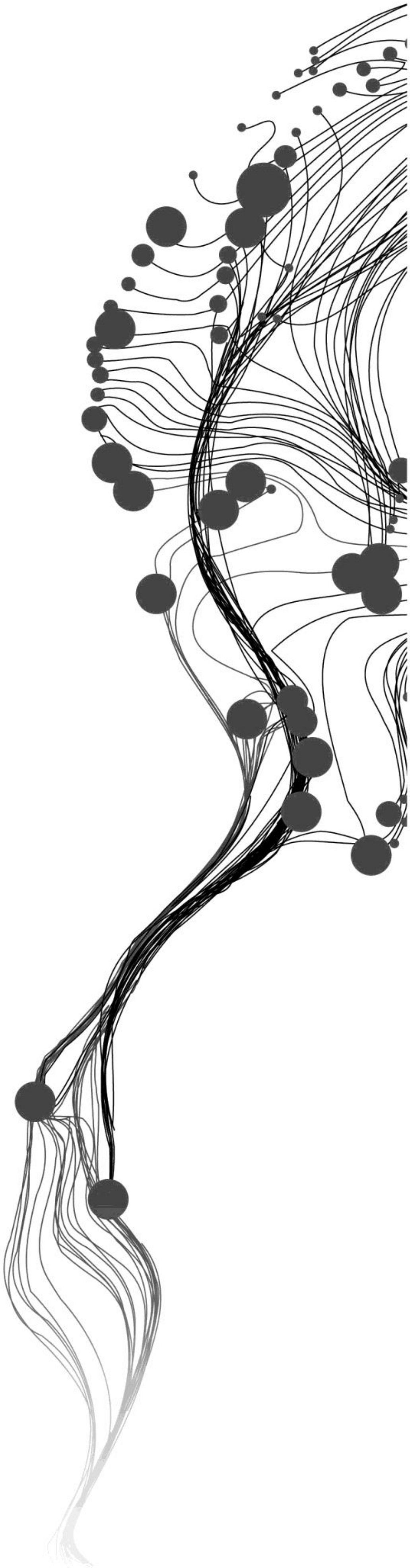

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Enschede, The Netherlands, March, 2013

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Specialization: Urban Planning and Management

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ABSTRACT

Flooding is the most frequent global natural disaster; and with the increasing trend of rapid urbanisation, urban areas are becoming more vulnerable to flooding due the effect of climate change. Flash flood is one of the prominent phenomenon caused by increasing impervious surface in the urban environment. Numerous strategies have been applied for prevention of flash floods which include structural as well as non structural strategies. These strategies in most cases have shifted the flood problem from one area to another. The lowland areas have been the recipients of the problems of increasing impervious surface upstream. Traditionally the evaluation of the strategies has been based on the economic and technical aspect. Less focus has been paid to the balancing of urban hydrology system and sustainable development. In developing countries drainage channels is the most common strategy employed for urban flooding. The failure of preventive measures has led to most authors and researchers to advocate a shift in thinking from flood prevention measures to flood risk management measures.

This study focuses at evaluating different strategies of flash flood risk reduction in an existing built up area that can be implemented upstream for sake of downstream inhabitants at Lubigi catchment. The study analysed the baseline information which include physical development of the catchment, permeability of the soil, rainfall pattern and the existing drainage channel. The study further identified and evaluated possible feasible strategies that can be implemented in flood risk management and finally evaluated the integration of the identified strategies into the existing legal policies.

Different data collection techniques were employed which included field measurements and observations, laboratory experiments, and key informant interviews. Physical computer rainfall runoff model was used for the evaluation of the strategies. It was found that the ongoing physical development, topographic nature and the existing drainage system are the major causes of the flash flooding at Lubidi catchment. The combination of rainwater harvest, infiltration trenches and detention/retention ponds strategies might substantially reduce the risk of flash flooding at Lubigi. These strategies can sufficiently be integrated in the existing legal policies however the enforcement of the existing rules and regulation has to be strengthened.

Key words: Lubigi catchment, flash flood, flood risk management, rainfall runoff model, peak discharge

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Aidan Z. Mhonda
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1. BACKROUND

1.1. Introduction

Flooding is the most frequent global natural disaster. The world disaster report of the year 2011 show that flooding events accounted for 47% of all reported natural disaster events in the world in year 2010 (Lindsay, 2011) and it is believed that the amount and scale of flood events will continue to increase in the next 50 years due to rapid urbanization trend and overwhelming environmental change which attribute to the climate change (Jha et al., 2011; Nirupama & Simonovic, 2007). A study on the 2007 flood event in Jakarta showed that the flood related disaster is not only the result of the natural event (e.g. heavy rainfall) but also the product of social, economic, political, historical events and the cultural issues (Vojinovic & Abbott, 2012). Human actions like building in the natural drainage and in flood prone areas, lack and /or blockage of drainage system (Brody, Zahran, Highfield, Grover, & Vedlitz, 2008; Noah, 2009), increasing of impermeable surfaces (Hosseinzadeh, 2005a) due to rapid urban development, poor solid waste management, and weak law enforcements influences the propagation of flash floods.

APFM, (2008) and Douglas et.al, (2008) indicate the problems associated with flash flood and (Shrestha, Chapagain, & Thapa, 2011) group them into socioeconomic and environmental problems. The socioeconomic problems include tangible direct losses, tangible indirect losses as well as the intangible human losses. Tangible direct losses are related to destruction of physical and utility infrastructure, buildings, loss of human life and the associated economic loss. Environmental problems are related to the land degradation and destruction of ecological system. Urban poor are more vulnerable in these problems due to their low capacity in dealing with such disaster (Jha et al., 2011).

There are number of strategies to reduce flood risk, ranging from local to regional, simple to complex. These strategies are normally grouped into two categories; structural and non structural strategies (APFM, 2007a, 2008, 2012; Carlos, 2007; Shrestha et al., 2011). For effective flood management both approaches has to complement each other (APFM, 2012; Jha et al., 2011). Most developed countries adopted the so called multi-level approach which includes protection, prevention and preparedness (PPP) for effective flood risk reduction. Under this approach structural and non structural strategies are normally employed. Structural engineering tailed strategies include construction of dikes, levee, detention ponds while non structural strategies include flood forecasting and warning systems, insurance as well as land use planning (Casale & Margottini, 2004; Smith & Petley, 2009; Wisner, Gaillard, & Kelman, 2012). Structural strategies are more protective measures while non structure measures are preventive measures.

The choice, application and effectiveness of each strategy depends on the intensity, causality of flooding, financial capability of the responsible authority, organisational or institutional capacity and the local situation of the area (Gersonius, Veerbeek, Subhan, Stone, & Zevenbergen, 2011). Traditionally the evaluation of the strategy has been based on the economic and technical aspect (Wisner et al., 2012) and less emphasis has been given to the hydrological aspects and social adaptability this leads to the temporary solution in one area and cause more problem to the other areas (Wisner et al., 2012).

African cities are not an exception. Kampala in Uganda is one of the urban areas that face frequent flash flooding events in each rain season due to unregulated urban development in the flood prone areas, topographic nature, inadequate drainage system, poor management of drainage system and solid waste (Douglas et al., 2008; Sliuzas, 2012). Informal development in the wetland areas propagates the flooding problem in Kampala. Wetlands have been invaded leaving no room of rainstorm water. Kampala has two major wetlands namely Lubigi and Nakivubo. These acts as the primary drainage channels which drains rainstorm water out of the city but they have been encroached leaving no room for rainstorm from upstream. On the other hand, uncoordinated developments and decrease of open vegetated areas due to rapidly urban expansions upstream leads to the decrease of water infiltration and increase in rainstorm (NEMA, 2009), drained downstream which can hardly be accommodated in an existing drainage system. All these human actions lead to the increasing flood hazards to the downstream inhabitants during every rain seasons. To deal with the frequent flood hazards, Ministry of Local Government and Kampala City Council in 2002 made a Kampala Drainage Master Plan whose aim was to ensure sustainable management of the city drainage system through multi-sector approach.

The drainage system alone can hardly succeed to reduce flood hazard (KCC, 2002a). However, KCC, 2002) report is silent about what are other possible measures apart from drainage system (as a structural measure) and land use zoning (as non structural measure). This study aims at evaluating the possible measures of flash flood reduction in the built up environment of Kampala cities especially in the Lubigi catchment.

1.2. Research Problem

Lubigi catchment is not only covered by housing developments but also industries, institutions and commercial development to almost in the banks of the Lubigi primary channel. The Lubigi wetland now changes from being a potential area for urban ecosystem conservation as it used to be (NEMA, 2009), rather to socioeconomic base by providing employment opportunities and cheap land for housing development that makes it difficult for the government to reallocate the people in the wetland. Despite of the effort of the government to rehabilitate and upgrade the Lubigi primary channels (KCC, 2002a), the experience of flash flood at Bwaise III Parish shows that, the lowland get flooded before storm water reaches the primary channel (Lubigi channel). This signifies that the flooding in the lowland is not due to overtop of the primary channel but is due to incapacity of the secondary and tertiary drainage channel upstream. This brings up another challenge in the flood risk management because the people who suffer from the problem (downstream) are not the core source of the problem. Thus, even with an upgrade of

Lubigi primary channel as proposed in the 2002 Kampala drainage master plan, the flash flood problem in the lowland cannot be solved.

This demonstrates the need for integrated flood risk management approach (APFM, 2007a, 2007b, 2008, 2012) that emphasises the coordination of what has to be done upstream for the sake of downstream inhabitants. Thorough study has to be done to come up with strategies which will incorporate physical as well as social aspects to bring multiple stakeholders in the flash flood risk management. Unfortunately currently there is no such study has been done. This study will bridge this gap through evaluation of sets of strategies of flash flood risk reduction strategies from physical and social point of view to come up with the possible strategies which can be executed collectively upstream to solve the flood problem downstream.

1.3. Research objectives

The main aim of this study is to evaluate different strategies of flash flood risk reduction in an existing built up area. To accomplish this, three objectives and a set of research questions have been formulated.

Objectives	Questions
To analyze the physical development and soil baseline information related to the runoff generation and propagation in the Lubigi catchment area.	What is the nature of physical development within Lubigi catchment?
	What is the temporal rainfall variation in the Lubigi catchment?
	What is soil characteristic of the Lubigi catchment?
	To what extent does physical development intensity affect rainstorm discharge?
	What is the nature and capacity of existing drainage system?
	What is the extent of deficit of the existing drainage system?
To identify and evaluate the possible flash flood risk reduction strategies in Lubigi catchment	What are possible strategies that can be implemented in different sub catchment?
	How can the suggested strategies be implemented in the LISEM model?
	Can the proposed strategies be institutionally and socially affordable and adoptable?
To suggest the possible adjustments on the infrastructure and housing design and spatial planning principles related to flash flood risk reduction.	What land use planning, housing and infrastructure design aspects should be taken into consideration in the new developed areas?
	How can the proposed strategies be incorporated in the designing and planning principles?

Table 1.1. Research Objectives and Questions

1.4. Justification of the study

Cities are growing so fast, demand of water supply is increasing and water table in urban areas is decreasing (Carlson, Lohse, McIntosh, & McLain, 2011). On the other hand the rainfall intensity is expected to increase as a result of climate change which results to the increase of flash floods in urban areas. Urban floods challenge can be turned into an opportunity of addressing urban water supply and the decreasing of water table problems in cities (APFM, 2012). This creates another challenge to urban planners, engineers, and hydrologist on how the cities and infrastructures should be organised, to facilitate the balance of urban hydrological system. This goes in line with the recommendation made by (Montz & Gruntfest, 2002) that suggests the use of multi objective solutions and multi disciplinary efforts to reduce flash flood risk.

1.5. Organisation of the thesis

The research report contains five chapters. Chapter one is the introduction which describes the background of the problem, problem statement, research objective and questions, justification of the study and organisation of the study.

Chapter two is the literature review. Different theories and concepts applied in similar studies and their relevance in this study have been discussed. The relevance of the theoretical framework applied in the study also has been discussed in this chapter.

Chapter three contains the methods and tools applied in the data collection, data processing and analysis.

Chapter four presents and discusses the results on the evaluations of the flash flood risk reduction strategies while conclusion and recommendations are in chapter five.

2. LITERATURE REVIEW

2.1. Types of floods

There are different types of floods, categorized according to the source (Dhar & Nandargi, 2003), spatial scale (Douglas et al., 2008) and temporal scale. In all cases there common agreement on the following major types

Flash floods: is a special type of flood which is caused by extreme heavy rainfall or snow melt within short period of time which leads to the excess runoff which cannot be manage by natural and manmade drainage systems (APFM, 2007a, 2012).

River floods: this is the type flood mainly due to river flow exceeding the stream channel capacity and over-spilling the natural banks or artificial (Smith & Ward, 1998).

Coastal floods: this is the flood in low-lying coastal area, including estuaries and deltas, involve the inundation of land by blackish or saline water, normally due to high- tide or large wind generated waves are driven into semi-enclosed bay during severe storm (Smith & Ward, 1998).

2.2. Characteristics of flash flood and associated risks

Flash flood is characterised by high flow velocity thus posses high kinetic energy, short occurrence period which make it more destructive and unpredictable (APFM, 2012; Vojinovic & Abbott, 2012; Wisner et al., 2012). Generally they are small in scale, locally (normally at catchment area 100 -200 km^2) (APFM, 2012) and frequently associated with other events like, riverine floods on large stream and mudslide.

Due to its suddenness, flash flood can hardly be predicted and thus make it difficult to warn people for evacuation (Borga, Anagnostou, Blöschl, & Creutin, 2011; Montz & Gruntfest, 2002). In the study on the flood management in The Netherlands it was found that for the inhabitant to evacuate safely in the expected flooding area they should be warned more than 9 hours before flood reach time (Gersonius et al., 2011), while the reaching time of flash floods is less than six hours (APFM, 2007a).

APFM (2012) distinguishes flash flooding from riverine flood that flash flood has short basin response to heavy rainfall that allows for very short lead time for detection forecast and warning and thus concluded that flash flood management require more specific strategies basing on its characteristics.

2.3. Flash flood risk reduction strategies

There two main categories of flood risk reduction strategies which are structural and non structural. Structural strategies are engineering works aim to moderate the stream channels, while non structural are non engineering based strategies mainly aims at loss sharing (e.g. disaster aid and insurance) and loss reduction methods (e.g. preparedness, forecast, warning and land use planning) (Smith & Ward, 1998) as referred to figure 2.1 below. It is argued that structural measures can directly reduce the magnitude of flash flooding but is not always efficient and cost effective due to the fact that structural measures in some instances can enhance the flooding in the other areas. Good drainage upstream can drain water very fast downstream and leads rapid water rise downstream and cause flash flood. In this regard Walesh (1989) presents two runoff quantity control approaches which are conveyance oriented approach (including culvert, drainage channels, sewer system etc) and storage oriented approach (including detention /retention facilities rainwater harvest etc. Conveyance oriented approach is commonly used due to its direct advantages on cost effective and applicability to both existing and newly developed areas while storage oriented approach has the disadvantage on incorporating in existing developed areas although it has advantage on the cost reduction in newly developed area and prevention of floods downstream. Table 2.1 below shows selected component of the storage oriented approach as described in Walesh (1989).

Component	Runoff control function
Permeable land surface and associated vegetal cover	Permit interception and infiltration and provide for runoff
Swale and open channel	Receives, concentrate and transmit surface runoff from the land surface to other subsurface components of the storm water system
Parking lots, rooftops, and other impervious surfaces	Provide, during minor and major runoff events, for the collection, temporary storage and conveyance of storm water to minimize disruptive pending. It can also provide rainwater harvest for domestic use
Detention facility	Provides, in a normally dry area or enclosure, for the temporary storage of storm water runoff for subsequent slow release to downstream channels or storm sewer, thus minimizing disruption and damage in downstream areas during both minor and major events.
Retention facility	Provide, in a reservoir that normally contains a substantial volume of water at a predetermined conservation pool level, for subsequent slow release to downstream channels or storm sewers thus minimizing disruption and damage in downstream area during both minor and major runoff.

Source: (Walesh, 1989)

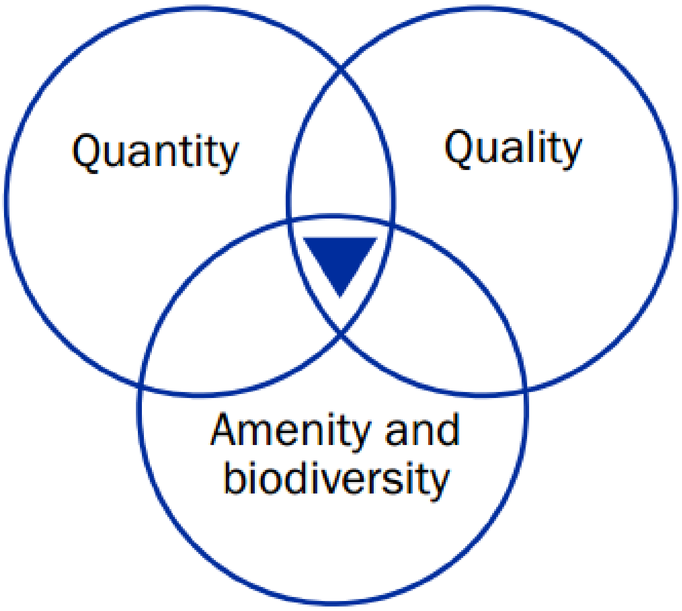
Table 2.1: Storage oriented approach component

2.4. Flash flood risk management concept

Managing risks of flash flood need to consider both short and long term uncertainties. This will improve not only ability to cope with extreme rainfall event, but also with the changes in frequency and severity of the perturbation over time (Bruijn, Green, Johnson, & McFadden, 2007). This can be achieved by changing the management perspective by looking flooding events as a dynamic process rather than static (Bruijn et al., 2007). The changes in socio economic characteristics (e.g. population and economic growth) affect the physical system which also affects the hydro-meteorological system consequently the socio economic system again get affected and this is what referred by Bruijn et al. (2007) as system dynamic perspective.

2.5. Sustainable drainage system (SuDS) approch

Surface water drainage systems developed in line with the ideas of sustainable development are referred to as sustainable urban drainage system (SuDS) (Woods-Ballard et al., 2007). The aim of this approach is to manage run-off from development in an integrated manner to reduce the quantity of water entering drains, sewers, watercourses and rivers especially at peak period; to improve the quality of run-off; and promote amenity and biodiversity benefits by using water in the environment (David, 2012). SuDS aims to achieve three main aspects presented which includes reduction of run-off volume, increasing the water of the run-off and promotes amenities and biodiversity as shown in Figure 2.1 below.



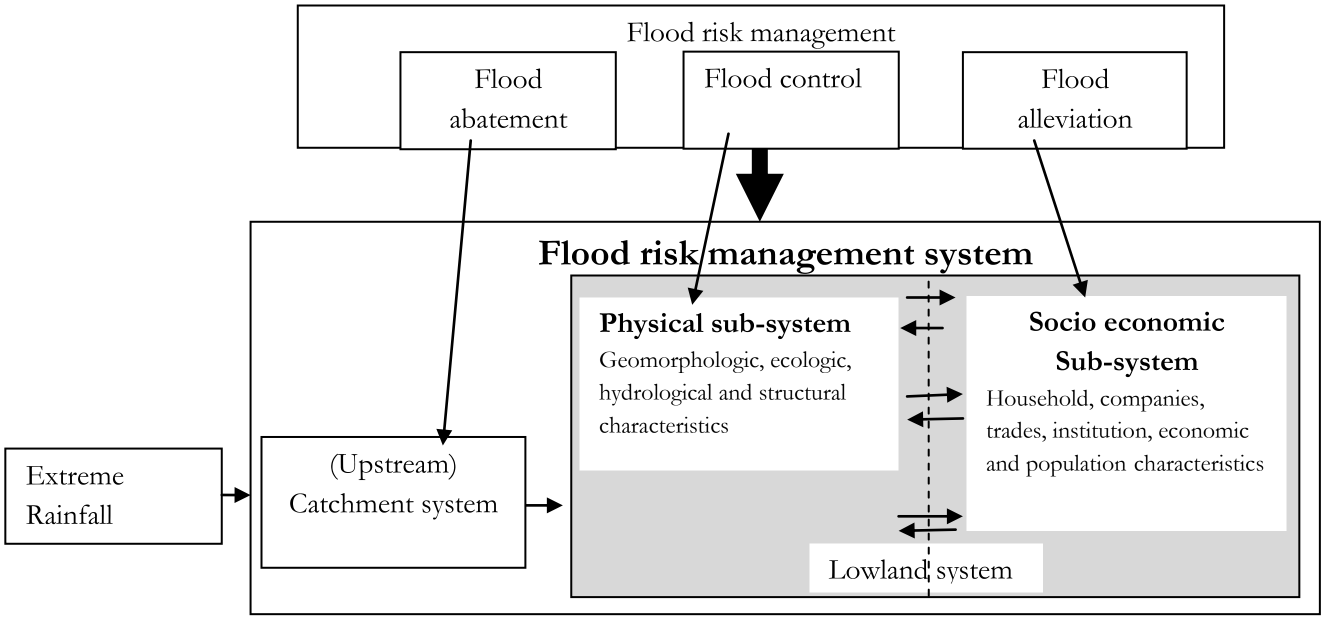
Source Woods-Ballard et al. (2007)

Figure 2.1. Three-way concept

2.6. Theoretical Framework

In searching the common understanding of the concepts used to explain the flood risk management (FRM), and identify the their relationship Bruijn et al. (2007) found that, the concepts used are the same like resilience, resistance, vulnerability, hazards, susceptibility and uncertainty but there is shifting in terms of thinking. The current thinking of flood risk is more dynamic rather than a static concept of flood control. It is argued that flood risk management has to be considered in the context of sustainable water management and sustainable development. Flood risk management activities should not be considered in isolation with the current global challenges like global warming, rapid urbanisation, decreasing of groundwater, climate change etc.

According to Bruijn et al. (2007), flood risk management consists of two systems which are upstream catchment) and the lowland system. Upstream system is where the extreme rainfalls occur and the peak discharge generated while the lowland system is the recipient of the run-off generated in the upstream system. Lowland system comprised of two other subsystems which are physical (i.e. geo-morphological, ecological, hydrological and structural characteristics) and socio economic subsystem (i.e. Household, companies, trades, institution, economic and population characteristics). The role of the flood risk management is to create balance between them, and to be able to manage the changes in the socio economic and the physical characteristics which consequently will affect the peak discharge generated. Figure 2.2 shows the relationship among the components of the flood risk management.



Source: Bruijn et al. (2007)

Figure 2.2: Conceptual frame work

3. RESEARCH METHODOLOGY

3.1. Research Approach

This research was organised in three main parts. The first part focused on the; the second part focused on the identification and evaluation of the flood reduction strategies while the third part focused on the policy implication of the proposed strategies. The first part aimed to collect, process and analyse the basic data related to the runoff generation and propagation. The basic data needed includes topographic data from Digital Elevation Model (DEM), land cover classes from satellite image, soil infiltration properties from undisturbed soil samples, rainfall pattern and the drainage system. The second part meant to identify and evaluate the possible flash flood risk reduction strategies using LISEM model while the third part was meant to suggest the possible adjustments on the existing legal policies so that the proposed strategies easily be integrated. The summary of the research approach is illustrated in Figure 3.1.

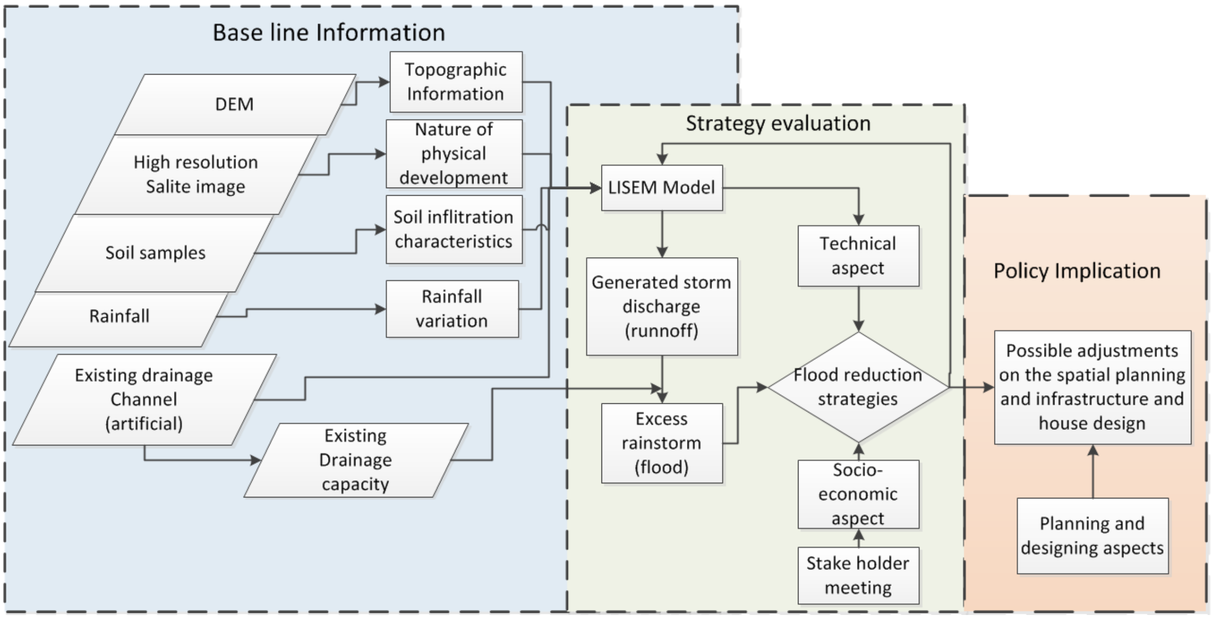


Figure 3.1: Flow chart

3.2. Study area

Lubigi catchment is located on the North Western part of Kampala City (see Figure 3.2) and it about 4 km away from Kampala Central Business District (CBD). It contains Lubigi wetland which is one of the largest wetlands in Kampala. Large portion of the catchment is found at Kawempe division while small portions are found at Nakawa and Central division.

The topography of the catchment is characterized by valleys and hills whose slope range from 0% to 90 % along Lubigi primary channel and the hill tops, respectively. The catchment receives the annual rainfall ranging from 1200mmm to 1700 mm (Kityo & Pomeroy, 2006).

The catchment is accessible in all directions by three major roads namely, Northern Bypass road, Bombo road and Gayaza road. Northern Bypass road which is passing along Lubigi Primary channel bisect the catchment in almost two equal parts.

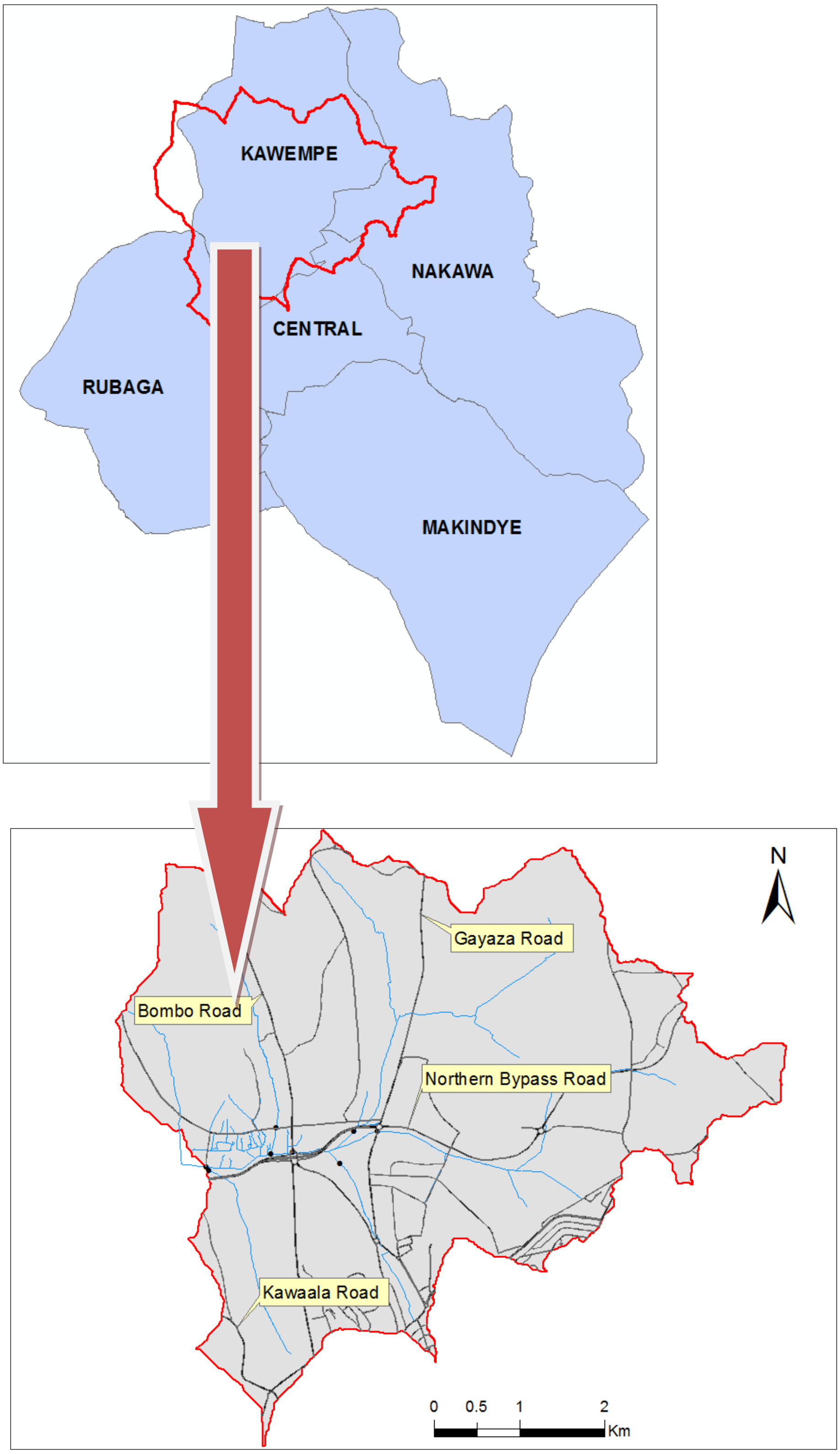


Figure 3.2: Case Study

3.3. Data collection

The field work was conducted in Kampala Uganda from 16th October 2012 to 6th November 2012. Primary and secondary data were collected as indicated in the Table 3.1**Error! Reference source not found.** below.

S/N	Type of data	source	Method
1	Topographic data	secondary	Derived from DEM
2	Land cover	secondary	Derived from 2010 Geo Eye satellite image 50 cm resolution later updated in the field
3	Rainfall	Secondary	Makerere University rain gauge
4	Drainage system	Secondary/Primary	KCCA, Field measurement and observation
5	Soil infiltration properties	Primary	Laboratory measurement and field observation

Source: Field work in Kampala October 2012

Table 3.1 Primary and secondary data collection

3.3.1. Image classification

The high resolution Geo Eye satellite image 50 cm was classified to derive the land cover map. Three major steps were carried out. The first step was to classify the image into vegetation and non vegetation cover classes using NDVI techniques (Pravara et al., 2007). The second step was to subtract the building footprint from non vegetation class. The third step was to extract road network from none vegetation class. The roads network was updated from the 1993 road network data set. Roads were further classified into tarmac, gravel and earth road because these surfaces have different infiltration properties. The rest of the area from non vegetation class was considered as bare land.

3.3.2. Collection of Soil Samples

To obtain the representative soil sample for soil permeability properties, 32 soil samples were collected in the field according to the land cover classes and the topography of the catchment. The samples were collected in the upland vegetated soil, lowland vegetated soil bare soil earth road and earth drainage channel. The number of soil sample of each class is shown in the Table 3.2 below.

Land cover	Number of sample
Up land vegetated	14
Lowland vegetated	5
Bare soil	4
Earth road	6
Earth drainage	3
Total	32

Source: Kampala fieldwork October 2012

Table 3.2 Soil sample distribution

The undisturbed soil samples were collected with the assistance from soil expert from Faculty of Agriculture of Makerere University. The top soil were removed to avoid organic materials and the soil ring of 5cm was driven up to 15 cm deep and dug out by using hand hoe. The protruded soil underneath were care cut by the knife before the ring was covered. The coordinates of point were recorded for mapping and further analysis (Figure 3.3). In addition to that field observation was also recorded to support further analysis. Finally the samples were taken to the Makerere University laboratory for infiltration experiment.

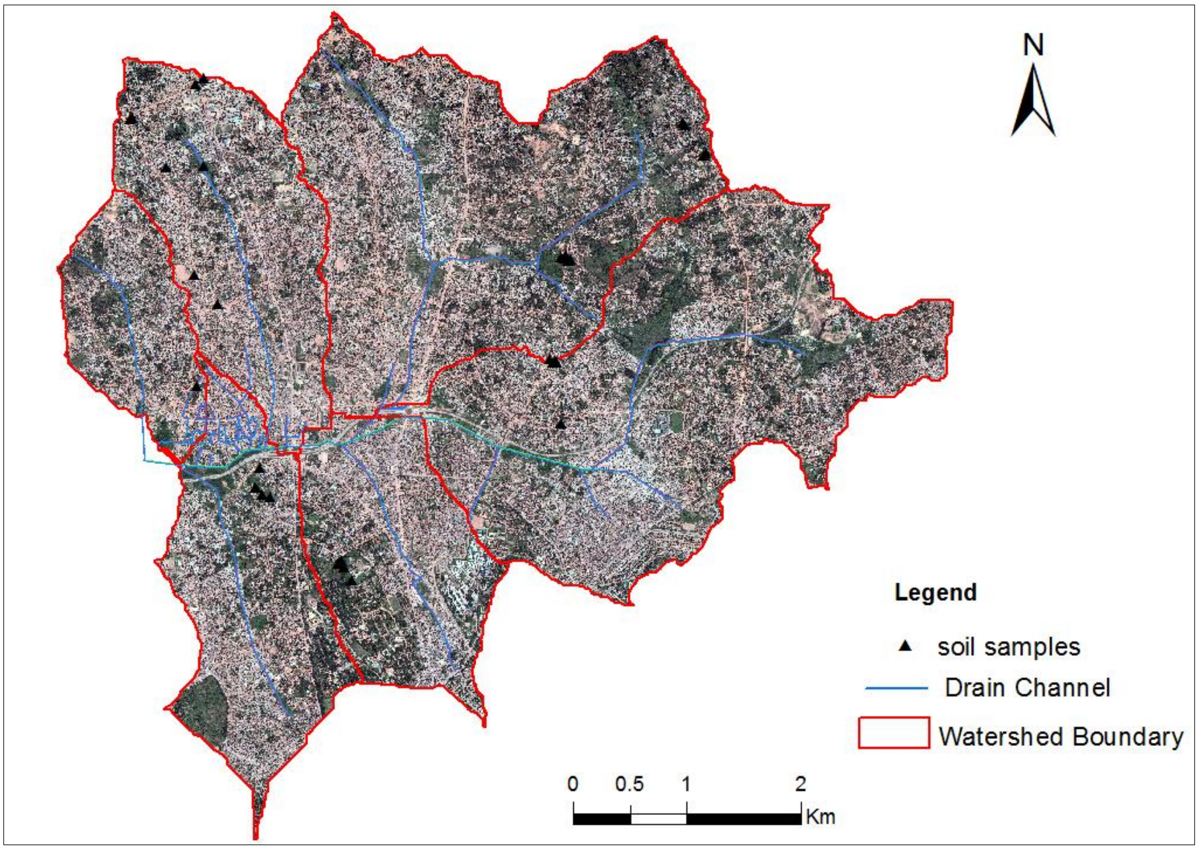


Figure 3.3: Distribution of soil samples and land cover classes

3.3.3. Measurement of Drainage channels

To enable the determination of the capacity of the drainage channels, measurement of top width, bottom width and depth were taken using the 8 metres measuring tapes. 25 and 91 locations were measured in the upper and lower catchment, respectively while 53 measurements were obtained from KCC (2002b) inventory. The coordinates of the point were also recorded for mapping as presented in Figure 3.4 below.

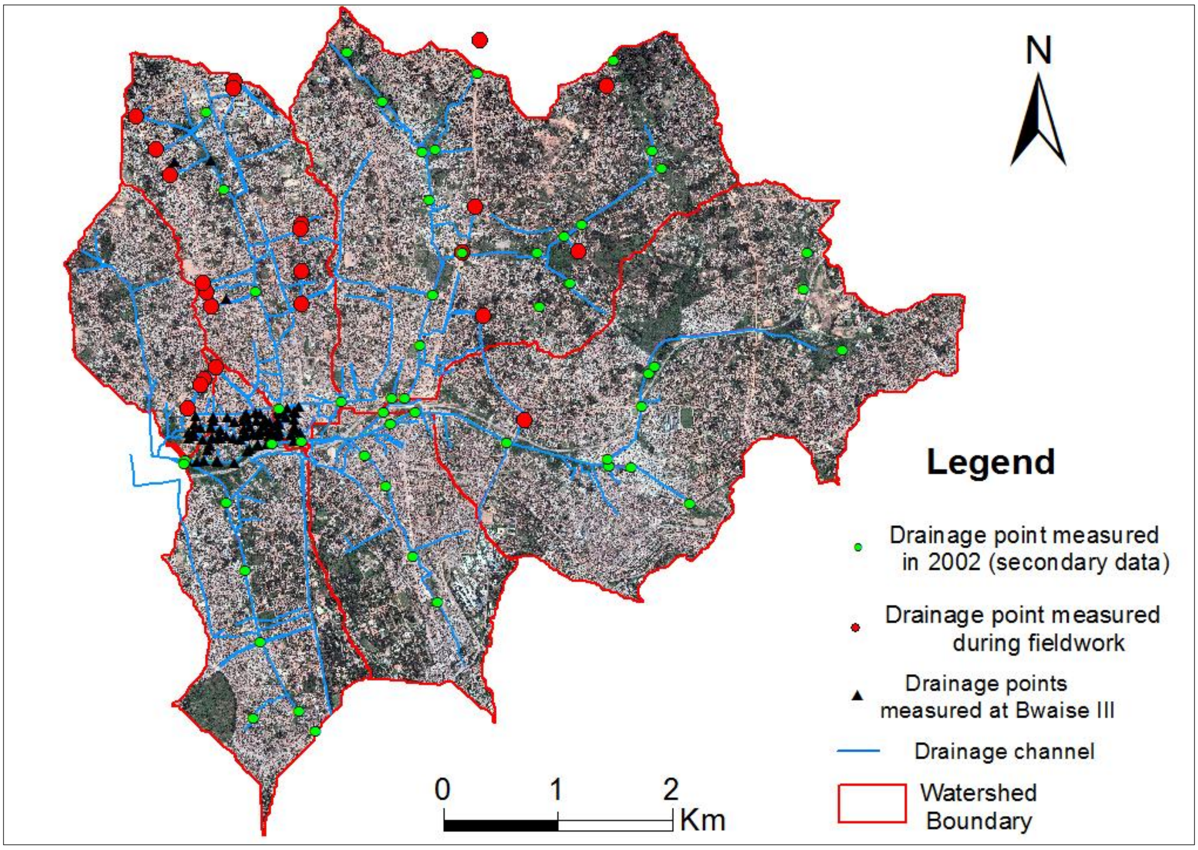


Figure 3.4: Points where measurement taken

3.3.4. Stake holder meeting

Stakeholder meeting was conducted during an Integrated Flood Management (IFM) workshop to collect opinions of stakeholders on the preliminary findings. The workshop was attended by ITC staff (Dr Richard Sliuzas and Prof Victor Jetten) and Hydroc Consult as organiser, physical planners from Kampala City Capital Authority (KCCA), and representatives from Prime Ministers Offices, Ministry of Lands and Housing, National Slum dwellers Federation, Environmental Management Agency, UN Habitat, National Slum Dwellers from Bwaise III, Makerere University and ITC students. During the workshop different flood risk reduction strategies were presented which included rooftop rainwater harvest, upgrading of the drainage system, drainage cleanness, construction of landfills, detention/retention ponds and infiltration trenches buffer zone. The stakeholders deliberated on the feasible strategies out of the presented and other appropriate ones in Lubigi catchment and the entire city, respectively. Affordability, adaptability and the source of funds were also discussed.

3.4. Data processing and analysis

3.4.1. Land cover classification for LISEM Model

LISEM model requires raster data layer, thus the land cover map was converted to raster of 1 m pixel size to ensure the information in the smallest land cover unit is not lost. Although LISEM has no limitation on pixel size (de Roo, Weseling, Jetten, & Ritsema, 1996), more than 20 m pixel size may give unrealistic result while less than 5 m pixel size requires more processing time (Jetten, 2002). For these reasons, 1m pixel land cover map had to be re-sampled to 10 m pixel size but the proportion of each land cover class in the pixel was maintained.

3.4.2. Determination of soil infiltration capacity

Initial soil moisture content, saturated conductivity (Ksat), and the porosity tests of 29 undisturbed samples were conducted in Kampala at Faculty of Agriculture soil laboratory. The tests of the remaining 3 undisturbed samples were taken to ITC laboratory because of the fieldwork time limitation. After collection from the field, the samples were weighed **(W1)** to determine the initial soil moisture content. The hydraulic conductivity (Ksat) experiment was then performed as described in (Klute & Dirksen, 1986). The experiment was arranged as shown in the Figure 3.5 below.

Source:Klute and Dirksen (1986)

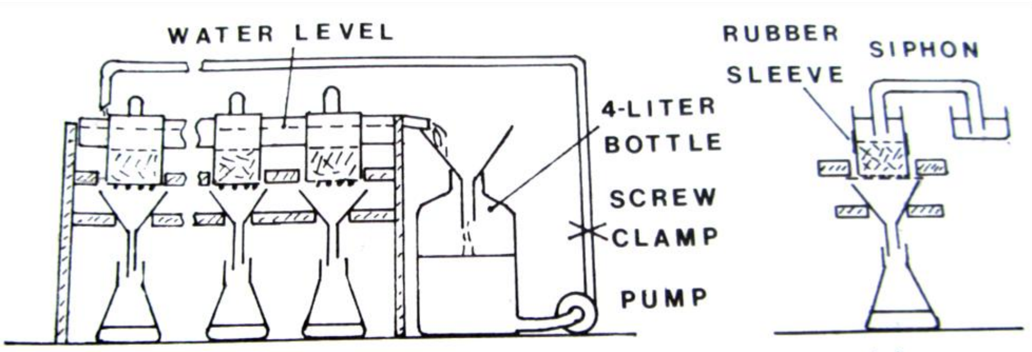


Figure 3.5. Theoretical Experiment arrangement

The water volume infiltrated through the soil sample was measured after every 2 minutes for 23 samples of the collected samples. In cases where the percolation was very high, the water volume was measured after 1 minute and this was done for only 2 samples. For 2 samples with medium percolation rate, the water volume was measured after 5 minutes. 2 samples had high percolation rates, thus the measurements were taken after 10 minutes. After the Ksat experiment, the samples were left to drain the water for 24 hours. Then the samples were dried in an oven at 105 ^{0}C for 24 hours and weighed **(W2)** to determine the weight of the dried soil. Finally, the empty soil rings, wrapping cloth and rubber were weighed **(W3**) which were used in the subtraction from the total weight to determine the real weight of the soil sample.

3.4.3. Saturated Hydraulic conductivity (Ksat)

The constant method was used to determine the Ksat value (Klute & Dirksen, 1986). The following formula was used to determine the saturated hydraulic conductivity.

$K_s = VL/[At(H_2-H_1)]$ [1]

Where V is the volume of water that flows through sample of cross-sectional area A in time t, and (H_2-H_1) is the Hydraulic head difference imposed across the sample of the length L.

3.4.4. Initial soil moisture content

Initial soil moisture content is the ratio of field moisture volume and the soil ring volume expressed as percentage. The field moisture volume is the difference between weight of the dry soil sample **(W3)** and field sample **(W1)**. It has to be note that the relationship between the weight and the volume is 1g = 1cm^3.

Field Moisture Volume **(FMV) = W1 – W3** [2]

Initial soil Moisture content = ***(FMV/RV)*100*** [3]

Where, ***W1*** is the weight of the field soil, ***W3*** is the weight of a dried soil, ***RV*** is the ring Volume.

3.4.5. Porosity

The porosity is the ratio of pore volume (bulk density) and the particle density expressed as percentage. Alternately porosity can also be a ratio of pore volume (bulk density) and ring volume expressed as percentage. In this study the porosity was determined as a ratio of bulk volume and the particle density which is 2.7. The bulk density was determined using formula [4] while the porosity was determined using formula [5].

Bulk Density (***PV) = W2–W3*** [4]

Porosity = (PV/2.7)*100 [5]

Where ***PV*** is a bulk density, ***W3*** is weight of the dried soil and ***W3*** ring volume.

3.4.6. Drainage capacity determination

To estimate the deficient of the drainage channels in the catchment, the flow capacity of all the channels was calculated using the formulae below

$$Q = AV \quad [6]$$

Where ***Q*** is the discharge in (m^3/s), ***A*** is the channel cross section area (m^2) and ***V*** is the flow velocity (m/s). The flow velocity was calculated using manning equation which is the function of surface roughness, hydraulic radius and the longitudinal channel slope.

$$V = \frac{1}{n} R^{2/3} S^{1/2}. \quad [7]$$

Where **V** is flow velocity, ***n*** is the manning roughness coefficient which depend on the surface of the drainage(Alfred, Steven, & Timothy, 2009; Arcement, Schneider, & USGS, 1984), ***R*** is Hydraulic radius which is ratio of cross section area of the channel and the length of the wetted perimeter, ***S*** is longitudinal channel slope which was derived from the digital elevation model (DEM).

3.5. Watershed deliniation

The watersheds were delineated using ArcSWAT software based on the DEM. A total of 5 major sub-catchments were found in the catchment as shown in Figure 3.6. The outlet of each sub-catchment was also determined for further analysis.

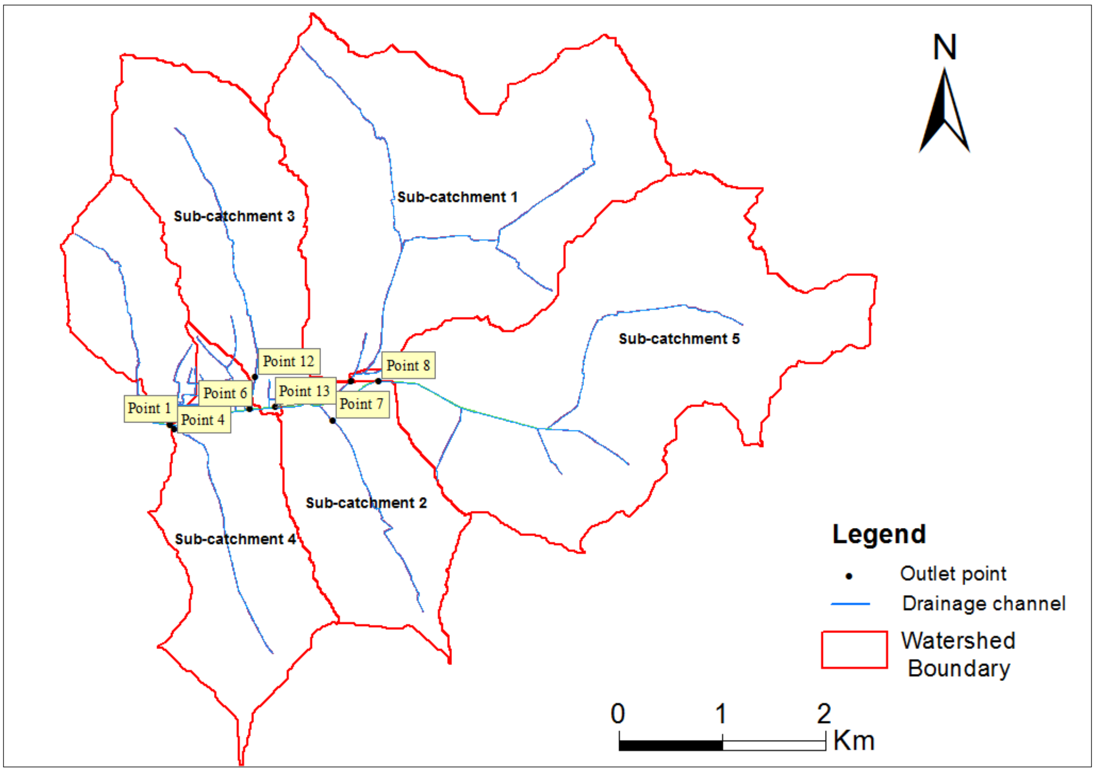


Figure 3.6: Lubigi Sub Catchments and outlet points

3.6. Rainfall pattern

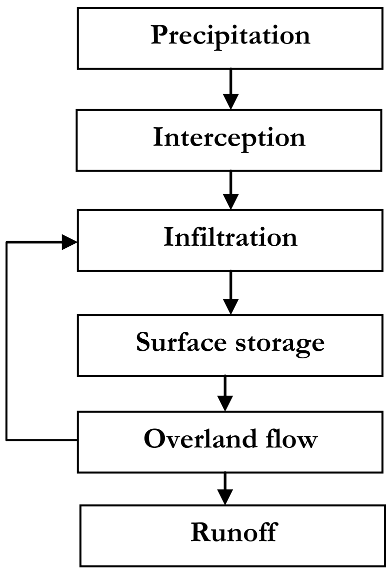
For rainfall runoff modelling using, high temporal resolution were required (Jetten, 2002). Daily rainfall data of 10 minutes time series was collected from May 14th 2012 to October 31st 2012 at Makerere University rain gauge station. However to get the understanding of the annual rainfall pattern the average rainfall data calculated from 1943 to 1999 was used (KCC, 2002c).

3.7. Modelling flash flood risk reduction strategies

All the scenarios were evaluated using LISEM model. The simulated hydrographs were displayed in Ms excel and the summary of the peak discharges of all the sub-catchments were presented in tables.

3.7.1. LISEM model

The Limburg Soil Erosion Model (LISEM) is a physical rainfall runoff and soil erosion model. Primarily it was made to simulate the hydrological processes and sediment transport during and soon after single rainfall event (Jetten, 2002). The hydrological processes that have been integrated in the model include precipitation, infiltration, interception, surface storage in a micro depression and overland flow (Figure 3.7). During rainfall event water will be stored in the vegetation leaves as interception, some will be infiltrated, some will be stored in the micro depression and the rest will flow as runoff.



Source: Adopted from Jetten lecture notice 2012

Figure 3.7 Schematic representation of runoff process without erosion

The LISEM environment allows the user to upload the run file, model input parameters and directories for maps, rainfall table and output results (Figure 3.9). It also allows the user to specify the simulation time, the beginning, the end time and the time step to which the output will be recorded. In this study the simulation time was 500 minute reporting at every 60 seconds time step. The results directory allows the saving of the summary of the simulation results as text file and the discharges results as csv file of all the outlet points in a single file or as separate files. Model option panel allows the user to switch on/off runoff, erosion, channel infiltration, channel flow, allowing flooding in the channels, urban interception and to include rainwater harvest. Infiltration model panel allow choosing the infiltration model (e.g. Green & Ampt) depending on the available data while the calibration model option allows the user to calibrate the model by adjusting the Ksat, manning's n or initial soil moisture content and porosity. Conservation option enables the user to use the conservation measure for runoff or sediment transportation by introducing buffer or grass strips.

Conservation option was applied in this study to model the detention/retention ponds and infiltration trenches. Detention/retention ponds were modelled as buffer while the infiltration trenches were modelled as grass trips. Rainwater harvest was modelled using the global model option by allowing the urban area interception storage by including rainwater storage by drums (Figure 3.9).

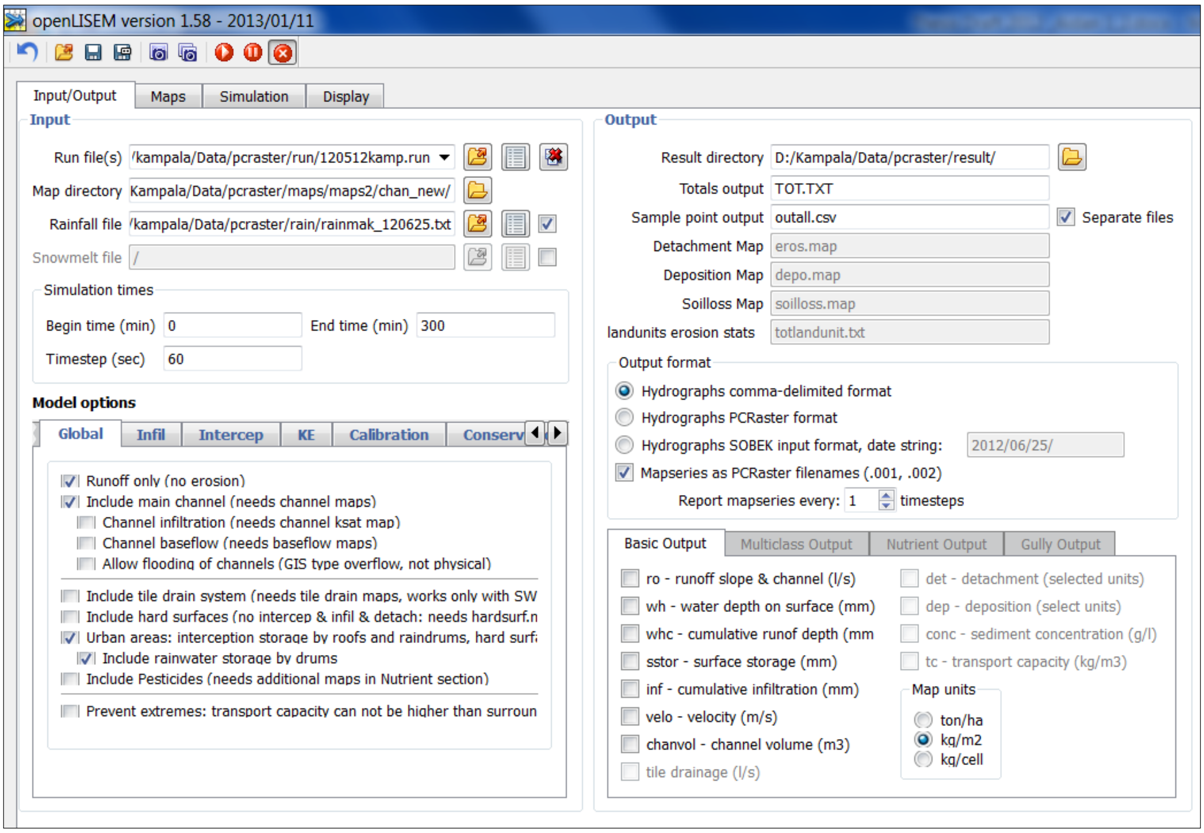


Figure 3.9 LISEM Interface

During simulation the user is able to see the summary of the simulation in progress including the hydrograph of the selected outlet point. The latest version (display) also allows visualizing the map and the hydrograph in the same interface. Also in the current development, the display has been integrated with digital elevation model to enhance hill shed visualisation (Figure 3.8).

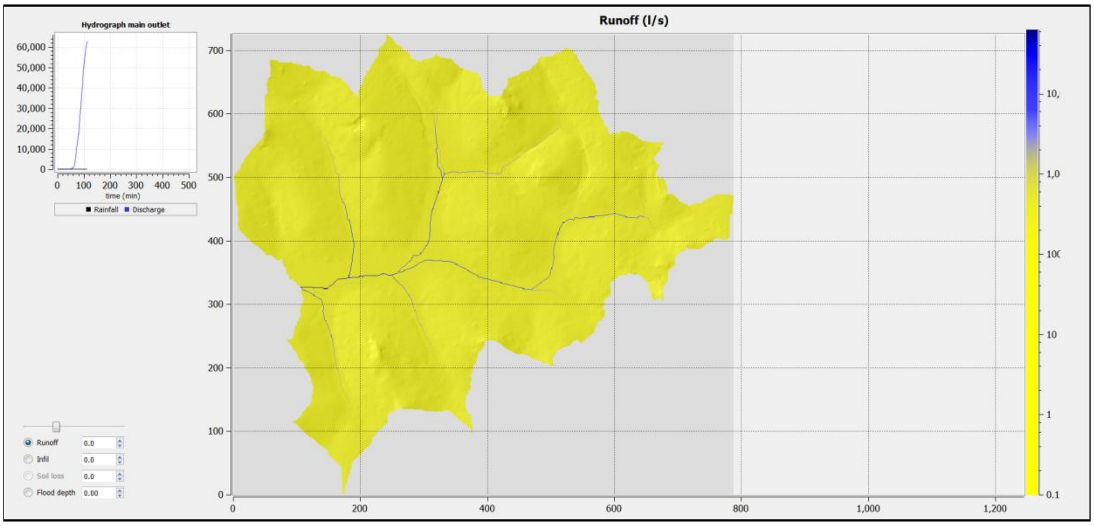


Figure 3.8 LISEM display interface

3.7.2. In put Maps for LISEM model

All the maps for LISEM model presented in Table 3.3 were generated in PC Raster environment using the script in Appendix 1. The maps produced include catchment, vegetation, soil surface, infiltration and channel maps. These maps were generated from three basic maps and one table of soil properties. The basic maps include, digital elevation model, land cover, impermeable surface maps (i.e. buildings and roads). The maps for scenario modelling were further generated using the script in appendix 2. On this scrip the user is able to change either the size of the facility (e.g. water tank, detention/retention pond or infiltration trench) or to change the proportion of the number of building that can have the water tanks or infiltration trenches.

Parameter	**Map name in LISEM**
Catchment maps	
Local drain direction	LDD.map
Catchment Boundary	AREA.map
Slope gradient	GRAD.map
Outlets	OUTLET.map
Outpoints	OPUTPOINTS.map
Rain data	ASCII.table
Vegetation maps	
Leaf area index	LAI.map
Vegetation cover	PER.map
Vegetation height	CH.map
Soil surface	
Manning's n	N.map
Random roughness	RR.map
Width of road	ROADWIDT.map
Hard surface	HARDSURF.map
Infiltration (Green & Amp: 1 layer)	
Saturated hydraulic conductivity	KSAT.map
Saturated volumetric soil moisture content	THETAS1.map
Initial volumetric soil moisture content	THETA1.map
Soil water tension at wetting front	PSI1.map
Soil depth	SOILDEP.map
Channels	
Local drainage direction of channel network	LDDCHAN.map
Channel gradient	CHANGRAD.map
Manning's n for channel	CHANMAN.map
Width of channel	CHANWIDT.map
Channel cross section shape	CHANSIDE.map
Scenario maps	
a) Rooftop rainwater harvest	
Rain-drum location	DRUMLOCA.map
Rain-drum volume	DRUMSTORE.map
Buildings	HOUSE.map
b) Infiltration	
Infiltration trench location	GRASSTRIP.map
Infiltration trench width	GRASSWID.map
Ksat of infiltration trenches	KSATGRAS.map

c) Detention/retention pond	
Buffer ID (detention Pond ID)	BUFFERID.map
Buffer Volume (detention Pond Volume)	BUFFERVOL.map

Source: Adapted from Jetten (2002)

Table 3.3 Input maps for LISEM model

3.7.3. Rooftop Rainwater harvest scenario

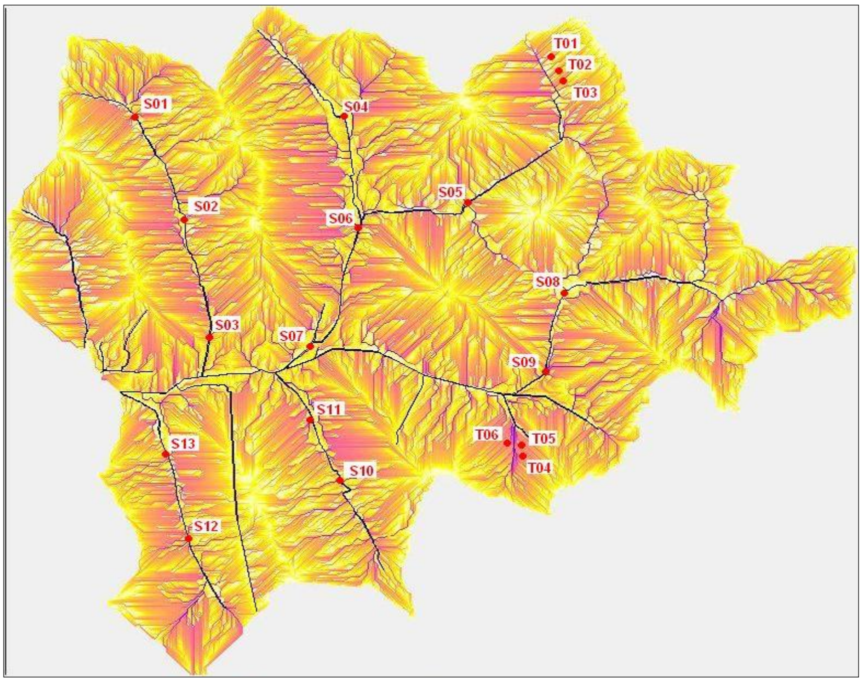
To evaluate the effectiveness of rainfall harvesting from the rooftops of the buildings in the catchment, 500 litres water tank were used. This was because 500 litres water tanks were the smallest tanks that were found during fieldwork which has an implication that a large proportion of the people can afford the tanks. The building sizes ranged from 1 m^2 to more than 1000 m^2 but only the 8 m^2 and above could be used in modelling this scenario because it was estimated that, the smallest size of building that could harvest at least 500 litres of rain water for the given rainfall event (i.e. 66.2mm) would be at least 8 m^2. The volume of the water tanks was fixed in all the buildings irrespective of their sizes (Matthew & William, 2008). This helped in determining the total number of tanks that might be required for the whole catchment for the given number of buildings.

The building footprints polygons had to be converted into pixel of 10x10m because PC raster software which was used in this study requires input raster maps. The conversion led to more built-up pixels than the total number of building polygons counted in vector building footprint. Therefore, the number of water tanks had to be determined by the number of building polygons in vector and not by the number of built-up pixels in raster map. The number of water tanks was randomly allocated per given number of built-up pixel using PC raster.

For the simulation of rooftop rainwater harvest scenario, LISEM model required three maps; building location map, water tank location map which were randomly located in the building pixels and water tank volume map. During simulation, the rainwater fills the tanks first before it overflow and continue as overland flow and eventually as runoff to the outlet of the catchment.

3.7.4. Detention/retention ponds

Construction of Detention/retention pond scenario was implemented under conservation model option. Two input maps were required by LISEM model. The first map is a buffer volume map which specifies the volume and the location of each buffer while second map is a buffer ID map which shows the unique numbers of each pond. The ponds were allocated in the secondary channels to ensure the ponds are in the water ways. The location of the detention/retention ponds was determined according to the water flow directions by Hydroc Consult. 19 locations were proposed (shown in Figure 3.10) out of which 15 were adopted in this study with minor adjustments depending on the available land. The 4 ponds (T01, T02, T03 and T04) were not considered because they are placed at peripheral of the catchment which might have little effect on runoff reduction. It has to be noted that the size of the ponds depends of the available land (people would be reallocated to pave the way for construction), topography of the catchment to reduce the excavation cost and the normal seasonal water table (Walesh, 1989). EPA (2006b) suggested that, the base of pond to be at least 1.2m above the normal seasonal ground water table. In addition, Kampala has a complex land tenure system which led to large part of land to be informally developed including the wetlands (UN-Habitat, 2007). In this regards the small size and distributed ponds were assumed to be convenient. Thus in the same reasons 15 detention/retention ponds each of 1000 m^3 were implemented in the whole catchment. Under this scenario water overflows when the ponds were filled.



Source: Hydroc Consult 2012

Figure 3.10. Proposed location for location detention/retention ponds

3.7.5. Infiltration trenches

Infiltration scenario assumed that rainwater from the rooftop would be infiltrated in the grass trips (trenches) of 1m long and 0.5m wide next to the buildings. Considering the fact that infiltrated water might have no domestic use, residential building will hardly implement it. In this regards, commercial and institutional buildings was assumed to implement this scenario. However due to lack of building use data, the size of the building was used as an indicator of the building use. However, it was noted in KCCA (2012) that by 2011 the average residential building was 55 m^2 while the maximum for low density houses was 200 m^2. In this regard buildings above 200 m^2 were assumed to be commercial and/or instructional buildings. In addition to that, lower land soil has low draining capacity and high water table, thus buildings in the lowland of less than 6% slope were considered unsuitable for infiltration trenches. Therefore only 10% of the buildings were considered for infiltration scenario. It's important also to note that, in this scenario the limiting factor was only percolation rate and the number of the trenches that can be implemented in the catchment. Thus in the simulation the size of the building was not considered.

This scenario was implemented under the conservation model option in LISEM model. Three basic maps were required to run the scenario. The first map was a house map derived from house cover map which shows the location of the buildings. The second map was grass strip location map which shows the location of the trench, and the third map was grass strip map which is used to assign the size of the trench. PCRaster software randomly allocated the trenches according to the proportion of the buildings in the catchment and the trenches were assumed to be filled with porous material of 200 mm/h saturated hydraulic conductivity (e.g. gravels) (EPA, 2006a).

3.7.6. Model simulation

Simulation of LISEM model was performed using the discharge adopted from KCC, (2010). The simulation result of the current situation was compared with simulation results of 2010 for a two year return period rainfall event. Three outlets were used for comparison which included Kawaala, Bombo and Gayaza road crossing (Figure 3.11). Based on field observation and expert knowledge, three model parameters (Ksat, surface manning n and channel manning n) were adjusted. Ksat was multiplied by factor 2.50 while surface manning and channel manning were multiplied by factor 2.

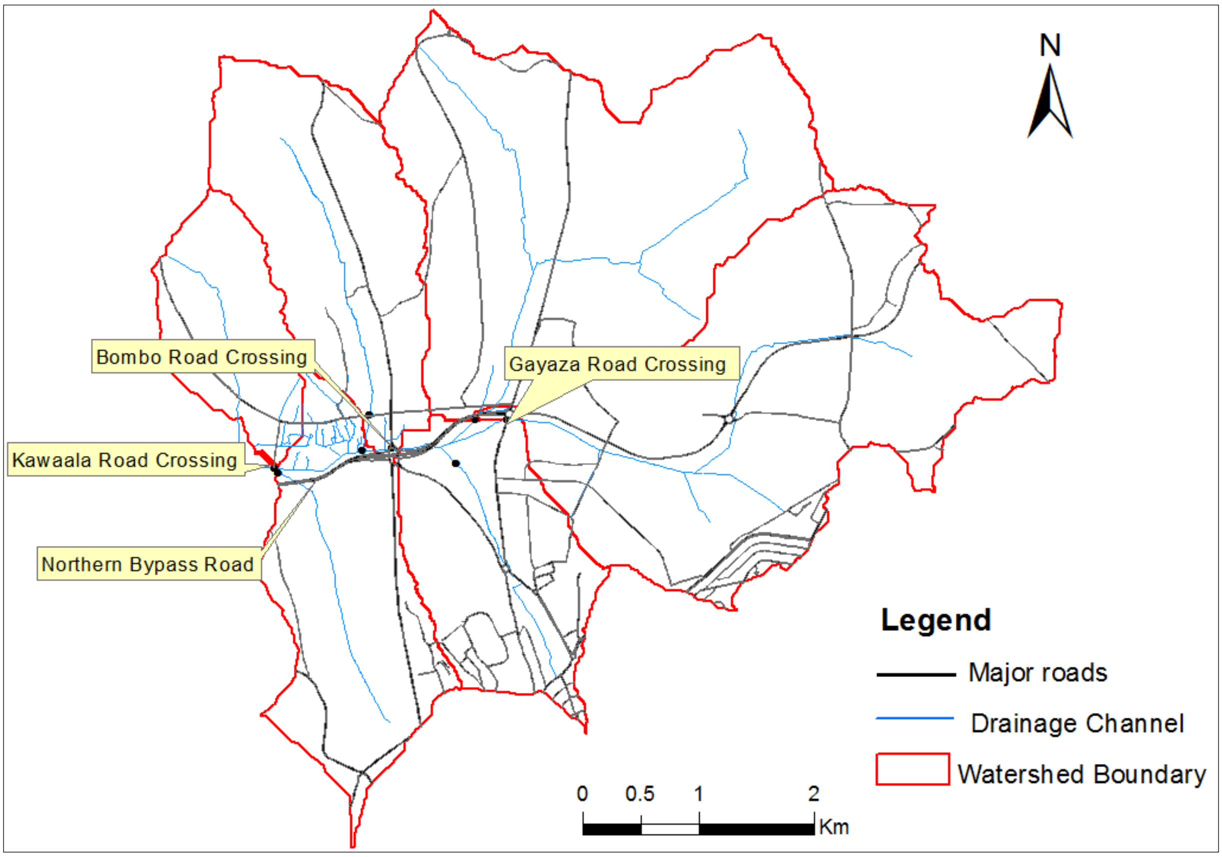


Figure 3.11 Points for model validation

To understand how the scenario simulation results closely related to the reality, validation was done for rooftop rainwater harvest and detention/retention ponds scenarios. For infiltration trench scenario the validation was not done due to data constraints. The validations of the rainwater harvest and detention ponds were performed by comparing the total volume from the simulation and the expected volume according to the number of water tanks and ponds respectively.

3.8. Land use and infrastructure planning aspects

To understand the implication of the proposed strategies on the spatial and infrastructure planning, further analysis was performed on the following aspects:

- Size of the facilities particularly detention/retention ponds and infiltration trenches,
- The possible location of the facilities,

The determination of maximum allowable depth of the infiltration trench was governed by the formulae provided MDE (2000)

$$dmax = fT/n \quad [8]$$

Where ***dmax*** is the maximum allowable depth of the trench, ***f*** is the final infiltration rate in mm per hour ***T*** is the maximum allowable storage time in hours, and ***n*** is the porosity of the pervious material expressed as a ratio of pore volume and the total volume of soil. The porosity of gravel used was 50% (GMS, 2000). The infiltration of the gravel applied was 200mm/h while the total volume of the pond was 1000 m^3. The dimensions of the detention/retention ponds were not determined at this level because it varies with the nature of the available land.

The criteria of allocation of detention/retention ponds were adopted from Walesh (1989) which includes the slope of the site, land availability and ground water level . The wetland area along primary channel was used as an indicator for high water table due to lack of water table data. The slope of up to 6% along the secondary channel was used as suitable for the pond although, EPA (2006b) suggest the slope of up to 15%. The location of detention ponds was analysed in ArcGIS by overlaying the slope map and the building footprint map. Ponds were located at undeveloped land.

4. RESULTS AND DISCUSSION

This chapter present the results and discussion of the analysis of baseline information particularly on the physical development, soil characteristics and drainage system at Lubigi catchment. Discussion of the evaluation of proposed strategies and policy implication is also presented.

4.1. Baseline information on the cause and propagation of rainfall runoff at Lubigi catchment

4.1.1. Physical development at Lubidi catchment

The results of the land cover classification indicates that 22% represent buildings, 4% are roads while 74% of the total area is covered by vegetation and bare soil (Figure 4.1). This means that 26% of the total land cover in the whole catchment consists of an impermeable surface. Figure 4.1 shows that the building development concentration is mainly along the road network and within Lubigi wetland. This could be due accessibility to transport and other social services along the roads and availability of cheap land in the lowland (Lubigi wetland). This was also confirmed through fieldwork observation and in the discussion with slum dwellers of Bwaise III during the workshop. The workshop revealed that the physical development in the wetland was mainly because of lack of an alternative affordable housing area. Field observation also revealed that the observed nature of development could be the closeness to employment opportunity. Bwaise III and Makerere III (some residences refers this area as Kalerwe) parish are 2 km from Makerere University (the largest and oldest university in Uganda) and 4km from Kampala city centre (Braun & Assheuer, 2011; Douglas et al., 2008; Hosseinzadeh, 2005b; Noah, 2009; Parker & Harding, 1978; Wilma, 2007).

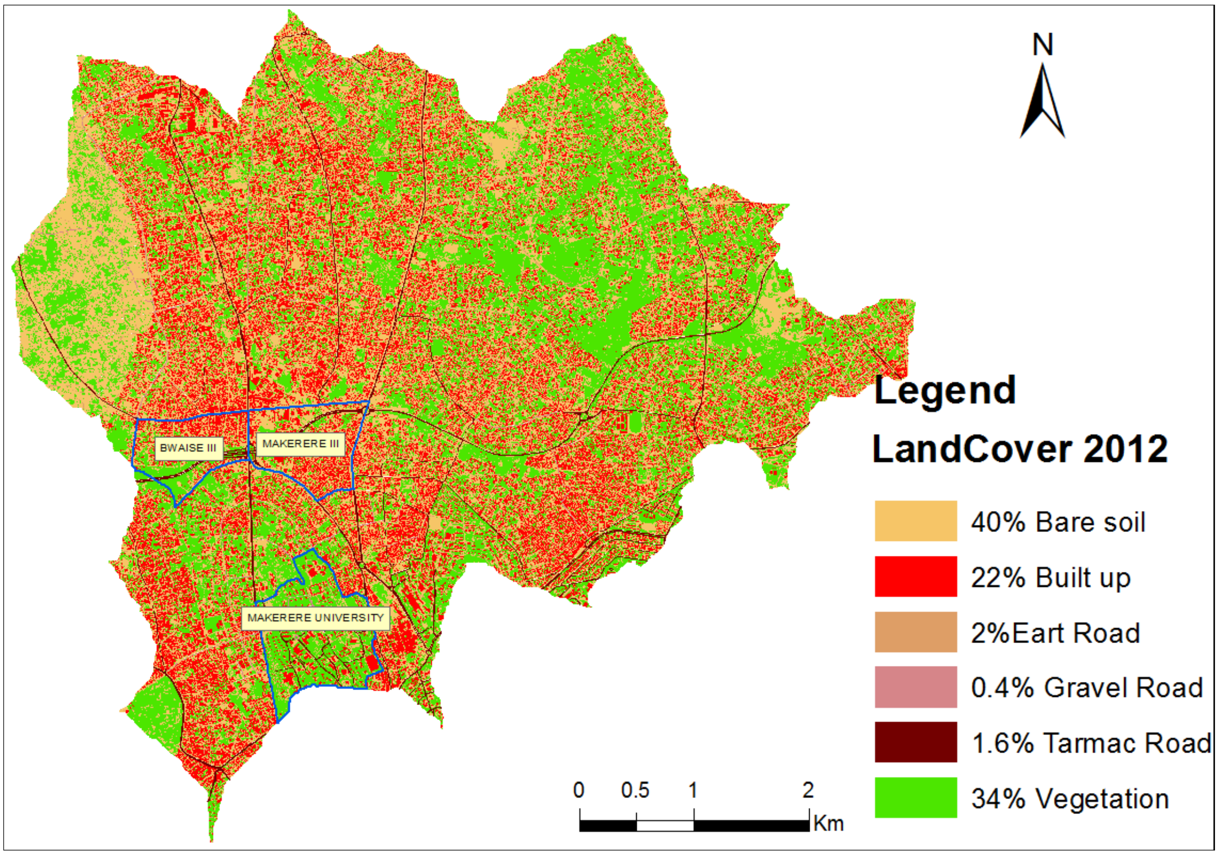


Figure 4.1: Physical development at Lubigi catchment

4.1.2. Rainfall pattern in the Lubigi catchment

To enhance the understanding of rainfall pattern, daily rainfall data from Makerere University rain gauge station was used. Figure 4.2 shows the plot of the daily rainfall events from 14th May 2012 to 31st October 2012. The figure indicates that the maximum precipitation was 66.2 mm in June 25th. However, there were frequent rainfall events between September and October.

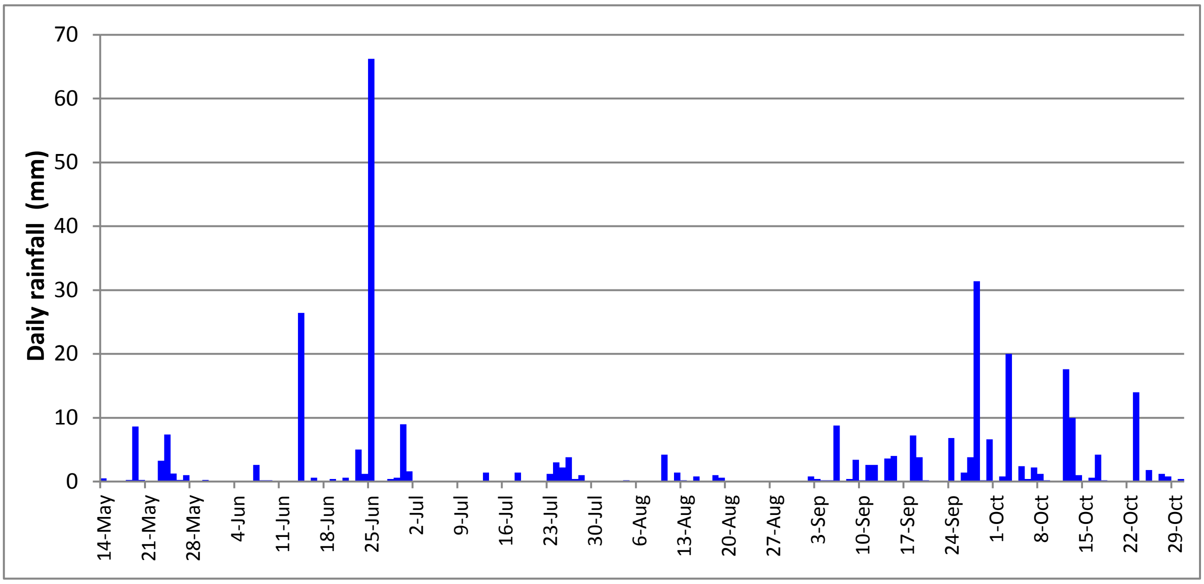


Figure 4.2. Daily rainfall pattern form May 14th to October31st

The observed rainfall pattern correlates to the annual seasonality especially from September to October 2012 (Figure 4.3). The similarity in the average annual rainfall pattern (Figure 4.3), and the observed rainfall amounts (Figure 4.2) illustrates that the pattern observed between September and October was expected. However the pattern observed around May and June was unexpected because much rainfall was expected during May and less rainfall was during June. This gives an indication that there still high chance of the extreme event to occur even in relatively dry months of the year. This can be even more dangerous because people and responsible authorities might have not been prepared for such event (UCAR, 2010).

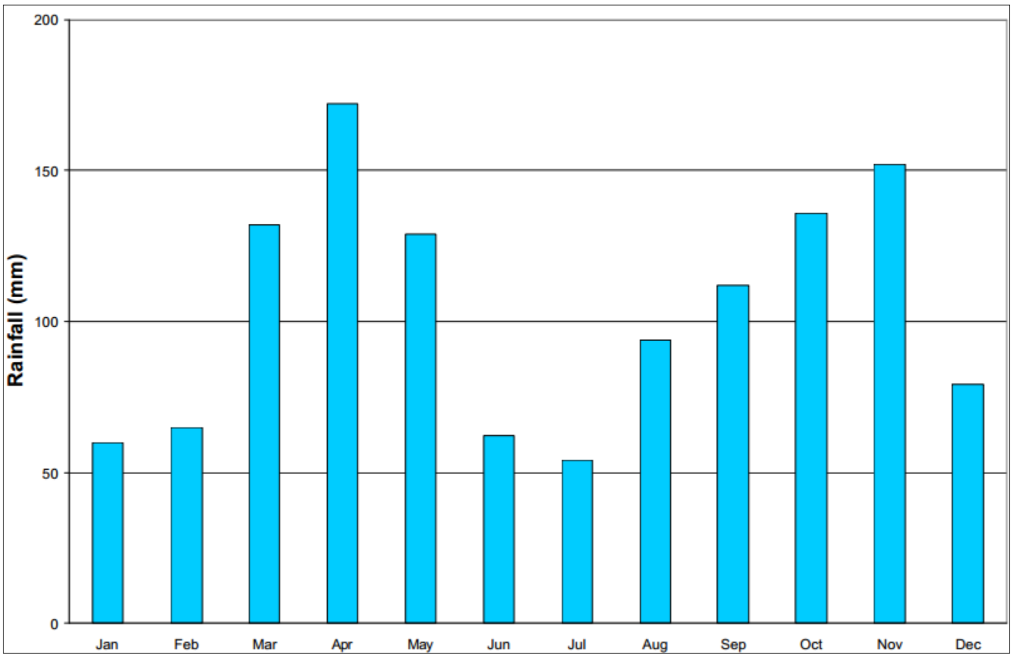


Figure 4.3. Annual monthly average from 1943 to 1999

Figure 4.4 shows the 25th June rainfall event in 10 minute time series. It is evident that the event started at 2:10pm up to 3:40pm real time and the maximum rainstorm was 17.8mm at 3.00pm. This implies that the 25th June event was not only the highest event (of 66.2 mm), but also occurred in a very short period of time which gives a very high chance of flash flood.

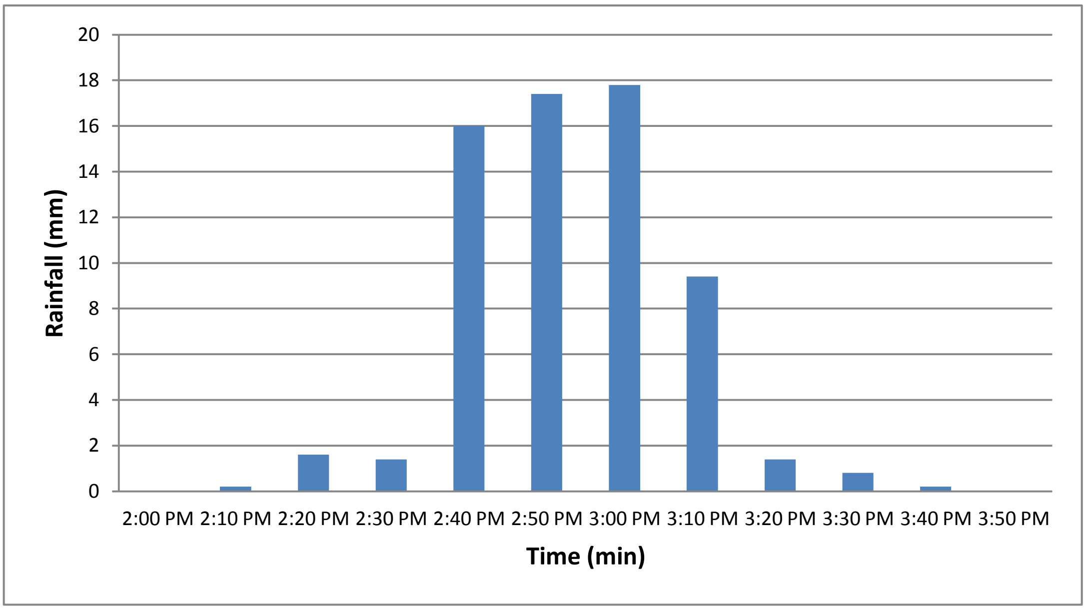


Figure 4.4. Rainfall on 25th June in 10 minute time series

4.1.3. Soil properties in relation to runoff generation and propagation at Lubigi catchment

To get the understanding of the soil infiltration properties the saturated hydraulic conductivity (Ksat), initial soil moisture and porosity were measured in the laboratory and the results are presented in Table 4.1, Table 4.2 and Table 4.3 respectively. Table 4.1shows that the lowland has the lowest (Ksat) while the upland (vegetated) soil marks the highest Ksat value of up to almost twenty times that of the lowland soil. This might be due to the fact that, the lowland has mortal clay characteristics while upland is loamier in nature. On the other hand the average infiltration rate of bare soil is almost seven times lower than the upland (vegetated) soil. This is due to the fact that, bare areas are mostly used as walk ways or play fields which results to the compaction. This implies that upland vegetated soil is relatively permeable compared to other classes (i.e. the lowland soil, bare soil earth road and earth drainage). Moreover, according to the permeability classification by Schoeneberger, Wysocki, Benham, and Broderson (2002), upland vegetated soil has moderate permeability while the rest of the class are have low permeability. Comparatively, this results also concur with that of soil survey of 1960 which showed that lowland soil has low draining capacity and permeability than upland soil (Radwanski, 1960). However the permeability of the upland soil might be affected by the slope of the catchment (Fox, Bryan, & Price, 1997) bearing in mind that Lubigi is a hill area with a slope ranging from 0 to 49%.

Land cover	Minimum	Maximum	Mean	Median	Std	n
Up land vegetated	0	104.43	20.98	5.17	32.81	14
Lowland vegetated	0.29	1.97	1.07	1.76	23.28	4
Bare soil	0.39	6.06	3.34	11.50	2.35	4
Earth road	1.40	4.97	2.5	1.78	1.47	6
Earth drainage	1.79	2.29	2.04	2.04	0.36	3

Table 4.1. Ksat experiment results

Table 4.2 shows the initial soil moisture content of the catchment. The results clearly postulate that the initial soil content of lowland soil is relatively higher than the upland vegetated, bare soil and earth road. The differences observed in these results were expected due the fact that lowland has low draining capacity than upland soil. On the other hand, lack of vegetation cover makes bare soil and earth road to have lower initial soil moisture content. However the value of the earth drainage might be influenced by where the soil sample was taken; in this case, the soil samples for the earth drainage were taken upstream where there was no water logging on the channels so the soil was almost bare, that is why the initial soil moisture content is closer to the bare soil and earth road.

Land cover	Minimum	Maximum	Mean	Median	Std	n
Up land vegetated	20.88	43.60	31.71	31.78	6.24	14
Lowland vegetated	29.84	46.35	35.52	33.27	6.4	5
Bare soil	10.08	30.66	23.71	27.04	9.26	4
Earth road	9.68	50.52	23.61	20.68	16.5	6
Earth drainage	21.08	26.69	23.43	22.51	2.91	3

Table 4.2. Summary of experiment results of initial soil moisture content

Table 4.3 shows the porosity of the soil in the catchment in different land cover classes. This explains the geological structure of the soil in the catchment. It is clearly shown that earth drainage has higher porosity while lowland vegetated soil has the lowest porosity. Due to lack of the detailed soil classification of the catchment, the mean variation of porosity can hardly be explained properly or even compared with the other parameters like infiltration and soil moisture content. However according to the results presented in

Table 4.3 it can only generalized that earth drainage soil has large pore space while lowland has the lowest pore space, thus earth drainage can drain much storm water.

Land cover	Minimum	Maximum	Mean	Median	Std	n
Up land vegetated	45.33	57.85	52.06	52.63	3.71	14
Lowland vegetated	47.28	52.44	50.52	50.78	1.97	5
Bare soil	52.52	60.63	56.63	56.69	3.40	4
Earth road	33.70	60.67	51.96	53.71	9.46	6
Earth drainage	52.00	63.41	58.69	60.67	5.95	3

Table 4.3. Summary of experiment results of porosity

4.1.4. Impact of physical development on the rainstorm discharge

The results of the LISEM model simulation on the impacts of the physical development on rainstorm discharge clearly indicates that the peak discharge increases with the increase in the impermeable surfaces which resulted from building development in the catchment (Table 4.4). The increase in the peak discharge in each of the sub-catchment observed in Table 4.4 is the indication of the impact of the physical development on the generation and propagation of rainfall runoff.

Sub catchment	Total area (Km^2)	% Impermeable surface 2004	% Impermeable surface 2012	Peak Discharge 2004 (m^3/s)	Peak Discharge 2012 (m^3/s)
1	8.3	13.61	23.6	3.78	14.45
2	3.1	25.01	33.9	8.25	12.73
3	3.3	22.88	35.0	10.32	17.69
4	3.7	23.30	34.2	8.23	12.50
5	8.8	15.41	26.00	8.17	15.45

Table 4.4. Impact of the buildings on the peak discharge

Figure 4.5 shows the general simulation results of the two years 2004 and 2012 at the main outlet of the catchment. It clearly indicates that in 2004, 89% of the rainstorm could be infiltrated and only 8.9% of the precipitation could be taken as run-off whilst in 2012, 79.78% of the rainstorm is infiltrated and 17.85% of the precipitation is taken as runoff. Moreover, the total discharge in 2012 at the main outlet is twice as much that of 2004. In addition, the land cover classification revealed that from 2004 to 2012 the impermeable surface has increased by 34%. This implies that the increase in the total discharge and the runoff can largely be caused by the increase of physical development in the catchment.

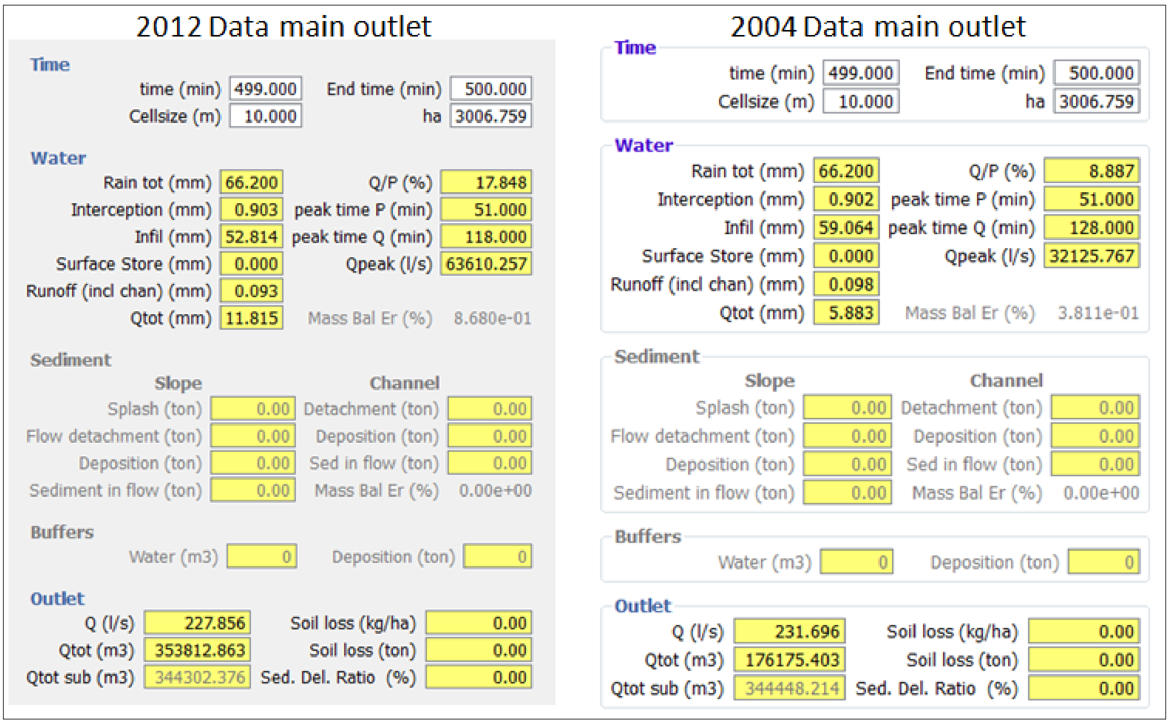


Figure 4.5 Main outputs for 2004 and 2012 run off simulations

Furthermore Figure 4.6 indicates the variation on the peak discharge of the three simulations. It is clearly seen that undeveloped catchment account the lowest discharge of the same rainfall event while the discharge 2012 is twice higher than that of 2004. Apart from that the lag time in 2012 has been reduced dramatically due to the reduction of surface roughness which results into increase in flow velocity. This postulate that if the same event would happen in 2004 the intensity of the rainstorm could be less than that experienced in 2012 just because of the increase of physical development. This result concur with the observation made by David (2012) that "in urban areas, all parts of the catchment area are potentially at risk from flooding or have the potential to make the flood risk worse elsewhere, even if they have been developed with well-designed drainage system" due to land cover change.

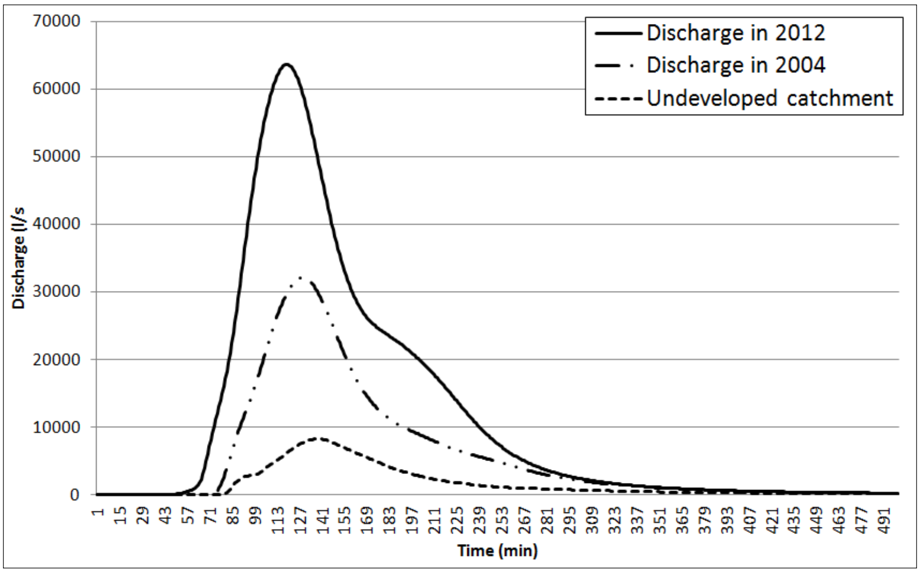


Figure 4.6 Discharge due to land cover change

4.1.5. Nature and condition of drainage system at Lubigi catchment

The fieldwork observation revealed that there exist three levels of drainage channels at Lubigi catchment as noted in (KCC, 2002a) which include primary, secondary and tertiary channels (Figure 4.7). Tertiary drains are local channel that collect storm water from individual building and roads to the secondary drains which links to primary channels which drains out the catchment. Furthermore the analysis revealed that, the catchment is covered by around 84.4 km of the drainage network of the three levels, out of which about 80% are paved and the rest are unpaved (natural drainage).

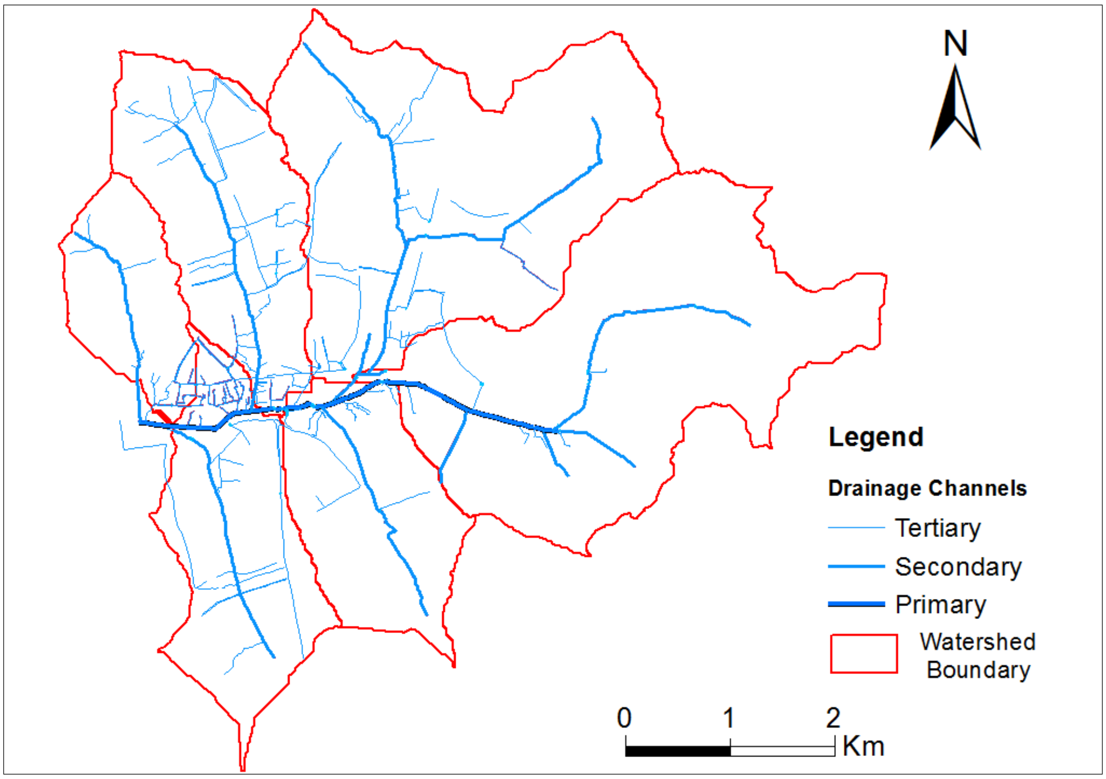


Figure 4.7 Drainage channels at Lubigi Catchment

Moreover field observation revealed that tertiary drains are along the road sides (Figure 4.8 (a)) and others are found between the buildings (Figure 4.8 (b)). This is due to the informal nature of development which leaves no space for infrastructure development. In addition to that field observation found that the drains in between the houses are poorly designed and managed. This was found in the discussion with the Outspan primary school head teacher who clearly mentioned that during heavy rainfall drains at Bwaise III cannot drain storm water to the secondary or primary instead water are drained back to the settlements resulting to the water clogging in the houses; the same case was found at Makerere III (Figure 4.8 (c & d)).

Figure 4.8 Condition of tertiary drainage upstream

Furthermore field observation also revealed that most of the existing tertiary drains are not linked. This might be due to the fact that constructions of the drainage channel especially tertiary drains are not well coordinated. It was pointed out in the discussion with city engineer and also documented in KCC (2002c) that, it is difficult to organise the information of drainage channels because construction of drainage channels are determined by road construction companies depending on the available budget.

It was also found that most culverts have insufficient capacity that poses another challenge on the infrastructure management since they have been identified as flooding hot spots accumulation of sediments particularly downstream (Figure 4.9).

Figure 4.9 Many culverts are often blocked by sediments and garbage

Besides, field observation revealed that apart from the aforementioned challenges on the existing drainage channels, the residence of Bwaise III and KCCA have tried their best to deal with these challenges. The live example is the channel cleanness campaign initiated by Bwaise III residence which already showed satisfactory results on the reduction of frequency of flooding event. On the other hand KCCA is upgrading Lubigi primary channel from the current 6 metre wide and 1 metre deep to 31 metre wide and 1.75 metre deep. However the ongoing construction of primary channel has resulted into blockage of secondary and tertiary channels leading to more disturbances to the people and traffic flow even for small rainfall event.

4.1.6. Capacity of the existing drainage channels at Lubigi catchment

The analysis of the capacity of the existing drainage channels showed in Table 4.5 indicate that, outlet of the secondary channel for sub-catchments 1 to 4 have insufficient capacity to handle the rainstorm produced in these sub-catchments. This is due to the fact that the rainfall event exceeded the designing capacity. The drainage inventory report of 2002 clearly indicates that the designing capacity of these channels was less than 2 return period. It has to be noted that the 25th June rainfall was a two year return period thus the results indicated in Table 4.5 for sub-catchment 1 to 4 are not surprising. However the result of sub-catchment 5 was unexpected but this is due to the fact the culvert at the outlet was upgraded during the construction of Northern Bypass road which was constructed after the inventory. Sub-catchment 5 is among the least urbanized sub-catchment, thus more rainwater could be infiltrated. These results concur with field observation during the visit along primary channel at Makerere III and Bwaise III. During field visit it was observed that, there was an indication of frequent over flow from secondary channel (i.e. outlets of sub catchment 1 to 4). However there was no clear evidence of overflow at Gayaza road crossing which is the outlet of sub-catchment 5.

Furthermore the review of Kampala Drainage Master Plan 2002 revealed the master plan proposed to improve the capacity of the drainage system by first upgrading the primary channels; however the simulation results presented in Table 4.5 show that the overflow occurs on the secondary channels. This implies that the upgrading of the primary channels alone might not have significant effect on the reduction of flash flood risk in the lowland area like Bwaise III and Makerere III, because flooding happens before water reaches primary channel.

Sub catchment	Area of sub-catchment (Km^2)	Drainage Discharge Capacity (m^3/sec)	Peak Discharge according to 66.2 mm rainfall (m^3/sec)	Excessive discharge (m^3/sec)
1	8.3	5.6	14.45	8.85
2	3.1	5.87	12.73	6.86
3	3.3	12.44	17.69	5.25
4	3.7	10.4	12.5	2.1
5	8.8	19.88	15.45	-4.43

Table 4.5: Capacity of the 5 outlets of existing secondary drains

4.2. Identification and Evaluation of flash flood risk reduction strategies

4.2.1. Identification of flash flood risk reduction strategies

Field work observation, literature review and discussion with stakeholders during integrated flood risk management workshop five possible strategies were identified; the strategies includes, rooftop rainwater harvest, cleaning drainage channel, detention/retention ponds upstream, infiltration trenches at the building and buffer zone in the wetlands to give water more room. This study focuses only on the strategies can be implemented upstream; in this case are rooftop rainwater harvest, detention/retention ponds and infiltration trenches.

4.2.2. Evaluation of flash flood risk reduction strategies

4.2.2.1. Rooftop Rainwater harvest scenario

The results presented in Figure 4.10 marks slight reduction on the peak discharge with the assumption that all the buildings of 8 m^2 and above will have 500 litres water tank. This seems to be logical because most people are likely to afford small rain drums. However the validation analysis revealed that, the model result underestimates the storage capacity by a factor of about 3.4. In addition, the storage capacity can be improved by increasing the size of the tanks which is determined by the surface area of the rooftops of the buildings (CEHI, 2009). This implies that, large buildings like commercial, industrial and institution buildings in the catchment could be in a good position to use large water tanks, not only as a means of runoff reduction but also as a alternative source of water supply (Abdulla & Al-Shareef, 2009).

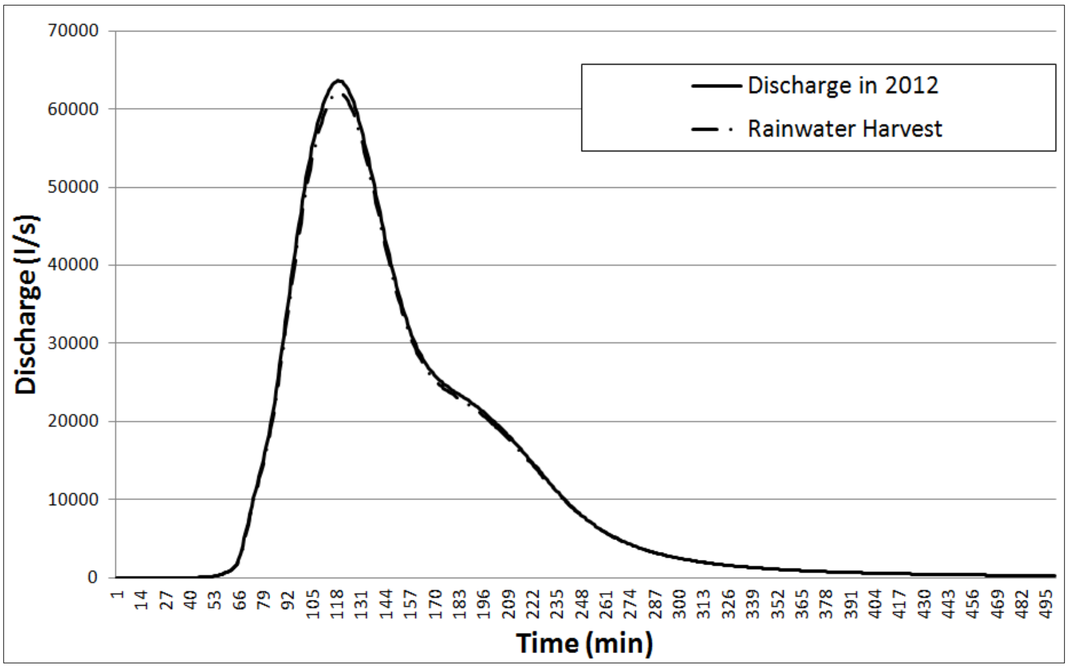


Figure 4.10. Hydrograph due to the rainwater harvest scenario at main outlet

Sub-catchment	Area of sub-catchment (Km^2)	Before rainwater harvest (m^3/s)	1st case rainwater harvest (m^3/s)	2nd case rainwater harvest (m^3/s)	Decrease of peak discharge in 1st case (m^3/s)	Decrease of peak discharge in 2nd case (m^3/s)
Main outlet	27.94	63.61	62.08	63.40	1.53	0.21
1	8.3	14.45	14.09	14.40	0.36	0.05
2	3.1	12.73	12.44	12.69	0.29	0.04
3	3.3	17.69	17.31	17.64	0.38	0.05
4	3.7	12.5	12.17	12.46	0.33	0.04
5	8.8	15.45	15.01	15.39	0.44	0.06

Table 4.6. Result of the rainwater harvest for the two cases

4.2.2.2. Infiltration trenches

The result presented in Figure 4.11 shows substantial reduction of peak discharge. On the other, the results reveal that the runoff duration has also been reduced proportionally. This implies that the strategy might be effective for reduction of the peak, but might have less effect on the runoff time. The result on Table 4.7 indicates that, there is substantial decrease of peak discharge to all sub-catchments. These result correspond with study conducted by Warnaars, Larsen, Jacobsen, and Mikkelsen (1999). Although in their study they used a very low soil permeability of about 7.56mm/h in the compacted urban area but still it was concluded that the storm water infiltration was a feasible measure.

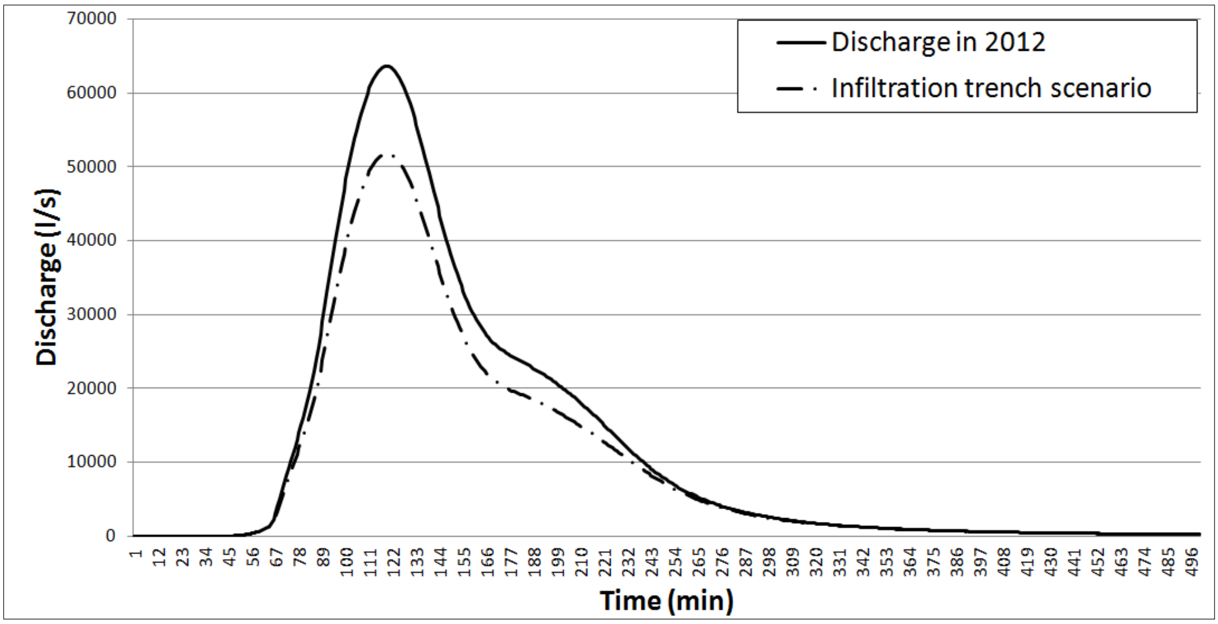


Figure 4.11. Hydrograph due to infiltration trenches scenario at the main outlet

Sub-catchment	Area of sub-catchment (Km²)	Discharge without strategy	Discharge with infiltration strategy	% Decrease of peak discharge
Main outlet	27.94	63.61	51.76	11.85
1	8.3	14.45	11.67	2.78
2	3.1	12.73	10.53	2.20
3	3.3	17.69	14.73	2.96
4	3.7	12.5	9.77	2.73
5	8.8	15.45	12.28	3.17

Table 4.7. Results of the infiltration scenario for each sub-catchment

4.2.2.3. Detention/retention ponds

The hydrograph presented in Figure 4.12, show that, there is slight reduction on the peak discharge. In addition Table 4.8, indicates that the amount of discharge produced in was still high to be accommodated in the existing drainages system. This is implies that there needs to be either more ponds or to increase the capacity of the ponds or both. On the other hand Figure 4.12 shows slight a shift of peak discharge towards right. This has an indication that, there was also a delay in the peak discharge. The delay might be due to time elapse in the filling of the ponds. The delay effect will lower the flood risk downstream due to the reduction of flow velocity.

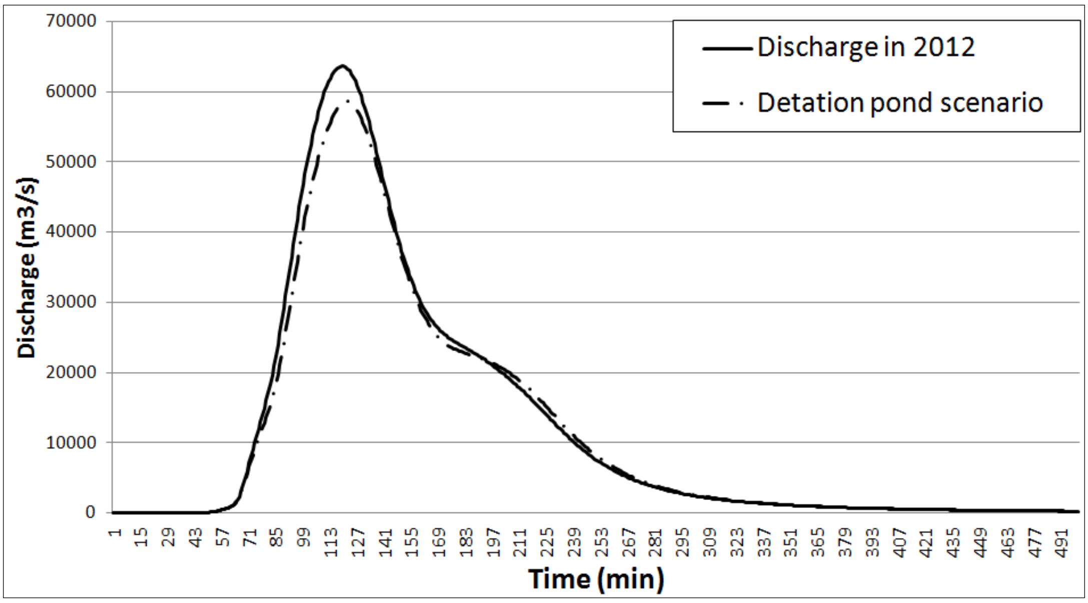


Figure 4.12. Hydrograph due to dentations/retention ponds scenario at the main outlet

Sub-catchment	Area of sub-catchment (Km²)	Discharge without strategy	Discharge with detention/retention pond scenario	Decrease of peak discharge
Main outlet	27.94	63.61	58.56	5.05
1	8.3	14.45	13.98	0.47
2	3.1	12.73	11.82	0.91
3	3.3	17.69	16.58	1.11
4	3.7	12.5	11.34	1.16
5	8.8	15.45	13.78	1.67

Table 4.8. Results of the detention retention ponds scenario for each sub-catchment

4.2.2.4. Combined strategies scenarios

Combined strategies scenario integrates the rainwater harvest, infiltration trenches scenario and the detention/retention ponds scenarios. As it has been in the discussion of the all the scenarios above none of the scenario can closely give ultimate solution on the flash flood risk reduction. The results in Figure 4.13, shows the remarkable decrease on peak discharge as expected. The peak discharge has been decreased almost by 25% at the main outlet while the peak discharges at the sub-catchment level are also reduced proportionally (Table 4.9) in each of the sub-catchment. This implies that, the ultimate risk reduction could be achieved through the combined scenario. However this might need multiple stakeholders on board for the implementation. This results goes in-line with the concept of integrated flood risk management approach (APFM, 2008) and the sustainable drainage system approach by David (2012).

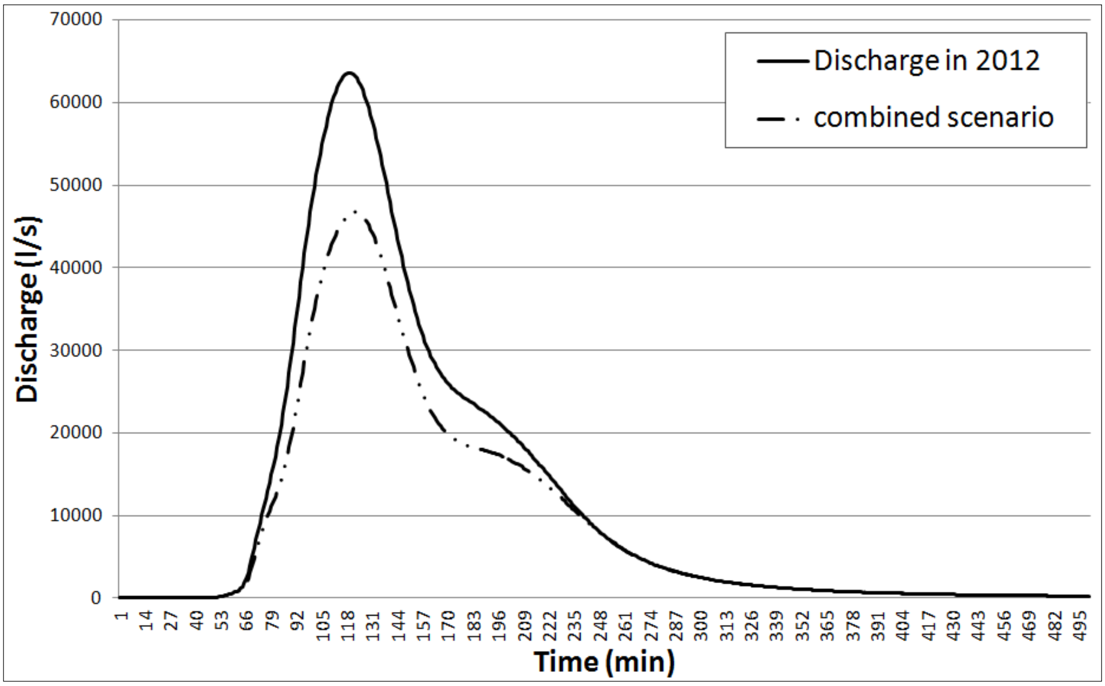


Figure 4.13. Hydrograph of the combined scenario at the main outlet

Sub-catchment	Area of sub-catchment (Km²)	Discharge without strategy	Discharge with combined scenario	Decrease of peak discharge
Main outlet	27.94	63.61	46.72	16.89
1	8.3	14.45	11.26	3.19
2	3.1	12.73	9.66	3.07
3	3.3	17.69	13.57	4.12
4	3.7	12.5	8.79	3.71
5	8.8	15.45	10.62	4.83

Table 4.9. Results for the combined scenario at each sub-catchment

4.2.3. Affordability and adaptability of the strategies

4.2.3.1. Affordability

The discussion with stakeholders in the workshop revealed that, for the rainwater harvest can be affordable since most people have been using as alternative source of water supply. Moreover the detention/retention ponds and infiltration trench strategy might be unaffordable to most individuals due to construction and maintenance cost. It was further mentioned that generally site clearance and excavation accounts for large proportional of the construction cost (EPA, 2006b). However the stakeholders proposed that, cost sharing mechanism to be applied whereby individuals, community, private sector, government and NGOs have to work together during implementation. The cost sharing mechanism will enhance the adoption of integrated flood risk management (IFM) approach (APFM, 2008) and flood risk management concept (Bruijn et al., 2007).

4.2.3.2. Adaptability

Field observation revealed that some household and institutions like schools have been harvesting rain water for domestic purposes (Figure 4.14). In this regards rain water harvest might easily be adapted. On the other hand detention/retention and infiltration trench are not commonly used in most developing countries. This might challenge the adaption during and after implemention; that is why stakeholder during the workshop insisted on the community sensitization prior implementation. However it was mentioned during group discussion in IFM workshop that community sensitization should be done prior the implementation of the strategy.

a) Rain drum in residential house b) Rain drum at Outspan primary school

Figure 4.14 Rain water harvest tanks at Bwaise III

4.2.4. Model validation results

Table 4.10 shows the comparison between LISEM simulation results and the simulation results of KCC (2010) at three selected outlet points. LISEM shows high peak discharge than that of KCC; however at small area of sub-catchment the discharge is very close. This might be due to differences in assumptions and data used. For example KCC used curve number method which assumes uniform infiltration per land use class while LISEM assumed areas covered by building were impermeable. This implies that KCC simulation expected to have less runoff than that of LISEM due to the fact that more water would be infiltrated. In addition to that, Gayaza road crossing is the outlet of sub-catchment 5 which is among the least developed sub-catchment; this means that more water was infiltrated in this catchment in the LISEM simulation and that made the peak discharge to be close to that of KCC (2010). This postulate that, in urban environments where there is heterogeneous development like Lubigi, LISEM can be a good model for peak discharge prediction.

Outlet point	Area of Sub-catchment from previous study (Km²)	Area of Sub-catchment in applied in LISEM (Km²)	Peak discharge from previous study(m3/s)	Peak discharge by LISEM (m3/s)
Kawaala road crossing	27.94	27.93	29.6	63.6
Bombo road crossing	19.86	20.25	24.8	34.5
Gayaza road crossing	8.55	8.77	11.7	15.5

Table 4.10 Validation results for the existing situation

Table 4.11 shows the validation results of rainwater harvest and detention/retention pond scenarios simulations. It clearly shows that, for rainwater harvest scenario, the modelled result is underestimated by almost 3.4 times. The detention/retention pond scenario overestimated the storage by about 9%. The excess storage might be due to infiltration in the ponds. Infiltration trench scenario could not be validated due to limited data for the infiltration process. However, in respect to the number of trenches (about 5,744 trenches) with high infiltration rate of 200 mm/h, the results obtained in this study are reasonable and can therefore be adopted.

Scenario	No of facility	Storage capacity of the facility (m^3)	Expected storage (m^3)	Modelled storage (m^3)
Rainwater harvest	53461	0.5	26730.5	7830.6
Detention pond	15	1000	15000	16417.1

Table 4.11 Validation results for the rainwater harvest and detention pond scenario

4.3. Integration of the flash flood risk reduction strategies into existing land use planning and infrastructure policies.

This section aims to discuss the possible adjustments that can be integrated into existing land use and infrastructure planning policies. The description is based on the land use and infrastructure aspects to be considered prior, during and post implementation.

4.3.1. Land use and infrastructure planning aspects

4.3.1.1. Detention / retention ponds

To ensure best performance of detention/retention ponds, they have to be located immediately upstream and should be as close as possible to the channels for easy water routing (Walesh, 1989). In addition, the slope of the site should not exceed 15% and there should be enough land for reasonable size of the pond (EPA, 2006b).

Furthermore, the community problem and opportunity should be identified in the proposed sites. This will ensure good multi-functional pond (Walesh, 1989). The analysis of the slope as derived from digital elevation model shows that the suitable areas for allocating the ponds range from 0 to 6%. However further analysis of land cover map revealed that large part of the suitable area is intensely developed (Figure 4.15).

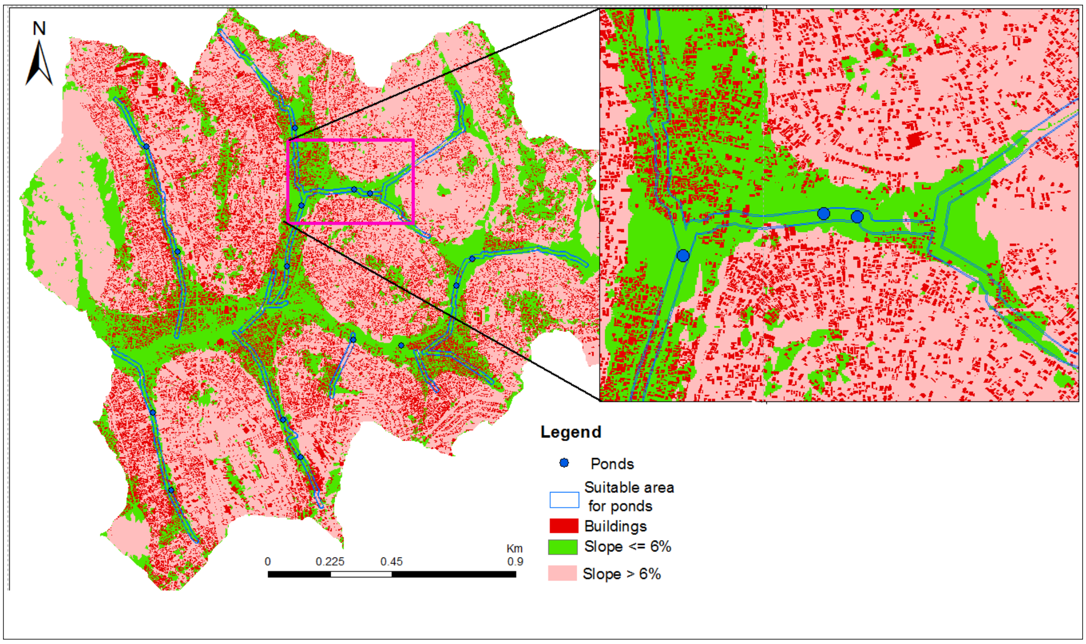
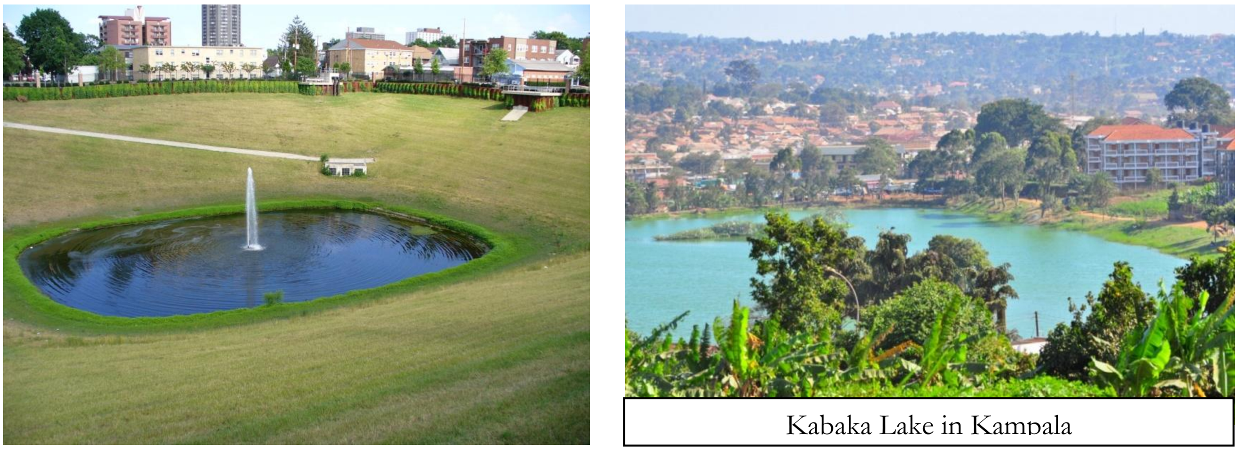


Figure 4.15 Locations and suitable area for ponds

Moreover it was noted that public owned land should be preferred for the location of detention/retention facilities. Nevertheless where necessary fully or partially developed public or private lands that need redevelopment can be also considered. On the other hand issues of land acquisition have to be taken care of particularly to the area like Kampala where the land tenure system is very complex and the land ownership is not very clear (UN-Habitat, 2007).

The depth of the ponds can be dictated by the pond utility and the land availability (Walesh, 1989). For example the pond that can be used for recreation or fish breeding can interact with the ground water but dry detention/retention pond should be about 1.2 m above the ground water level. Due to limited data for ground water level, the study adapted a generally rule that, primary channel have high water table and floods frequently; thus the detention/retention pond should be located along secondary channel where the water table is much lower. The simulation results show that a volume of 1000 m^3 per pond has considerable effect on the reduction of runoff. This is equivalent to about 25x20x2 m each or higher. Therefore about 25 m buffer from secondary channel has to be free from other type development (Figure 4.15)



Source: Boneyard detention basin, 2006 and Nel's travel blog, 2010

Figure 4.16 Multifunctional Detention ponds

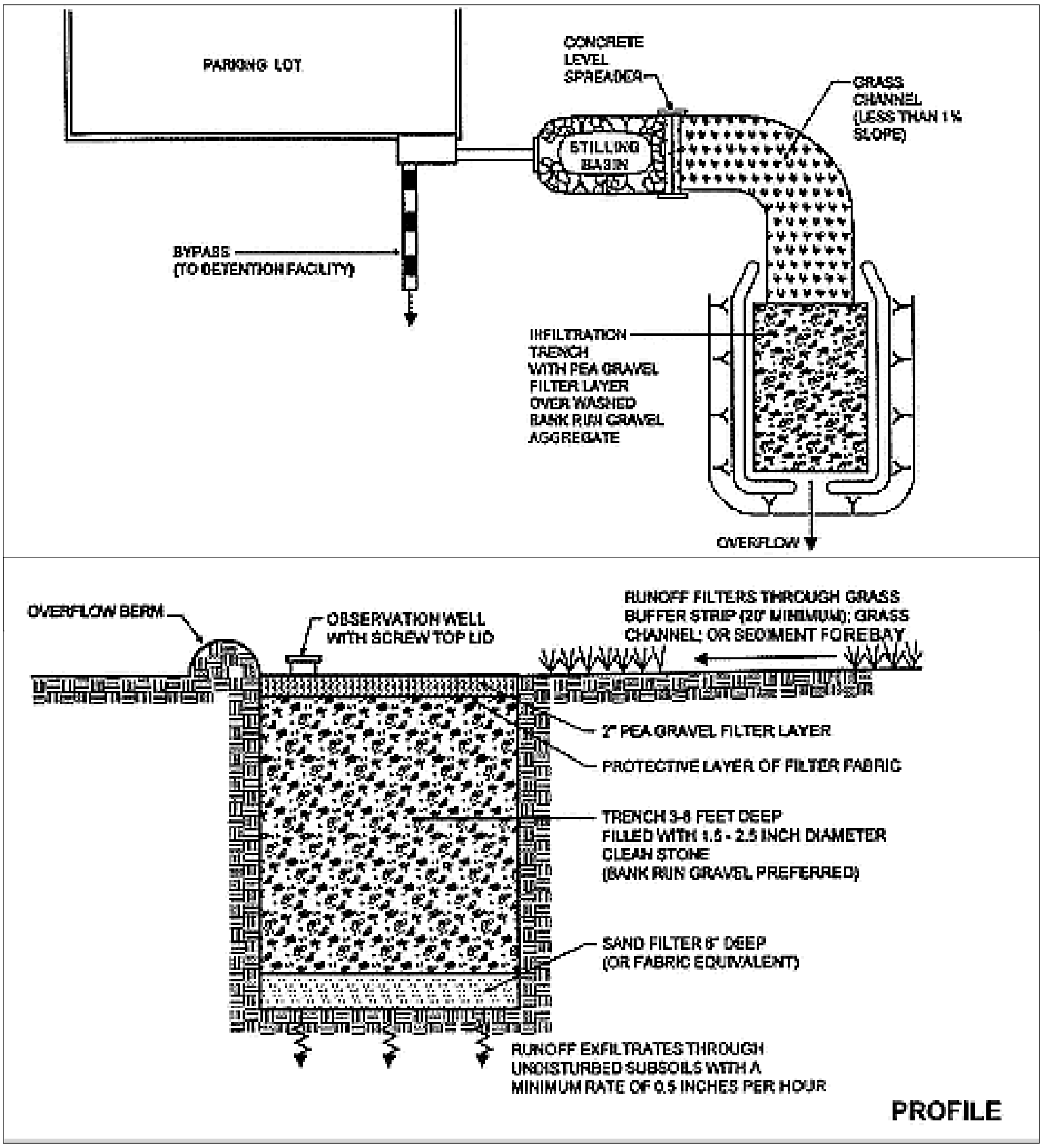
In addition to the aforementioned aspects, Osman and Houghtalen (2003) pointed other general aspects to be considered during planning and designing of detention/retention ponds which include, basin length-to-width ratio of at least 3.0 and pond side slope should be limited to 3:1 or flatter. Moreover as a rule of thumb it was pointed out that to prevent clogging, the outlet should be fitted with trash racks and the side slope should be stabilized by vegetation or gravel/ stones to prevent erosions (Figure 4.17).

Source: Ken mark Turf 2013 and B&B Contracting 2007

Figure 4.17. Stabilized slope detention pond

4.3.1.2. Infiltration trench

It was clearly stipulated that infiltration trenches should be filled with porous material (EPA, 2006a) (Figure 4.18). The preferred porous material on the basement should be at least 30% void space (porosity) with the diameter of about 38-76mm.



Source: MDE, 2000

Figure 4.18 Schematic of an infiltration trench

Furthermore Lubigi catchment soil porosity was found to be above 50% which implies that the soil at Lubigi is suitable for infiltration trench. It was further revealed that, infiltration trench has to be up to 3m deep but the base should be at least 1.2m above the ground water level. In addition, the maximum allowable depth formula presented by MDE (2000), suggested that the depth of the trench is the function of the maximum allowable storage time and the permeability of the soil which is governed by infiltration rate and the porosity of the soil. This implies that, for the 3 m deep trench with the soil permeability properties at Lubigi the maximum allowable storage time should not exceed 6 hours.

4.3.1.3. Rooftop rainwater harvest

The planning and designing of the rooftop rainwater harvest facilities are entirely governed by level of water quality that has to be achieved (CEHI, 2009). The tanks can be fitted below ground or above ground (Figure 4.19). It was further noted that the choice of the system and design depends on the topographic nature of the area and the financial capacity o f the developer CEHI (2009). In this regard buildings in the lowland areas are not suitable for below ground storage system.

a) Below ground storage system

b) Above ground storage system

Source: CEHI, 2009

Figure 4.19 Below ground and above ground water storage systems

Furthermore it was noted in the modelling scenario that fixed storage capacity of 500 litres was used. However in practice the storage capacity of the tank could be determined by annual rainfall intensity and the surface are of the roof top. Under this consideration the rational formula [9] might be appropriate (CEHI, 2009).

$$V = AIC \qquad [9]$$

Where V is a storage capacity of the tank (m^3), A is an Area of rooftop (m^2), I is the annual rainfall intensity (mm/year) and C runoff coefficient of the roof material.

This would increase the storage capacity and enhance runoff reduction downstream compared to the modelled storage.

4.3.2. Legal and policy aspect

Kampala Physical Development Plan (KPDP) suggests that with the ongoing urban sprawl, compact development is fundamental. This includes infilling undeveloped area within the city boundary and promoting high-rise buildings (e.g. apartment development). On the other hand KPDP propose that the wetlands have to be reserved for environmental conservation and recreation. This implies that the implementation of KPDP might result into loss of more vegetated land upstream due to densification of building development. However this would require clear and strong development mechanism of the existing laws and regulations particularly the Physical Planning Act 2010 and the Kampala Physical Development Plan 2012 (RU, 2010) to ensure reduced flood risk in future.

5. CONCLUSION AND RECOMMENDATIONS

This chapter present conclusion and recommendations of the study. The findings, conclusion and recommendation are structured according to the specific objectives. Thus the conclusion and recommendations are presented based on analysis of baseline information, identification and evaluation of flash flood risk reduction strategies and integration of the strategies on the spatial and infrastructure planning policies.

5.1. To analyze baseline information related to the generation and propagation of rainfall runoff at Lubigi catchment

This study postulates clearly that Lubigi catchment is informally developed with a fragmented nature type of development. Large proportion is covered by vegetation and bare land. Wetlands in the catchment particularly Bwaise III and Makerere III have been intensely developed leaving no room for storm water to drain. Natural drains have been disturbed by the physical development like human settlement and infrastructure development. The live example found was the construction of Northern Bypath road, Lubigi primary channel and solid waste disposal site in the Lubigi wetland. Moreover the study showed clearly that, the existing drainage channels have insufficient capacity to drain heavy rainstorm event (e.g. 2 year return period and above). However the study also showed that the permeability of the vegetated soil upstream is relatively high compared to that of bare soil which might be potential for infiltration of surface runoff. Furthermore Kampala has a bimodal rainfall pattern with the first season starts around March up to May while the second season starts around September up to November. The daily average rainstorm duration is about 30 minutes which cause sudden rise of rainstorm that cannot be handled by existing infrastructure which makes it potential for flash flood downstream.

It was realized that, the rainfall runoff at Lubigi is largely influenced by the existing nature of development, condition and capacity of the existing drainage channels. Clearing of vegetated land to pave for physical development activities and leaving bare also play a major on the propagation of the rainfall runoff. The nature of development devastates not only the natural flow of rainstorm water but also increase the flood risk to the downstream residences.

This study therefore recommend that the ongoing informal development should not be underestimated especially when it is not only threatening the available wetlands in the city and natural flow of rainstorm but also taking into account that sizeable proportion of the urban poor live in slums which are vulnerable to flooding (Lwasa, 2010). Even though, compact development is the best option for the future physical development still development control has to be strongly encouraged. To enhance infiltration of the soil, tree planting and gardening at the household level should be encouraged to reduce surface runoff in facilitate ground water recharge. Furthermore this study agrees with drainage cleanness campaign initiated by Bwaise III residences and thus has to be promoted and extended in the entire catchment.

5.2. To identify and evaluate the possible flash flood risk reduction strategies in Lubigi catchment

The results clearly showed that the possible strategies that can be used to reduce the risk of flash floods include; rooftop rainwater harvest and construction of infiltration trenches and detention/retention ponds. This study found out that construction of infiltration trenches and detention/retention pond strategies can substantially contribute to the runoff reduction while rooftop rainwater harvest strategy showed negligible effect and therefore it can be concluded that infiltration trench and detention/retention pond is a better option at Lubigi catchment if they are properly planned and designed. However, coupling rooftop rainwater harvest strategy with the infiltration trench and detention/retention pond would cumulatively provide superior outcome.

5.3. Suggestions on the Integration of the proposed strategies on the spatial and infrastructure planning policies

To enable of adaption of infiltration trench and detention/retention ponds the existing legal policies would need to be adjusted and strengthened (David, 2012). In reverence to the evaluated policies in this study, it suffices to conclude that streamlining the existing land tenure system would enhance acquisition of wetland for public use and protection of wetland in the catchment. This is because all the land in the catchment is privately owned either under *mailo,* customary, or freehold tenure system (UN-Habitat, 2007). This implies that currently there is no publicly owned land that can be used for detention/retention ponds.

The Kampala physical development plan does not provide the extent of the wetlands areas which would have made it easier to enhance environmental protection and therefore this study recommends comprehensive identification and mapping of all the wetlands and flood prone area in the general physical/ structure plan of the city as well as the entire catchment. Coupling this with the strengthening of the existing development regulation as stipulated in the physical planning act of 2010 initiative is likely to pave the way for implementation of proposed strategy.

Clear stipulation of mandatory inclusion of rooftop rainwater harvest or infiltration trenches for the new industrial, institutional, commercial and residential building plans in the building regulations can enhance implementation of the strategy. However, the existing building development community sensitization is recommended prior the implementation of the strategies.

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APPENDIX 1 SCRIPT USED GENERATE THE LISEM MAPS

a) General script for basic maps

```
#! --matrixtable --lddin

##################################################################
##############
# PCRASTER script for the generation of a LISEM input database          #
# Victor Jetten 16/05/12                                  #
# Data for the BWAISE catchment, KAMPALA                              #
#
##################################################################
##############



binding
#####################
### input maps   ###
#####################

   dem =  dem10m.map;
   # digital elevation model, area must be <= mask
   unitmap =  lu10.map;

   # consisting of basically two units: bare soil and vegetation,
   # vegetation is grass, crops and trees if possible
   # NOTE soil parameters can also be relted to this
   # e.g. grass infiltrates more than bare soil

   # texture =  soils.map;
   # NOT USED
   # assumed all one soil type or else specify a soil map

    road = tarmac.map;
   # road map, 20 = tarred road (8 m wide), 21 is narrow dirt road (4 m wide)
   # PROVIDED FROM OUTSIDE SOURCE for different roadwidths
   # only tarred roads and not wider than gridcell

#    chanmask= chanmask.map;
   # mask for channel maps, other channel dimensions are derived from that
   # if different widths exist these should be provided
   drains=chanmasknew.map;
   #primary and secondary dra1ns
   #hardsurfcov = hardsurfcover10m.map;
    bypass = northern.map;
```

```
housecover =house_cover.map;
house_cover = house_cover.map;
#####################
### input tables ###
#####################
    unittbl = unitbase.tbl;
    # table with crop and soil parameters for each id

# unitbase table layout   #
#-------------------------#
# 01 ksat (mm/h)
# 02 porosity (cm3/cm3)
# 03 psi initial (cm)
# 04 initial moisture content (cm3/cm3)
# 05 RR (cm)
# 06 Manning's n (-)
# 07 surface cover (-)
# 08 Crop height (m)
# 09 cohesion sol (kPa)
# 10 cohesion roots (kPa)
# 11 aggregate stability (number)

########################
### input constants ###
########################

 Soildepth = 5000;
 d50 = 30;        # median texture loess = 30 mu
 #channel properties:
 Chancoh = 10;    # high cohesion, kPa
 Chanman = 0.05;   # medium
 Chanside = 0;    # rectangular
 Chanwidth = 2;   # 2 meter

######################
### output maps   ###
######################

  # basic topography related maps
    Ldd =  ldd.map;         # Local Drain Direction
    grad =  grad.map;       # max slope
    id =  id.map;           # pluviograph influence zones
    outlet =  outlet.map;   # location outlets and checkpoints

  # impermeable roads
    roadwidth =  roadwidt.map;
```

```
  # crop maps
    coverc= per.map;
    lai= lai.map;
    cropheight= ch.map;
    grass= grasswid.map;
      # soil maps
    ksat= ksat1.map;
    psi= psi1.map;
    pore= thetas1.map;
    thetai= thetai1.map;
    soildep= soildep1.map;

  # maps for G&A 2nd layer
#   ksat2= ksat2.map;
#   psi2= psi2.map;
#   pore2= thetas2.map;
#   thetai2= thetai2.map;
#   soildep2= soildep2.map;

  # surface maps
    rr= rr.map;
    mann= n.map;
    stone= stonefrc.map;  # crusted fraction, only used when option chosen in LISEM
    crust= crustfrc.map;
    comp= compfrc.map;
    hard=hardsurf.map;

  # erosion maps
    cohsoil =  coh.map;
    cohplant =  cohadd.map;
    D50 =  d50.map;
    aggrstab =  aggrstab.map;

  # channel maps
    lddchan =  lddchan.map;
    chanwidth =  chanwidt.map;
    changrad =  changrad.map;
    chanman =  chanman.map;
    chanside = chanside.map;
    chancoh =  chancoh.map;

    mask=mask.map;
    prim  = prim.map;
out=out.map;
```

initial

```
######################
### BASE MAPS      ###
######################
mask = dem/dem;

report prim = if (drains eq 3, drains, 0);

# correct topo for local depressions
report Ldd = lddcreate (dem-out*5-prim, 1e20,1e20,1e20,1e20);
report outlet = pit(Ldd);

chanmask = scalar(if(drains ge 1,1));

# reference catchment boundaries, based on watershed from outlet
# OBSOLETE  report area = catchment(Ldd, outlet);
# LDD is reference in later LISEM eversions

# sine gradient (-), make sure slope > 0.001
report grad = max(sin(atan(slope(dem*mask))),0.001);

##########################################
### MAPS WITH RAINFALL INFLUENCE ZONE ###
##########################################

report id = nominal(mask);
# use spreadzone for thiessen polygons when more than 1 rainfall station

#######################
### LAND USE MAPS   ###
#######################

# fraction soil cover (including residue)
report coverc = veg_cover.map;#lookupscalar(unittbl, 7, unitmap) * mask;
# crop height (m)
report cropheight = lookupscalar(unittbl, 8, unitmap) * mask;

# 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);
# or read from table:
#lookupscalar(unittbl, 9, unitmap) * mask;
```

```
#################################################################
### INFILTRATION MAPS for option one layer GREEN & AMPT ###
#################################################################

report ksat = lookupscalar(unittbl, 1, unitmap) * mask;
report ksatcomp.map=5*mask.map;
report pore = lookupscalar(unittbl, 2, unitmap) * mask;
report psi =  abs(lookupscalar(unittbl, 3, unitmap)) * mask;
#report thetai = lookupscalar(unittbl, 4, unitmap) * mask;
report thetai = pore * 0.8;
report soildep = scalar(Soildepth);

################################
### SOIL SURFACE MAPS     ###
################################

# micro relief, random roughness (=std dev in cm)
report rr = max(lookupscalar(unittbl, 5, unitmap) * mask, 0.01);
# Manning's n (-)
# take from table
 mann = lookupscalar(unittbl, 6, unitmap) * mask;
report  mann = mann + 0.05*house_cover;
# report mann = 0.051*rr+0.104*coverc;
# or use simple regression from Limburg data: CAREFULL this is not published

report crust=mask*0;
# crust fraction map, SWATRE option 2 in LISEM. Note that this demands an extra
# profile definition in PROFILE.INP and PROFILE.MAP

report stone = 0 * mask;
# stone fraction

report  comp = murrum_road.map;
#0*mask;
#fraction compacted

report  hard = 0*mask;
#hard surface cells

report roadwidth = road*celllength();
# road width, 21 is tarred road = 8 m, dirt rods are 4 m wide

########################
### EROSION MAPS   ###
########################
```

```
   report D50 = d50*mask;
   report cohsoil  = lookupscalar(unittbl, 9, unitmap) * mask;
   report cohplant = lookupscalar(unittbl, 10, unitmap) * mask;
   report aggrstab = lookupscalar(unittbl, 11, unitmap) * mask;

  ########################
  ### CHANNEL MAPS   ###
  ########################

   chanmask=chanmask/chanmask;
   report lddchan=lddcreate((dem-out*5)*chanmask,1e20,1e20,1e20,1e20);
   report changrad=max(0.001,sin(atan(slope(chanmask*dem))));
   report chancoh=chanmask*scalar(Chancoh);
   report chanman=chanmask*scalar(Chanman);
   report chanside=chanmask*scalar(Chanside);
   report chanwidth=chanmask*if(drains eq 3,5,if(drains eq 2, 3, 1));

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

   raindrumsize = scalar(0);
   report roofstore.map=if(housecover gt 0,1,0)*mask;
   report drumstore.map=if(housecover gt 0,raindrumsize,0)*mask;
#    report housecover.map =
   report hardsurf.map = hard;#if(unitmap eq 5 or unitmap eq 11 or unitmap eq 12,hardsurfcov,0)*mask;
```

APPENDIX 2: SCRIPT FOR GENERATING SCENARIO MAPS

```
report drumloca.map = cover(scalar(uniform(house.map eq 1) gt 0.1),0)*mask.map;   # 0.1 is fraction of houses without drum
report drumstore.map= drumloca.map*0.5;      #0.5 is drum size m3
report grasloca.map = cover(scalar(uniform(house.map eq 1) gt 0.9),0)*mask.map;   # 0.9 is fraction of houses without grass strips
report grasswid.map = grasloca.map * 0.5;  # 1 meter grass/gravel width
report ksatgras.map= mask.map*200;   # grass/gravel ksat
report buffervol.map = scalar(if(detpond.map eq 2, 1000, 0));                    # 1000 is the volume of pond in m3
report bufferid.map = nominal(scalar(clump(nominal(buffervol.map gt 0)))-1);
```

APENDIX 3: SOIL INFILTRATION EXPERIMENT RESULTS

Ring No	X	Y	Porosity	Initial soil moisture content	Ksat	Land cover	Remarks
2	450,982	38,796	52.44	46.35	1.94	Lowland	Grass on the valley
18	450,953	38,624	57.63	26.28	0.39	Bare soil	Bare soil
14	450,941	38,622	60.63	27.81	6.06	Bare soil	Bare/ loam clay/Play ground
10	451,004	38,559	54.48	31.68	1.60	Upland	Long grass loam clay with gravel
23	451,073	38,542	57.85	31.88	0.31	Upland	Cultivated land
16	451,665	37,959	55.59	26.28	21.01	Upland	Grass Makerere-loam clay with gravel
5	451,718	37,928	54.30	30.35	48.89	Upland	Grass - loam clay
15	451,699	37,986	53.81	33.41	6.88	Upland	Grass- loam
12	451,791	37,815	48.63	36.67	104.43	Upland	Grass - loam
22	453,626	39,188	54.52	26.18	2.29	Upland	Grass - loam Residential
21	453,592	39,719	53.44	30.05	178.52	Earth road	Bare soil/ earth road/footpath
8	453,563	39,728	52.15	9.68	2.75	Earth road	Bare soil/ earth road/footpath
9	453,581	39,743	55.74	10.08	3.90	Bare soil	Bare soil
13	453,530	39,757	57.44	11.31	1.78	Earth road	Bare soil/ earth road/footpath
7	453,673	40,672	50.48	29.84	1.76	Lowland	shrub/downstream
19	453,666	40,636	50.78	32.49	53.09	Lowland	shrub/downstream
4	453,632	40,650	51.63	35.65	0.31	Lowland	shrub/downstream
24	453,687	40,620	48.30	32.59	14.13	Upland	shrub/Upstream
17	453,717	40,627	45.33	26.38	77.99	Upland	shrub/Upstream
6.B	454,907	41,566	51.44	43.60	2.60	Upland	Cultivated land/banana farm
9B	454,888	41,541	56.41	20.88	3.06	Upland	cultivated land
16B	454,989	41,782	49.48	27.30	7.03	Upland	cultivated land/vegetables
23B	455,016	41,768	52.52	30.66	3.02	Bare soil	Footpath/Bare soil loam
19B	450,410	42,165	60.11	21.08	2.29	Earth Drainage	Earth drainage
20B	450,489	42,222	63.41	22.51	184.76	Earth Drainage	Earth drainage
3B	449,860	41,870	60.67	9.68	1.62	Earth road	Earth road/footpath
15B	449,842	41,865	33.70	50.52	1.40	Earth road	Earth road/footpath
11B	450,407	40,493	54.37	30.46	4.97	Earth road	Gravel road
X	450,419	39,520	52.00	26.69	1.79	Earth Drainage	Earth drainage
16C	450,161	41,441	49.84	41.56	0.00	Upland	Vegetation compact soil
10C	450,611	40,239	48.81	35.21	0.29	Upland	Vegetation
XC	450,484	41,541	47.28	33.27	3.47	Lowland	Vegetation valley