THE CURRENT AND FUTURE FLOOD SITUATION, BWAISE III, KAMPALA, UGANDA, AFRICA

JIGME CHOGYAL
March, 2013

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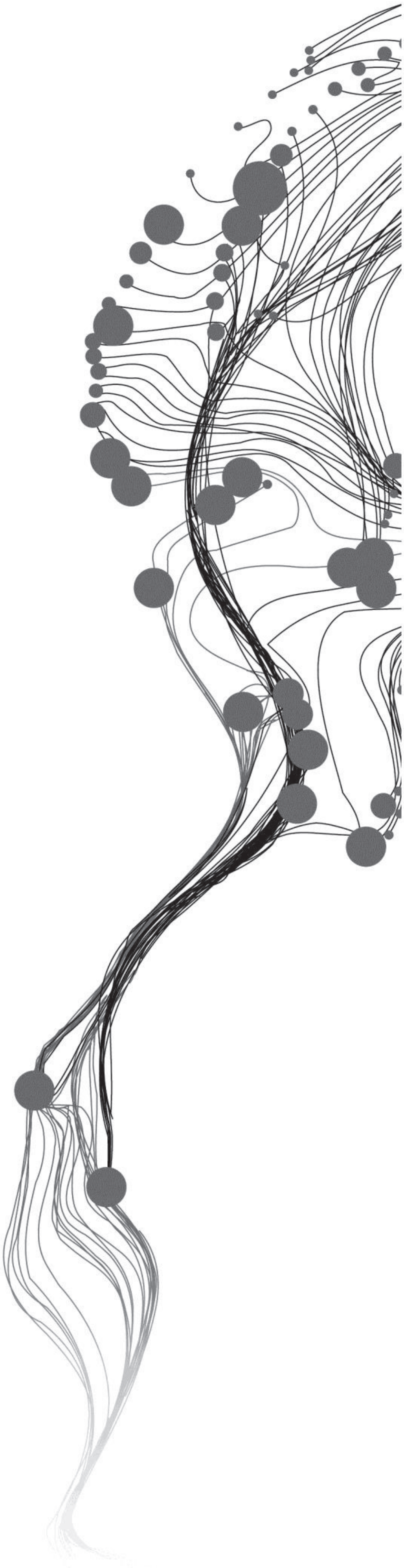

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JIGME CHOGYAL

Enschede, The Netherlands, March, 2013

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

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ABSTRACT

This study is carried out in Bwaise III, a subsection of Kampala, Uganda that is affected by floods every year. Heavy rainfall causes the overflowing of the drainage systems which causes widespread nuisance and disturbances. This study analyses in detail the functioning of the current drainage system, but also the effects of major enlargement works of the primary drainage channel. Such studies could be the basis for the local authorities and the public to initiate flood preparedness and mitigation works proactively.

The main objective of this study is to analysis the current and future flood situation in Bwaise III, Kampala, Uganda and to evaluate the effectiveness of flood mitigation actions by the inhabitants and of the new enlarged primary drain. This study will focus on the effects of the small dikes constructed around the buildings and of the drainage blockage by garbage and siltation. Their effect on the flood characteristics were assessed for both the present (current primary drain) and future (enlarged primary drain) scenarios. The SOBEK 1D2D flood simulation software was employed to simulate and analyse the flood characteristics for all the scenarios. The model results for the current scenarios were calibrated using the observed flood depth data from the June 2012 flood event. The flood depth and extent of the future scenarios were smaller than that of the present scenarios showing the positive effects of the enlarged primary drainage. However, drainage blocking by garbage and siltation will increase the flood depth and extent significantly. In both the scenarios, the small dikes around the buildings reduce the flood extent but slightly increase the flood depth.

In this study it was found that SOBEK 1D2D is very good at simulating these kind of floods, however, this study also showed that the simulation results are very sensitive for the digital elevation model (DEM), the surface roughness map and the upstream boundary conditions. Uncertainties in these data affect the model results seriously.

Keywords: SOBEK 1D2D, DEM, Surface Roughness, Boundary Condition.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATION

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AAI	Action Aid International
BTC	Belgian Technical Cooperation
D	Datum
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DSM	Digital Surface Model
EIA	Environmental Impact Assessment
FEMA	Federal Emergency Management Agency
FLS	Flood Level Switch
GIS	Geographic Information System
GWP	Global Water Partnership
HEC-RAS	Hydrologic Engineering Centers River Analysis System
IFRC	International Federation of Red Cross
ILWIS	Integrated Land and Water Information System
IPCC	Intergovernmental Panel on Climate Change
ITCS	Inter-tropical Convergence Zone
KCC	Kampala City Council
KDMP	Kampala Drainage Master Plan
KIIDP	Kampala Institutional and Infrastructure Development Project
LiDAR	Light Distance and Ranging
LISEM	Limburg Soil Erosion Model
MoLG	Ministry of Local Government
NEMA	National Environment Management Authority
TIFF	Tagged Image File Format
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNISDR	United Nations International Strategy for Disaster Reduction
USGS	The United State Geological Survey
UTM	Universal Transverse Mercator
WMO	World Meteorological Organization

1. INTRODUCTION

1.1. Background

The floods, particularly of medium scale events, have been increasing at the fastest rate the world has ever recorded in its history. These floods have claimed millions of worth of properties, altered vast environment and took away a large number of lives (IPCC, 2007; World Bank, 2011). The trend of flooding has been increasing consistently and it is expected to be more in future, incurring great toll on properties, infrastructure, the environment and lives (Kundzewic, 2003; Prudhomme et al., 2003).

According to the record of Red Cross as mentioned by Kundzewicz (2002), more than 1.5 billion people were affected by floods from 1971 to 1995, of which 318,000 people got killed and over 81 million were left homeless. Floods are becoming more severe now than before. The floods in the period 1990-1998 were greater than those in the period 1950-1985.

As the world become more populated and more developed, the societies and properties are more exposed to flooding(Gasper et al., 2011). According to Kundzewicz and Menzel (2003), the reasons for increasing floods are due to changes in terrestrial systems, changes in socio-economic systems and changes in climate. All these three changes are inter-related, one leads to another. The changes in terrestrial systems distort the hydrological systems due to deforestation and encroachment into wetland areas. This has decreased the areas for natural water storage and increases the size of impervious area leading high surface runoff during precipitation. The recent socio-economic development has brought a lot of construction such as industries and settlements particularly in the low lying flat valleys because of its proximity to water, fertile soils and convenient and less investment for construction. This has exposed people and infrastructure to floods in the low lying flat valleys. The climate change has increased the proportion of precipitation worldwide and caused very erratic weather triggering heavy flooding.

Floods in Africa as per UNISDR record shows that Africa gets more than 568 floods a year and Uganda has floods events at an average of 15 times a year. All those floods were levelled as disaster since the impact goes beyond the coping capacity and available recourses of the country (UNISDR, 2010). Africa is reported to be affected by natural disaster in general and floods in particular that affected one-third of 3.3 million people between 1997 and 2008. The pertinent reasons for increasing the effect of floods are rapid growth of low- and middle-income urban population and development of urban infrastructure that are directly exposed to floods (IFRC, 2010).

Flooding in Uganda, particularly in the capital city of Kampala is aggravated by many underlying factors such as large population (due to its high growth rate and huge immigrants from within and from outside the country); unregulated settlements; encroachment into wetland areas, poor drainage systems, lack of waste management system and lack of human- and financial-resources to initiate preparedness, mitigation and response against flooding proactively (AAI, 2006; Gumm, 2011; KCC & BTC (Uganda), 2008; Mabasi, 2009; UN-HABITAT, 2009).

Flood hazard assessment is the perquisite for flood risk assessment and also the basis for planners and decision makers for carrying out flood management proactively instead of reactively as intended by United Nations (Mabasi, 2009; UNISDR, 2011). Flood hazard assessment defines the frequency, magnitude, speed, onset, affected area and duration, which is the initial steps for flood risk assessment(UNISDR, 2004).

Flood hazard assessment with hydraulic modeling has become popular due to availability of various flood models ranging from simple one-dimensional (1D) to complex three-dimensional (3D). It is furthermore enhanced by recent development of high-tech computer which can compute complex flood scenario within shorter time and able to determine several flood dynamic characteristics. Moreover, development of Geographic information system (GIS) tool has made the pre- and post-processing of flood data management and mapping easy (Els, 2011; Pender & Néelz, 2007).

Uganda is a signatory to the Hyogo Framework for Action 2005-2015 and pledged to campaign 'Making Cities Resilient: My City is Getting Ready' (UNISDR, 2005, 2012).

1.2. Problem Statement

Kampala city has changed a lot in terms of its land use and land cover over a period of three decades (1973-2007) as shown in Appendix-1. This is largely due to deforestation as a result of urbanization and high growth of population(NEMA, 2009). The population of Kampala according to Uganda Bureau of Statistics (2002) was 1.4 million in 2008 and it is estimated to grow at 1.6 million by 2011. Its population growth rate is 3.7 percent per year (UN-HABITAT, 2009) and there is also a high immigration from within and from outside the country. This is because of more welfare facility and job opportunities as it is the capital of government administration and the center of commercial economy of the country. However, development plans, policies and infrastructure have not been abreast with the growth of demand of the people. Therefore, the pressure on social services, housing, infrastructure, the environment and land has increased drastically which resulted into informal urbanization. The unplanned urbanization has concurrently engulfed all the small satellite towns and villages nearby increasing its peripheral (Kulabako et al., 2007).

According to AAI (2006) the settlements in Kampala are reported to be more of unregulated, which led to the development of unplanned construction all over the place. This unregulated settlement results in a lack of proper drainage channels and has caused an increase of impervious area reducing the infiltration of rain. As a result the surface runoff from hills towards low-lying valleys has increased to 6 times than what would have been in natural terrain. According to WMO and GWP (2007) the surface runoff in a heavy built-up area is 2 to 6 times greater than natural vegetation area such as fields, meadows and forests.

The unplanned settlements in the low laying valleys have encroached into wetland areas, which are supposed to be the natural reservoir for flood water. The wetlands in Kampala was decreased by 50 percent from 1995 to 2005 (Gumm, 2011). The development of unplanned settlement is not only attributed to the growth of population and unregulated urbanization but also because of the low economic status of the people. Almost 60 percent of urban is poor people. They are economically resorted to settle in a wetland area where the social facility is very poor and prone to floods (Lwasa, 2010).

Another pertaining factor that makes Bwaise III prone to floods is its geographical location and the type of soil it has. Bwaise III is located at the confluence of natural drainage systems that drain surface runoff from a large catchment area of almost 24 km^2 upstream. The top thin layers of soil is composed of sand and underneath it lays deep mottle clay, which acts as impervious (MoLG & KCC, 2002d; S.A. Radwanski, 1960).

Flooding at Bwaise III is aggravated due to poor drainage system, lack of sanitation and waste management systems. The construction of houses over the drainage channel (Figure 1-1a) and along the drainage lines has not only reduced the size of the drainage channels but also affected the alignment of the drainage channels (Matagi, 2002; NEMA, 2009; UN-HABITAT, 2009). Furthermore, it is observed during field work that in the lower part of the study area people piled soils and dike of sandbags around their houses up to certain height to keep their houses protected from incoming flood water (Figure 1-2). But this mitigation practice did not help much. When flood came, the water got into their houses and could not drain out the water from inside. Therefore, many houses are being abandoned with a pool of water inside (Figure 1-1c). Those who have no choice have to live with it and they raised their beds on stones and hang their belongings on the walls and ceiling to protect them from water (Figure 1-1b).

The deformation of ground elevation will have a great impact on the flood dynamic. This research would investigate the impact of raised and without raised dikes around the buildings on flood characteristics.

Figure: 1-1 Issues related to flooding
(A)House constructed over the drainage channel. (B) Bed raised on stone and belongings hanging on the wall. (C) Abandoned house with stagnant water inside.

In pursuit of flood mitigation, the government of Kampala has redesigned the Lubigi primary channel (Figure 4-7) that runs through Bwaise III. This research will also study the difference between the present primary channel and the future primary channel on the flood characteristics.

The flood in Kampala as of now has been more of disturbing than immediate threat to the physical infrastructure. It disturbs traffic, commuters, business activities and causes health related problems such as water borne diseases(UN-HABITAT, 2009).

Figure 1-2: Raised small dikes around buildings

1.3. Main Research Objective

The main objective of this study is to analysis the current and future flood situation in Bwaise III, Kampala, Uganda with SOBEK flood modeling.

1.4. Specific Objectives

1. To simulate floods triggered by the highest and the second highest rainfall events of 2012 by using a 1D/2D flood model and assess their corresponding return period.

2. To calibrate the flood model based on the observed flood data.

3. To assess the impact of raised dikes around the buildings in the lower part the Bwaise III on flood characteristics.

4. To assess the effect of garbage on flood characteristics.

1.5. Research Questions

Sub-objective 1:

1. What are the characteristics of flood of the two rainfall events (the highest rainfall event - 25th June and the second highest rainfall event - 28th September 2012)?
2. What are the return period of the highest and the second highest rainfall events of 2012?

Sub-Objective 2:

3. What are the characteristics of recent floods for model calibration?

Sub-objective 3:

4. What is the impact of raised dikes around the buildings on the flood characteristics?

Sub-objective 4:

5. What is the effect of garbage on the flood characteristics (differences between clean channels versus blocked channels)?

1.6. Research conceptual framework

Figure 1-3 shows the conceptual framework for this research. The conceptual framework gives a general idea about the processes involved in the research from beginning till end. According to this conceptual framework there are 5 phases.

The first phase was to prepare a geo-data set. The data set included information such as elevation, surface roughness, drainage channel cross section, hydrographs and historical observed flood data. All these maps were prepared based on secondary data and the primary data that were collected during field work.

The second phase involved the development of scenarios based on the objectives and field experience and available data. In the field it was observed that the construction of primary channel has just begun (Figure 4-7). It was also observed that land around the buildings; particularly in the lower half of the study area was raised with soil and sandbags, which has altered the normal elevation. Therefore, three scenarios were developed: **1)** Present scenario would be based on the cross section of the present drainage channel, which was measured during field work. The sub-scenarios under the Present scenario are raised and without raised dikes around the building footprints **2)** Future scenario would be based on the cross section of the future new primary channel. The cross section of secondary and minor channels remains the same as that of Present scenarios. The Future scenario would also have the same sub-scenarios as the Present scenario. **3)** Garbage scenario was to see the impact of garbage on the floods for both present and future scenarios.

The third stage was about the calibration of the model result and simulation of the rainfall event for all the scenarios that are mentioned above.

The model calibration would be done on present raised dikes around the building footprints, which represents the actual present ground elevation. The model calibration would be done in comparison to the flood observed depth data.

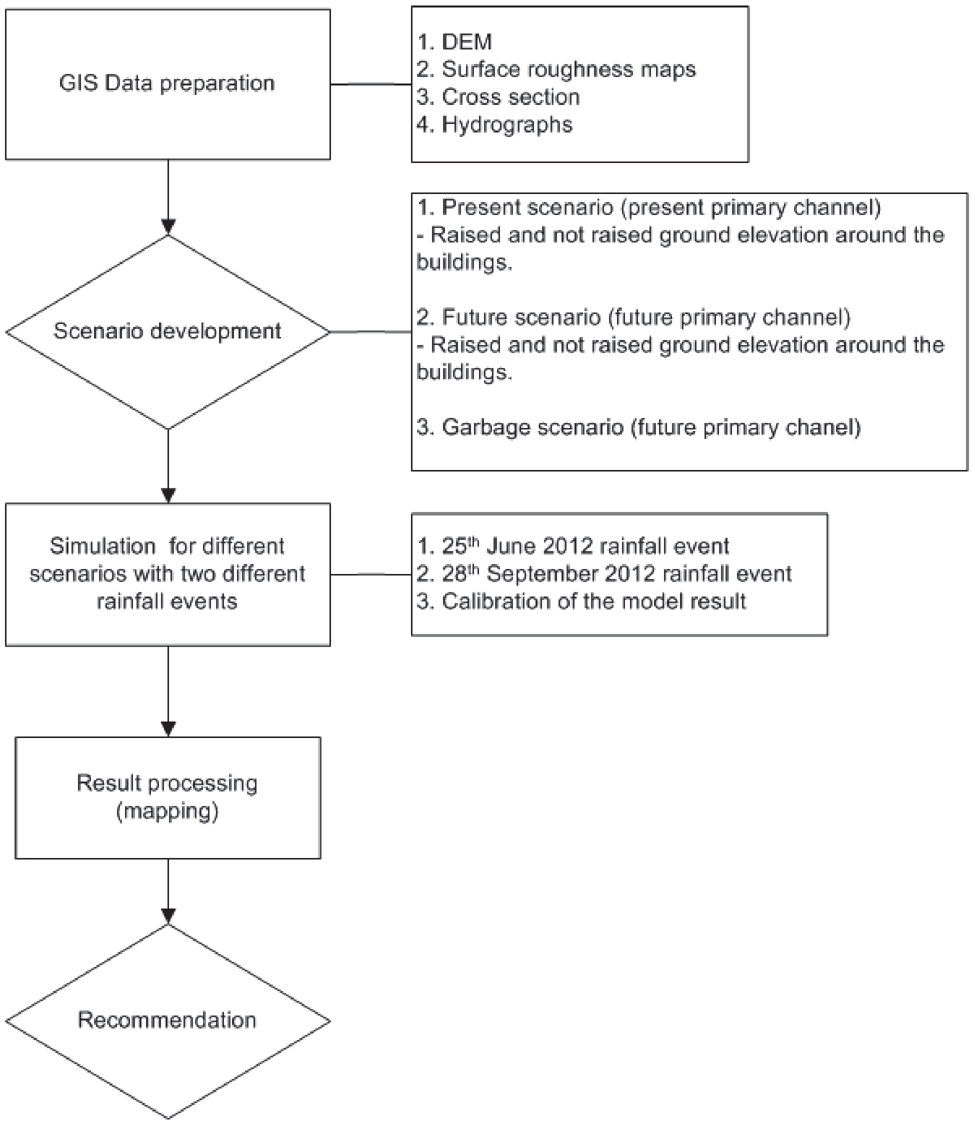

Figure 1-3: Conceptual frame work

1.7. Thesis Outline

This thesis has 6 chapters. The summary of each chapter in is presented as follows:

Chapter one introduces the general back-ground of the research, stating from the research problems in the study area. It also introduces the research objectives, sub-objectives, research questions. Finally, this chapter explains about the conceptual methodology of the research.

Chapter two contains the literature review. The literature review begins with the definitions of various floods in general and their association with the hazard assessment based on the opinion of various organizations, scholars and authors. It also reviews the probability of the flood return period based on rainfall data analysis and water discharge analysis. The literature review also contains the conception and conceiving of flood modelling, which includes 1D and 2D flood models. Finally, coupling of 1D and 2D flood modelling like SOBEK is being reviewed pertaining to their pros and cons.

Chapter three introduces the study area and its associated topics such as drainage system, population, climate, topography and land use/cover.

Chapter four describes the methodology employed and materials adopted for this research. It starts with the description of the methodology flow chart, development of scenarios, data preparation, collection of flood observed data and probability of rainfall analysis and finally it describes in detail about 1D2D SOBEK flood model schematization.

Chapter five discusses the flood model outputs including flood depth accuracy assessment, model calibration and analysis of the flood characteristics of the different scenarios.

Chapter six answers to the research questions and concludes with recommendations.

2. LITERATURE REVIEW

2.1. Flood Hazard Assessment

There are different types of floods. A flood is defined as water inundating land which is rarely submerged and in the processes causing threat to the properties and lives (Westen et al., 2011). Floods become disaster when they come in contact with society, properties and the environment and destroy them beyond the coping capacity of the affected society (UNISDR, 2009). The effect of floods all over the world has become increasingly unprecedented which increases the concern of both public and government of all parts of the world. Many countries focus on strengthening their capacity in hydraulics, hydrology, hydrometeorology, probability, geography information systems, statistics, remote sensing, hydrometry, socioeconomic analysis, etc to combat their impact through flood risk assessment and management (Han, 2011).

The causes of floods are attributed to different hydro-meteorological events. The UNISDR (2009) states that floods are caused by hydro-meteorological events such as thunderstorms, tropical cyclones, blizzards, tornados, hailstorms, heavy snowfall, coastal storm, avalanches, surges and volcanic eruption materials. Therefore, floods could be differentiated based on the different types of events. The types of floods are local floods, riverine floods, coastal floods, flash floods, fluvial floods, pluvial floods, urban floods, groundwater floods, ice jam floods and dam break floods etc. (FEMA, 1997; Han, 2011; WMO & GWP, 2007).

The study related to flood hazard is known as flood hazard assessment. The flood hazard assessment includes the probability of return period, temporal and spatial occurrence, the magnitude and its parameter such depth, velocity, impulse, rising water level, warning time and duration of the floods (Alkema, 2007; Schanze et al., 2007; Westen et al., 2011). The flood hazard assessment is the basis to carry out further study about vulnerability and elements at risk.

2.2. Flood modelling

Flood modelling is about the simulation of water that flows inside and outside the drainage channels by means of digital representation. Flood modelling in urban area has been considered very important for several seasons. Firstly, urban areas are the central administrative, economic and social affairs where large elements such as buildings, roads, vehicles and people are exposed to floods. This has demanded the need to manage floods. Secondly, the development of information and communication technology (ICT) has paved opportunities for the development of effective flood management information systems. Thirdly, the development of urban hydro-informatics has enabled flood modelling for different flood parameters such as flood depth, extent, flood rising water level and time (Vojinovic & Tutulic, 2009). Furthermore, flood modelling has enhanced flood management because of its potential in the simulation of flood dynamics within a certain time frame, giving enough time for decision makers and society to response to floods proactively. Flood modelling shows how much water can be accommodated inside the river bed or drainage channels and how much will flow out during floods. This has proven to be very useful for flood hazard assessment and mapping flood hazard in order to analysis the consequences of floods and the effects of measures (Jonge et al., 1996). There has been tremendous development in GIS-based flood modelling, ranging from simple 1D to sophisticated 2D flood models. Sui and Maggio (1999) stated that in the last 10 years much progress has been made in the development of hydrological modelling techniques and simulation due to integration of geographical information system and hydrological modelling by GIS users. All this hydrology and hydraulic modelling techniques has been widely used for flood risk assessment and management (Pender & Neelz, 2007).

2.2.1. 1 dimensional (1D) flood modelling

1D flood modelling is purely about the simulation of surface runoff that has a predefined direction of flow. It is assumed that water in the river bed or drainage channels flows parallel to the centre line of its bed or channel (Susetyo, 2008). It is assumed that water in the river bed or drainage channels flows parallel to the centre line of its bed or channel (Susetyo, 2008). It means that water flowing perpendicular to its river bed or channel is not considered by 1D modelling. Therefore, 1D modelling cannot be applied for overland floods and backwater effects due to coastal tides or dams (Lindenschmidt et al., 2008). However, Werner (2001) states that 1D modelling can be used to assess the extent and depth of flooding through calculating water level using a 1D flow model and an extended inverse distance interpolation method within lesser computational time than 2D modelling. 1D model is largely used for simulation of surface runoff, soil erosion processes, mud flows, effect of rainfall on the soil erosion and vegetation (Baartman et al., 2011; Chaplot et al., 2005; Jetten, 2012).

Some of the popular 1D hydrology models that are widely used are HEC-RAS, which is produced by the US Army Corps of Engineers, MIKE 11 by Danish Hydraulic Institute (DHI) and LISEM (the Limburg Soil Erosion Model) by Utrecht University, the Netherlands(Els, 2011; Pappenberger et al., 2005; Rahman, 2006).

2.2.2. 2 dimensional (2D) flood modelling

2D modelling is used for modelling estuaries, lakes, bays and coastal area when it was developed initially in the late 1970s, but now due to development of high-tech computer, which has more computational power, it has been applied to flood simulation in larger and more complex areas. 2D model is very suitable for assessing flood hazard in the low laying plain areas which cannot be done by 1D model. It is becoming more popular in flood modelling as it can provide flood extent, flood depth and flood velocity based on user-defined time frame (Tennakoon, 2004). 2D modelling basically considers the inputs and outputs uniform within a single pixel depending on the terrain topography. Therefore, as Bishop and Catalano (2001) noted the digital elevation model (DEM) plays a major role in 2D modelling. They suggested that the resolution of DEM should be defined to the smallest size of the features that needs to be presented in the modelling, however, taking into account the computational time that could be handled by the computer. Despite 2D model being more dynamic than 1D model, it has its own drawbacks such as too much demanding for the requirement of data, lengthy computation and furthermore, 2D model cannot incorporate complicated morphology (Lindenschmidt et al., 2008; Purwandari, 2011; Werner, 2001).

Some of popular 2D models are FLS, LISFLOOD-FP, FUFLOW, TELEMAC, MIKE_21 and SOBEK (Combination of 1D and 2D flood models) (Els, 2011; Pappenberger et al., 2005; Rahman, 2006).

2.2.3. SOBEK 1D2D flood modelling

SOBEK 1D2D has been developed at WL|Delft Hydraulics, the Netherlands in the hope of meeting a need that has been growing worldwide to manage excess water that flows from river basins and drainage channels, which creates floods and affects people and properties. SOBEK 1D2D is the combination of 2D over land flow model called 'Delft-FLS' and 1D flow model called 'SOBEK (Rural and Urban)'.In Delft-FLS model, the water level and depth at the centre of cell and its movement between the cells is computed based on the mass conservation and momentum equations respectively. Whereas, in SOBEK 1D model, the mass conservation equation is applied at 1D nodes and the momentum equation is applied at the reached between the 1D nodes based on the equation derived by De Saint Venant (Alkema, 2007; Laguzzi et al., 1998).

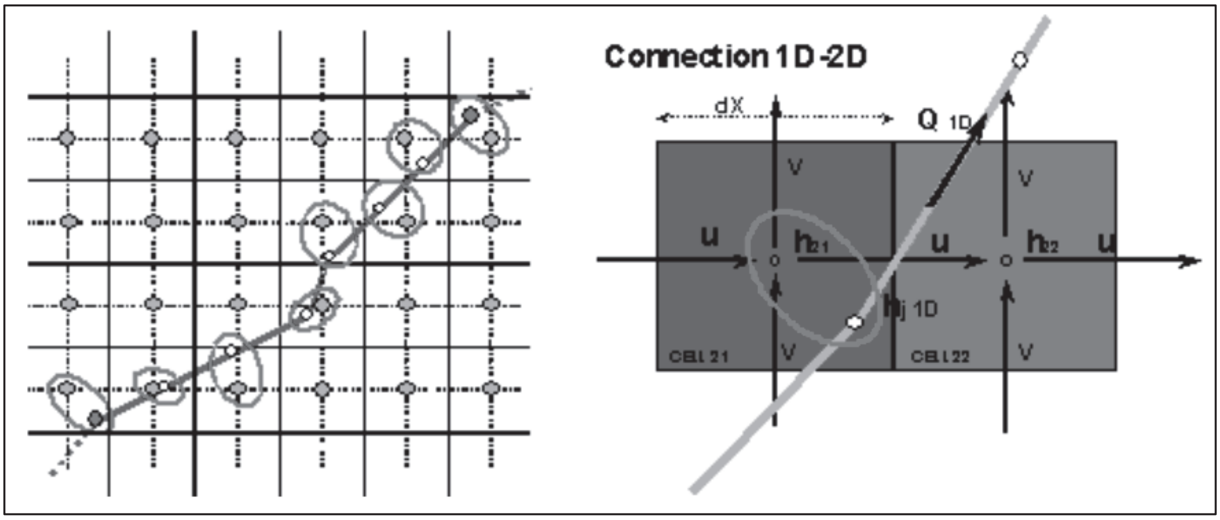

Figure 2-1: Integration of 1D and 2D flood model

(h: water level; u, v: velocities in x and y direction; dx: grid size; Q: discharge in 1D branch)
Source: (Laguzzi et al., 1998)

The above figure 2-1 shows that a 2D grid cell and the 1D node at the same place are fully integrated. The cell 21 is connected with cell 22 by the "u-velocity" (flow in the x-direction). The surface level and slopes of the reaches is determined by the ground levels of the cells 21 and 22. The movement of water in 1D2D model happens between the 4 connected cells. The water that flows diagonally is not being calculated (Alkema, 2007). SOBEK 1D2D flood model is very dynamic flood model that can simulate water for flood forecasting, to plan drainage, irrigation and sever flow systems, river morphology, salt intrusion and water quality as stated in the SOBEK help functionality. The detail mathematical equations of the SOBEK 1D2D flood model as stated in the SOBEK help functionality is explained in Appendix-2.

The advantages of SOBEK 1D2D model as per (Alkema, 2003; Shaviraachin, 2005; Usamah, 2005) are as follows:

1. Coupling of 1D and 2D in SOBEK has enhanced simulation results by replicating the physical behaviour similarly. This has been possible due to 1D model calculates channel flow simultaneously when 2D model calculates over land flow in detail.
2. 2D model alone is less feasible to simulate narrow drainage channel and curving stream as it requires high resolution, which makes 2D model less successful. Whereas 1D2D model has been able to simulate these things as 1D model calculates the narrow drainage channel and curved stream separately.
3. It is suitable for short event predictions like dike break scenario in hours or in days.
4. It is an appropriate model for simulating flow over initially dry area and complex topography.
5. It is very convenient for modeller as pre-processing of data and post-processing of the results works in the same user interface.

2.3. Data Requirement for SOBEK 1D2D Flood Modeling

The data requirements for the SOBEK 1D2D flood modelling are as follows:

2.3.1. Digital terrain representation

Digital terrain can be represented either in digital elevation model (DEM) or digital surface model (DSM) as explained below:

The digital elevation model (DEM) is the digital representation of the elevation of surface topography, which provides level for the flow of water and source for the extraction of hydrologic features (Wechersler S.P, 2007; Wechsler S.P, 2003). The DEM according to Rahman (2006) is the model that defines the elevation of earth surface without considering vegetation and man-made features. According to U.S Geological Survey (USGS) as cited by (Maune, 2001), the DEM is the representation of the elevation of the terrain at regularly spaced intervals in x, y and z direction in digital cartography. The z value refers to a common datum. The resolution of the DEM determines the accuracy of the terrain. The coarser the resolution, the lesser the accuracy it is and vice-versa. The resolution of a DEM recommended for urban flood modelling is between 1x1 to 5x5 meter, which can cover the width of the roads, sidewalks and houses (Mark et al., 2004).

The DEM could be constructed from topographical maps that contain contour lines, spot heights, stream lines and water bodies. More accurate and higher resolution DEMs can be obtained using LiDAR (Light Distance and Ranging). According to Cobby et al., 2001 as cited by (Rahman, 2006), LiDAR can produce very dense elevation information with vertical accuracy of 15 to 20 cm. Other ways of deriving a DEM with comparable terrain accuracy and resolution is Radar Interferometry or InSAR (Rahman, 2006).

Another way of representing terrain for hydraulic modelling is digital surface model (DSM), which is quite different from DEM. A DSM includes the elevation of flow influencing objects such as buildings, roads, embankment, etc., that act like an obstructions against the flow of flood water (Tennakoon, 2004). In case of urban flood modelling, there are many structural elements such as buildings, roads and other infrastructure that has direct influence on the flow of flood water. Therefore, representing those elements on the DEM would have significant effect on the flood characteristics (Bishop & Catalano, 2001; Werner, 2001). Schmitt et al. (2004) suggest that the DEM should include street cross sections, sidewalks and street curbs and border line between public street, sidewalk and private space so as to have real scenario for flood modelling. However, they are receptive that such type of detail information about the surface element would increase the computational time and information may not be available unless one does detail conventional ground observation or obtained by LiDER. El-Ashmawy (2003) found that if the flood plain has more than 10 percent built-up area, the flood extent is affected significantly and flood level rises double than if build-up area is lesser than 10 percent. Tennakoon (2004) used heights of the buildings and roads for the development of DSM for urban flood modelling.

2.3.2. Surface roughness

The second required input for flood modelling is the surface roughness map. The surface roughness map contains different land use/cover features. Land use/cover features determine the resistance against flood water as it flows over. The resistance of the land use/cover features are expressed as values of Manning's coefficient (Alkema & Middelkoop, 2005). The resistance of flood water in the main channels is different from that of the floodplains (Han, 2011).Some of the surface features that have high influence on the velocity of floods are elevation, irregular surface area and depth, density, scale and obstruction of vegetation as per

Kalyanapu, et al., 2009 as cited by (Damayanti, 2011). As per Vente Chow (1959) as cited in (MoLG & KCC, 2002a), the following factors have great influence on the value of Manning's coefficient:

- Surface roughness
- Vegetation
- Irregularities
- Alignment
- Siltation and scouring
- Obstructions
- Discharge or flow depth
- Seasonal changes
- Suspended materials and bed load

There are no concrete standing norms for assigning Manning's coefficient to a particular land use/cover feature. Table: 2-1 shows the different Manning's coefficients for some land use/cover classes. Therefore, assigning Manning's coefficient for particular land use/cover class is usually done during calibration of the flood model, while comparing simulation results with historic flood data such as flood depth, extent or duration etc. The sensitivity of the Manning's coefficient is tested until flood model results get closer to the observed historic flood data.

Table 2-1: Manning's Coefficient from different authors

Land use/cover	Manning's coefficient	Land use/cover	Manning's coefficient
Riverbed	0.008	River bed	0.027
Floodplain	0.011	Flood plain	0.032
Urban area	0.100	Arable land	0.030
Forest	0.150	Pasture	0.050
Arable land	0.050	Forest	0.200
Dike	0.030	Roads and canals	0.020
Heather	0.050	Built-up	0.250
Main road	0.020	*Source: Dinand Alkema (2007)*	
Railway	0.020	Bare land	0.020
Secondary road	0.015	Building	0.100
Water	0.012	Grassland	0.035
Grassland	0.018	Settlement	0.100
Source: D. Alkema and H. Middlekoop (2005)		Water course	0.010
Roads	0.025	*Source: Frieta Damayanti (2011)*	
River	0.030	Low flow earth channels	0.035
Commercial zone	0.032	Papyrus and reeds	0.070
Residential area	0.035	Masonry channels	0.023
Agricultural zones	0.050	*Source: KIIDP (2010)*	
Building footprints	1.000	Bare soil	0.005
Source: Tennakoon (2004)		Built-up	0.150
Bare land	0.020	Forest	0.050
Building	0.100	Grass & Shrub	0.050
Grassland	0.035	Road	0.050
Settlement	0.100	Water	0.130
Water course	0.010	*Source: Ezra Pedzisai (2010)*	
Source: Frieta Damayanti (2011)			

The values for Manning's coefficient in this study were based on the values in the table 2-1, but were adjusted during the model calibration, in the same manner as described by (Pedzisai, 2010).

2.3.3. Boundary Conditions

The boundary conditions define the amount of water that enters from upstream into the area and that leaves the study area downstream. It is, in fact, transition points between the study area and the rest of the world. The water flow at the boundary condition is specified either in discharge (m^3/s) or in water level (m). The discharge could be represented by constant, tabulated function of time or tabulated function of the water level, and the water level by constant or tabulated function of time. The discharge at the upstream boundary condition is usually represented by water level or by discharge in time series. Whereas, the boundary condition at the downstream is either by water level or by a rating curve (Q-relationship) (Alkema, 2007; Rahman, 2006).

2.3.4. Modelling output

The SOBEK 1D2D flood model produces various outputs of flood characteristics, such as maps, time series and a video-animation. The maps can be processed in a GIS to obtain additional flood characteristic maps. All in all, the following maps can be derived from a SOBEK model simulation: (Alkema, 2003, 2007):

- Water level (unit : m) – Maximum inundation depth
- Flow velocity (unit : m/s) – Maximum flow velocity
- Impulse (unit : m^2/s) – Water level * velocity = Quantity of moving water
- Rising (unit : m/h) – Maximum speed of rising of the water level
- Duration (unit : h) – Estimated duration of the inundation
- Warning time (unit : h) – The first flood water to reach a certain location

2.4. Model Calibration

Model calibration is about bringing the results of the model and the field observed data closer by adjusting parameter values within the model. Some of the flood parameters that are mostly used for comparison during the calibration of urban flood models are flood extent and flood depth (Mark et al., 2004). In 1D and 2D flood modelling, it is important to define Manning's coefficient for both drainage channel and overland plain. The surface roughness of drainage channel has more impact on the flood characteristics than that of overland plain. Therefore, while assigning Manning's values, the emphasis should be given more on the drainage channels (Werner et al., 2005). The model calibration is largely done based on adjusting Manning's coefficient that was linked to the land use/cover (Hsu et al., 2000). The Manning's coefficient of surface roughness ranges from 0.001 to 0.9 (Pappenberger et al., 2005)

However, according to the study carried out by Pappenberger et al. (2005), they found out many uncertainties in flood inundation modelling which impacts the modelling results. These uncertainties are structure, numerical scheme, topography, model input/output and parameters. The structure of the model constitutes the development of cross section; density and hydrostatic pressure; interactions between channel and flood plain, which some time include complex flood plain flows; channel boundaries and resistance of surface roughness. All these structural components require a lot of simplifications. The numerical scheme depends on the one's choice about the use of numerical equation for flood modelling. The more detail about the numerical scheme, the better the accuracy of the model result. But, it requires a lot of computational time. Therefore, choosing numerical scheme within the computation time compromises the accuracy of the model result. Another uncertainty under numerical scheme is about the simulation time. It is not clear about the accurate requirement of time step for the simulation. The time step has a great impact on the model result. Regarding the topography, it plays a vital role in the flow of flood water. A small variation in the topography could lead to significant effects on the model result. It is more complex when there are a lot of new development on the topography such as raised land and infrastructure. Whether or not to include such kind of development on the topography has direct effect on the modelling result. The uncertainties are also involved in the input data we used for the flood model. Basically, the input for the flood model is quantified by a discharge hydrograph, which can be rating curves or output of another model. In both the cases, uncertainties have to be considered. The flood modelling output such as flood depth is used to compare with the observed data that are acquired by either manual survey or remote sensing. Such kind of comparison could also cause uncertainties. Another factor that leads to uncertainties is parameter such as surface roughness. The surface roughness influences the flood dynamic significantly at local scale.

3. STUDY AREA

3.1. Location

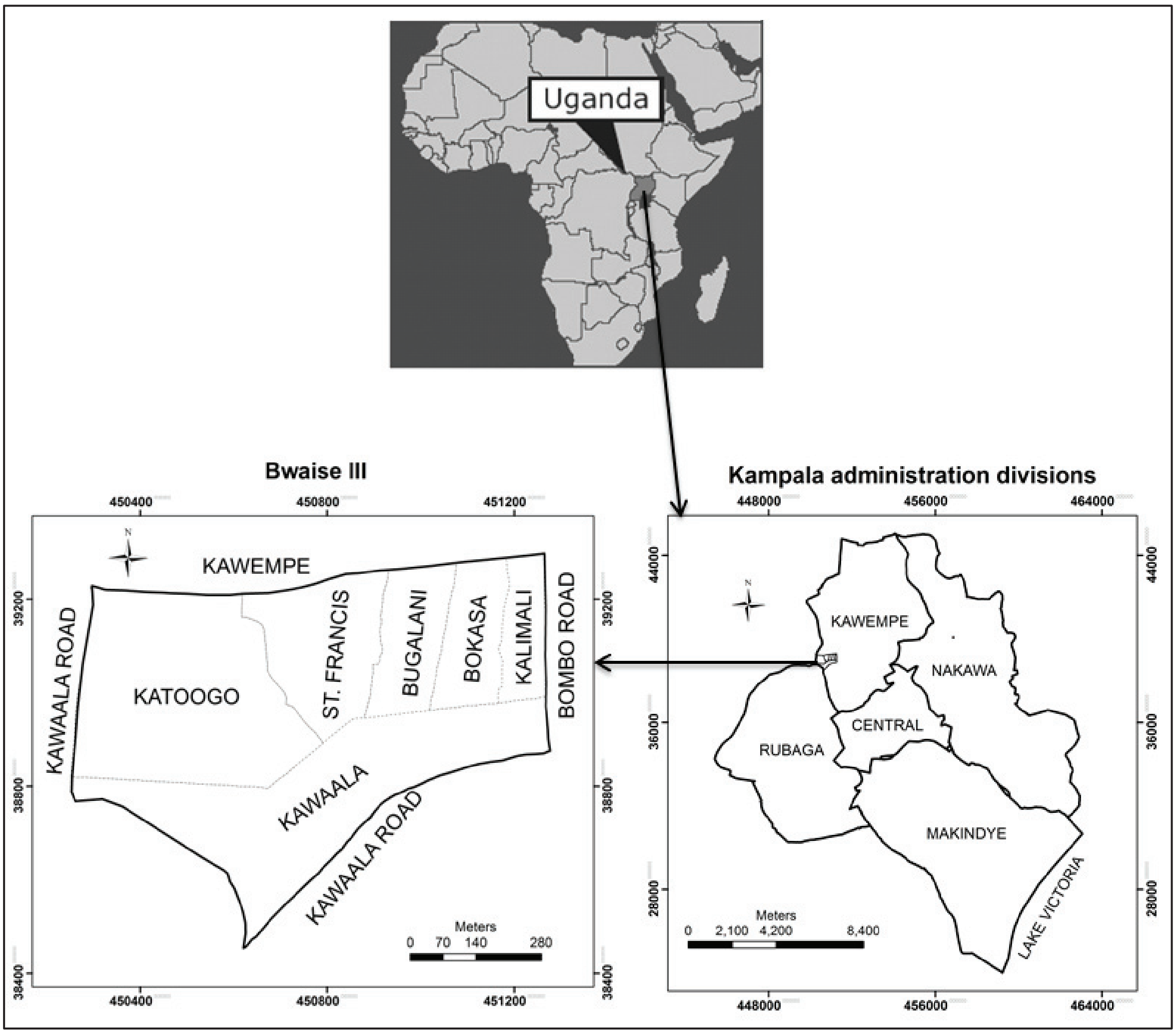

Figure 3-1: Study area(Upper map shows the location of Uganda in Africa and right map shows the Kampala administration divisions and the left map is the study area, Bwaise III, Kampala.)

Uganda is a landlocked country in the east Africa surrounded by Kenya on the east, Democratic Republic of Congo on the west, South Sudan on the north, Rwanda on the southwest and Tanzania on the south.

Kampala is the capital city of Uganda. It is located at $0^{0}18$' north to $32^{0}34$' east and 1,161 meters above the sea level. It is aesthetically located on the northern shores of Lake Victoria, which is the second largest inland fresh water lake in the world. The topography of Kampala runs from gentle to steep slopes joined by valleys with natural streams and wetlands covering an area of 195 km^2 (UN-HABITAT, 2009). Kampala is the centre of economy, political and administration activities. It has a surface area of 190 km^2 and is composed of five divisions: Kampala Central Division, Kawempe Division, Makindye Division, Nakawa Division and Rubaga Division.
This research will be undertaken at Bwaise III Parish, which covers the low laying area of south western part of Kawempe Division located in the north of Kampala city. Its geographical location is $0^{0}21$'02" N and

32°33’30” E. It has an area of 52.469 hectares (KDMP, 2002). The area under Bwaise III Parish is said to be a reclaimed wetland (Kulabako et al., 2007). Bwaise III comprises six local administrative zones, namely: Kalimali, Bokasa, Bugalani, St. Franscis, Katoogo and Kawaala.

3.2. Drainage system

The drainage systems in Kampala city is basically categorised into two parts: Major and Minor systems. The major drainage system comprises natural water channels, streams or rivers, whether or not its bed is artificially channelized. The low laying valleys are being drained by the main major drainage system, which is so called **‘primary channel**’ and its major tributaries are called **‘secondary channels’**. Kampala has eight primary channels (MoLG & KCC, 2002b).

The primary and secondary channels are designed for less frequent storms of higher intensity rainfall events particularly 10 to 20 years return periods(MoLG & KCC, 2002a). Bwaise III is located in the Lubigi wetland areas, which is one of the largest wetlands in Kampala District. The drainage channels in this area falls under the Lubigi drainage system.

Minor drainage system comprises pipes or small open drains that convey surface runoff from roads and in between buildings into major drainage systems. Minor drainage system is being designed for storm water discharges of shorter return periods ranging from one to ten years return period (MoLG & KCC, 2002a).

Figure 4-3 (land use/cover map) shows that the primary channel runs from Bombo Road to Kawaala Road in between Kalimali, Bokasa, Bugalani, St. Francis and Katoogo zones on the right bank and Kawaala zone on the left bank. It is natural earth channel. The secondary channel that joins the primary channel through Bokasa and Bugalani zones is a stone paved channel.

In the hope of minimizing floods and its associated problems, Lubigi primary channel is being redesigned to the capacity of 10 to 100 years return period floods and reconstruction is being carried out under the Kampala Institutional and Infrastructure Development Project (KIIDP) (KCC, 2010).

3.3. Population

The population of Kampala City as a whole is 1.2 million in 2000 and it is projected to grow up to 2.7 million by 2020 and to 4.8 million by 2040 (MoLG & KCC, 2002b). The population density is 27,000 people per km^2 (Herzog, 2007). The population of Bwaise III is 15,015 with an annual growth rate of 9.6% (Kulobako, 2010), which is double the average rate (3.8%) of Kampala City. The population of Bwaise III is projected to grow to 21,887 by 2020, to 33,719 by 2030 and to 54,241 by 2040. The population density was 200 per hectare in 2010 and projection is 751 per hectare in 2040 (MoLG & KCC, 2002c). The average household size in Kampala as a whole is 4.2 persons (MoLC & KCC, 2002).

3.4. Climate

The climate in Kampala is generally tropical associated with the inter-tropical convergence zone (ITCZ), a low pressure and heavy precipitation zone that occurs near the equator (NEMA, 2009). The migration of ITCZ towards south in October to December and towards north in March, April and May causes two distinct rainfall seasons in Kampala. The rainfall between October to December is the lighter and between March to May is heavier and longer. The monthly average precipitation as shown in Figure 3-2 is between 50 to 200 mm with some months exceptionally exceeding 300 mm per month (C. McSweeney et al., 2006-2013). However, some form of lighter precipitation occurs in between dry seasons which make seasons wet throughout the year (S.A. Radwanski, 1960).

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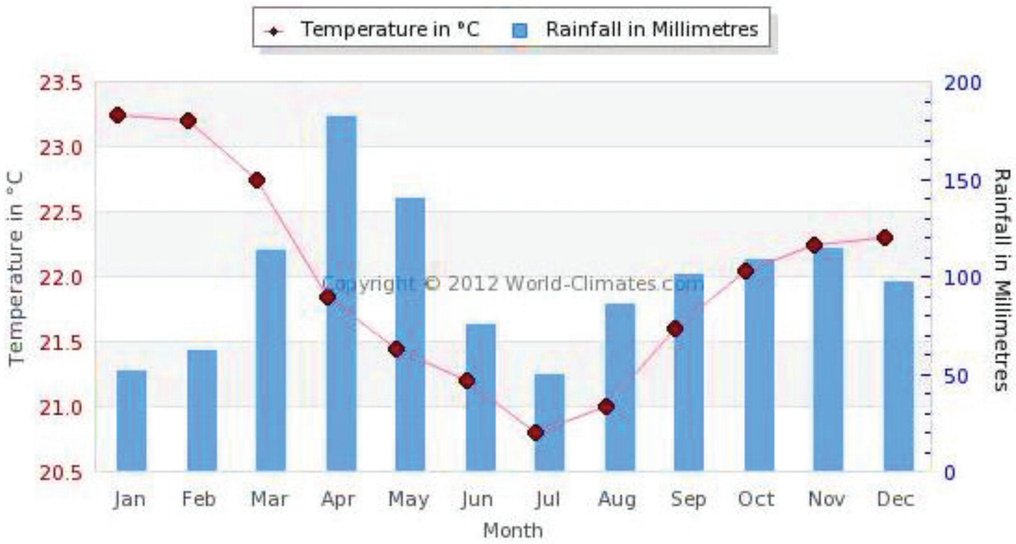
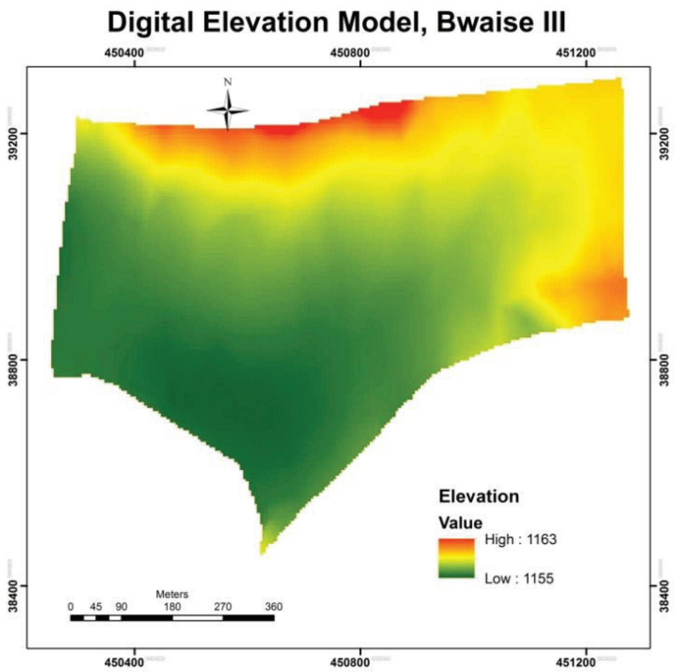


Figure 3-2: The climate graph of the average temperature in degree Celsius and the average monthly rainfall in millimetres for Kampala, Uganda

Kampala despite being in the tropical zone, its average temperature is cooler than what is typically seen in other parts of the tropical climate. This is because of its high altitude (1,161 m) that moderates the hot temperature. The Figure 8 shows the average monthly temperature ranges between 20^0C to 24^0C, which is very moderate.

3.5. Topography



The topography of Kampala comprises gentle undulating hills connected with low lying flat wetlands. Bwaise III is located in one of the low lying flat valleys of Kampala. The topography of Bwaise III is largely flat area with small differences between low and high elevation. The elevation ranges from the lowest 1155 m to the highest 1164 m above the sea level covering an area of 0.53 km^2.

Figure 3-3: Digital Elevation Model (2 meter pixel resolution) of Bwaise III

Source: ITC

3.6. Land use/cover

There has been a drastic changed in the land use/cover over a period of three decades (Appendix-1). This changed in land use/cover is mainly attributed to the deforestation and urbanization as it is the capital city for administration and commercial business(NEMA, 2009).

Upon validation during field work the land use/cover of Bwaise III comprises buildings, highway road, unpaved road, paved road, grass, open area, minor channel, secondary channel and primary channel (Figure 4-3).

The total area coverage of the study area is 0.53 km^2 (Table 3-1).

Table 3-1: Area coverage by land use/cover

Sl.No.	Land use/cover	Area (Km2)	Area (%)
1	Open area	0.193	36.7
2	Building	0.133	25.4
3	Grass	0.120	22.8
4	Highway road	0.029	5.5
5	Unpaved road	0.021	4.0
6	Paved road	0.013	2.4
7	Minor channel	0.009	1.8
8	Primary channel	0.007	1.3
9	Secondary channel	0.001	0.2
Total		**0.525**	**100.0**

4. METHODOLOGY

4.1. Scenario design

The detail processes of methodology of the research is shown in Figure 4-1. Two different DEMs were prepared upon field observation. One DEM contains the raised highway and the another DEM contains raised higheay and the dikes around the buildings . The resolution of the DEM was resampled to 2 meter in order to accommodate for the drainage channels. The land use/cover map was initially digitised as per satallite Geo Eye image, which has 50 cm resolution and it was later validated in the field work.

Two different land use/cover maps were parpared based on availability of data. First, the Present scenario map (Figure 4-3a) is based on the current cross-section of the channel, which was measured during field work. The second scenario map (Figure 4-3b) so called the "Future scenario", was based on the future – enlarged - cross section of primary channel as designed by the Kampala Institutional and Infrastructure Development Project (KIIDP) document as shown in Figure 4-7.

Historical flood data such as flood depth, duration and extent were collected during field work. However, only the observed flood depth was used for model calibration. The accuracy assessment of observed food depth data was carried out according to participatory approch (detail in section 5.1) before it was being used for the model calibration. The model calibration was done based on the Present scenarion with Raised dikes aroung the building footprints, which represents the present topography. Upon calibration, the same Manning coefficient of 1D channel and 2D surface roughness map was applied for the simulation of other flood scenarios.

Scenarios were designed based on criteria described in section 1.6 as reiterated hereunder:

1) Present scenario based on the present cross section of the drainage channels, which was measured during field work. The sub-scenarios were created as raised and without raised dikes around the building footprints.

2) Future scenario based on the cross section of the future new primary channel. The cross section of the future primary channel is shown in Figure 4-7. The cross section of secondary and minor channels remains the same as that of present scenarios. The Future scenario would also have the same sub-scenarios as the Present scenario.

3) Garbage scenario was developed to see the impact of garbage on the floods for both present and future scenarios. Garbage scenarios were modelled on Present scenario with dikes and Future scenario with dikes taking into account that 50 percent of drainage depth was reduced for Present scenario and 25 percent, 50 percent and 75 percent of drainage depth reduced for the Future scenario. The Garbage scenario for the Future scenario was given more focus than the Present scenario as Bwaise III would be receiving the new big primary channel very soon. The reconstruction of new future Primary channel is underway.

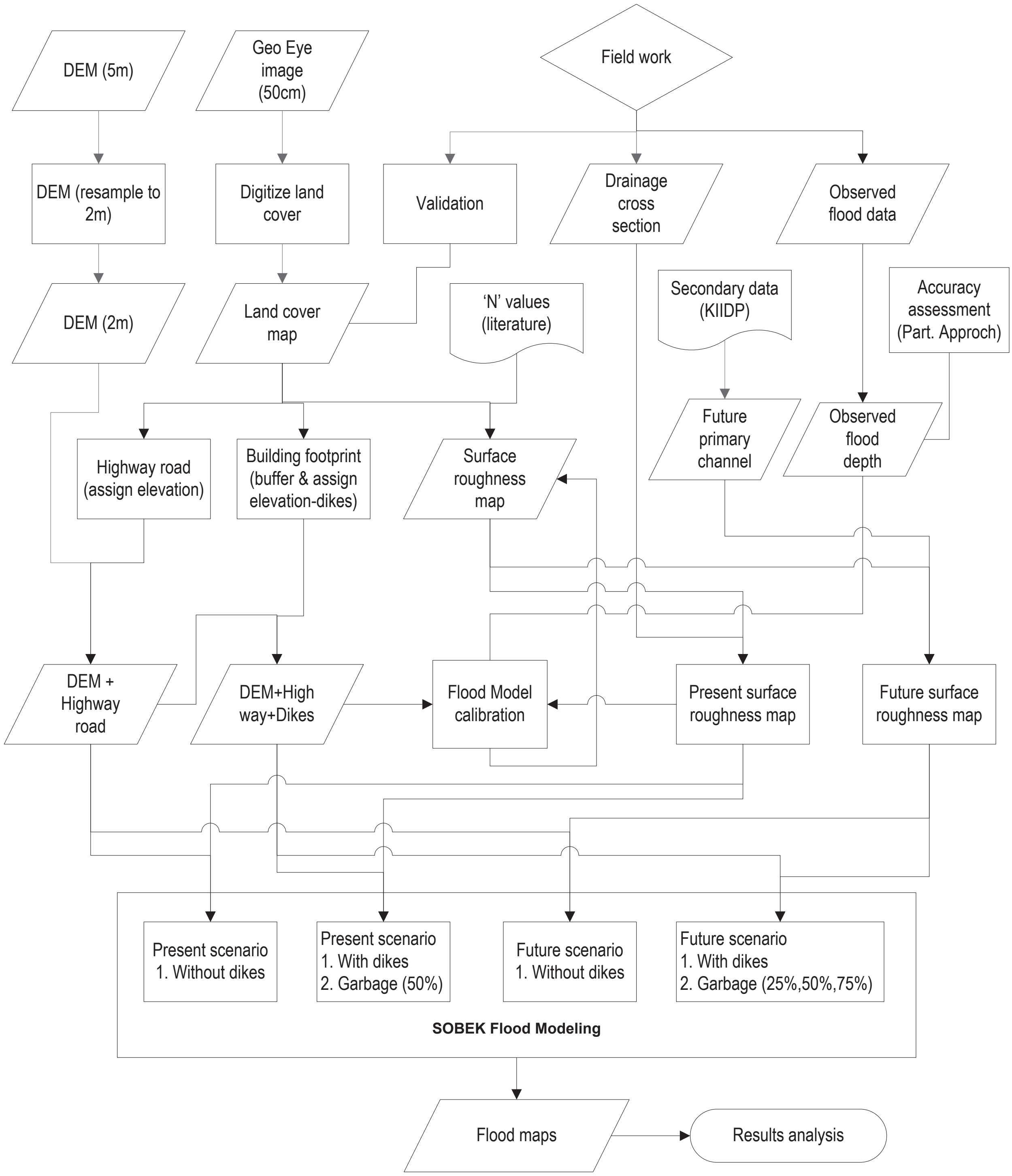


Figure 4-1: Methodology flow chart

4.2. Elevation data

A 5 meter resolution DEM was provided to us for this research purpose (source: ITC). To make it suitable for this research, the original DEM was masked with the study area boundary and resampled it to 2 meter pixel resolution. The pixel resolution of 2 meter was found an appropriate for this flood modelling as it not only shows small drainage channels but also computes within reasonable time frame. It has 513 columns and 422 rows.

This DEM does not contain recent developments such as highway that runs through Kawaala zone and raised dikes around the buildings which was put to protect from incoming flood water.

The elevation of the highway was collected during field work with GPS and leaser measuring tool. The lowest point of the highway at Kawaala road is 2 m above the surface level and it rises consistently up to 7 m till Bombo road. The dikes around the building footprints was buffered to the length of 3.5 m and allotted height of 0.25 m. The elevation of the highway and the dikes were added on 2 m pixel resolution DEM as shown in Figure 4-2.

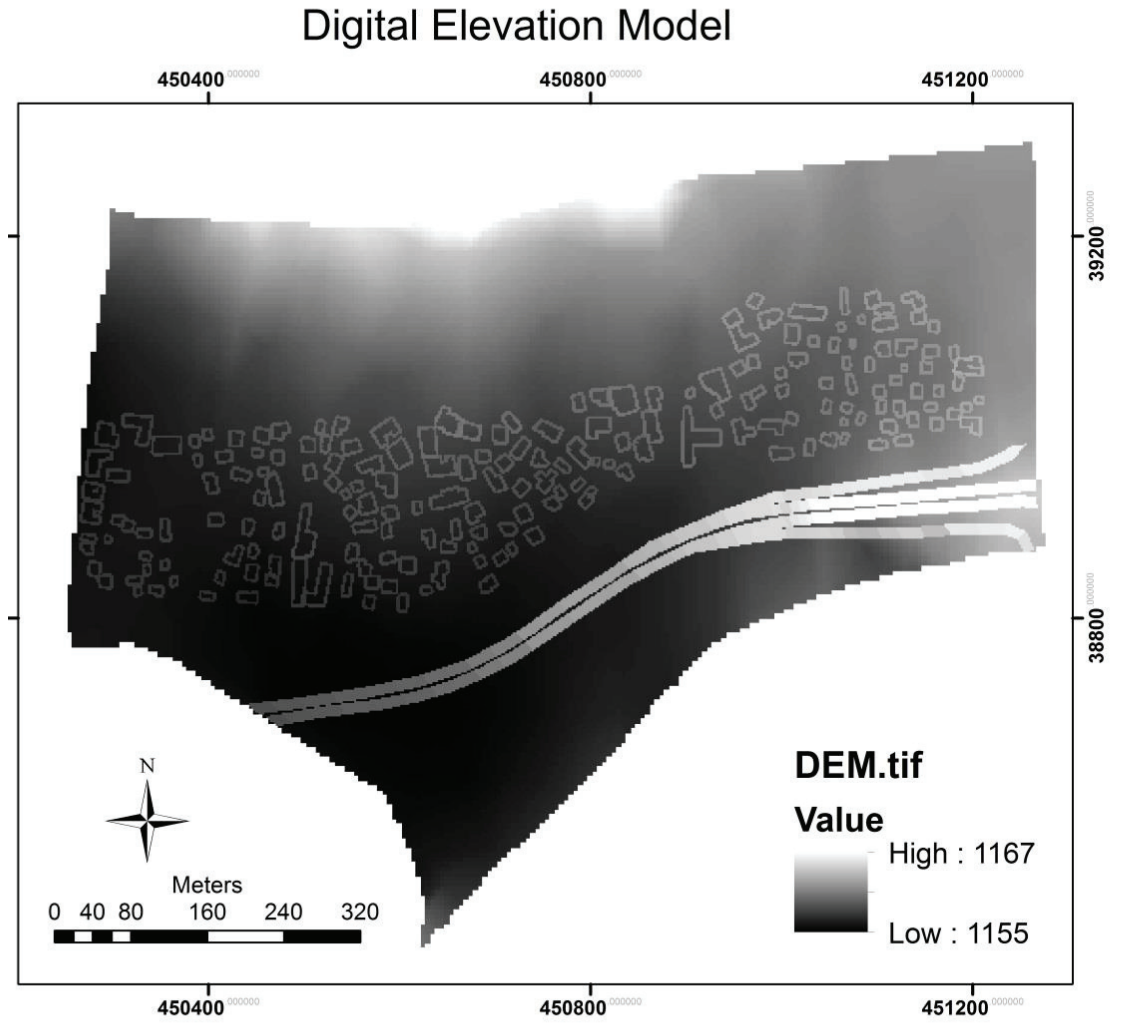


Figure 4-2: The modified DEM of the study area.

Finally, the DEM was converted into asci (.asc) format, which is suitable for SOBEK 1D2D flood model.

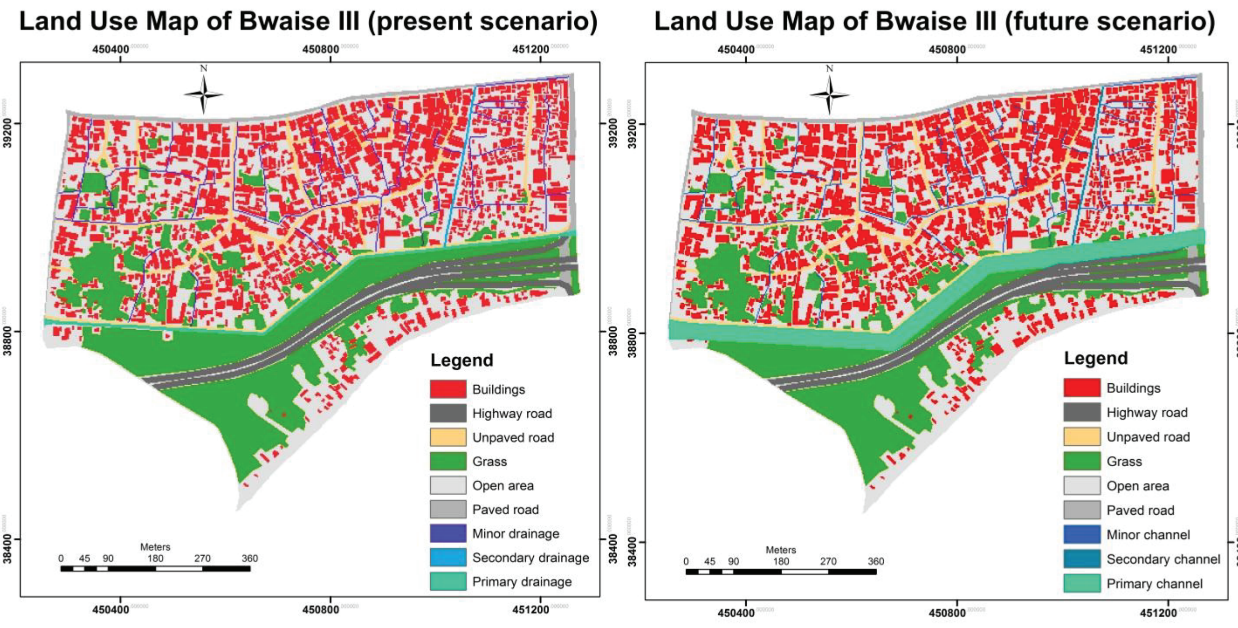
4.3. Surface roughness map

The surface roughness map is derived as attribute map from the land use/cover map. The land use/cover map was derived from a high resolution satellite Geo Eye image (50 cm resolution) and later validated with field observation. All land use/cover features were digitized except building footprints. The building footprint map was done by Makerere University, Kampala. The steps involved for processing the surface roughness map were as follows:

- Each land use/cover feature was digitized;
- Primary, secondary & minor channels were buffered according to the respective width of the channels (5m and 31m for present and future primary channel respectively, 4m for secondary channel and 1m for minor channel);
- Merge all the land use/cover features and inserted column in the attribute table with Manning's coefficient values. The Manning coefficient values of respective land cover features were derived from literature review as discussed under section 2.3.2 (Table 2-1).
- Rasterised the land cover map with field value (Manning's coefficient value) at 2 meter resolution, which is the same as DEM.

The land cover map comprises nine classes (buildings, open area, grass, highway road, unpaved road, paved road, minor channel, primary channel and secondary channel) as shown in figure 4-3.The spatial reference for both the land cover maps were allotted the same as that of DEM.

The land use maps were converted into asci (.asc) format as desired by SOBEK 1D2D flood model.



a) **b)**

Figure 4-3: Land use/cover of Bwaise III

(The land cover map for present scenario (a) is based on field observation and the future (b) land use map has the same cross section for secondary and minor channel, but the cross section of primary channel is based on future plan (KIIDP-Figure 4-7). The future primary channel is bigger than present primary channel.

4.4. Drainage cross-section

The drainage cross-sections were measured during field work. The cross-section includes bottom width, top width and depth. It was observed that all drainage channels are open channels. Though there are a few culverts and small bridges, they don't have any effect on the size of the drainage channels as they were just a concrete slab laid over the channels. This does not have any effect on the flow of water nor flood propagation. Therefore, drainage channel in this research is considered as open channels. Altogether 92 points of cross-sections were measured during field work.

During measurement of the drainage cross-section, garbage inside the channels was also looked into so as determine whether or not the drainage dimension is being undersized due to garbage blockage. However, it was observed that garbage was not an issue as the community do cleaning two times a week under the supervision of Kampala City Council.

4.5. Observed flood data

The flood observed data such as flood depth, duration and extent were collected from the local people who had experienced floods in the last year. 13 flood depth points were collected. The local people do not have clear memory of the exact date of the floods. Therefore, it is assumed that the observed flood depth would correspond to highest rainfall event of the last year (25th June 2012), which caused floods. Flood depth was obtained from the height of a man and wetting marks on the wall. The wetting marks on the wall seem deceiving as soil in-filled around the building has distorted the real ground elevation. Therefore, most of the flood depth obtained was from the height of the people. The people's lack of knowledge about the flood extent was the main setback for obtaining flood extent. The flood extent shown in Figure 4-4 was based on personal perception. Upon interview, lower part of the area gets flooded and upper part of the area is not flooded. People in the upper part of the area say that water comes and goes and does not create floods. The flood duration obtained from the local people ranges from 12 hours to 72 hours (Appendix: 3). 7 upstream boundary condition (one-Primary channel, one-secondary channel and 5-minor channels) and 3 downstream boundary condition were observed as shown in Figure 4-6.

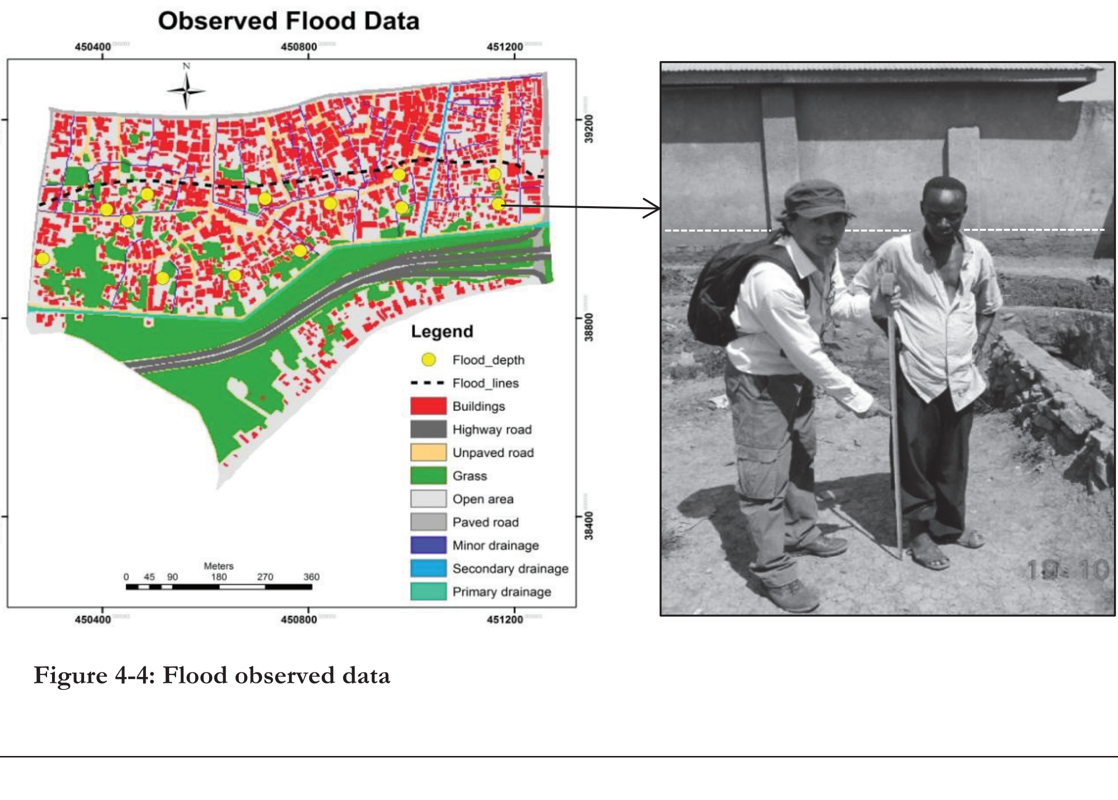


Figure 4-4: Flood observed data

4.6. Frequency analysis

The frequency analysis is to see the relationship between the magnitude of the event and its frequency of the occurrence. In most cases, the relationship between the magnitude and the frequency of the event is an inverse relationship. The bigger the magnitude, the lower the frequency and vice-versa. In any case, both of them could lead to disaster. Low magnitude of rainfall may lead to drought and high magnitude of rainfall could cause floods. Therefore, the hydrologic data could be assessed to relate the magnitude and frequency of the event through the use of probability distribution by means of selecting hydrologic data that could be space-independent, stochastic and time-independent. One of the methods that consider all these requirements is extreme value distribution by Gumbel method, which has been used worldwide. For return period analysis of rainfall, an annual maximum rainfall is considered and for floods the annual maximum discharge is considered (Khazaei et al., 2012; Westen et al., 2011).

According to Chow et al., 1988 as cited by Rugai (2008) the rainfall frequency analysis is designed based on extreme values, which could be either the largest or the smallest with a constant time interval of one year between the values of the event. If the largest value is considered, it is an annual maximum series and if the smallest value is considered, it is an annual minimum series.

In this research the Gumbel extreme method is employed since the extreme rainfall event is likely to cause floods. This extreme annual rainfall analysis will determine the return period of rainfall event that is used for this flood modelling. The observed annual maximum daily rainfall (mm/day) from 1991 to 2009 (19 years) recorded at Makerere university, which is just one and a half kilometre away from the study area is considered for this research. The processes of Gumbel extreme method according to Viessman et al., 1989 as stated by (Coto, 2002) is described in Appendix-6.

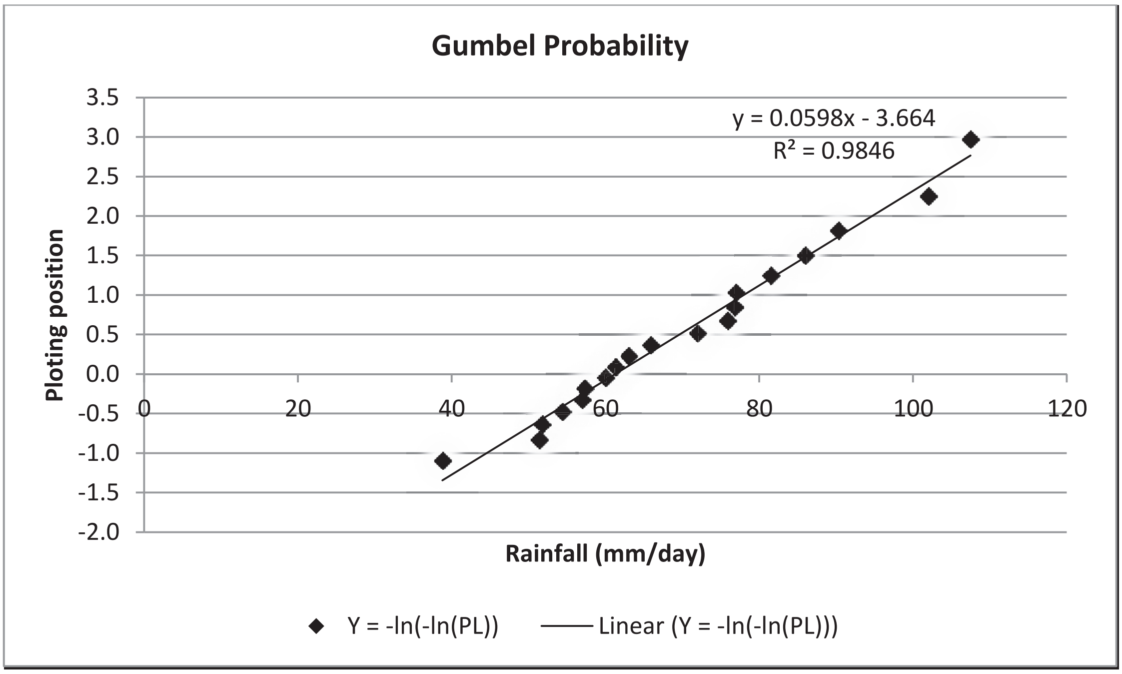


Figure 4-5: Gumbel extreme probability distributions

The Figure 4-5 shows the plotting position of each observation against the annual maximum daily rainfall with the trend line, which gives Y formula. This formula is used to calculate the return period of the rainfall event (Appendix-6).

The highest rainfall in 2012 was 66.2 mm of 25th June and the second highest was 31.4mm of 28th September (Appendix-7) in Kampala. The two rainfall events were used by Mr. Aidan, MSc, UPM, ITC for hydrology assessment with 1D LISEM model to determine surface runoff. According to Gumbal extreme probability distribution as calculated in the table (Appendix-6), the two rainfall events correspond to 2 and 1 year return periods respectively.

4.7. Schematising the model

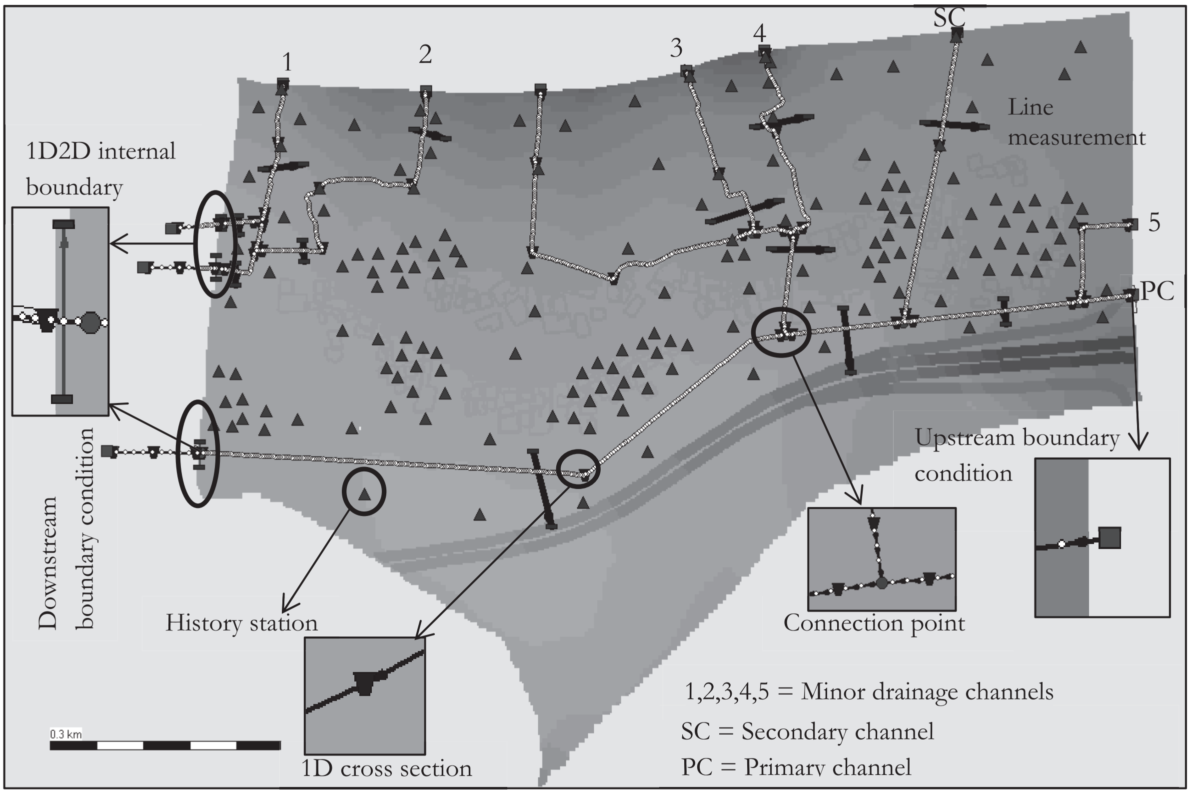


Figure 4-6: Model schematizations

The model schematization is all about replicating the real-world in flood model. The interface provides all the required tools such as import of GIS map layer, add or delete node and reaches, coloring of maps, adding title, zooming, viewing results and printing maps or schematizations.

The first activity is to import the 2D grid, the DEM in ASCII format. Upon importing DEM, a drainage channel shape file was imported. The drainage channel shape file is the bases for creating 1D drainage channel network over the DEM. The connection between the DEM and the drainage channel network is very important as model models 1D flow for the water that flows within the channel. When the flow of water exceeds the capacity of 1D drainage channel, the 2D model activated automatically to simulate over land flow and water that leaves the study area at downstream.

The cross sections define the dimension of the drainage channel for 1D flow calculation. The surface level was obtained from the DEM and bed level was obtained by subtracting the depth of the cross section from surface level. The type of cross section that defines the geometry of drainage channel is Trapezium. The following cross section was based on the average measurement that was taken from the field work and the KIIDP document for present and future scenarios respectively.

Present Scenario:

Primary channel cross section	: Top width ~5m; Bottom width ~ 3.5m; Depth ~ 2m
Secondary channel cross section	: Top width ~ 4m; Bottom width ~ 2.5m; Depth ~ 1m
Minor channel cross section	: Top width~ 2m; Bottom width ~ 1.5m; Depth~ 1m

Future Scenario:

Primary channel cross section (Figure 4-8): Top width~ 31m; Bottom width ~ 31m; Depth ~ 1.75m.

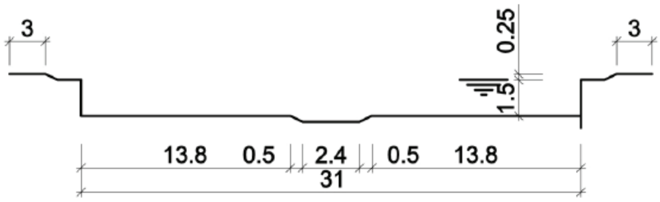


Figure 4-7: New cross section for future primary channel
Source: (KCC, 2010)

Secondary& Minor channel cross section: Remains the same as present scenario.

4.7.1. Adding boundary data

There are 7 upstream boundary conditions and 3 downstream boundary conditions as shown in Figure 4-6.

The following hydrographs of 25th June 2012 rainfall event were used for upstream boundary conditions.

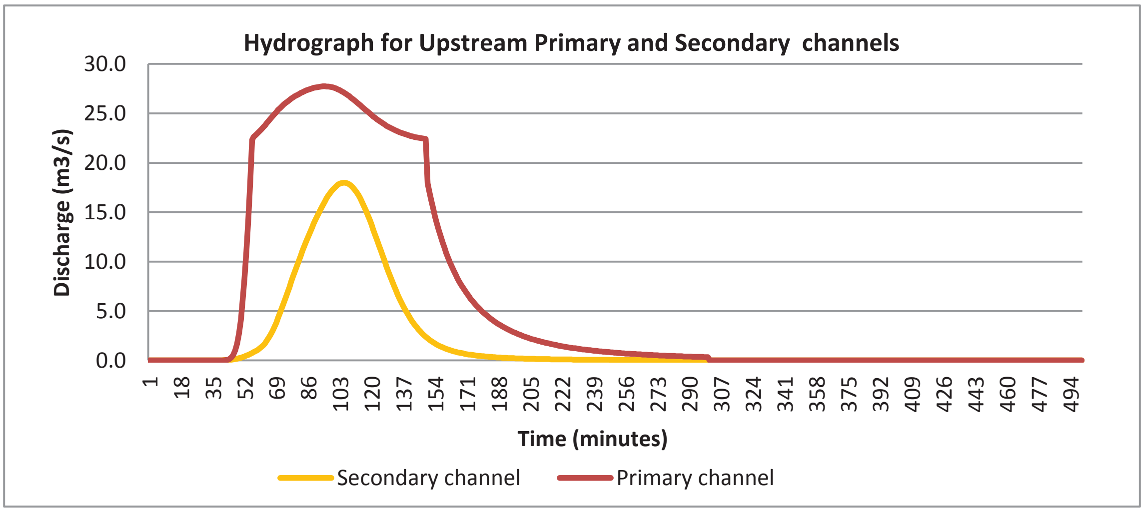


Figure 4-8: Hydrograph of 25th June 2012 rainfall event for upstream primary and secondary channels

(Source: Aidan, MSc, UPM, ITC)

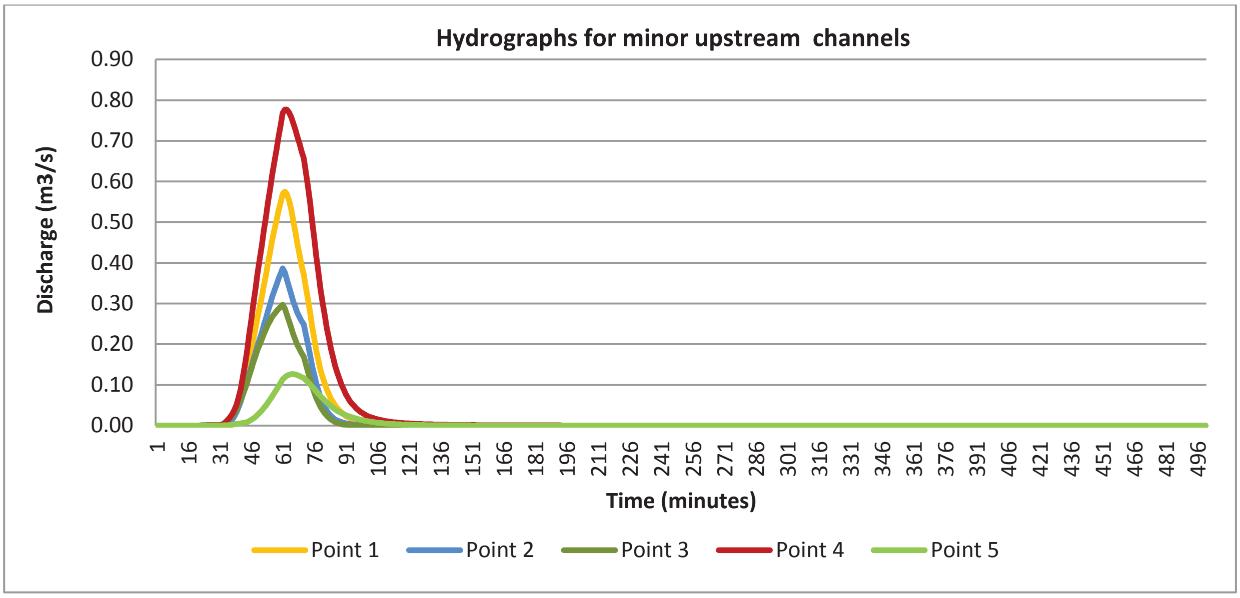


Figure 4-9: Hydrographs of 25th June 2012 rainfall event for upstream minor drainage channels

(Source: Aidan, MSc, UPM, ITC)

The downstream boundary condition of the study area was considered as constant water level above the reference level.

5. RESULTS AND DISCUSSION

There are six different types of flood characteristics that can be derived from the SOBEK 1D2D flood model as mentioned in section 2.3.4. This research has analysed only the flood depth owing to the limited time. The simulation was carried out based on the 25th June 2012 rainfall event, which was the highest rainfall event of the year. The rainfall measured was 66.2 mm/day. The second heaviest rainfall of the year was 29th September 2012 rainfall event, which measured 31.4 mm/day. The probability of the return period of the two events is 2 years and 1 year respectively according to Gumbel probability method mentioned under section 4.6 and it corresponding calculation shown in Appendix-6.

In this chapter we present the results of participatory approach, model calibration and flood model outputs.

5.1. Participatory approch

The first step in the analysis was to check the validity of the flood depth values as they were reported during the survey. The flood depth observations were transferred to water level, by adding the elevation at the observation points (derived from the DEM) to the depth values. Logically all water level points should be located on a plane – that maybe slightly inclined, corresponding to the natural flow gradient. To test this the observation points were ordered from the North-East (Upper Right in the map) of the area towards the South-West (Lower Left in the map). The process is shown in Appendix-8. Figure 5-1 shows that all observed water levels are closely aligned with the general gradient. From this it was concluded that the observed flood depth observations were sufficiently reliable to be used in the further analysis.

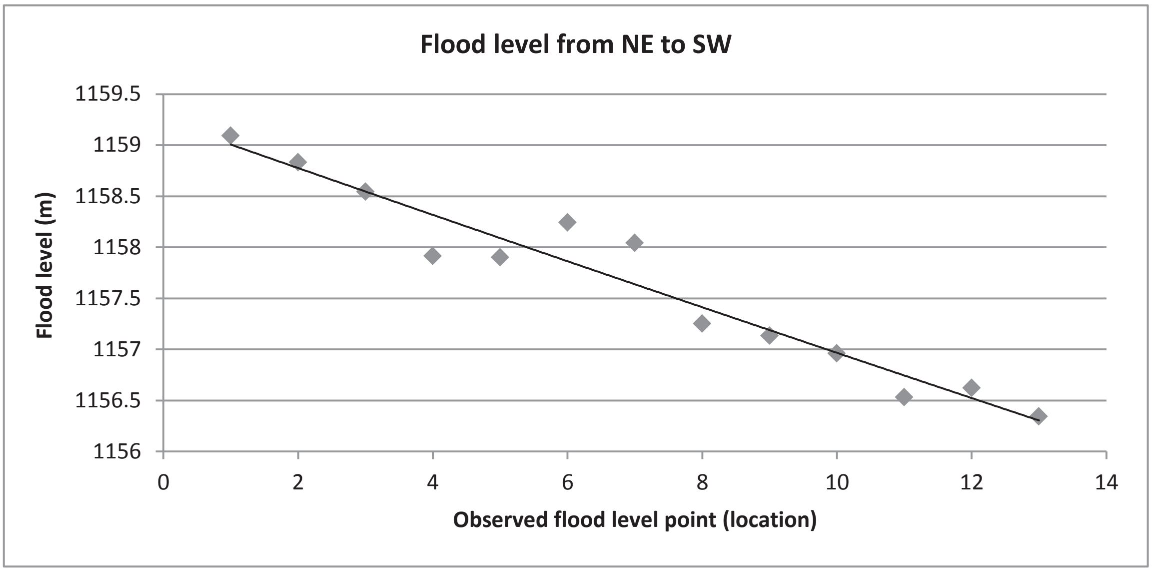


Figure 5-1: Flood level from Northeast to Southwest

The Figure 5-1 shows that the four observed depth are below the trend line and two above the trend line. The points below and above the trend line shows the flood depth is under estimated and overestimated respectively. The possible reasons based on the field observation for those flood depth deviating from the normal trend line could be as follows:

- As stated above the actual elevation around the buildings have been altered due to infilling of soils around the building. Some flood depths measured from the wetting marks on the building wall have led to over estimation and some under estimation of the flood depth.
- The wetting marks on the building wall could have been increased from the actual flood level due to capillary suction as building materials are made of mud and cement. This could overestimate the flood depth.
- The flood depth obtained from the people's body seems over estimated. The people seem to be exaggerating while giving flood information in the hope of receiving support from outside or government.

5.2. Calibration

Model calibration is to fine-tune the parameters of the model so as to reduce the deviation between the model results and the observed flood data. As discussed in section 2.4, there are many factors that affect the flood model results. In this research, the Manning coefficient values of 1D channel and 2D surface roughness were considered for the calibration of the model results besides considering the observed flood depth and the Present scenario, which represents the real elevation.

The Manning coefficient values of 1D channel and 2D surface roughness for initial Run-1 were selected based on the literature review (Table 2-1) that befits the surface roughness of the study area.

First, 5 runs were made mainly focussing on the Manning coefficient values of 2D surface roughness of land use features as shown in the Table 5-1.

Table 5-1: Different Manning coefficient values used for 1D and 2D land use.

Run	Manning coefficient values for 2D land use and 1D channel										Remarks
	Building	Primary channel	Secondary channel	Minor channel	Unpaved road	Highway road	Paved road	Grass	Open area	1D channel	
1	1.000	0.035	0.023	0.023	0.050	0.020	0.020	0.070	0.020	Secondary & Minor channels:0.023 Primary channel: 0.035	Initial run
2	1.000	0.053	0.035	0.035	0.075	0.030	0.030	0.105	0.030	Minor channel: 0.035	1D & 2D Increased by 50%
3	1.000	0.053	0.035	0.035	0.075	0.030	0.030	0.105	0.030	Minor channel: 0.1	2D remains the same
4	1.000	0.070	0.046	0.046	0.100	0.040	0.040	0.140	0.040	Minor channel: 0.2	2D increased by 2 times
5	1.000	0.140	0.092	0.092	0.200	0.080	0.080	0.280	0.080	Minor channel: 0.2	2D increased by 4 times

The simulated flood depth was recorded and plotted along with the observed flood depth data as shown in the Figure 5-2 to see which simulation result is closer to the observed flood depth.

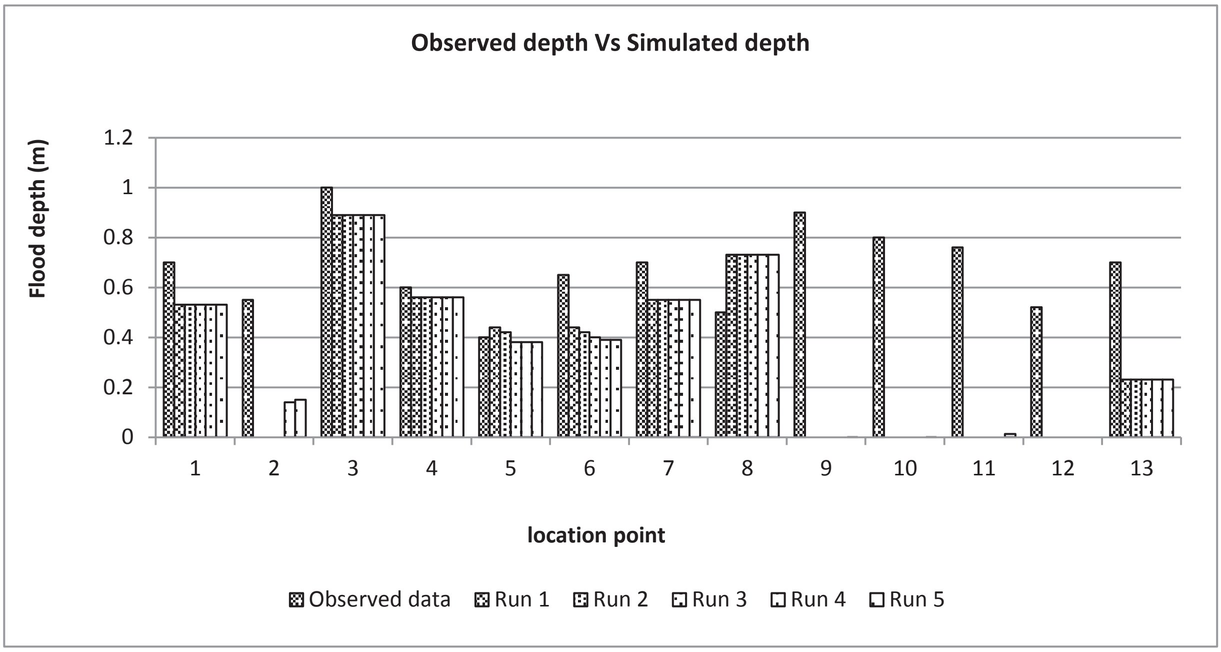


Figure 5-2: Observed blood depth versus simulated flood depth of Run-1 to Run-5

Second, another 5 Runs were carried out based on mostly Manning coefficient of 1D channel. It was observed that Manning coefficient of 1D affects the flood depth & extent more than that of 2D overland. The Table 5-2 shows the Manning coefficient used for 1D channel. The first Manning coefficient value assigned for 1D channel was 0.2, which gave a big flood. The consecutive 5 runs were made with consistent reduction in the Manning coefficient values for 1D channel until the simulated result showed closer to the observed data.

Table 5-2: Manning coefficient values for Run-6 to Run-10.

Run	Manning coefficient values for 2D land use and 1D channel										Remarks
	Building	PC	SC	TC	Unpaved road	Highway road	Paved road	Grass	Open area	1D channel	
6	1.000	0.140	0.092	0.092	0.200	0.080	0.080	0.280	0.080	All channel: 0.2	MC and SC : increased by 10 times; PC: increased by 6 times Huge flood
7	1.000	0.035	0.023	0.023	0.050	0.020	0.020	0.070	0.020	MC: 0.2; SC: 0.09 ; PC: 0.035	MC: increased by 10 times; SC: increased by 4 times
8	1.000	0.035	0.023	0.023	0.050	0.030	0.020	0.070	0.020	MC: 0.138; SC: 0.046; PC: 0.07	MC: increased by 6 times; SC: increased by 2 times; PC: increased by 2 times
9	1.000	0.035	0.023	0.023	0.050	0.020	0.020	0.070	0.020	MC: 0.0138; SC: 0.0335; PC: 0.0525	MC: increased by 6 times; SC & PC: increased by 50%
10	1.000	0.035	0.023	0.023	0.050	0.020	0.020	0.070	0.020	MC: 0.138; SC: 0.028; PC: 0.043	PC & SC increased by 25%

Where MC : Minor channel; SC : Secondary channel; PC : Primary channel

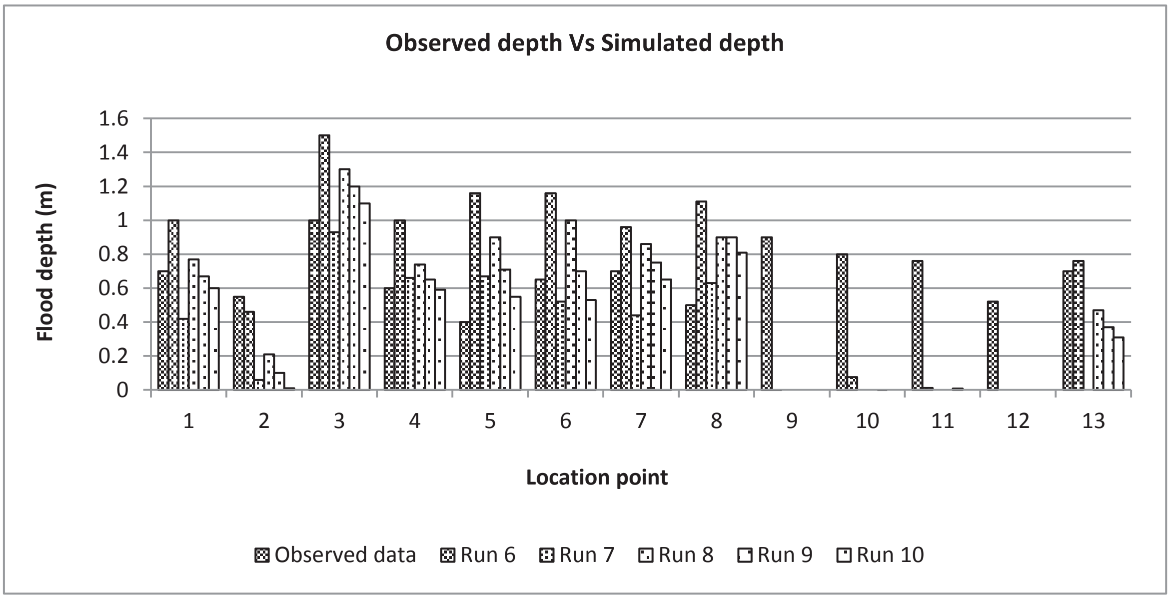


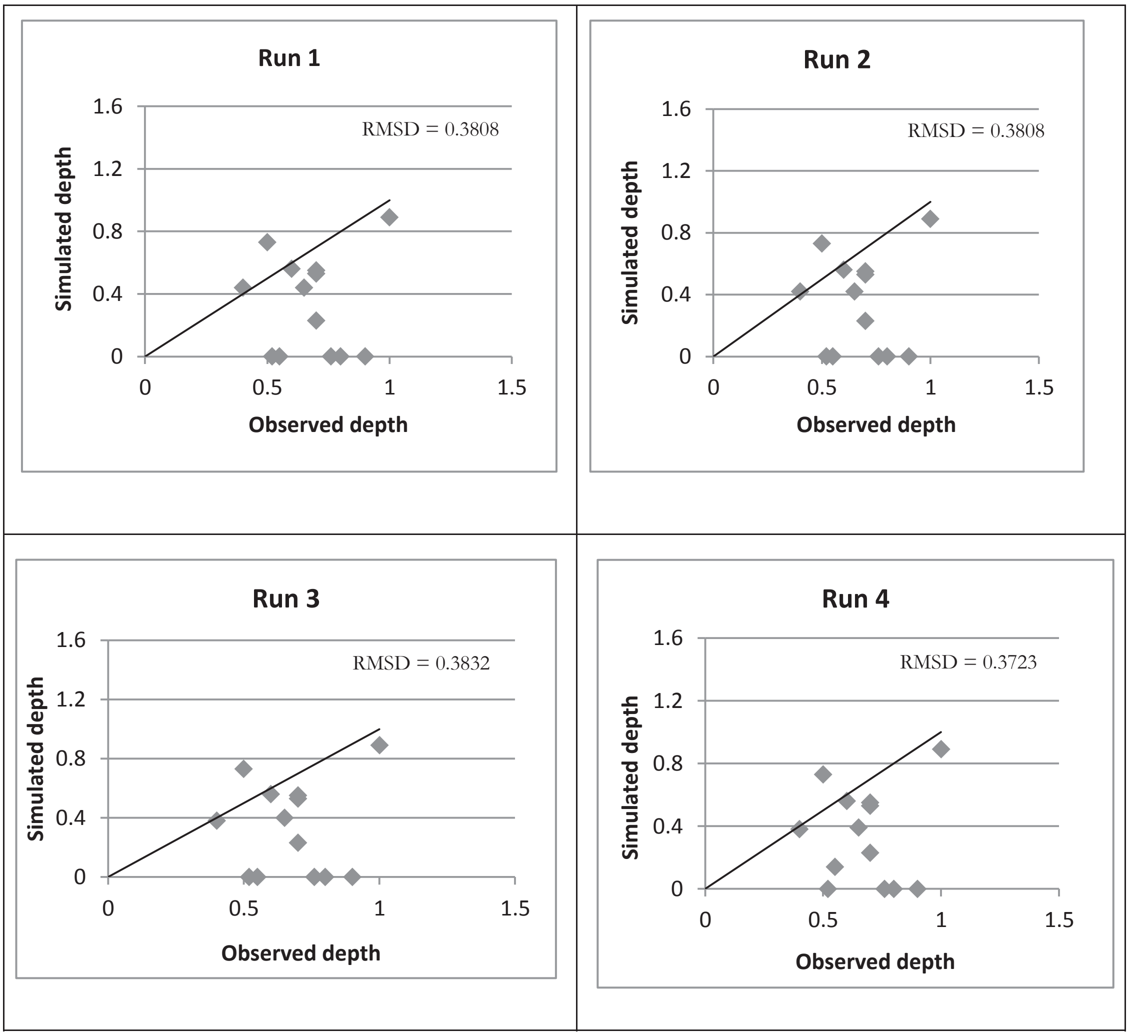
Figure 5-3: Observed flood depth versus simulated flood depth

In order to determine which simulation has the least deviation from their corresponding flood observed depth, the root mean square deviation was calculated for each run. The root mean square deviation is calculated as follows:

$$\text{Root mean square deviation (RMSD)} = \sqrt{\frac{\sum_{i=1}^{n}(Yi-Xi)^2}{n}} \quad \text{.......... Eq 5-1}$$

Where n = total number of observation
Yi = the simulated flood depth
Xi = the observed flood depth

The simulated flood depth was plotted against the flood observed depth for each run as shown in the Figure 5-4. The line indicates the location of points where simulated and observed values are equal. Most simulated depths are lower than the observed flood depth with the exception of run 6, 8 and 9.



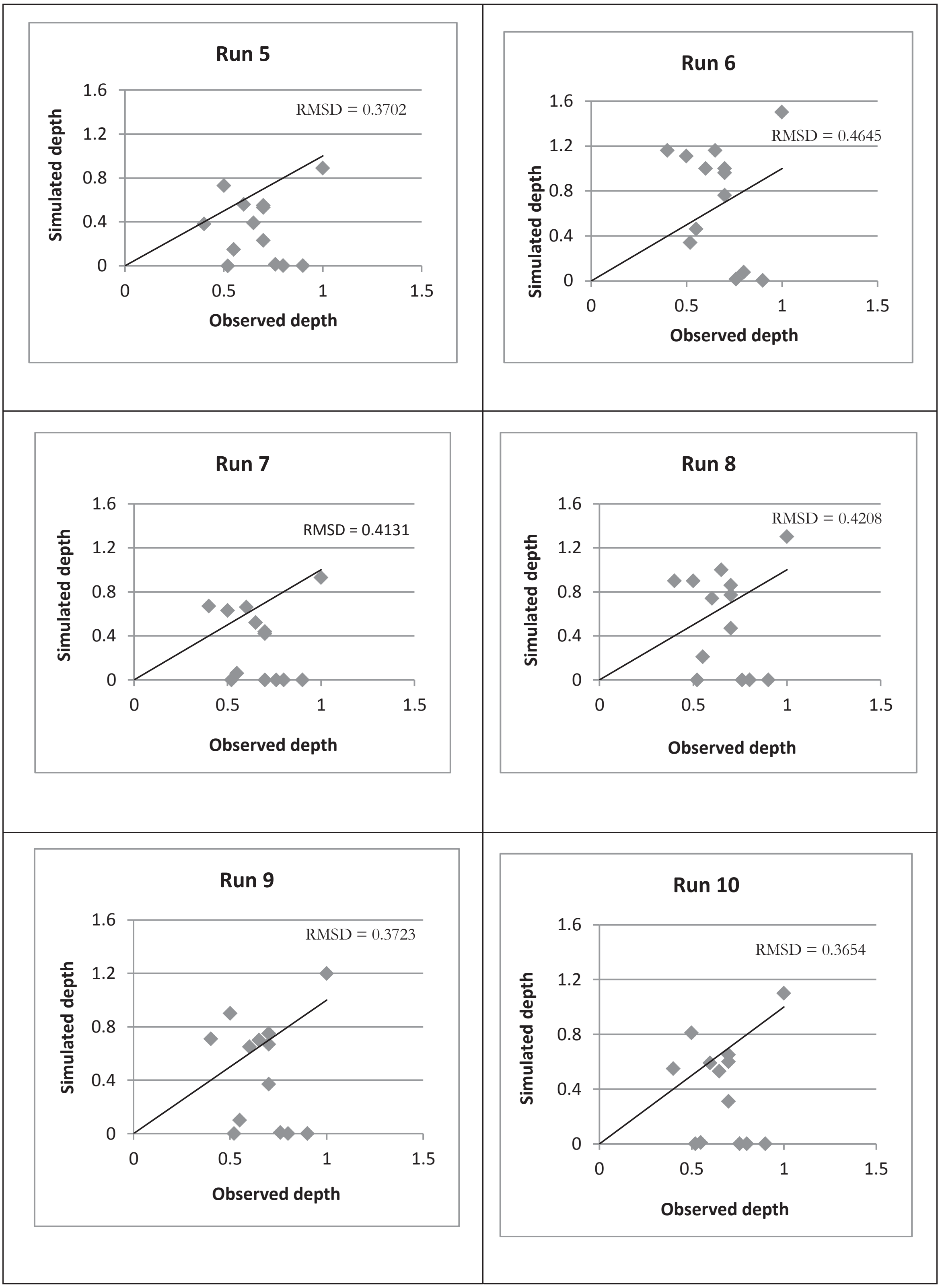


Figure 5-4: Scatter plots for simulated depth (m) versus observed depth (m) for 10 Runs

According to above Figure 5-4, the Run-10 shows the RMSD of 0.3654 m, which is the least deviated between the simulated depth and observed depth than any other Runs. The scatter plots show the main cause of deviation is due to '0' value of the simulated depth. 5 locations that experienced flood depths up to 0.9m were not flooded in the simulation. The 5 locations, which simulation has not given flood depth are located along minor drainage channels in the middle of Katoogo, St. Francis and Bugalani areas. These areas experienced floods in the last year from minor drainage that conveys surface water that flows from Kawempe roads. This is one of the mains reasons for causing greater deviation between flood observed depth and simulated flood depth.

Furthermore, the sub-set of RMSD for all Runs were calculated without considering the '0' value of the simulated flood depth and its corresponding flood observed depth of those 5 locations. The sub-set of RMSD of Run-10 is found to be the best as its RMSD is 0.153 m where the margin of deviation is reduced by more than 50 percent.

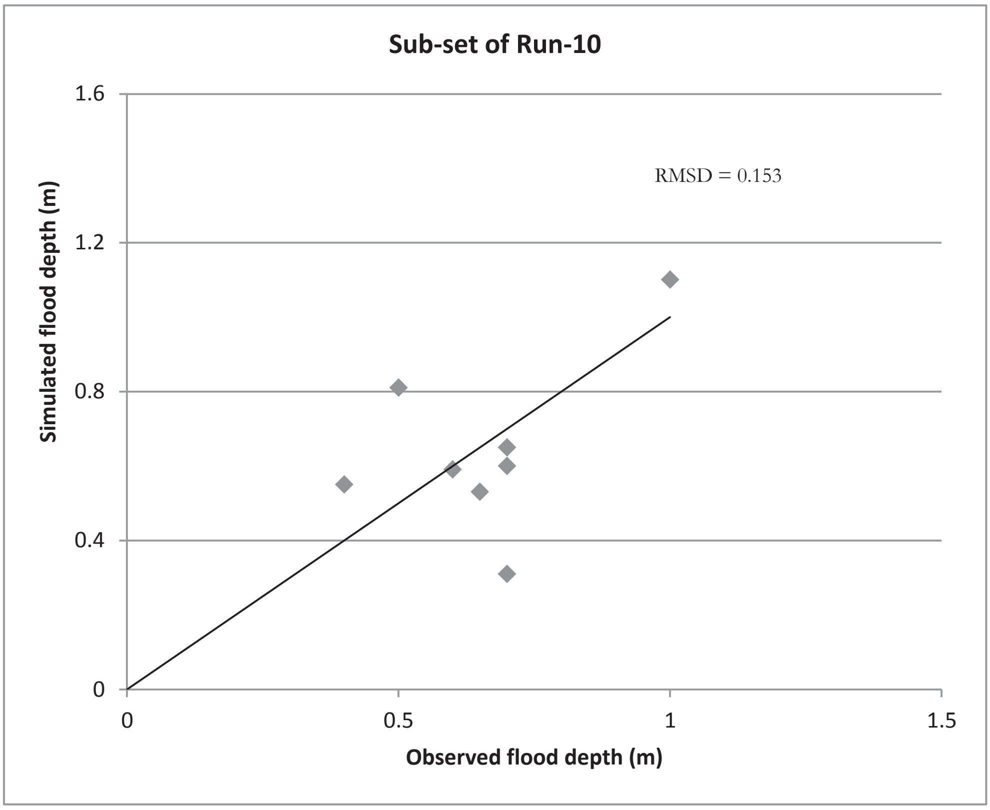


Figure 5-5: Scatter plot for simulated depth and observed depth for sub-set of Run-10

Upon calibration, the Manning coefficient values of 1D channel and 2D overland of Run-10 was suitable and considered for the simulation of all other scenarios.

5.3. Present scenario

The present scenario as mentioned in section 1.6 is based on the actual cross section of the drainage channel measured during field work. The actual cross section of the present scenario is mentioned in sub-section 4.7. The two sub-scenarios were developed under present scenario: “with small dike” and “without small dike” around the building footprints. The small dike was built by the people in order to protect their houses from incoming flood water. Upon field visit, it was observed that the dikes around the building were mostly found in the lower half part of Bwaise III, which is mostly affected by floods. Therefore, the elevation around the building footprints of lower part of Bwaise III has been raised with 0.25m at 3.5m distance from the building footprints. Another sub-scenario is without dike, meaning it does not consider the raised elevation around the building and it is purely based on the plain DEM.

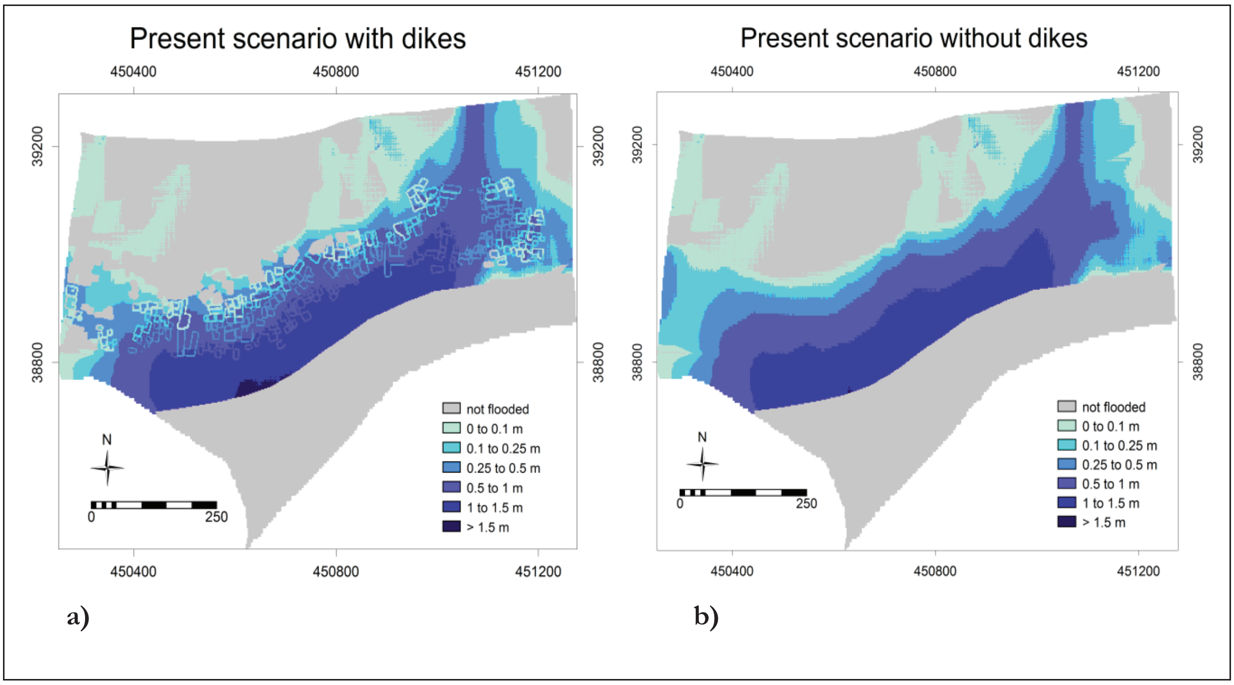


Figure 5-6: Present scenario with dikes (a) and without dikes (b)

The Figure 5-6 shows the differences of flood depth between with dikes and without dikes around the building footprints. The Figure 5-6a shows that the flood depth over the dike is low and the dikes acted like a barrier against the flood water. There are patches of areas without flood water at the periphery of flooded areas (north, northwest and northeast). Whereas, the Figure 5-6b shows that the effect of flood depth and extent is consistent.

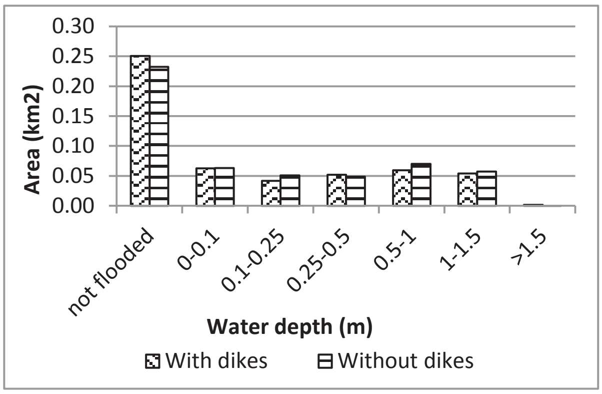


Table 5-3: Percent of area not flooded and flooded under Present scenario.

Area	With-dike (%)	Without- dike (%)
Not flooded	48	44
Flooded	52	56

Figure 5-7: Area inundated under different flood depth for Primary scenario with dikes and without dikes.

The Figure 5-7 shows the total area covered under different flood depth between with dikes and without dikes. The graph indicates that with dikes has more area not flooded than that of without dikes. The Table 5-3 shows that the without dikes has 56 percent area flooded and 44 percent area not flooded. With dikes has 52 percent of area flooded and 48 percent not flooded. Therefore, the dikes help to reduce the flood extent but increase flood depth in the parts that are flooded.

5.4. Future scenario

The Future scenario as mentioned in section 1.6 is differentiated from the Present scenario by the cross section of the primary channel. The primary channel has two different cross sections. One based on the field measurement, which has been used in the Present scenario. The second one is based on the future cross section of the primary as mentioned in section 4.7, which is considered as Future scenario. The cross section of other channels such as secondary and minor remains the same as that of Present scenario.

The Future scenario too has two sub-scenarios the same as Present scenario: "with small dikes" and "without small dikes" around the building footprint (Figure 5-8 a,b). This is to see the impact of dike around the building on the flood depth and extent in the future.

Furthermore, the differences of flood depth and extent between the Present scenario and the Future scenario would convey the impact of the future primary channel on the flood depth and extent. The Future scenario would also reveal whether or not the future primary channel would contain the flooding issue in Bwaise III.

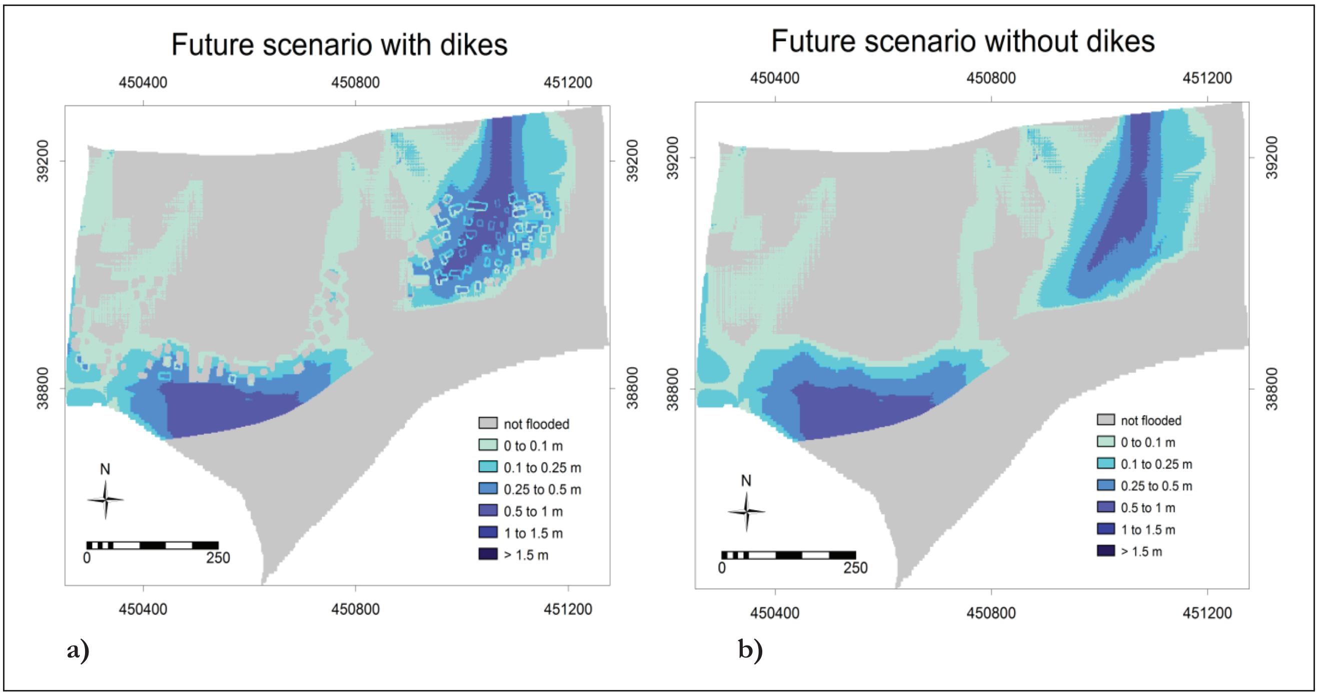


Figure 5-8: Future scenario with dikes (a) and without dikes (b).

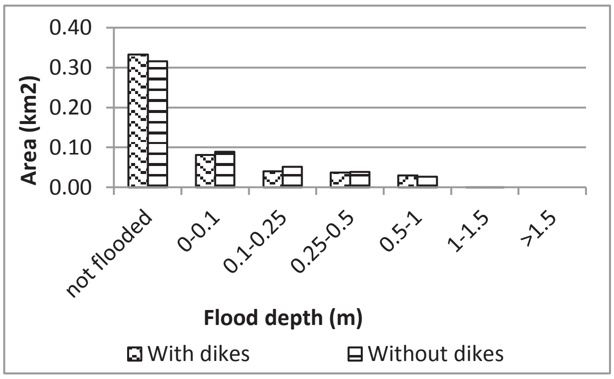


Figure 5-9: Area inundated under different flood depth for Future scenario with dikes and without dikes.

Table 5-4: Percent of area not flooded and flooded under Future scenario.

Area	With-dikes (%)	Without-dikes (%)
Not flooded	64	60
Flooded	36	40

The Figure 5-8(a & b) shows the flood depth and extent of future scenario of its “with small dikes” and “without small dikes” respectively. In future the flood extent and depth will be very small. There will be flood only along the secondary channel and downstream primary channel. The Table 5-4 shows the area not flooded and flooded indicating the flood extent of two scenarios. Both the scenarios have more than 60 percent of the areas not affected by floods.

The flood depth and extent between the Present and Future scenarios are clear from the Figure 5-6 (a,b) and 5-8 (a,b). The Present scenario (Figure 5-6 a,b) shows that both secondary and primary channel causes floods. Whereas the Future scenario (Figure 5-8 a,b) shows that the secondary channel causes floods but the primary channel does not cause the floods except a small downstream flood. There is no flood at upstream primary channel. The flood depth and extent along the future primary channel is far smaller than present primary channel. The floods along the secondary and minor channels in both Present and Future scenarios remain the same as there is no change in its cross section.

Table 5-5: Flood extent differences between Present and Future scenarios (km²)

Area (km2)	Present Scenario		Future Scenario		Difference		Remarks
	With dikes	Without dikes	With dikes	Without dikes	With dikes	Without dikes	
Not flooded	0.25	0.23	0.33	0.32	0.08	0.09	Increase
Flooded	0.27	0.29	0.19	0.21	-0.08	-0.08	decrease

The flood depth and extent in Future would be reduced very much in comparison to Present situation. The Table 5-5 shows that in future the flood extent has been significantly reduced by 0.08 km^2 in both with dikes and without dikes scenarios and not flooded is increased by more than 0.08 km^2. And in the area that is affected by flood, the flood depths have been significantly reduced, ranging between 0.1 m to 0.5 m instead of between 1.0 and 1.5 meters. There is no area inundated deeper than 1 m.

5.5. Garbage scenario

Flooding due to garbage is not an issue in Bwaise III at present. During field work it was observed that the drainage channels are being cleaned twice a week under the supervision of KCC. The garbage will not cause floods so long as the trend of cleaning is being continued. If the cleaning of drainage channels is discontinued in future, it is hypothesised that the garbage and siltation will aggravate the floods. Bwaise III being located in the low laying valley has great potential for siltation, which would directly affect the cross section of the drainage channels and magnify flooding. During the field work at the same time, it was observed that the garbage and siltation would directly impact the depth of the drainage channel. Therefore, to simulate the possible consequences of garbage clogging, the depth of all drainage channels (primary, secondary and minor) was reduced by 50 percent to see their impact on flood depth and extent.

5.5.1. Present scenario with drainage blockage

The Figure 5-10 shows the flooding situation of the Present scenario taking into account that its drainage channel depth is blocked by 50 percent.

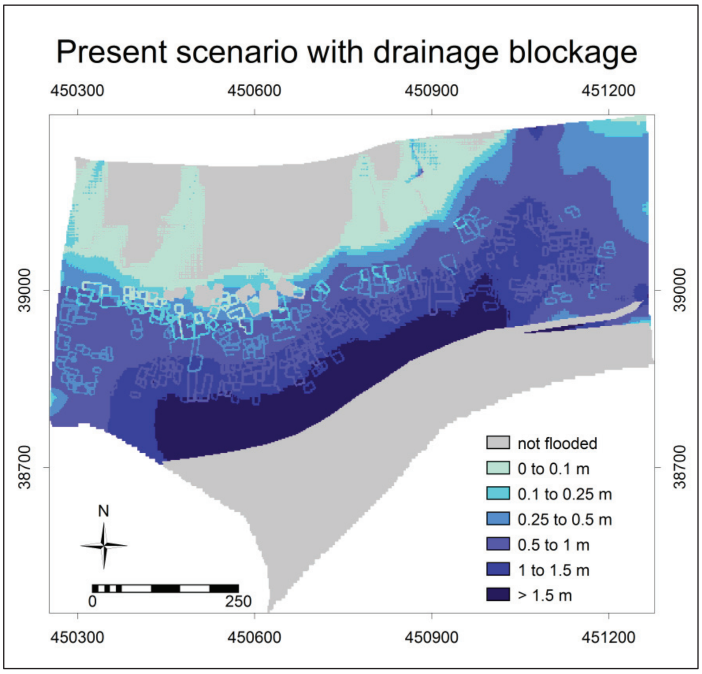


Figure 5-10: Flood depth of Present scenario considering 50 percent of its drainage channels blocked by garbage and silts.

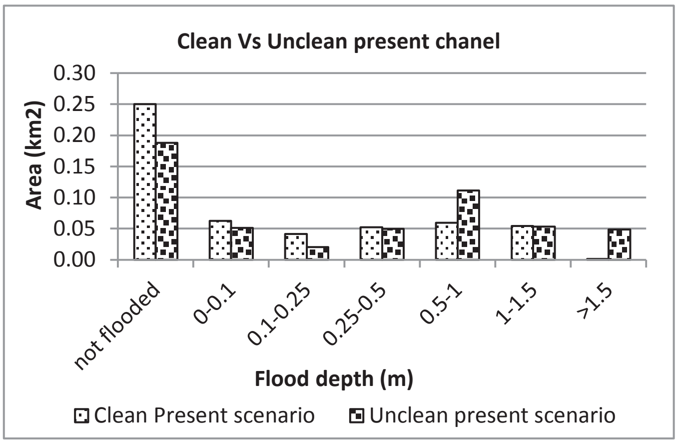


Figure 5-11: Area inundated under different flood depth.

Table 5-6: Percent of flood extent between clean and unclean present scenarios.

Area	Clean Present scenario (%)	Unclean Present scenario (%)
Not flooded	48	36
Flooded	52	64

The impact of garbage and siltation on the flood depth in comparison to clean Present drainage channel (Figure 5-6a) is shown in Figure 5-11. The Figure 5-11 clearly shows the comparison of areas inundated by different flood depth for both clean and unclean Present scenarios. The unclean Present scenario has greater flood depth (more than 1.5m) than clean Present scenario. The Table 5-6 shows that the unclean Present scenario has 64 percent of area inundated by floods whereas the clean Present scenario has 52 percent of area inundated. This difference is clear in Figure 5-10, which shows that areas along both the secondary and primary channels have been extremely flooded.

5.5.2. Future scenario with drainage blockage

The investigation of the impact of garbage and siltation on flood depth and extent is given more importance on the Future scenario because Bwaise III is now getting a new big Primary channel very soon and also to raise awareness about the consequences if they do not continue the present cleaning practice. This research has considered 25 percent, 50 percent and 75 percent of the depth of the drainage channels being reduced by garbage and siltation. Three different simulation based on three different drainage depth gave three different flood depth and extent maps. The comparison of this three scenario maps with clean channel map of Future scenario with raised elevation has demonstrated the impact of garbage and siltation on the flood depth and extent. The flood depth maps of three scenarios are shown below in Figure 5-12.

The Figure 5-12 maps show very distinct and clear differences among three different type of drainage blockage. The flood depth and extent increases consistently from smaller drainage blockage (25 percent) to larger drainage blockage (75 percent). In clean future channel map (Figure 5-8a), there is no floods in the upstream primary channel and middle of the area along primary channel. And the flood in the area between Kawaala and Katoogo is shallow. Considering 25 percent of drainage channel being blocked, the flood extent increases in general. However, the flood depth remains the same as that of clean future channel, below 1 m and there is still no flood at upstream primary channel. When increasing drainage blockage to 50 percent, there is a huge floods all along the secondary channel till downstream primary channel. But, there is still no flood at upstream primary channel. After considering drainage blockage to 75 percent, all area along the drainage channel including upstream primary channel gets flooded. The flood extent goes to large extent and the maximum flood depth also increases to 1.5 m.

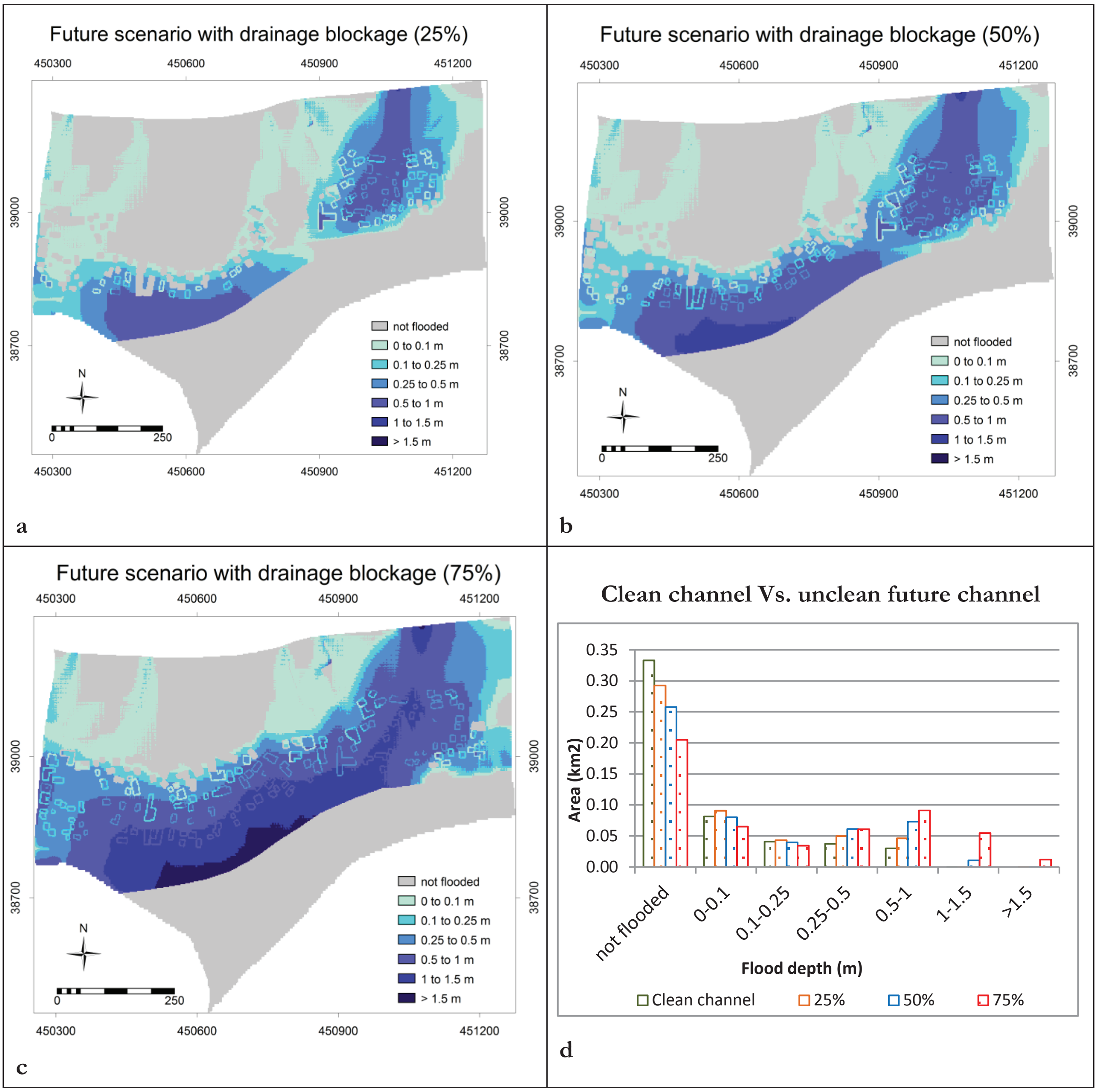


Figure 5-12: Future scenario with three different drainage blockages.

a. 25 percent of future drainage blocked by garbage; **b.** 50 percent of future drainage blocked by garbage; **c.** 75 percent of future drainage blocked by garbage; **d.** The bar graph shows the amount of area inundated at different flood depth between clean channels and un-cleaned channels

In all the scenarios, there is no severe flooding caused by minor channels. The depth of floods along minor channels remains below 0.1 m even after increasing the drainage blockage to 75 percent. The hydrographs of the minor channels (Figure 4-9: hydrograph for upstream minor boundary conditions – 1,2,3,4,5) received for this research is very small.

Table 5-7: Differences of flood extent between clean and unclean under Future scenarios

Area	Clean channel (%)	25 percent drainage blockage (%)	50 percent drainage blockage (%)	75 percent drainage blockage (%)
Not flooded	64	56	49	39
Flooded	36	44	51	61

The table 5-7 shows that during clean channel the area flooded was only 36 percent. But it increased to 61 percent when 75 percent of the drainage depth was considered blocked by garbage and silts.

Furthermore, there is no flooding in Kawaala as it is protected by highway road from primary channel. The highway road has its elevation ranging from 2 m at Kawaala road to 7 m at Bombo road. This highway acts like a barrier against the flooding caused by primary channels. Therefore, so long as the depth of floods remains below 2 m, Kawaala is save from flooding.

5.6. Discussion

5.6.1. DEM

The function of the DEM was discussed in detail in section 2.3.1. The 10 m resolution of DEM was made available for this by ITC. However, it was modified upon field visit as discussed in section 4.2. It requires a paramount experience of making an appropriate DEM for specific flood modelling, particularly urban area where there are various sizes of drainage cross sections. The resolution of DEM chosen for this flood modelling is 2 meter, which could compute one run in 8 to 13 hours. Therefore, making DEM resolution higher than this to get more detail flooding was not feasible.

Another sensitivity of DEM experienced in this research was its modification. Raising dikes around the building footprint has great impact on the flood depth and extent as it is clearly seen in flood maps of with dikes and without dikes as shown in section 5.3, 5.4, and 5.5. The dimension of the dikes is assumed to around 0.25 m above the actual surface level and width of the elevated ground is assumed to be 3.4 m away from the building footprints. This assumption was made as far as possible unbiased based on the field observation. However, detail information about the raised dikes is required so as to represent exact DSM. But this might be difficult to obtain in a place like Bwaise III where settlements are clustered and unplanned.

5.6.2. Hydrological data

There is no secondary water discharge data available for this flood modelling. The input discharge data used for this research are hydrographs of Mr. Aidan's, MSc, UPM, ITC. As mentioned above, there is no flood along minor drainage channels, which in reality there had been floods along these minor channels in the last one year according to the information obtained from the local people. In this regard, detail investigation about the upstream catchment for defining surface runoff is very important.

5.6.3. Surface roughness values

The surface roughness is represented by land use/cover features and their corresponding Manning's coefficient values are assigned in the surface roughness map, which provides resistance against the flow of flood water. Many authors, as discussed in section 2.3.2, used surface roughness of 2D land use/cover features for flood modelling and model calibration. In this research, the result of model calibration (section 5.2) showed that the Manning's coefficient values assigned for 1D channel were more sensitive than that of 2D surface roughness map. Therefore, while assigning Manning's coefficient values for surface roughness map, the due importance should also be given for assigning Manning's coefficient values for 1D channel during flood model schematization.

5.6.4. Model calibration

Model calibration is very important in any kind of modelling as it was explained in detail under section 2.4. The model calibration requires a very good field observed data. Model calibration in this research was based on the observed flood depth, which was obtained during field work through interviewing the local people and measuring wetting marks on the building walls. The margin of error in this calibration is 0.153 m as stated in section 5.2. There are a lot of discrepancies observed in the field work which could attribute to the error of deviation as explained in section 5.1. In view of obtaining the best flood data that could be used for model calibration, one has to experience and observe the flooding in person and take record of flood depth, extent and duration by oneself. So long as one experiences flooding by oneself, there could be discrepancies in the flood observed data that is obtained from the third people.

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

The main objective of this study is to analyse the current and future flood situation in Bwaise III Parish, Kampala, Uganda with SOBEK flood modelling. Based on the research questions of the respective sub-objectives, this study has concluded with the following research answers:

Question 1. What are the characteristics of flood of the two rainfall events (the highest rainfall event - 25th June and the second highest rainfall event - 28th September 2012)?

The hydrograph of 25th June 2012 rainfall, which was the highest rainfall event of the year 2012 was simulated to determine flood depth and extent in Bwaise III. Upon simulation, Bugalani and Bokasa along secondary channel and area along primary channel between Kawaala and Katoogo are the 'hotspot' that was being affected by floods in all the scenarios.

The flood extent in Present scenario covers 52 percent and 56 percent under with dikes and without dikes respectively. The flood extent in Future scenario covers 36 percent and 40 percent under with dikes and without dikes respectively. The flood extent of the Present scenario with dikes increases to 64 percent considering its drainage depth being blocked by garbage and silts. The flood extent of the Future scenario with dikes increases to 61 percent considering 75 percent drainage channel blockage, which is still lower than Present scenario.

The hydrograph of primary and secondary channels for the second highest rainfall event is shown in Appendix-7. But, it is not used for this research as its discharge is very small.

Question 2. What are the return period of the highest and the second highest rainfall events of 2012?

The highest rainfall event of the last year e.i. 25th June 2012, which measured 66.2 mm/day, corresponds to two year return period and the second highest rainfall of the last year e.i. 28th September 2012, which measured 31.4 mm/day, corresponds to one year return period.

Question 3. What are the characteristics of recent floods for model calibration?

Flood depth and duration were collected through interviewing the local people. The flood depth ranges from 0.4 m to 1 m and flood duration from 1 day to 6 days. The exact flood extent was not available. The general flood extent is being drawn in Figure 4.4 based on the perception as lower part of Bwaise III gets flooded and upper did not as per local people's information.

Question 4. What is the impact of dikes around the buildings on the flood characteristics?

The dikes around the building footprints act like a barrier and helps decreasing the flood extent. But, it increases the flood depth. It was challenging task to create dikes around the building footprints without proper spot height data of Bwaise III. All that was done was based on the assumption according to field observation. The raised dikes have direct impact on the flood extent and depth. A case in point, the Present scenario shows that 52 percent of the area gets flooded in the presence of dikes and 56 percent of area gets flooded without dikes. Therefore, dikes reduced the flood extent.

Question 5. What is the effect of garbage on the flood characteristics (differences between clean channels versus blocked channels)?

The impact of garbage on the flood depth and extent is visible in the figures under garbage scenarios. In Present scenario, the 50 percent of drainage blockage led 64 percent of Bwaise III area flooded. In the Future scenario, the flooded area under normal condition was 36 percent. But, considering 25, 50 and 75 percent of the drainage blockage, the flooded area was 44, 51 and 61 percent respectively. It was clearly indicated that garbage or siltation in the drainage would certainly aggravate floods.

6.2. Recommendation

Upon the completion of this research, the following issues have been identified which need to be considered if similar type of research is being carried out in Bwaise III in near future:

1. The upstream catchment discharge has direct relation with the downstream flooding. The detail hydrology assessment of the upstream catchment will determine the accuracy of flood depth and extent in the downstream area. Therefore, the detail hydrology assessment is necessary for flood hazard assessment.

2. Thinking of developing dikes around the building footprints like it was done in this research requires detail spot height data. The way it was done in this research was based on the assumption and it might have created deviation from the actual elevation. A better DEM will produce flood results with less margin of error from the actual flooding.

3. This research had found out that the future primary channel would definitely solve flooding issue to certain level but not completely. The future primary channel was able to accommodate the discharge of 2 years return period as there was no flood at area between Kawaala and Kalimali. However, the flooding begins after it meets with the secondary channels from Bugalani and become bigger when it reaches at area between Kawaala and Katoogo, which is low lying flat area and has elevation lower than its downstream boundary. If that low elevation has not been taken into account during the reconstruction of future primary channel, it will be the bottle neck for the cause of flooding in Bwaise III.

4. Upon interviewing the local people, it was found out that the middle part of Bwaise III is being affected by floods from minor channels. The main reason for causing floods by minor drainage is because of their poor alignment and lack of connectivity with the lower primary channel. In order to minimize flooding issue in Bwaise III, those minor channels should be realigned and need to be connected with the lower main part of primary channel.

5. This research results could be used as a basis for further analysis of social vulnerability and elements at risk in Bwaise III.

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8. APPENDICES

Appendix-1: Change in land use/cover of Kampala from 1973 to 2007

1973 2007

Source: NEMA, Kampala, Uganda

Appendix-2: SOBEK 1D and 2D formula as stated in the SOBEK online help functionality

The following momentum and continuity equations describe about the flow of 1D in SOBEK flood model.

1D Momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + g \cdot A_f \cdot \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 R A_f} - W_f \frac{\tau_{wi}}{\rho_w} = 0$$

…………………..…………Eq A-1

Where:

Q	Discharge [m^3/s]
t	Time [s]
x	distance [m]
Af	Wetted area [m^2]
g	Gravity acceleration [m/s^2] (=9.81)
h	Water level [m] (with respect to the reference level)
C	Chezy coefficient [$m^{1/2}/s$]
R	Hydraulic radius [m]
Wf	Flow with [m]
twi	Wind shear stress [N/m^2]
rw	Water density [kg/m^3]. Normally 1000

1D Continuity equation:

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

…………………………..Eq A-2

Where:

Af	Wetted area
qlat	Lateral discharge per unit length [m^2/s]
Q	Discharge [m^3/s
t	time [s]
x	distance [m]

The following two momentum equations and one continuity equation describe about the flow of 2D in SOBEK flood model.

2D Momentum equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{u|V|}{C^2 h} + au|u| = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + g\frac{v|V|}{C^2 h} + av|v| = 0$$

……………...……….Eq A-3

Where:

u	velocity in x-direction (m/s)
v	velocity in y-direction (m/s)
V	velocity: V= $\sqrt{u^2 + v^2}$
ξ	water level above plane of reference (m)
C	Chezy coefficient (√m/s)
d	depth below plane of reference (m)
h	total water depth: ξ +d (m)
a	wall friction coefficient (1/m)

2D Continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0$$

…………………………Eq A-4

Where:

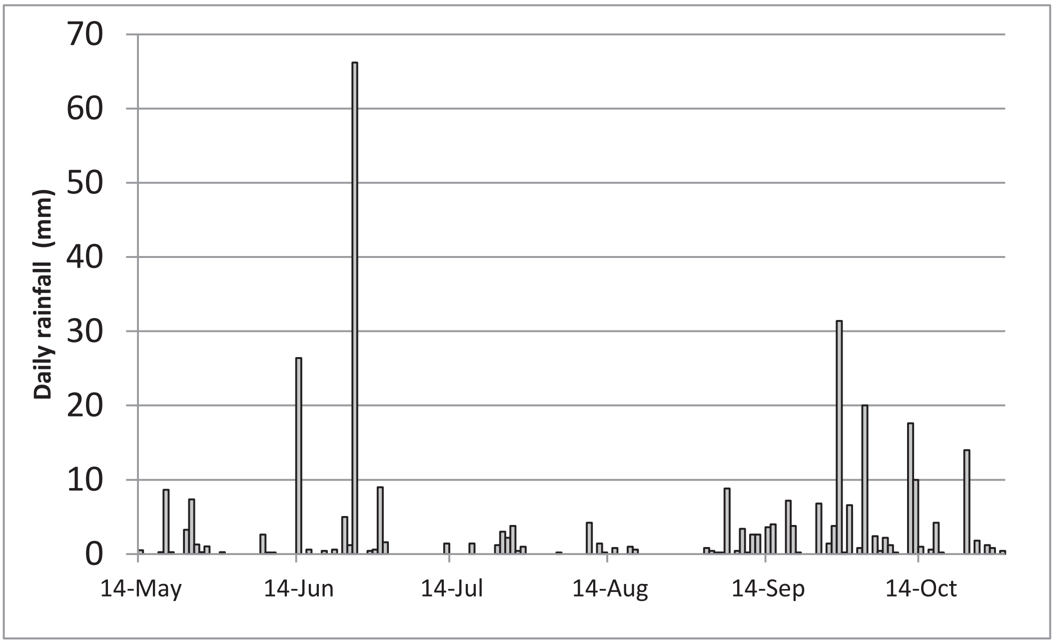
U	velocity in x-direction (m/s)
V	velocity in y-direction (m/s)
V	velocity: V = $\sqrt{u^2 + v^2}$
ξ	water level above plane of reference (m)
h	total water depth: ξ+d(m)
d	depth below plane of reference (m)

Appendix-3: Flood historic data of depth and duration obtained from interviewing the people.

S/N	UTM_X	UTM_Y	Name of place	Depth (m)	Duration (hr)
1	450517	38881	Katoogo	0.7	48
2	450842	39031	St-Francis	0.55	48
3	450981	39023	Bugalani	1	48
4	450976	39089	Bugalani	0.6	48
5	451161	39090	Bukasa	0.4	12
6	451169	39030	Bukasa	0.65	24
7	450784	38936	Katoogo	0.7	48
8	450657	38886	Katoogo	0.5	48
9	450487	39050	Katoogo	0.9	48
10	450449	38996	Katoogo	0.8	72
11	450408	39019	Katoogo	0.76	48
12	450716	39041	Outpan school	0.52	48
13	450292	38905	Katoogo	0.7	48

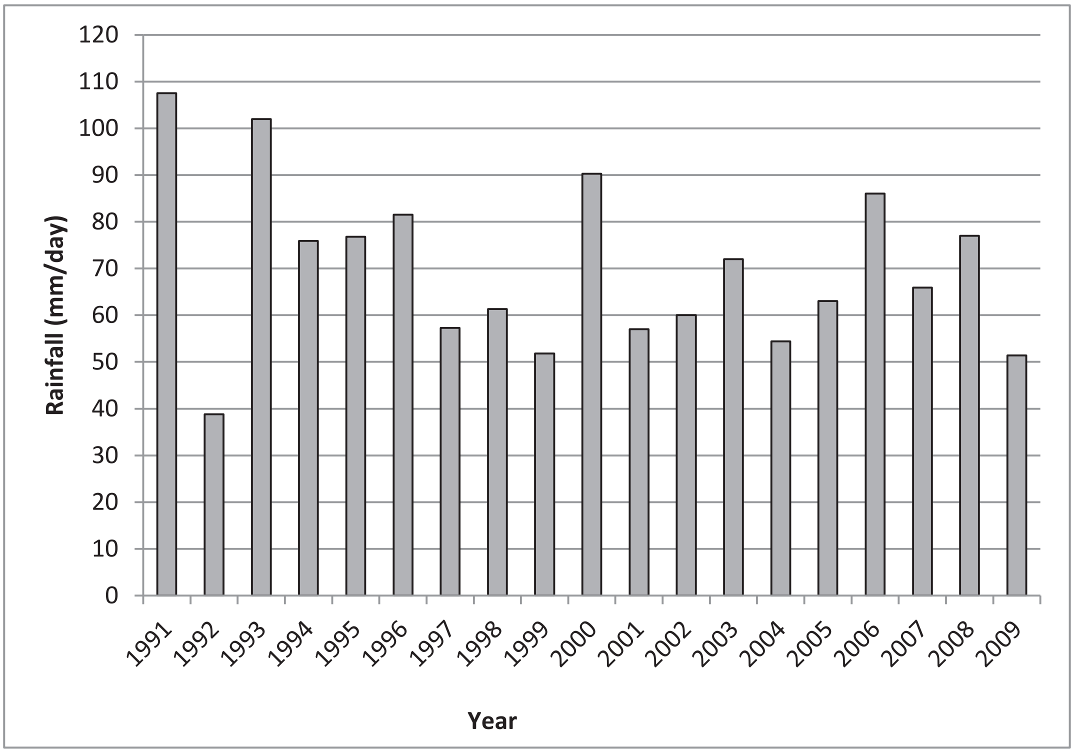
Source: Field observation (2012)

Appendix-4: Daily rainfall at Makerere University, Kampala, Uganda



Source: Aidan, UPM, ITC (2012)

Appendix-5: Annual maximum daily rainfall



Source: (KCC, 2010)

Appendix-6: The Gumbel extreme method is described below which is according to Viessman et al., 1989 as stated by Coto (2002).

- Sort the annual maximum daily rainfall data from lowest to highest.
- Assign value 1 to the lowest and assign value N to the highest annual maximum daily rainfall data.
- Calculate for each observation the left sided probability as:

  PL = R/N+1…………………………………………… EqA-5

  Where:
  PL = left sided probability (probability of having less values in the series)
  R = is the rank
  N = number of observations

- Calculate the return period for each observation as:

  Return Period (T) = 1/PR = 1/1-PL………………………EqA-6

- Calculate the plotting position for each observation as:

  Y = -LN (-LN (PL))……………………………………..EqA-7

- The plotting position is plotted against the annual maximum daily rainfall and linear trend line is derived to get Y formula.

Y = 0.0598x – 3.664……………………………………..EqA-8

- Finally return period is calculated as:

PL = EXP(-EXP(-Y))……………………………………...EqA-9

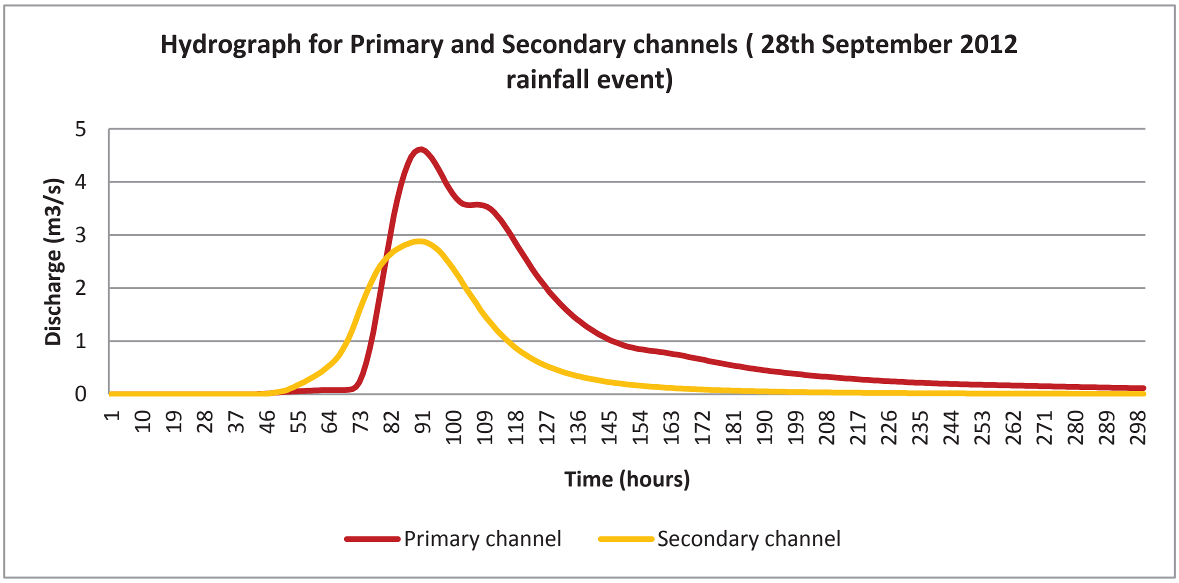
Calculation of rainfall return period using Gumbel Method

Observed Annual maximum daily rainfall (mm)	Sorted Observed (ascending order)	Rank (R)	N+1 (N=19)	Left Prob	Probability (PR)=1-PL	Return Period (T)	y=-LN(-LN(PL))
				PL = R/N+1		T=1/PR=1/1-PL	
107.5	38.8	1	20	0.05	0.95	1.05	-1.1
38.8	51.4	2	20	0.1	0.9	1.11	-0.8
102	51.8	3	20	0.15	0.85	1.18	-0.6
75.9	54.4	4	20	0.2	0.8	1.25	-0.5
76.8	57	5	20	0.25	0.75	1.33	-0.3
81.5	57.3	6	20	0.3	0.7	1.43	-0.2
57.3	60	7	20	0.35	0.65	1.54	0.0
61.3	61.3	8	20	0.4	0.6	1.67	0.1
51.8	63	9	20	0.45	0.55	1.82	0.2
90.3	65.9	10	20	0.5	0.5	2.00	0.4
57	72	11	20	0.55	0.45	2.22	0.5
60	75.9	12	20	0.6	0.4	2.50	0.7
72	76.8	13	20	0.65	0.35	2.86	0.8
54.4	77	14	20	0.7	0.3	3.33	1.0
63	81.5	15	20	0.75	0.25	4.00	1.2
86	86	16	20	0.8	0.2	5.00	1.5
65.9	90.3	17	20	0.85	0.15	6.67	1.8
77	102	18	20	0.9	0.1	10.00	2.3
51.4	107.5	19	20	0.95	0.05	20.00	3.0

Return period of the rainfall events used for hydrology assessment to determine hydrograph based on Gumbel extreme probability method.

Return period (T) for rain (mm)	Y=0.0598x-3.664	PL=EXP(-EXP(-y))	T=1/(1-PL)
66.2	0.29	0.47	1.90
31.4	-1.79	0.00	1.00

Appendix-7: Hydrograph for upstream Primary and Secondary channels of 28th September 2012 rainfall event.



Source: Aidan, MSc, UPM, ITC (2012)

Appendix-8: Accuracy assessment of Flood observed depth.

Observed flood depth points (North-east to South-west)	Observed Depth (m)	DEM Value (m)	Water level (depth + DEM)
1	0.65	1158.44	1159.09
2	0.4	1158.43	1158.83
3	0.6	1157.94	1158.54
4	0.52	1157.39	1157.91
5	0.55	1157.35	1157.9
6	1	1157.24	1158.24
7	0.9	1157.14	1158.04
8	0.8	1156.45	1157.25
9	0.76	1156.37	1157.13
10	0.7	1156.26	1156.96
11	0.5	1156.03	1156.53
12	0.7	1155.92	1156.62
13	0.7	1155.64	1156.34