Modelling and assessment of urban flood hazards based on end-user requirements. Kigali-Rwanda

FRED MUGISHA
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SUPERVISORS:
Dr. R.V. Sliuzas
Dr. J. Flacke

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SUPERVISORS:
Dr. R.V. Sliuzas
Dr. J. Flacke

THESIS ASSESSMENT BOARD:
Prof. dr. A. van der Veen (Chair)]
Dr. Dinand Alkema (External Examiner, University of Twente)

ABSTRACT

Urban flooding is a significant challenge which today increasingly confronts the residents of the expanding cities and towns of developing countries. Kigali like many other tropical cities is facing severe flood problems. At least each year Kigali faces a flash flood during rainy season in different locations. Such flood event is a recurring phenomenon in Kigali. A study has been done to perform an assessment of the cause of regular flooding in Mpazi basin which is said to be the root cause of flooding in Kigali due to its characteristics. The committees has been commissioned and consultants have been hired but their reports come up with strategies which are costly and politically sensitive where they suggested that wetlands and marshes have to be restored to their original condition which is very costly if not impossible. Flood hazard mapping was another option to delineate the hazard areas which communicate risk areas. However, this practice of flood mapping in Kigali shows some deficits. Firstly, the contents of flood maps do not meet the requirements of different stakeholders. This means that maps are more generic and information contain may perhaps not understood by citizens at risk or may not be suitable for the respective needs of different stakeholders. This means that stakeholder's preferences are not incorporated while mapping hence these maps fail to communicate their potential since different stakeholders respond to them by disagreeing the contents believing them to be inaccurate. This leads to a problem that the maps are not effective in promoting the public to take actions in reducing their vulnerability. This shows that different users have different needs with regard to contents of flood hazard maps.

Due to the above deficits, this study was examined to find out "**who** needs **what**, **why, how** and **where**". Based on the empirical findings from participatory approaches that incorporates interviews conducted in Kigali city with various stakeholders, it was found out that these stakeholders have different needs and requirements. This study showed how these requirements were used to prepare flood hazard maps that should in principle satisfy these requirement.

This study discusses how stakeholder's requirements can be satisfied by application of urban flood model. Coupled 1D2D hydrodynamic models (SOBEK) for flood simulation was used to assess flood hazards and its output was further post processed in ILWIS software to contribute better understanding and quantification of floods with respect to stakeholders needs. The flood calibration was done by comparing the observed flood depths obtained from fieldwork through interviewing the citizens prone to flooding and compared it with the simulated flood depths using objective function. Sensitivity analysis was carried out to find the parameters that have highest influence on flood depths.

Finally, usefulness of these products was assessed by delivering the flood hazard maps to different stakeholders to cross check if their requirements are satisfied. The monkey questionnaire was designed which intends to determine if different stakeholders are satisfied or not.

Keywords: Urban floods hazards, modelling, stakeholders, User requirements.

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Fred MUGISHA
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LIST OF ABBREVIATIONS

ASCII: Raster file format
DEM: Digital Elevation Model
DTM: Digital Terrain Model
DSM: Digital Surface Model
EIA: Environmental Impact Assessment
FEMA: Federal Emergency Management Agency
GIS: Geographical Information System
GPS: Geographical Positioning System
RS: Remote Sensing
RMSE: Root Mean Square Error
1D: One Dimensional
2D: Two Dimensional

1. INTRODUCTION

1.1. General background and justification

Urban flooding is a significant challenge which today increasingly confronts the residents of the expanding cities and towns of developing countries (Jha, Abhas K. Bloch, Robin, Lamond, 2012). Impervious surface and manmade hydrologic structures contribute to flash floods in urban areas even in a rain fall of moderate intensity. Therefore urban areas are more vulnerable to flood events. As urban development continued, the capability of natural drainage system have been exceeded and flooding problems have become more frequent and severe. The expected results of urbanization include reducing infiltration, base flow, lag times, increasing storm flow volumes, peak discharge, frequency of floods, and surface runoff (Hollis, 1975). Flooding have significantly increased over the last decades, due to urban centers and continued development of infrastructure without taking into consideration drainage aspects (Tennakoon, 2004)

Due to rapid urbanization, flood plains are more attractive areas of human settlements and development (Alkema, 2007). However, human activities may sometimes cause interference with nature resulting destructive consequences such as floods (WMO/GWP, 2008). To avoid such situation it is important to have clear knowledge of how development and management activities have impact on flood risks.

Flood management approaches have to consider all aspects of both flood behavior and urbanization process. Traditionally surface water management was seen primarily as an engineering problem (Sliuzas, 2012). Menzel and Kundzewicz,(2003) highlighted that, both structural and non-structural flood management approaches do exist. Structural methods focus on physical protection such as dikes, levees, dams, reservoirs, diversions, floodway, and channel improvements. Non-structural methods concentrate more on flood warning and evacuation, watershed management, and insurance mechanism (Parodi G, 2009). However, none of the methods mentioned above guarantees an absolute safety against flooding (Menzel & Kundzewicz, 2003). Therefore, considering the limitations of existing methods, bringing together structural and non-structural approaches into Integrated Flood Management (IFM) is seen as the only way forward to reduce flood risk (Jha, et al. 2012; Kundzewicz and Takeuchi, 1999; WMO, 2006).

The integrated flood management (IFM) approach takes a more holistic view of flood management than the traditional engineering perspective (Sliuzas, 2012). It integrates both structural and non-structural measures. IFM is distinguished by its shifting of the focus from a reactive to a proactive response to flooding i.e. from flood control to flood management (APFM, 2006).

In order to understand and mitigate the consequences of floods, flood hazard maps can be a prominent tool. Flood maps are increasingly regarded as important for mitigating the impacts of natural hazards. (Alkema, 2004). Hazard maps are important for planning different development activities in area and can be used as supplementary decision making tools (Alkema, D. Cavallin, A and De Amicis, 2001). They should therefore be easy to interpret, and understandable by both technical and non-technical individuals (FEMA, 2000). In practice these maps often fail to communicate their potential to fulfill the needs of different users, to raise awareness and provide a clear and understandable source of information for planning. Kienberger, Lang, & Zeil, (2009) and (EXCIMAP, 2007) found that flood maps are not very effective in promoting the public to take actions to reduce their vulnerability. Author continued and found out that public or different user groups would often respond to map by disagreeing with the contents, believing them to be inaccurate because these target user are only considered as the receiver of information and the maps are generic and the contents of the maps are not focused on the end users' needs. There is therefore a need to generate potential maps based on the end user requirement whether for individual or institutional purposes (Jha, Abhas K. Bloch, Robin, Lamond, 2012). Therefore, the needs of all users (target group) should be taken into account in developing flood hazard maps

Different users or different groups have different needs with regard to flood maps and that these requirements might not necessarily be understood by those producing the maps. EXCIMAP, (2007) urges that the map creation should be led by the requirements of the users. In this study also the creation of hazard maps of Kigali were created based on the demands of different users. The aim of this study is to understand the needs of different end users of hazard maps and develop hazard maps based on user specific demands.

Flood maps are usually divided into hazard maps showing information on the spatial extent and depth of inundation for flood events of different probabilities and the risk maps showing consequences of these events. In this study, it focuses only on flood hazard maps. Various flood hazard maps are obtained from modelling approaches. These modelling approaches provides insight into the severity of urban flooding and its impacts on the vulnerable groups. The following paragraphs describes various urban flood models.

1.2. Urban flood models

Today different types of urban flood models exists. Pender & Neelz, (2007) reviewed some of existing 1D and 2D flood models. These models have the same principle of conservation of mass, momentum and energy (Horritt & Bates, 2002). If water is confined in a channel, it is best simulated as an unsteady 1D flow model (Verwey, Stelling S. 2006) which solves 1D Saint Venant equation (Horritt & Bates, 2002). This 1D model defines flood only in terms of discharge and water level as a function of space and time. However, it has a limitation of simulating floods in the overland, this situation causes a shift from 1D to 2D model that simulates flood in the overland (Horritt & Bates, 2002). 2D flood model predict flood inundation based on 2D shallow water equation (Mignot, Paquier, & Haider, 2006). The system of 2D shallow water consists of 3 equations one for continuity and two for conservation of momentum in two orthogonal directions (Mignot et al., 2006).

Because 1D and 2D flood modelling both have their own advantages and disadvantages, there are extensive approach to integrate 1D and 2D flood models resulting in hydrodynamic model of flood plain. The integrated 1D and 2D flood model development focuses on the extension of model capabilities in order to simulate flood more accurately (Shaviraachin, 2005). There are various models offering such capabilities, the examples include 1D-2D SOBEK (Alkema, 2007) SWI2D (Finaud-Guyot, Delenne, Guinot, & Llovel, 2011), LISFLOOD and TELEMAC -2D (Horritt & Bates, 2002), and OPENLISEM (De Roo, Wesselling, & Ritsema, 1996). Among all mentioned models 1D 2D SOBEK model gives additional information on the flow characteristics of the flood like flow velocity and propagation characteristics. Hence coupled 1D2D SOBEK were applied in this research. In addition, SOBEK has been enhanced with facilities to import GIS data into the model and export computational results to GIS System for presentation and evaluation (Shaviraachin, 2005).

1.3. Flooding in Kigali

Kigali like many other tropical cities is facing severe flood problems. At least each year Kigali faces a flash flood during rainy season in different locations (refer to figure 1). These floods are driven by number of factors like heavy rainfall, insufficient capacity of drainage structures and rapid urbanization. The population of Kigali metropolitan area, covering an area of about 730 km2 was recently estimated to grow from 765,325 in 2002 to approximately 4.5 million in 2025 (KDMP, 2013). Urban growth of this degree and extent put much pressure on the city planners and local government in terms of city planning and development.

The flash floods of Kigali are not particularly of long duration, but they cause a significant disruption of social and economic life of the city. Some of transport routes get blocked by high speed water, economic shops are disrupted by floods as shown in Figure 1.1 below.

Figure 1.1: Flash floods in Kigali. (Source: Unknown)

In the effort to address the flooding problems, committees have been commissioned and consultants have been hired to perform an assessment of the cause of regular flooding which occurs along Nyabugogo flood plain that causes loss of lives and damages of properties to come up with effective strategies. However the reports of these committees and consultants emphasized structural design and improvement of drains as strategies to stop regular flooding in the city (SHER-Ingénieurs-conseils, 2013). The consultant suggested that to control urban flooding, wetlands and marshes have to be restored to their original condition. This approach is costly and politically sensitive because it will require demolishing infrastructure like residential and commercial areas prone to flooding zones. City planners and politician have been reluctant to pursue such plan. There is therefore a need to develop effective and targeted methods of dealing with urban floods hazards which includes identifying in the city zones that is prone to flooding for effective flood management.

1.4. Problem statement

Today flooding is a challenge problem in Kigali more than any other hazard. In February 23rd 2013, an intensive rainfall event hit the city of Kigali and this lasted about 2 hours killing 3 people and severely damaging nearly a lot of houses. Such flood event is a recurring phenomenon in Kigali. The event caused a flash floods that inundated part of Muhima market and bus station which are intersected by a steep channel which drains the Mpazi basin. This small basin of 8.7 km² has very steep slopes in the upper part and has elevations of more than 1800 m at Mt. Kigali and about 1200 m in downstream. Most of the basin is very densely urbanized and slopes are very steep (some > 30 degrees) (SHER Ingénieurs-conseils, 2013). Urban drainage structures have been developed to drain runoff quickly during rain storms. Despite the urban flooding control work across the city of Kigali, flood remains excessive threat to the people of Kigali and flood damages continues to rise. (Fig 1.2 below shows an impression of the flooded area based on the authors' knowledge.

A study has been done to perform an assessment of the cause of regular flooding in Mpazi basin which is said to be the root cause of flooding in Kigali due to its characteristics. The committees has been commissioned and consultants have been hired but their reports come up with strategies which are costly

and politically sensitive where they suggested that wetlands and marshes have to be restored to their original condition which is very costly if not impossible. Flood hazard mapping was another option to delineate the hazard areas which communicate risk areas. However, this practice of flood mapping in Kigali shows some deficits. Firstly, the contents of flood maps do not meet the requirements of different stakeholders. This means that maps are more generic and information contain may perhaps not understood by citizens at risk or may not be suitable for the respective needs of different stakeholders. This means that stakeholder's preferences are not incorporated while mapping hence these maps fail to communicate their potential since different stakeholders respond to them by disagreeing the contents believing them to be inaccurate. This leads to a problem that the maps are not effective in promoting various stakeholders to take actions in reducing their vulnerability. This shows that different users have different needs with regard to contents of flood hazard maps.
Due to the above deficits, this study was examined to find out "**who** needs **what**, **why**, **how** and **where**.

The effort in solving this gap could be assisted by application of mathematical models to simulate flood events for better understanding of flood behavior and consequences basing on the demands of the end user. 1D2D SOBEK gives additional information on the flow characteristics of the flood like flow velocity and propagation characteristics that is beneficial for flood hazard assessment (Alkema, 2007; Horritt & Bates, 2002; Tennakoon, 2004 & Shaviraachin, 2005). This is therefore calls this research to apply 1D2D SOBEK modelling technique to be able to explore the characteristics and extent of flood behavior of Mpazi plain in terms hazard assessment parameters (Depth, velocity, impulse. Etc.)

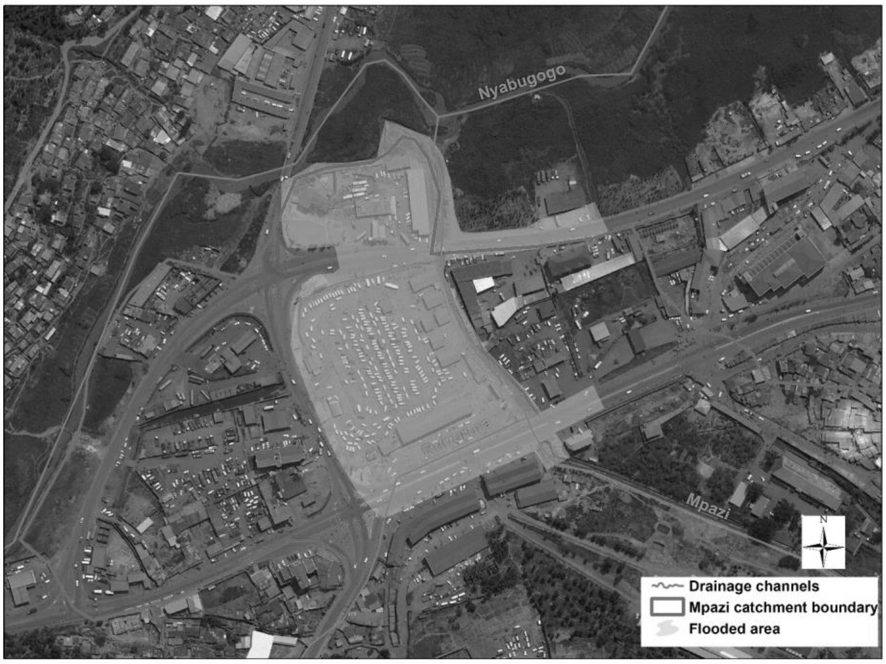

Figure 1.2: Impression of flooded area in the downstream of the Mpazi catchment based on the author's knowledge

1.5. Research Objective

The main objective of this research is to model and assess the usefulness of flood hazard maps at downstream areas of Mpazi catchment. Kigali – Rwanda.

1.6. Specific objectives and research questions

1. To identify the specific needs and requirements of specific end user groups of flood hazard maps
    - Who is the focus (target) group or end user of flood hazard maps?
    - What are the specific information the end-user need in food hazard maps?
2. To define an appropriate method to generate user requirements on flood hazard maps
    - Which is the appropriate tool to generate specific user needs?
    - What are necessary parameters to be integrated in method described?
    - What are the needed resolutions of those defined parameters?
3. To develop the contents of flood hazard maps by considering user specific needs
    - Which areas are likely to be inundated in different return periods?
    - What is the significant change of flood behaviour with changing return period?
4. To assess the usefulness of flood hazard maps developed.
    - How useful is the flood hazard maps developed for different target group?

1.7. Hypothesis

Different users of flood hazard maps have different requirements and preferences. 2D hydrodynamic modelling is an effective way of preparing flood hazards based on end-user requirements. It will provide the necessary flood hazard parameters to inform decision makers and city planners the process of future development planning.

1.8. Conceptual framework

The conceptual framework is used in the research to present the idea into preferred approach. The concepts of these research are linked as shown in the figure 1.3. It is briefly shows that, flood hazard parameters are shown in maps showing information on the spatial extent and depth of inundation for flood events of different probabilities. This study is about urban flood hazards, which can be assessed through modelling approaches which provide insight into the severity of urban flood map characteristics and its impact on vulnerable groups. Since the objective of this research is to assess the useful of flood hazard maps, it is essential to know various users and their requirements which are various too. The user requirements can be satisfied by application of flood models. The following figure 1.3 below simplified the concept of this research and more detail in chapter two.

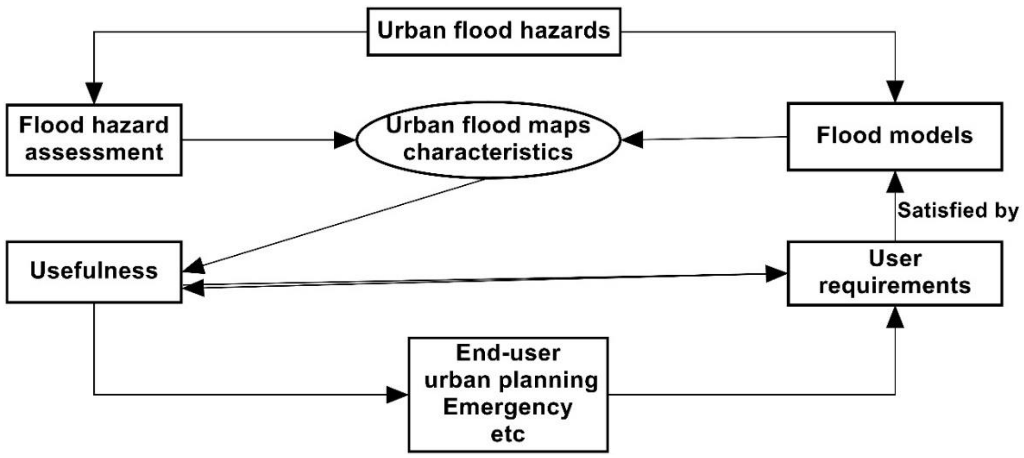

Figure 1.3: Conceptual frame work

2. LITERATURE REVIEW

This chapter is about the review of literature on urban flood hazards. The first part of this chapter discusses urban flood hazards and how they are assessed. The second part identifies flood hazard modelling approaches and its application and data requirements. The third part identifies the use of the flood hazard maps by explaining the users of the flood hazard map and what they do with it and it concluded by identifying different end-user requirements of flood hazard maps.

2.1. Urban flood hazards

Various authors have put forward different definition of flood hazards. According to (Thieken & Merz, 2006) defined flood hazard as the exceedance probability of the potentially damaging flood situation in a given area within specified period of time. (Alkema, 2003) defines flood hazards represents probability of occurrence of flood at certain severity. These flood severity should be expressed by water levels, flood velocity and duration, while the probability refers to the frequency (Campana & Tucci, 2001). In addition other authors add warning time, impulse and rate of rise of flood water. Flood extents and depth are usually considered the most important flood parameters, especially when it comes to mapping flood hazards. However some other parameters like velocity, duration, warning and rate of rising of water can also be important depending on the situation and purpose of the map. This study focus on the purpose and use of the map and prepare flood hazards according to situation and purpose of use by different stakeholders.

2.2. Flood hazard assessment

When assessing flood hazard maps, the first step is to check how often the floods occurred historically and magnitude of them (de Moel, van Alphen, & Aerts, 2009). This can be mapped as point events or extents of historical floods can be depicted on the flood extent map. With the advance of technologies, flood extents of current or recent events can be easily determined by using remote sensing imagery. This provides possibilities to calibrate and validate flood extents simulated by computer models (de Moel et al., 2009). To create and implement policy with respect to flood management, it is important to have up to date flood information which is consistent over the entire area. The use of historical flood hazard maps in this respect is restricted since it is not impossible to compare them as return period or not equal to boundary conditions (land cover etc...) has changed significantly overtime (Bellos, 2012). In order to overcome this problem, statistical and modelling tools are used to calculate the hazards of hypothetical floods. There are various parameters that can be used to denote flood hazard. These include flood extents, water depth, flow velocity, duration, warning time and the rate at which the water rises (Alkema, 2007). These flood hazard information can be obtained by application of mathematical models. This modelling approach helps to understand the flood hazard and serves as a tool which also useful in understanding the effect of mitigation measures (Bhattacharya, 2010). These models are available in many types nowadays, from simple 1D models to complex 2D models, taking flow direction into account (Prachansri, 2007).

2.3. Urban flood modelling approaches

Models are simplified representation of realities (Fura, 2013). The author continued that, they are instruments used to mimic and provide insight of process or phenomenon such as flow of water in channels, urban expansion etc. Although they are simplified representation of reality, models are powerful tool to simulate and predict the implication of certain actions in the future (Couclelis, 2005). However the form of representation depends on underlying theories and methods.

Today different types of urban flood models exists. Pender & Neelz, (2007) reviewed some of existing 1D and 2D flood models. These models have the same principle of conservation of mass, momentum and energy (Horritt & Bates, 2002). If water is confined in a channel, it is best simulated as an unsteady 1D flow model (Verwey, Stelling S. 2006) which solves 1D Saint Venant equation (Horritt & Bates, 2002). This 1D model defines flood only in terms of discharge and water level as a function of space and time. However, it has a limitation of simulating floods in the overland, this situation causes a shift from 1D to 2D model that simulates flood in the overland (Horritt & Bates, 2002). 2D flood model predict flood inundation based on 2D shallow water equation (Mignot et al., 2006). The system of 2D shallow water consists of 3 equations one for continuity and two for conservation of momentum in two orthogonal directions (Mignot et al., 2006).

Because 1D and 2D flood modelling both have their own advantages and disadvantages, there are extensive approach to integrate 1D and 2D flood models resulting in hydrodynamic model of flood plain. The integrated 1D and 2D flood model development focuses on the extension of model capabilities in order to simulate flood more accurately (Shaviraachin, 2005). There are various models offering such capabilities, the examples include 1D-2D SOBEK (Alkema, 2007) SWI2D (Finaud-Guyot et al., 2011), LISFLOOD and TELEMAC -2D (Horritt & Bates, 2002), and OPENLISEM (De Roo et al., 1996). Among all mentioned models 1D 2D SOBEK model gives additional information on the flow characteristics of the flood like flow velocity and propagation characteristics. Hence coupled 1D2D SOBEK were applied in this research. In addition, SOBEK has been enhanced with facilities to import GIS data into the model and export computational results to GIS System for presentation and evaluation (Shaviraachin, 2005).

2.3.1. OPENLISEM (Limburg Soil Erosion Model and its data requirements)

LISEM can be used to simulate the effects of the land cover and land use on the surface runoff (Jetten, Baartman . Ritsema, 2011). It is a process based model used for better understanding location of runoff hotspots to predict and to evaluate the effects of different overland flows and water conservation level as well (De Roo et al., 1996). LISEM is used to simulate surface runoff by calculating the discharge flux of land cover types based on the average water height in the grid cells of the raster land cover maps using kinematic wave of the water leading to the outlet (Jetten, et al. 2011). LISEM needs various types of maps depending on the input options which can be derived from four basic maps that include: DEM, land use, soils, and roads. LISEM has some limitation of incorporating culverts dimensions in model which is not the case for SOBEK (De Roo et al., 1996).

2.3.2. SOBEK 1D2D Hydrodynamic model

Studies of Leandro, Chen, Djordjević, & Savić, (2009) showed that flow of water over terrain are better modelled by 2D model and flow within channel by 1D model. These tradeoff between 1D and 2D called for integrated 1D-2D modelling approach. SOBEK 1D2D model was developed by WL Delft Hydraulics in the Netherlands (Delft, 2009). It is one of the sophisticated models in modelling complex terrain. It has the capacity to model both 1D and 2D models with a unique capability of conservation of momentum and mass (Bhattacharya, 2010). SOBEK is full dynamic 1D-2D hydraulic model, specifically designed for flood plain flood modelling (Alkema, 2007).

Horritt & Bates, (2002) justifies that the usability of the model can be evaluated by consistency in calibration which justifies it's suitability for practical purposes. Alkema, (2004) continued that SOBEK

1D2D model was designed to simulate flow of water both overland and in a channel over complex topography for different magnitude of flood. While another study for (Leandro et al., 2009) evaluated the model after calibration for two different scenarios and showed a satisfactory consistency in the model results.
The SOBEK uses the full two dimensional shallow water equations for describing flood plain flow in the main channel. the flow is described using full one dimensional De Saint Venant equation. Both modelling system produce implicit differential equations which are linked through an implicit formulation for joint continuity equation at locations where both modelling systems have common water level points.(Asselman, N.E.M. and Heynert, 2003) .The data requirements for the model are: Finer topographical data (DEM, roads, rivers and buildings), hydrological data (Boundary conditions), and roughness coefficient derived from land use map and river or channel cross sections. This study will apply SOBEK model to assess the usefulness of flood hazards. The main advantage of employing SOBEK in this study is that flow in open channels can be replicated with extensive detail by incorporating structure such as bridges, embankments, culverts and buildings (Alkema, 2007).

2.4. Application of 2D hydrodynamic model

2D modelling has a wide range of application areas and simulation possibilities (Bhattacharya, 2010). It is the most used model in flood and water quality modelling community. Alkema, (2003) put an effort to illustrate the capabilities of 2D approach in various application domain. He showed that 2D model can be used as decision support tool for evacuation planning and risk assessment purpose during polder flooding due to breach of dikes or dams.

2.4.1. Urban planning

Urban planners are on high pressure to identify new lands for development due to rapid urbanization and subsequent requirement of infrastructure facilities. Careful attention is utmost when proposing a development in urban flood plain. Low lying areas remains undeveloped in urban flood plain because they act as detention or retention ponds to ease the flood level in the surrounding the flood level to ease the flood event due to excessive water through runoff. This therefore calls scenario simulation as powerful tool to identify safe and suitable land for future development (Tennakoon, 2004)

2.4.2. Environmental impact assessment studies

Alkema, (2007) identifies that, 2D hydrodynamic models are powerful for identification of variation of flow pattern due to changes in terrain. Therefore construction of any structure especially in the flood prone areas has to prove that it is not lead to harmful changes in overland flow pattern to its surrounding neighborhood. To say in the words of (Alkema, D. Cavallin, A and De Amicis, 2001) *"2D models should be used during design phase of infrastructure projects in such way that positive impacts are maximized, and mitigation measures to reduce risks in rest of flood plain are incorporated"*

2.5. Model calibration and sensitivity analysis

Any model should be calibrated with the observed record to avoid the deviations from the reality so that both simulated and observed records are much close as possible. Nash & Sutcliffe, (1970) determined parametric values of models based on the set of pre-condition through automatic optimization. This determines index of agreement or disagreement between observed and simulated values.
Friction coefficient (Bed friction and wall friction) are the variables that determine the flow of water in a channel. These two variables are considered in calibrating a model for performance evaluation (Ramesh, 2013). The only parameter used to calibrate a 2D model for overland analysis is the roughness coefficient of the flood plain (Alkema, 2007). Once having discharges at particular river cross section, to prove that inundation extent at particular time by changing roughness coefficient of the inundation area. So it is

possible to control overland flow or the river discharge. For example once you decrease the roughness coefficient of the flood plain, it will results the higher flow towards the flood plain and lower discharge at the downstream (Alkema, 2007). The calibration of this study will be based y setting out or fine tuning roughness values of different land cover types.

2.6. Use of flood hazard maps

Flood hazard maps are used for variety of purposes by governments mostly for emergency planning and spatial planning. In spatial planning a distinction can be made between countries where flood maps serve as advisory purpose, and countries where there is a binding legislation to use flood hazard. Flood zones can serve as an informative tool for decision makers (EMA, 1999). Besides planning purposes, flood hazard maps are used to raise awareness about floods. Lending institutions and insurance companies use them to identify who needs flood insurance and to determine flood insurance rates. Planning officials, land developers, and engineers use them for designing new buildings and infrastructure to avoid flooding. Most importantly, states and communities use them for hazard mitigation planning and emergency management and all flood hazard parameters are not playing the same role to satisfy their needs (FEMA, 2000).

2.7. End-user involvement

Recently there has been a shift of paradigm of hazard based decision making (Merz, Thieken, 2007). This paradigm call for participatory approach in which different stakeholder's are involved in flood hazard assessment procedure (Amendola, 2002). Past experience has shown that interdisciplinary approach is beneficial when it comes to the aftermath managing of extreme flood events (LAWA, 2006). It is recommended that, collaboration of this type be applied to the realization of flood hazard maps and other mitigation measures since this would fulfil the different criteria for different multipurpose projects like, all users benefit from the realization of flood maps, all users are equally committed to ensure that flood hazard map gain acceptance as flood damage reduction tool, and various users contribute their data, expertise, interest, and experience to the realization of the maps. The needs of all users should be taken into account in developing flood hazard maps (Jha, Abhas K. Bloch, Robin, Lamond, 2012). This study will primary focus on the end user requirements in developing the flood hazard maps.

2.8. User requirements of hazard maps

The needs of all users (target group) should be taken into account in developing flood hazard maps. Different types of users have different needs of flood parameters for example decision maker, urban planner, engineers, emergency response workers, insurance companies etc...have different demands on hazard maps (EXCIMAP, 2007). Lending institutions and insurance companies use them to identify who needs flood insurance and to determine flood insurance rates. Planning officials, land developers, and engineers use them for designing new buildings and infrastructure to avoid flooding. Most importantly, states and communities use them for hazard mitigation planning and emergency management and all flood hazard parameters are not playing the same role to satisfy their needs (FEMA, 2000). All those mentioned user have different requirement with regard to flood hazard maps in order to satisfy their demands. Therefore before constructing those products you should clearly define the objective of hazard assessment like what is going to be used for? Who were the users? Should they have specific purpose in mind or should the map be generic or multi-purpose? Study of Alkema, (2007) showed how different end users have different needs. For example a relief worker can generate flood hazard map based on set of criteria like warning time, maximum water depth and rising of water level. Insurance company can generate specific hazard map based on maximum water depth duration and impulse.

3. STUDY AREA AND METHODOLOGY

This section briefly explains the background of the study area and how formulated research questions can be addressed. The second part of this chapter is about data collection and acquisition for this research. It describes the research methods and tools that have been applied during field work and how data was prepared for the model.

3.1. Study area

Kigali is the largest and the capital of Rwanda, it is located in the central part of the country. The terrain of Kigali is characterized by a series of hills which are separated by wetlands. Most of the developments of the city takes place on these hills which are connected by district roads. The population of Kigali metropolitan area, covering an area of about 730 km2 was recently estimated to grow from 765,325 in 2002 to approximately 4.5 million in 2025 (KDMP, 2013). Study area (Mpazi catchment) have different land uses predominantly low residential area and commercial zones in the low land as shown in figure 3.1 below.

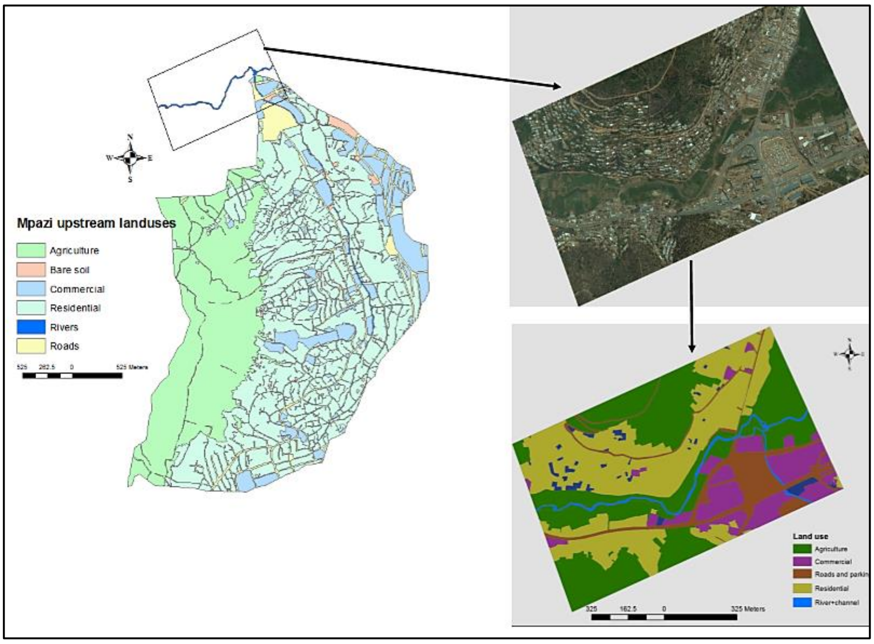

Figure 3.1: Land use types in the entire catchment (left) and downstream flood plain area (right)

Kigali city have different sub catchment, but this study will focus only in the Mpazi catchment which is said to be catchment that causes flooding problems in its downstream (SHER-Ingénieurs-conseils, 2013). The low land flood plain of Mpazi watershed has slope gradient of about 0 -2 % making area susceptible to flooding during rainy seasons which starts from October to May each year. (Refer to Fig.3.2)

For the frequent flooding in Kigali, Mpazi catchment plays a central hydrological role. This catchment is heavily urbanized, dense housing and steep slopes which causes flood waves in the drainage channels. This flood waves occurred when higher water stages moves faster than lower water. This is seen in the figure 3.2 below.

Figure 3.2: Flood waves in the drainage channels photo taken on 2 Oct 2014 during filed wok

Urbanization in the Mpazi catchment is seen due to high percentage of non-gutters roofs that cover the entire area which stimulates rainfall into surface runoff. Refer to fig 3.3. Masonry main channel with small tributaries drain the area. This main channel collects the water in upstream of catchment and drain it to Nyabugogo River. Refer to fig 3.3

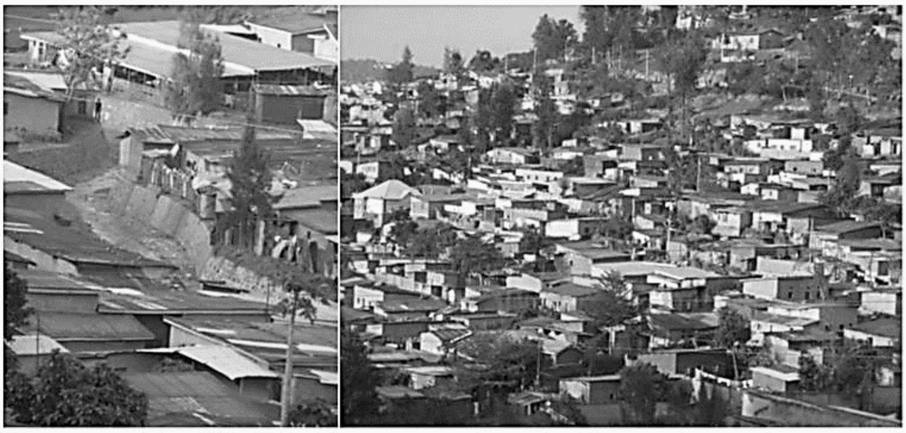

Figure 3.3: Densely urbanized neighborhoods in the upstream of the catchment

At the same time, this very flat floodplain location surrounded by undulating hills contributes to its vulnerability to flooding. The sub area floodplain is crossed by the Nyabugogo River and is located at the entry of a narrow valley between Mont Kigali and the adjacent hill, creating a bottleneck. It has been the convergent channel for overflow and runoff of both rainwater and sanitary drainage from several major sources, including northwest from the Muhazi and more immediately from the Mpazi watershed and other surrounding steep slopes. The combination of increased settlement and transport activity in the Nyabugogo flood plain coupled with increased runoff from multiple directions has created a crisis situation in the lowest land areas, especially where the current Nyabugogo taxi park is located. Refer to figure 3.4 below.

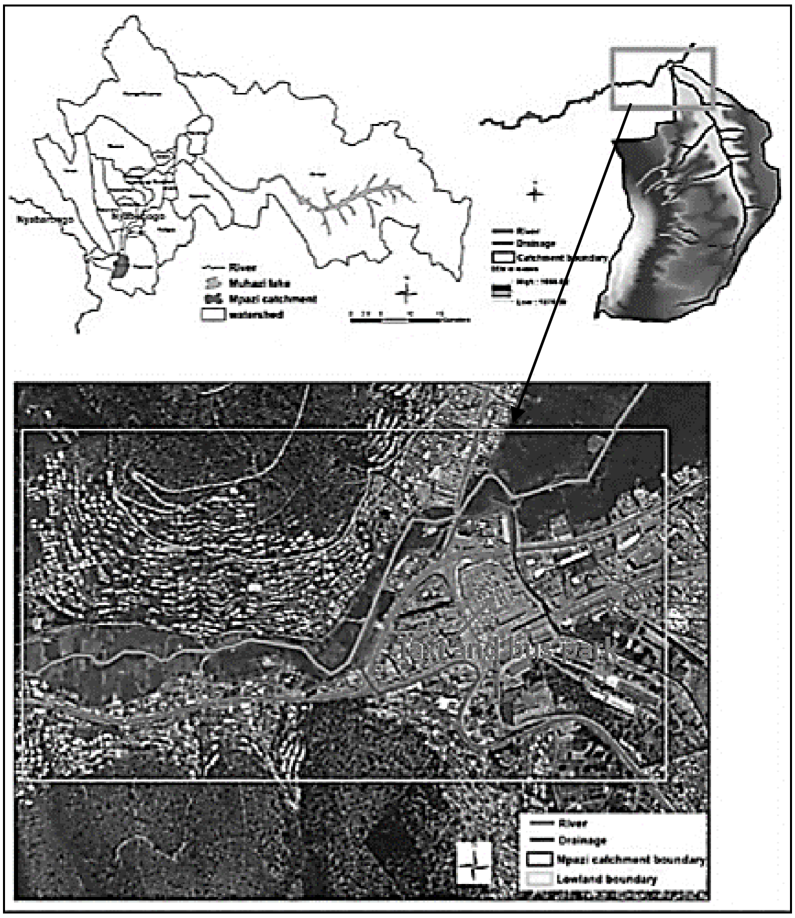

Figure 3.4: Map showing downstream of study area and Mpazi watershed.

3.2. Selection of study area

The study area is selected based on the prior knowledge of the area and purpose of the study. It has characteristics that make it worthwhile to study. Some of the reasons to why I choose this is study area are:

1. It is an area with yearly repeating problems with overloading of the drainage structures
2. It is an area with urban water storm flooding cause a serious problems on the in habitants and infrastructure
3. It is an area where downstream that faced flooding problems are the most commercial hub of the city.

3.3. Research methods

For accurate estimations of usefulness of flood hazards based on different stakeholders needs, this research method is organized in three main parts/phases, the first part/phase focuses on the interviewing of key informants/target group or end-user of flood hazard map in order to identify shortcomings of the existing maps (if any) and to discuss the potential improvements with regard to the flood hazard map contents. If there is no flood hazard maps available, potential requirements, needs and recommendation with regard to the content of flood hazard map for each target group were identified. The second stage was aimed to find out modelling tool, collect and analyze the basic data required to meet their demands. Last part was to model the flood behavior and propagation of Mpazi catchment and provide outputs map for different end user which is beneficial according to their requirements and assess their usefulness.

Summary flow chart of this research is presented in the figure 3.5 below. Calibration and validations are important steps used in this study. Step by step in archiving this is outlined in the figure 3.5 below and more detailed in the next chapters.

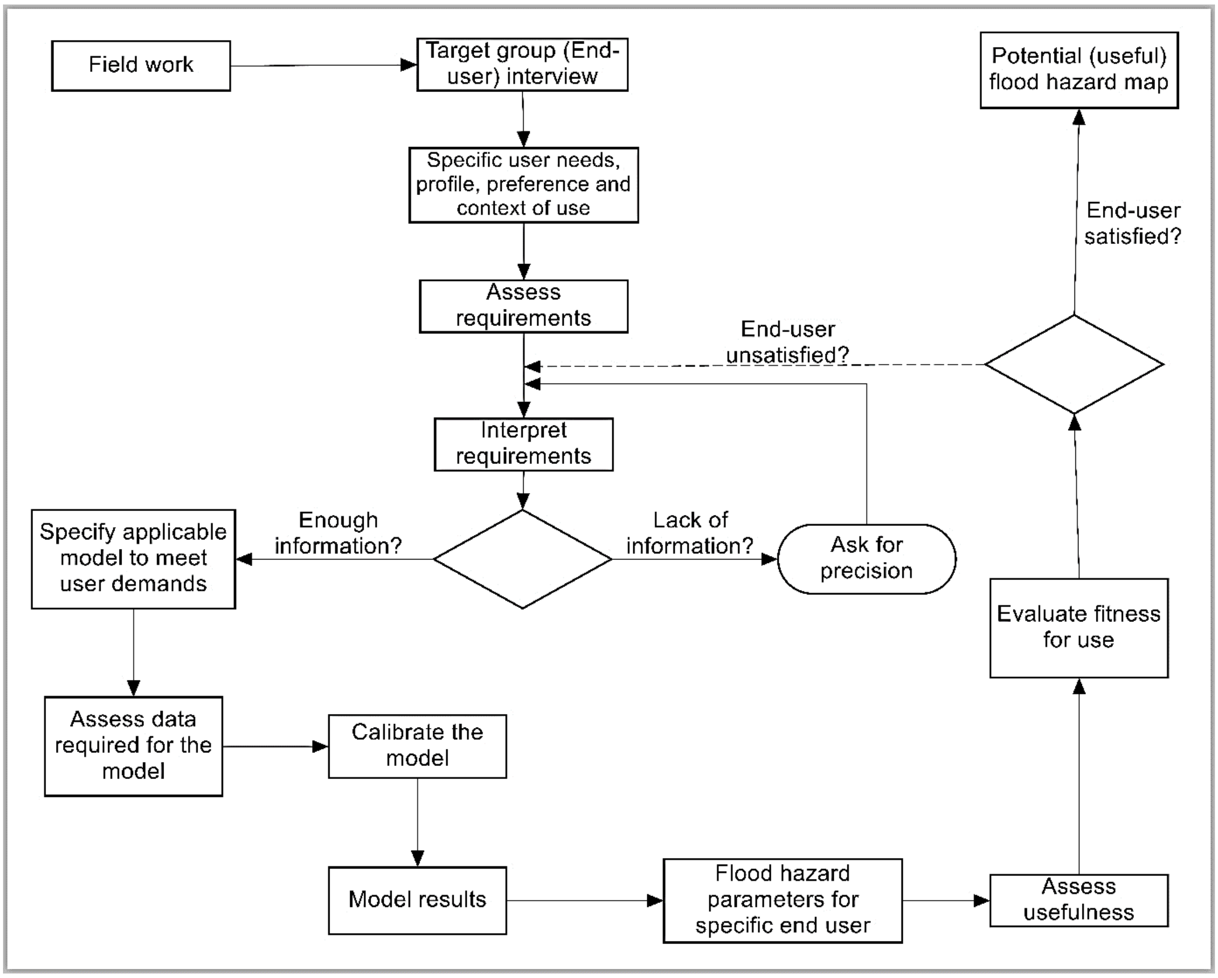

Figure 3.5: Overview of Methodology for hazard assessment in Kigali based on user requirements

3.4. Data collection

There are various sources of data that were collected in this research during field work ranging from primary data to secondary data. Primary data was collected through complete survey of the study area, key informants interviews, and field observation. From data obtained from respondents, model was selected to suite user's preferences and followed by collecting both primary and secondary data of the model. Secondary data was collected from different governmental organization. Details of both types of data are provided below.

3.4.1. Primary data (Phase 1)

Most of the data required to answer and validate research questions were collected from primary sources. Since in this research the user of hazard maps plays an important role, it was necessary to get views of flooding from different end-user of flood hazard maps through interview to investigate the information they have on flooding and their needs/ preferences on the hazard maps. After analyzing user demands, the next step was to select an applicable model that can satisfy their demand.

Delivery of questionnaire

Due to limited length (Only two pages) of the questionnaire and nature of open/closed questions, face to face delivery was most appropriate. This allowed the interviewer to be more actively involved in data collection. All target groups were selected through non probability purposive sampling technique where potential target group was approached directly. These end user (city planning agencies, disaster emergency response, engineers, water management agencies, insurance institution and citizen in flood prone areas) were selected as it is expected that they have an interest in the flood hazard mapping. Questions were read by interviewer and participants were requested to respond verbally. All answers in the questionnaire was recorded down with any other information communicated by participants which thought to be useful. The questionnaire was attached by an example of flood hazard maps just in case of communicating how flood hazard maps look like and content they reflect to those users who are not familiar with maps like private sectors and insurance companies. Appendix 1.

Interview with stakeholder (End-user)

In depth interview was conducted with different end users of flood hazard maps to check what information they need from hazard maps. From their needs (criteria) meaningful hazard map were generated incorporating the user demands. In this study the focus group were city planning agencies, disaster emergency response, engineers, water management agencies, insurance institution and citizen in flood prone areas. An open ended questionnaire (semi structured interview) was provided to different target group that have different needs on the content of flood hazard maps. Each group addressed his/her own preference on content that can be shown in the map that can be useful to his or her own institution and the context behind usefulness of contents was derived during in depth interview as described in next section. This research revealed that, users of the maps such as public or emergency response managers are only seen as a receiver of information and are not directly involved during flood mapping. Hazard communication is done in only one direction top down approach. This causes the users of flood maps to often respond to a map by disagreeing the contents information behind the map, believing them to be inaccurate. This leads to a problem that the maps are not effective in promoting the public to take actions in reducing their vulnerability.

Assessment of user's preferences

Assessment of end-users preference or needs were done in cautious way and tried to be interpreted. If there is lack of information during interpretation of the user requirements, asking for precision was done and again assessment continued see fig 3.5 above. If information provided are enough and well interpreted, the next stage were to specify and select the applicable model to satisfy end user needs.

3.5. Model selection and data required and preparation (Phase 2)

User's flood hazard map preferences can be satisfied through application of mathematical models to provide insight into the severity of urban flooding and its impacts on the vulnerable groups. Selection of mathematical model was done after receiving end user needs. Different models require different data, the next step was to determine the required data for the selected model. Running and calibrating model were done to minimize the deviation between observed and simulated results. Model out puts were converted into different hazard parameters that suit the user's needs. Each target group will obtain the hazard map according to what they demanded they think to be useful in their institution.

3.5.1. Mathematical model selection

Because 1D and 2D flood modelling both have their own advantages and disadvantages, there are extensive approach to integrate 1D and 2D flood models resulting in hydrodynamic model of flood plain. The integrated 1D and 2D flood model development focuses on the extension of model capabilities in order to simulate flood more accurately (Shaviraachin, 2005). There are various models offering such capabilities, the examples include 1D-2D SOBEK (Alkema, 2007) SWI2D (Finaud-Guyot et al., 2011), LISFLOOD and TELEMAC -2D (Horritt & Bates, 2002), and OPENLISEM (De Roo et al., 1996). Among all mentioned models 1D 2D SOBEK model gives additional information on the flow characteristics of the flood like flow velocity and propagation characteristics. Hence coupled 1D2D SOBEK were applied in this research. In addition, SOBEK has been enhanced with facilities to import GIS data into the model and export computational results to GIS System for presentation and evaluation (Shaviraachin, 2005). The main advantage of employing SOBEK in this study is that flow in open channels can be replicated with extensive detail by incorporating structure such as bridges, embankments, culverts and buildings.

3.5.2. Data requirement for 2D modelling

The required data for flood simulation in SOBEK are: Detailed digital elevation model which contains all major surface features that can influence the movement of water like roads and buildings, Surface roughness map which represents the resistance of flow of water that responds from various land cover types, boundary conditions which can be discharges in user defined time interval (May be derived from other models), water levels and channels cross sections and bridge and culverts profiles if any. More details are explained in next sections. The following table 3.1 refer to the possible data collected during field work, its format and source. The next section describes how the collected data was prepared and ready for input of the model.

Table 3.1: Summary of list of the spatial data and non-spatial data needed in this study

Data types required	Data format	Year	Existing collected data	Derivation of Non existing data	Data source
DEM 10 m resolution	Raster	2009	OK		Kigali city
Building footprints	Vector	2009	X	Digitized from Aerial photo 2009	Digitized from Aerial photo 2009
Aerial photograph (0.25 resolution)	Image	2009	OK		Kigali city
Land use/ cover map	Vector	2008	OK		Kigali city
Roads & Rivers	Vector	2009	OK		Kigali city
Drainage channels and rivers cross sections	m^2	2014	OK		Field work
Bridge and culverts profiles	m^2	2014	OK		Field work
List of end-user requirements	Questionnaire	2014	OK		Field work
Historical data	Questionnaire	2014	OK		Field work
Meteorological data	Dbf/Table	1993-2013	OK		Meteo- Rwanda
Hydrological data			OK		
Catchment discharge (Upstream boundary)	Hydrograph	2013	OK		SHER-Enginieur
River discharge (Q-H Relation): Rating curve	Table	2014	OK		Nemba station
River water levels	constant	2014	OK		Nemba station

3.5.3. Primary data for the model

Channel and river cross sections

In this study, cross section data were derived from DEM and by surveying during the field work. Channel width and slope were measured and visually estimated from field work. Bridge dimensions and main culverts were noted down and their position were recorded by Hand held GPS as a series of way points.

Channel and river cross sections was obtained during field work phase. During this phase an instrument called total station was used to derive cross sections and slope of primary channels and rivers which is important in 2D hydrodynamic modelling. Engineering features such as bridges and culverts were considered in this in this study for the reason that the inclusion of such structures may have an impact on flood propagation (see figure 3.6). Therefore one bridges and two culverts profile were measured as in put feature for the SOBEK hydraulic model.

Figure 3.6: Channels, rivers, bridge and culverts cross section measurements

Historic flood data

It was required to obtain the water level of the recent flood within flood plain for model calibration. These data were collected by interviewing the dwellers of the flooded area and observing recorded water level on the walls, bridge abutments etc.

The people interviewed were among the victims of floods and the questions asked were: How deep was the last observed flood in the area and their locations? And to what extent and duration was the last flooding occurred?

However, the reliability of this data is questionable due to contradicting statements made by different respondents. These respondents may not be referring to the same flood event, people normally remember the biggest event according to his or her own experience. The other limitation in this approach is that people want to exaggerate the actual flood levels that cannot match the actual records. This is possibly because, they think exaggerating flood depths may shock the decision makers in charge to take quick actions. Even though this is not technical issue, we learnt from fieldwork that, most of the urban floods were recorded by local municipality or professionals concerned, these people were contacted where we found out that the values they have are obtained by interviewing the local people too, so available information cannot be taken as unquestionable information.

Figure 3.7: Marking water level on walls of building and its spatial locations during fieldwork

Several observations on the history of flooding in Kigali were recorded, total of 20 records about water levels were observed through interviewing of dwellers in the flood plain and their locations were obtained by using hand held GPS as series of way points. Some of these records were used for calibration and validation purposes.

3.5.4. Available secondary data

This section covers available data and source of the data collected and applied in this research. All available data such as DEM, Aerial photos, GIS layers and all not mentioned as shown in the table 3.1 above were provided by Rwanda natural resource authority (RNRA), Kigali city and Meteorological department. Other available data useful for modelling are hydrometric and meteorological data as explained below.

Hydrometric data of Mpazi catchment: As there were no data on runoff production and runoff from the Mpazi catchment before December 2012, Rwanda natural resource authority (RNRA) commissioned some consultants to equip the main channel of Mpazi basin with a data logger to measure the flood waves. The logger was installed on December 5th 2012. Since then it has registered 16 floods (SHER-Ingénieurs-conseils, 2013) . The instruments have fully recorded the flood of February 23rd to quantify the amount of flow. The figure below gives the discharge from the data logger for the flood event of the 23rd of February 2013 i.e. Left hand diagram shows water levels and right hand diagram shows the corresponding discharges.

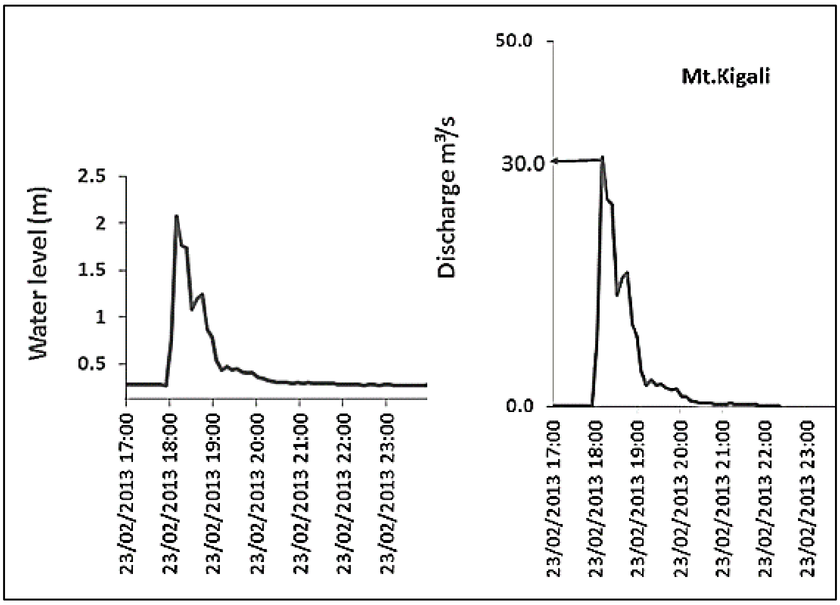

Figure 3.8: The flash flood observed in the Mpazi basin on 23rd of February 2013. Source :(SHER-Ingénieurs-conseils, 2013)

The consultants used HEC-HMS software to derive different discharges of flood waves from more or less rain fall extreme events (Return period of 10, 20 and 50 years). The annual maximum discharge values for Mpazi catchment with different return period was collected and was used as upstream boundary conditions of SOBEK model. The discharge measured by data logger on the event of 23rd February corresponds to an event of 10 year return period (see Appendix 2).

Hydrometric data of Nyabugogo River: This includes water levels (m) and corresponding observed discharges (m3/s), and was recorded at Nemba measurement or gauging station, and are available from 2011 to 2014. There were no available data (water levels and discharges) for different return periods in

Kigali. According to (Parodi G, 2009), Frequency analysis should be avoided when working with records shorter than 10 years. Therefore frequency analysis of discharges was avoided due to limitation of long records and only constant river discharge of 23rd February that corresponds to 10 year event was selected for the basis of determining other corresponding river discharges of 20 and 50 year return period.

Meteorological data: The meteo data collected to be applied in this research are daily rainfall recorded by Gitega and Kanombe station provided by Meteorological department in Rwanda. During field work, rainfall time series (meteorological data), flow discharge and water level variations of Mpazi catchment were collected. Daily rainfall data of Gitega and airport stations was recorded. Gitega station is currently located in the area of study and Kigali airport station is located about 5km away from study area. However, since after genocide of 1994, meteorological data has not been recorded in almost all stations except Kigali airport which is close to the catchment of interest, this triggered me to use rainfall data recorded by Kigali airport for the period of 30 years (1986-2013). This is due to the assumption that rainfall fall recorded by that station is uniformly distributed in the catchment of interest. It was necessary to determine the amount of rainfall that corresponds to different discharges of different return period provided by consultants since in their reports they didn't mention the quantity of rainfall that corresponds to given discharges. Therefore frequency analysis was carried out for rainfall data recorded as explained below.

Frequency analysis

This analysis helps to relate the magnitude of extreme hydrological events like floods, draught and severe storms with their number of occurrences such that their chance of occurrence with time can be predicted successfully. Frequent and magnitude of an event are inversely related. This means that, in rainfall context, low magnitude may lead to drought and higher magnitude may lead to flooding. Therefore the rainfall data could be assessed to relate the magnitude and frequency of an event through the use of probability distribution. One of the method that consider all these requirements is Gumbel extreme value distribution (Parodi G, 2009). According to the author, the objective of this distribution is to build relationship between the probabilities of occurrence of certain event, its return period and magnitude. In hydrology, extreme events are either heavy floods or rainfall. In this research Gumbel extreme method is employed since extreme rainfall is likely to cause floods. This extreme annual rainfall analysis will determine the return period of rainfall event that is used for this study (Table 2 and Appendix 1) and output from return period calculation will enable different stakeholder's/users to understand the "exceedance probability" of a given flood events.

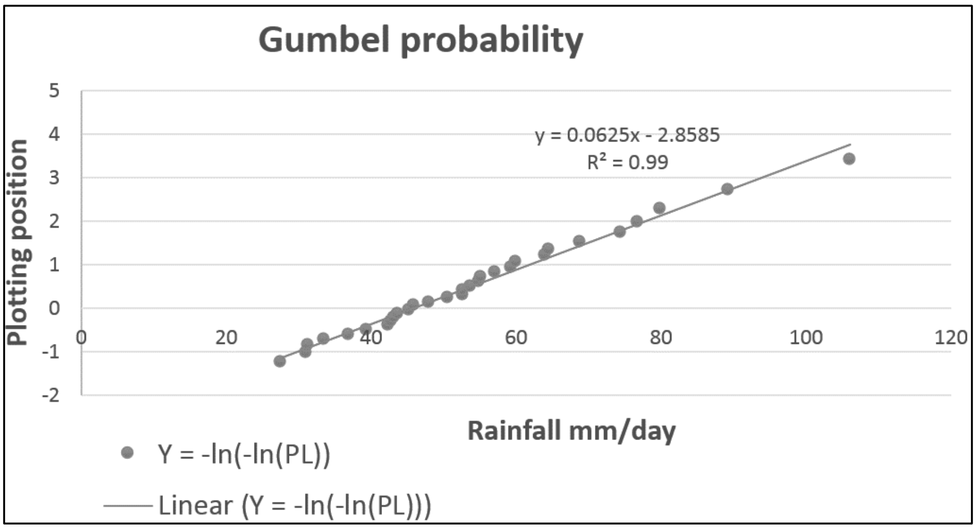

Figure 3.9: Gumble plot distribution for Kanombe airport station

Plotting positions of each observation against annual maximum daily rainfall with trend line which gives Y formula as shown in figure3.9. This formula is used to calculate the return period of rainfall event see table 3.2. The 10 year event rainfall was used by consultants during hydrology assessment to estimate runoff from the entire catchment (Mpazi catchment).

Table 3.2: Return period of the rainfall events used for hydrology assessment based on Gumbel extreme probability method.

Return period (T) for rainfall (mm)	Y=0.0625x-2.8585	PL=EXP(-EXP(-y))	Return period T=1/(1-PL)
79	2.079	0.9	10

This study uses runoff discharge derived from hydrological catchment model HEC-HMS (rainfall runoff model) as boundary condition input for flood propagation model. This hydrological catchment model uses soil data to estimate the infiltration rate and the amount of water that turns into runoff in different time steps (See appendix 2). The rainfall was designed for different return periods (10, 20 and 50) through the frequency analysis using extreme Gumbel distribution shown in figure 3.9 above. The peak discharges was calculated from its corresponding rainfall from different return period. These rainfall size for different events were only calculated for the purpose of relating consultant available discharge with corresponding rainfall which was not available in their report.

Table 3.3: Distributed daily rainfall and their corresponding return periods **Source:** (SHER-Ingénieurs-conseils, 2013)

Return periods	Rainfall (mm)	Mpazi catchment peak discharges outlet (m^3/s)
10	79	30
20	94	35
50	133	45

Model input data preparation and processing

There are four main input data used in 1D2D hydrodynamic modelling which includes: 1) The digital elevation model which represents the natural topography and manmade features such roads, embankments and buildings, 2) surface roughness that represents the flow resistance of the water on different land cover/land use a long the flood plain., 3) channel and river cross sections that represents the shape of the river as well as the shape of the channel, and finally boundary conditions which represents inflow and outflows of the model and can be represented by either water level, discharge in time series and also the Q-H relation or rating curve. All mentioned required data are described in detail in next sections.

Optimum pixel size for urban flood modelling

Selection of optimum pixel size is important to represent terrain characteristics of the study area. This is because in detailed urban flood modelling studies, urban features like roads and buildings must be represented as close as to reality. The study of Bishop and Catalano (2001) cited by (Rahman, 2006) suggested that minimum size of DTM should be defined approximately to the size of smallest features to be represented in flood modelling. These manmade features act like a barrier to the flow direction since the overland flow mostly conveyed through the road. This means that lesser pixel size gives better representation, however in general 2D models have upper limit for number of pixels (Tennakoon, 2004) The increase in number of pixel is directly proportional to increase in computational time.

Now days, DTM resolution of between 2m and 10m is commonly used in urban flood modelling which also depends on the scale of the study area and the purpose of the output (Tennakoon, 2004). Table 3.4 below shows optimum pixel size for various scales of flood modelling applications.

Table 3.4: Optimum pixel size for model application. (Source: Tennakoon, 2004)

Applications	5m DTM	7.5m DTM	10m DTM
Flood hazard mapping in urban areas			Adequate
Detailed studies related to velocity measurements, sedimentations and erosion		adequate	
Studies (EIA) relating to individual structures or reclamation of small lands	adequate		
Small scale EIA studies in regional level for investigating effects on new roads/small scale reclamation projects etc.			More than 10m

Therefore based on the above table and the application of this study, 10m pixel size was selected which is assumed to preserve urban features, maximize study area and optimize computation time

DEM construction.

The DEM as the name indicates is the model of elevation surface. It is a numerical representation of topography which is made up of equal sized grid cells each with elevation value (Chaplot et al., 2006). DEM is used to derive some key information which is important in distributed hydraulic and hydrological models, such as drainage networks, catchment boundaries, terrain slope flow paths...etc. Therefore one of scientific challenges for flood event modelling is the development of high resolution DEM of large areas which can represent urban topography with high accuracy in order to reflect the real flooding situation.

DEM flood plain construction.

In this study, DEM of the low lands of Mpazi catchment downstream stream area with 10m resolution was generated using spot height as a point to elevation data. These data were obtained from mapping division of Kigali city. These points was derived during Ortho-photo image production in Rwanda using aerial photograph. Contour lines with an interval of 5m and spot height information with vertical accuracy of 0.1m were used (refer to figure 3.10).

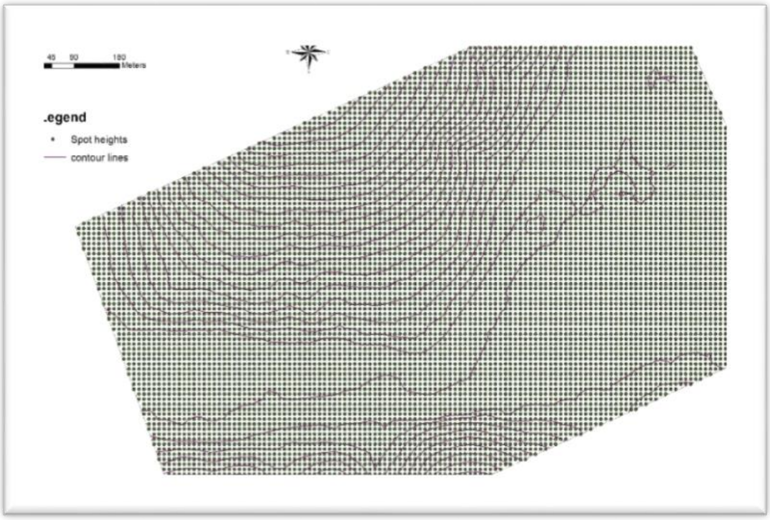

Figure 3.10: Spot heights and contour lines of Mpazi catchment flood plain

In general, DEM can be created using a number of interpolation methods. All these interpolation methods are available in Geostatistical extension analyst tool in Arc GIS and use observed point as input data. The selected interpolation methods were commonly used and suggested by many investigators.

Interpolation techniques.

The quality of DEM can vary greatly depending on the quality of data source and interpolation technique which is applied. Burrough & McDonnell, (1999) has defined interpolation technique as a technique to construct and predict the new data points within the range of known points. According to (Abd Rahman & Dinand, 2007) interpolation technique can be designed to create statistically correct points.

There are main interpolation technique (on inverse distance weighting (IDW), topo to raster, splines) which are deterministic and Geostatistics (spherical, circular, Gaussian, exponential). Ramesh, (2012) defines deterministic technique as a technique based on the mathematical equations to predict the new data points based on the assumption that the interpolating surface should be influenced mostly by nearby points and less by distant points. While Geostatistics methods applies both mathematical and statistical approach to predict the new data points at unknown locations. This technique is based on the assumption that interpolating surface should be influenced mostly by the nearby points and less by more distant points.

There are many typical methods used to produce many of today's DEMs (Ramesh, 2013). Since in this study, its aim is not to compare different interpolation techniques available, selection method was chosen based on the fact that it is the technique recommended by many investigators. Therefore kriging as interpolation technique was chosen to create the 10m resolution of flood plain areas since it is found to produce the best results in general tests of interpolators (Rahman & Dinand, 2007, Ramesh, 2012)

The DEM was created using point interpolation method and using ArcGIS environment and some required extensions such as 3D analyst and Geostatistics as shown in figure 3.11 below. The available elevation point was in form of point data with 10m spacing. Interpolation method chosen to create DEM from these elevation points is Kriging. This method is chosen based on fact that it is interpolation method which is based on statistical models that include autocorrelation. In kriging the only parameter is semi-variogram, which describes spatial correlation between points. The spatial correlation of the data set was checked. The interpolation was done by choosing the Gaussian semi-variogram model that appeared to fit the dataset best compared to spherical and circular semi-variogram. This assessment was done based on the least square method. The points was interpolated with a 10m pixel size using ordinary kriging interpolation method. This cell size was chosen based balance between computational time and urban feature representation.

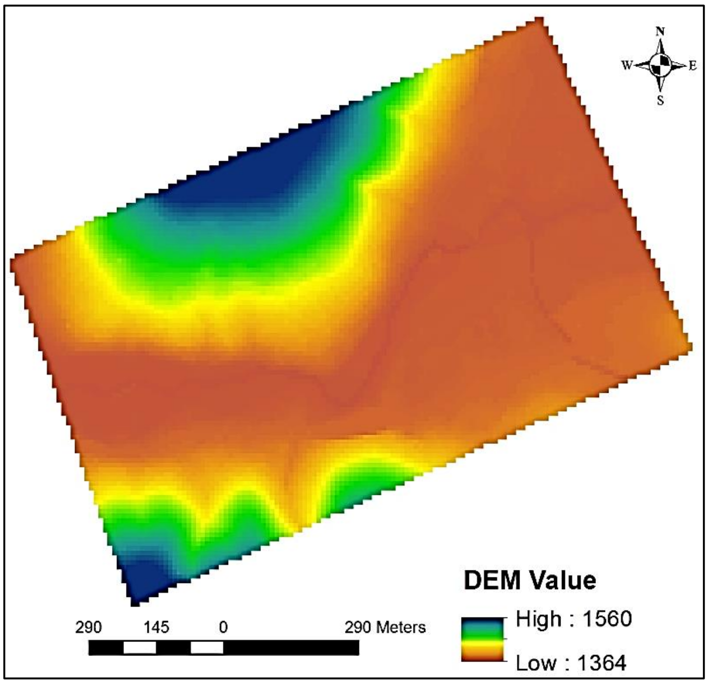

Figure 3.11: Digital elevation model of Mpazi catchment flood plain area

Adding feature surface to DEM.

In flood modeling, all surface features that affect the flow distribution of water must be represented in DEM. For this purpose, it was necessary to integrate the man-made features in the DEM, including roads and buildings and their respective values were obtained from the fieldwork.

Road elevation was made by increasing it to 5cm (fieldwork observation) and the building also added to DEM as solid blocks hinder the flow water as it surpassed the building. Due to limited data, heights of approximately 6m (one storey) were defined for all buildings. The final DSM was used in hydrodynamic modelling (see figure 3.12).

Building height representation.

In densely developed area, buildings and other structures present in the terrain will primarily decide the direction of overland flow. Therefore accurate representation of building footprints as an obstruction to the flow can be essential in 2D hydrodynamic modelling. In Kigali city, building footprints shape and building height information was not available. In this study, building footprints of the entire flood plain was digitized and since height information of the building is not most important in flood modelling, arbitrary heights of approximately 6m were defined in all buildings equivalent to one storey commercial buildings in the area of study. This arbitrary height attribute was used to convert footprints feature class into raster layer representing building height as pixel value. This raster layer was then added to actual DEM as solid blocks to hinder the flow as it surpassed the buildings to get terrain surface including buildings information. This separate layer file representing building footprints was created using 10m resolution the same with DEM pixel resolution.

Raising of road elevation.

It was noticed that the collected road elevation does not reflect the present situation of the terrain. This deviation is due to the fact that the elevation data sources were obtained before 2008 and ministry of infrastructure policy decided to raise or change road surface structure or surface for durability and safety. During field work, it was noticed that some of Kigali city roads was a bit at higher elevation than natural ground surface. There was therefore a decision of raising all road elevation by about 0.1m to the initial road DEM and rasterized to 10m pixel size. River network was converted to raster map and later glued with other parameters during final DSM construction shown in fig 3.12. Raster calculator in GIS environment was adopted in this operation.

Combined elevation model.

Three different elevation surfaces are obtained as mention in previous sections with the intention to get flexibility of changing the elevation of one feature without changing elevation of others. At last all individual elevation model combined to make a final model representing urban features in single grid. Raster calculator in GIS environment do this job. The combination of these three elements converted into Arc info ASCII raster format using Arc GIS tools. This is because SOBEK module accepts the elevation model in this type of format. The results final combination of individual elevation model (DSM) is shown in the figure 3.12 below.

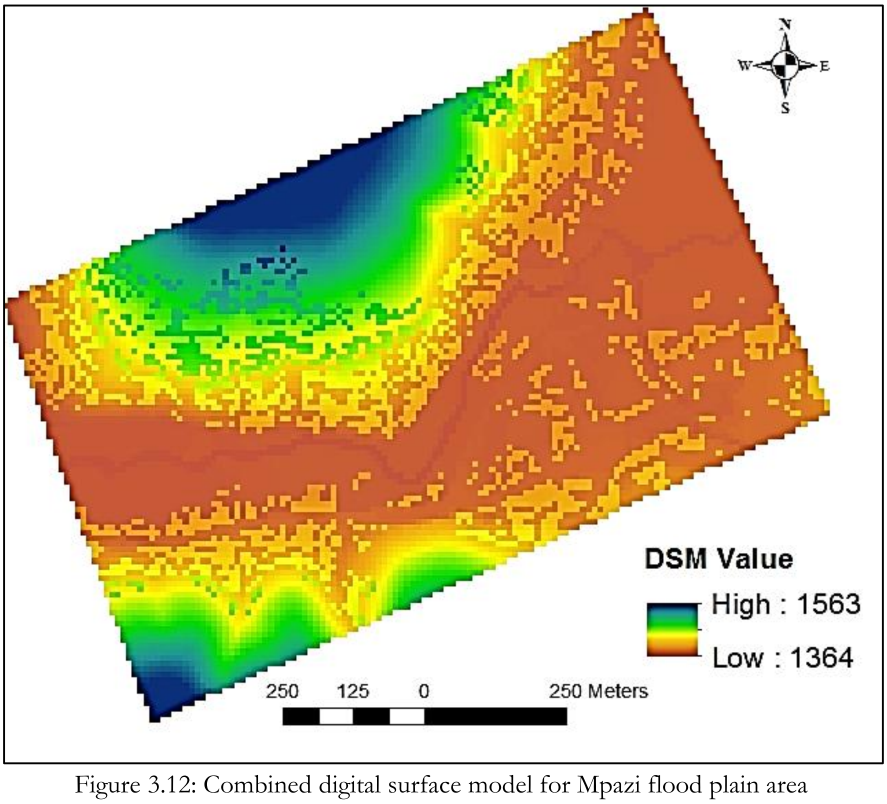

Figure 3.12: Combined digital surface model for Mpazi flood plain area

Boundary conditions:

They were defined in the form of upstream hydrograph data and downstream water level. Boundary conditions were applied to define the inflows and outflows at the model boundary. Alemseged & Rientjes, (2007) defined the boundary conditions as in commonly specified terms as inflow and outflow elements of the model domain. In study discharge data developed by SHER consultants from rainfall runoff model of the upstream catchment was used for the upstream boundary condition. Nyabugogo river water level and discharges was recorded at Nemba measurement station and are available from 2011 to 2014. There are no available data (water levels and discharges) for different return periods in Kigali. According to (Parodi G, 2009), Frequency analysis should be avoided when working with records shorter than 10 years. Therefore frequency analysis of discharges was avoided due to limitation of records. Therefore only constant maximum river discharge from 2011-2014 were selected and corresponding water levels as upstream and downstream boundary condition of the model respectively.

In this study there are three boundary conditions.

1D Upstream boundary of Mpazi watershed (constant discharge) derived from rainfall runoff model (HEC-HMS) done by SHER consultants for flood events with different return periods (10, 20 and 50 years). Refer to table 3.5

Upstream boundary of Nyabugogo River in the lowland downstream of Mpazi watershed. This boundary condition was taken as a constant discharge which assumed to be varied with different return period see table 3.5 below. That estimation was done based on the measured diver data.

Finally downstream boundary condition was defined as the constant water levels of Nyabugogo River. As mentioned in previous paragraphs, there were no enough recorded downstream data for frequency analysis, a constant water level was specified and free flow was allowed through the simulation. It is assumed that it will constrain the flow and create backwater effect.

Table 3.5: Upstream boundary condition (discharges) measured on the outlet of the catchment and Nyabugogo River. (source: SHER-Ingénieurs-conseils, 2013)

Return periods (Years)	Mpazi Upstream discharges (m3/s)	Nyabugogo corresponding upstream discharges (m3/s)
10	30	22
20	35	25
50	45	32

Cross section:

In this study, cross section data were derived from DEM and by surveying during the field work. Channel width and slope were measured and visually estimated from field work. Bridge dimensions and main culverts were noted down and their position were recorded by Hand held GPS as a series of way points.

Channel and river cross sections was obtained during field work phase. During this phase an instrument called total station was used to derive cross sections and slope of primary channels and rivers which is important in 2D hydrodynamic modelling. Engineering features such as bridges and culverts were considered in this in this study for the reason that the inclusion of such structures may have an impact on flood propagation. Therefore one bridges and two culverts profile were measured as in put feature for the SOBEK hydraulic model.

Surface roughness coefficient

In flood modelling, surface roughness represent the resistance that the water experiences as it flows over the surface of terrain. The resistance to flow is parameterized by the roughness coefficient. A surface roughness map has to be generated at the same resolution as DEM to ensure that for each cell, both roughness values and elevation information are available (Alkema, 2007)

This surface roughness is strongly related to Land cover. The parameter that is used to express surface roughness is Manning's roughness coefficient. The land cover map that was used for the downstream part of Mpazi catchment was derived using 2009 aerial ortho-photos of 0.25m resolution (see fig 3.13 a) by visual interpretation. Based on the available aerial photo, Units of the land cover were digitized and classified according to the land use classification standard in Kigali mapping division (Fig 3.13 b). Manning's (n) roughness (surface roughness) are derived from transformation of Kigali city land cover information into the corresponding manning's values derived from literature. The land use of Kigali city was reclassified into 6 classes, residential, commercial, rivers channels and agriculture, roads and building footprints was overlaid with land use data. Roughness coefficient (Manning's value) was assigned to new attribute field in land use map (see fig 3.13 c).

Buildings has given high roughness coefficient to make sure that flow of water in those pixels of buildings are highly restricted. This vector land use map was then rasterised using manning's attribute value refer to figure 16 below. The rasterised manning's coefficient map is shown below. Finally this layer is converted into arc info ASCII format and in put in the model.

Land cover	Manning's value
Roads	0.025
Rivers	0.03
Commercial zone	0.032
Residential zones	0.035
Agiculture	0.04
Building footprint	1

Source: (Tennakoon, 2004)

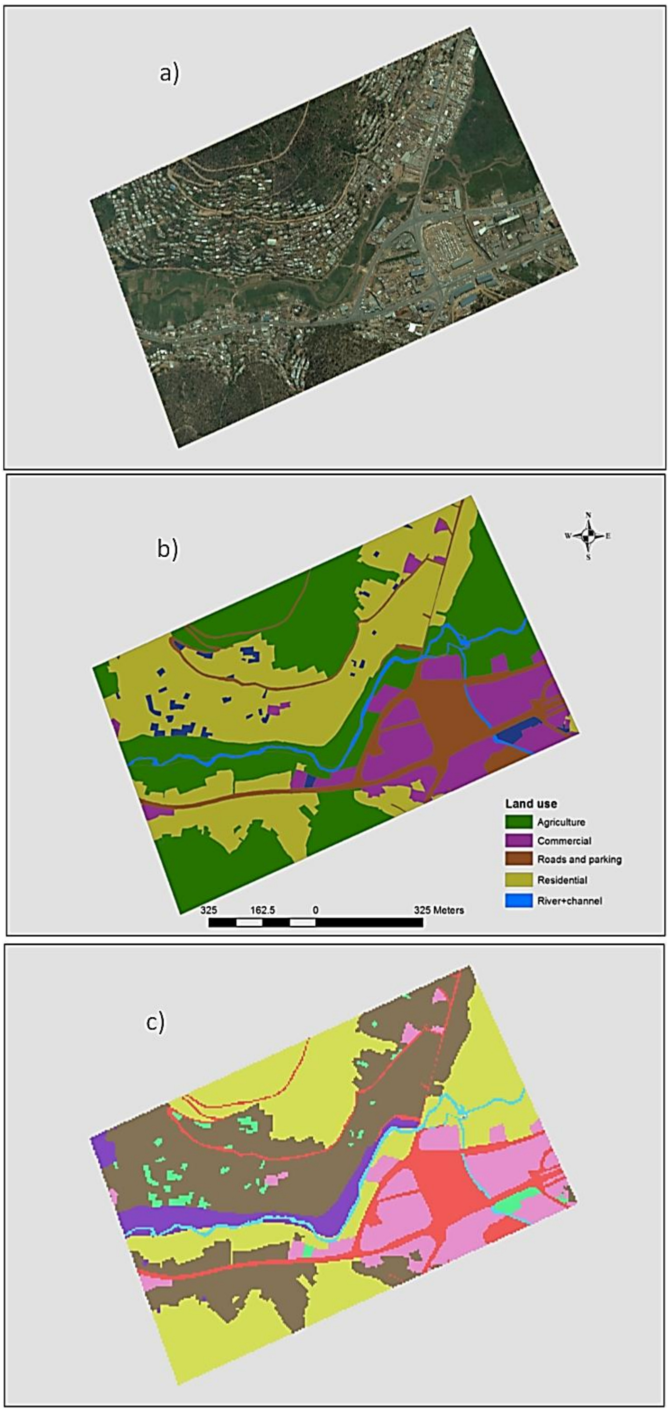

Figure 3.13: The model procedure to create roughness map. a) Available aerial photo, b) Land use map and c) the roughness map in raster format with estimates of Manning's n (table on the left)

4. URBAN FLOOD MODELLING

Development of flood hazard maps based on different stakeholder's requirements in Kigali city requires a computer based flood modelling which can produce realistic results. For this purpose SOBEK model developed by Delft hydraulics was used in this study. This flood modelling was conducted based on three return periods with corresponding peak discharges derived from rainfall runoff model performed by SHER consultant) and is aimed to transform discharges into a map of water depth and velocity as requested by different user's and this maps were post processed to fit end user demands. The following figure 4.1 is simplified work flow of flood modelling.

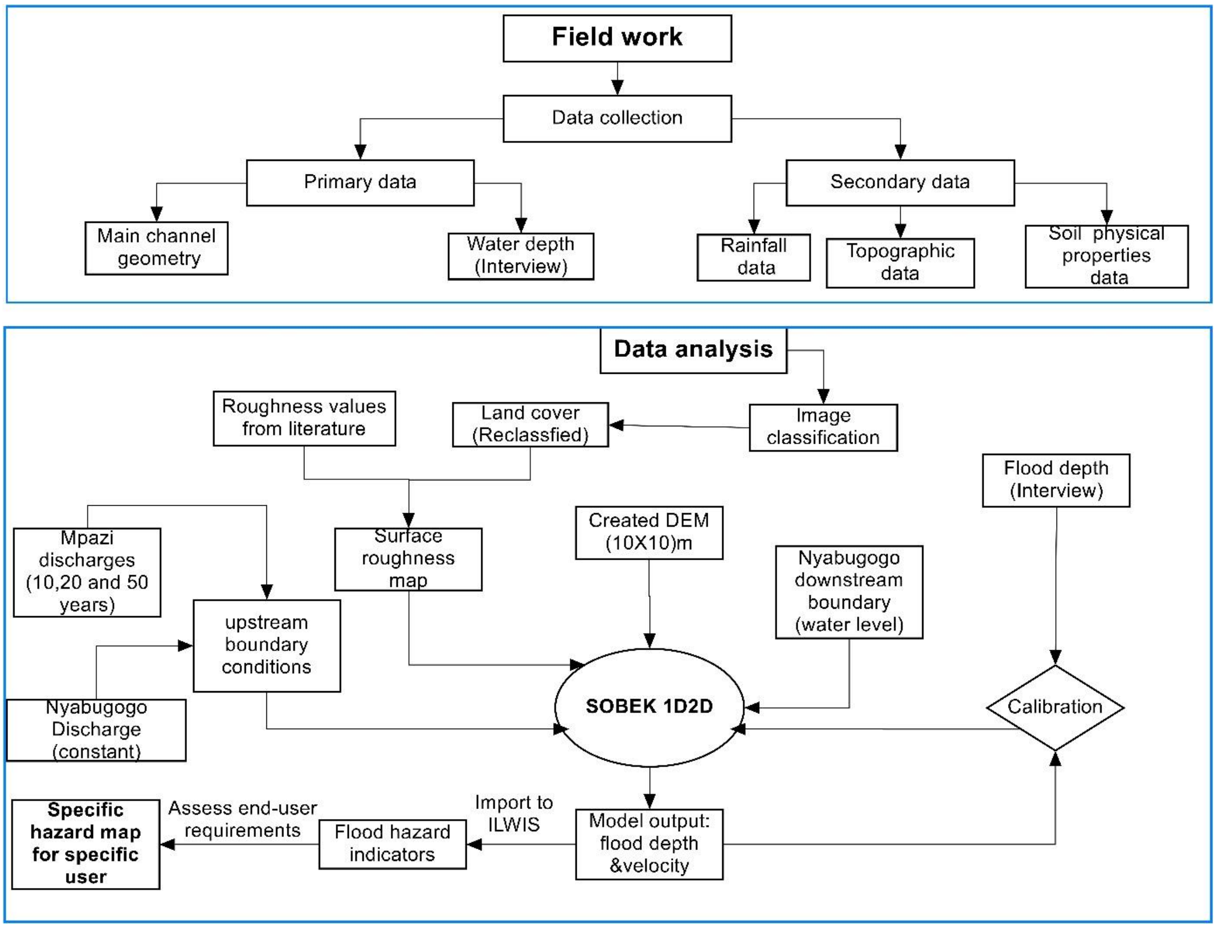

Figure 4.1: Model based methodological framework for flood hazard assessment

4.1. Model schematization

The interface of SOBEK where data input and editing takes place is called NETTER. This interface provides the possibility to set up the schematization and also offers advanced analysis tools to show model results. NETTER also provides two separate menu bars to input and edit 1D feature (river or drainage channel) and 2D grid layers representing floodplains (Deltares, 2003). Before starting schematization it is important to have a prepared 2D grid (DEM) imported to the NETTER, which was developed in ArcGIS environment as explained in previous sections, and imported directly to the schematization environment as an ASCII format. Then, the flow boundary conditions should be defined in 2D schematization. The flow boundary conditions will be connected using a flow connection node in order to define the 1D component. Figure 4.2 shows the schematization environment in SOBEK. History station nodes were defined to determine the exact value of parameters, such as depth of water in time on specific locations in 2D grids. ID flow was represented by different series of cross section in the direction of the river and channel flow. The river is defined by reaches connected together by connection nodes and its location was characterized by cross sections, bed and surface level as well as friction coefficient

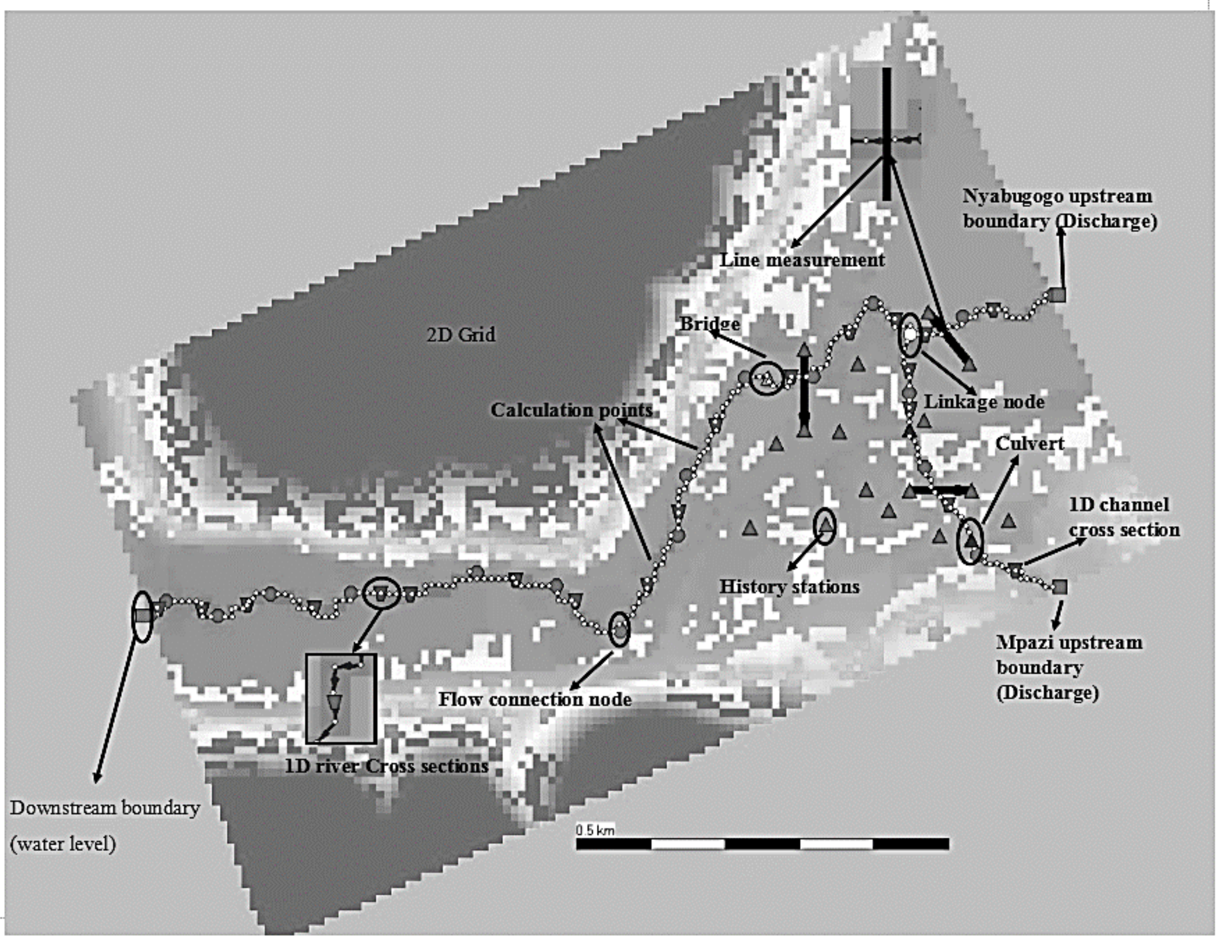

Figure 4.2: Model schematization in 1D2DSOBEK

4.2. 1D network schematization

The 1D network is represented by the flow of water along the channel or the river. The flow characteristics in both river and channels is determined by river or channel cross section, surface level, river bed and roughness coefficient. Defining 1D network in SOBEK is done by defining a reach that represent a river or a channel, and can be connected together using connection nodes. From here you will get the straight line of the channel or river network which can be edited to follow the shape of the channel/river using “edit reach vector” mode.

The shape of the river/channel affects the flow pattern, therefore each reach should contain at least one cross section. Furthermore the calculation nodes are added along the river network at given interval of 10m distance. The river bed and surface level of each cross section were derived from DEM. The cross section types was also defined, for this study trapezoidal section was defined on the channel network and rectangular section was defined in the river network based on the field observation.(refer to fig 4.3)

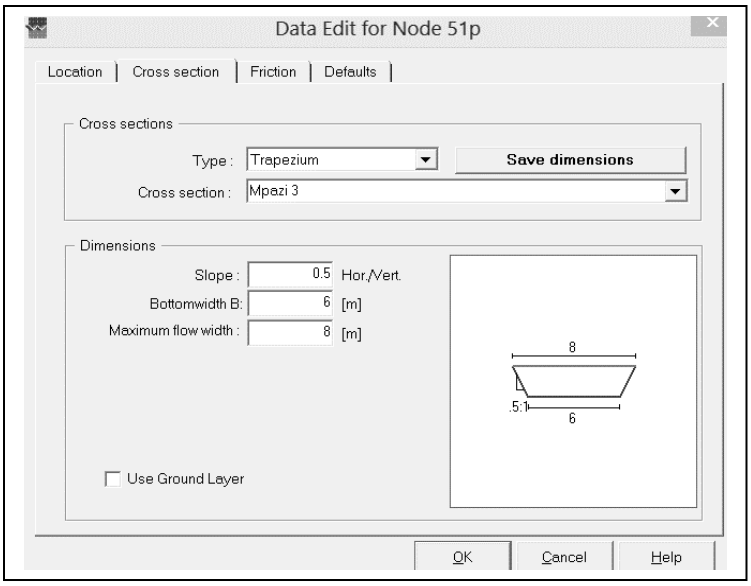

Figure 4.3: Channel cross section input window in SOBEK

4.3. Model calibration and validation

Generally speaking, hydraulic models are calibrated by minimizing the deviations between modelled and observed values. According to (Visser et al, 2001), these deviation between simulated and observed are reduced by expert judgment with regard to effect of various hydraulic roughness values. Optimization of the model needs a clear agreement or disagreement of the model. The calibration procedure used in this study are shown in figure 4.4 below.

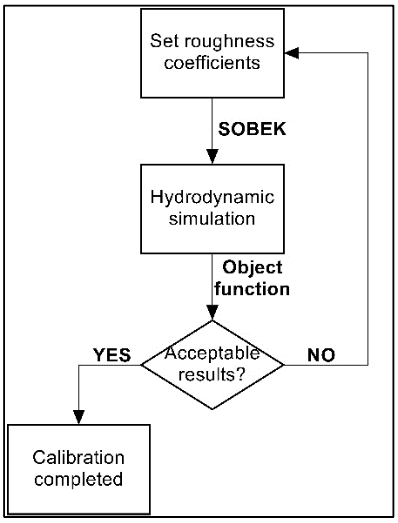

Figure 4.4: Calibration procedure used in this study

The algorithm is very simple. The function to be minimized represents the differences between calculated and measured water levels. The object function is based on a function of the roughness parameters which are calibrated. When the object function is minimum, it means that the roughness parameters are in an optimal case. The success of the model calibration were evaluated based on comparison of observed and modelled values and objective functions including biasness and root mean square error (RMSE).

The flood depth was obtained from field work by interviewing the citizens prone to flooding and the water levels marked on building walls as described in section 3.5.3. Information on flood extent was not available, thus flood calibration for this study is only based on flood depths. Since there are no flood extent in the study area for validation purpose, 20 different point of water levels were collected through interview where by 9 observed records was used for calibration while the remaining 11 was used for validation of the model.

Three trials were done in changing roughness coefficient in order to minimize deviations between simulated and observed data for an event with a 4.1 below.

Table 4.1: Statistical measure values for errors of flood model with initial run, trial 1 and trial 2

Land cover	**% area**	**Initial run**	**Trial 1**	**Trial 2**
Roads	10.0	0.025	0.028	0.026
Rivers+channels	1.8	0.030	0.033	0.032
Commercial zones	14.2	0.032	0.035	0.033
Residential zones	36.1	0.035	0.038	0.036
Agriculture	37.9	0.040	0.045	0.043
Building footprints	50.3	1.000	1.000	1.000

In each trial, simulated water depth was compared to the observed water depth obtained during fieldwork phase by using objective functions which includes model biasness and root mean square error (RMSE). The overview of this statistical values are calculated as below.

Statistical bias is calculated by

$$\text{Bias} = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \qquad (1)$$

Where n: Total number of observations

x_i: Observed value

y_i: Model simulated value

Bias is calculated from the mean differences between model simulated value and observed value. The bias values closer to zero indicate good overall model performance.

Again in order to check how the model reflects reality, Root Mean Square Error was calculated as shown in the equation below

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n-1}} \qquad (2)$$

Where n: Total number of observations

x_i: Observed value

y_i: Model simulated value

The RMSE measures the discrepancy between the two paired values i.e. simulated values and observed values on individual basis which indicates how accurate the model can be predicted. The smaller the RMSE, the better the model performs.

Table 4.2: Both statistical values for error data set are shown in the table below:

Statistics	Initial run	Trial 1	Trial 2
Bias (in meters)	0.241	0.209	0.046
RMSE(in meters)	1.106	0.960	0.210

As it can be seen in the figure 4.5 below, initially, the model underestimate the flooding based on the observed flood depths derived from interviews. The first trial, the model tends to overestimate the flooding as shown in figure 4.5 but after fine tuning the roughness parameters for the second trial the model neither underestimate nor overestimate the flood depths in the downstream of Mpazi catchment. After limited number of trials, a set of optimum values was obtained that can be used for further analysis. From the results of the mentioned statistics shown in the above table 4.2, we can draw a conclusion that trial 2 seems to be suitable for further flood analysis.

Source of errors: The deviations seen between observed data and simulated data can be originated from the information of water depth derived from interview which might be bias. In addition to that DEM used may not reflect the real topography.

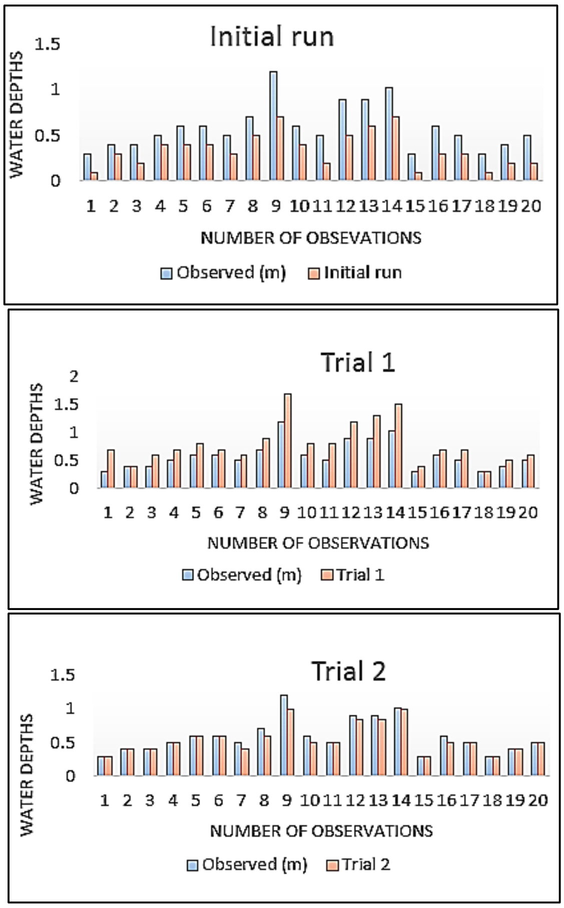

Figure 4.5: Observed and simulated water depths for flood modelling with different roughness coefficient.

4.4. Sensitivity analysis

The sensitivity analysis was done by changing each roughness values to check how sensitive roughness parameter is. Therefore, in this study the adjustment was performed using different Manning's values and the simulations were carried out by systematically a) increasing 10%, b) decreasing 10% of each initial roughness coefficient values while keeping others parameters to its initial settings. Table 4.3 below shows the comparison between modelled and observed values for water depth when initial roughness values are increased or decreased by 10% for each land use/cover. The map showing where each observation point is can be found in Appendix.

Table 4.3: Comparison between observed and modelled flood water depth when changing both roughness values

	Observed water depths (m) when roughness values for each land cover changes by +/-10%									
Observed water depths (m)	Agriculture		Residential		River+channel		Commercial		Roads	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
0.3	0.1	0.1	0.2	0.1	0.6	0.4	0.1	0.1	0.1	0.1
0.4	0.2	0.1	0.3	0.2	0.5	0.4	0.0	0.1	0.1	0.1
0.4	0.2	0.2	0.4	0.3	0.6	0.4	0.2	0.1	0.1	0.1
0.5	0.3	0.1	0.7	0.5	0.7	0.5	0.2	0.1	0.2	0.1
0.6	0.4	0.2	0.6	0.6	0.7	0.5	0.3	0.2	0.3	0.2
0.6	0.5	0.5	0.6	0.6	0.8	0.5	0.3	0.2	0.4	0.2
0.5	0.3	0.4	0.7	0.5	0.7	0.4	0.4	0.2	0.2	0.2
0.7	0.5	0.5	0.6	0.6	0.9	0.5	0.6	0.2	0.3	0.2
1.2	0.8	0.6	0.7	0.5	1.3	0.7	0.3	0.2	0.6	0.2
0.6	0.4	0.3	0.8	0.5	0.7	0.4	0.2	0.1	0.3	0.1
0.5	0.2	0.1	0.8	0.5	0.6	0.3	0.2	0.1	0.1	0.0
0.7	0.5	0.3	0.8	0.7	1.2	0.6	0.3	0.1	0.3	0.1
0.7	0.6	0.2	0.6	0.5	0.8	0.5	0.3	0.1	0.4	0.1
1.0	0.7	0.3	0.8	0.5	1.0	0.6	0.8	0.4	0.5	0.4
0.3	0.1	0.0	0.4	0.4	0.4	0.2	0.1	0.2	0.1	0.2
0.6	0.3	0.1	0.5	0.3	0.7	0.4	0.2	0.2	0.1	0.2
0.5	0.3	0.1	0.5	0.3	0.6	0.3	0.2	0.2	0.1	0.0
0.3	0.1	0.0	0.3	0.3	0.5	0.3	0.1	0.2	0.1	0.0
0.7	0.2	0.1	0.4	0.2	0.5	0.3	0.0	0.1	0.1	0.1
0.5	0.2	0.1	0.4	0.2	0.6	0.3	0.1	0.1	0.1	0.1

The results after increasing 10% of roughness values indicates that, increasing roughness value of channel is more sensitive compared to other parameters like agriculture. This is because surface roughness is strongly related to land cover, therefore smooth or non-vegetated surface offers less resistance while high vegetated surface offers high resistance and increase the infiltration capacity and slows down velocity hence increasing water depth.

The results of decreasing roughness value by 10% also shows that, the river still is more sensitive than other parameters where by the depth increases compared to other parameters and the extent of flood increases when all values are decreased by 10%. This is because as the roughness value decreases, the infiltration rate decreases, velocity increases hence the more the extent of flooding.

The results of testing show that the roughness coefficient (Manning's value n) of channel is more sensitive than other parameters. This means that distribution of roughness coefficient in channel or river is important aspect that needs to be addressed clearly. The lower frictions values in channel overestimate the discharge while higher roughness underestimate the discharges. Ramesh, (2013)found out that low Manning's value decrease the hydraulic depth. Inversely high Manning's value increases the hydraulic depth.

4.5. Modelling output

Flood extents

The first output of the model is the flood extent. It shows the spatial distribution of flooded area in different scenarios. In this study, as the return period increases, the spatial extent of flooded area increases. The largest inundated area was caused by 50yr return period which covers only 8.1% of the study area (see fig 4.6). In general, the difference of flood extents from low magnitude to high magnitude was significant, it was about 2.1 x 10^4 m^2 or about 36% difference. This means that level of exposure for low magnitude is less compared to high magnitude therefore impact might be higher in the event of higher magnitude. The low elevation values may contribute to higher spatial distribution of flooded area in this study.

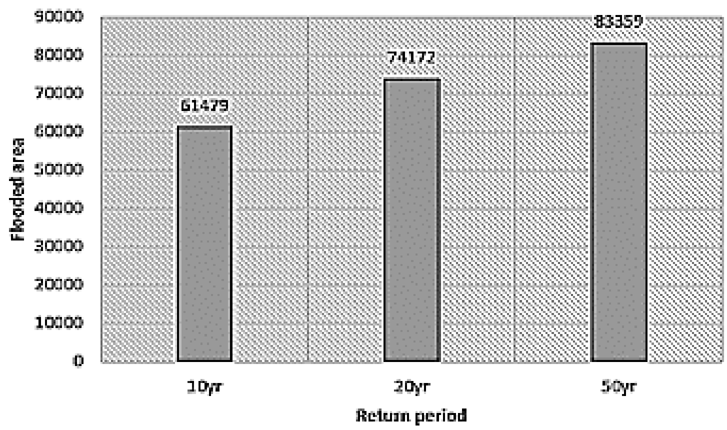

Figure 4.6: Comparison of inundated areas of different return periods

The output data of the model consists of series of water depth and velocity maps at predefined time step. The model also creates a summarized maps of the simulation, these includes maximum water depth map that represent highest water depth value reached in the pixels at some point of simulation, a maximum water velocity that represent the highest velocity value that was reached in pixels at some point of simulation, Two maps that indicate the time at which the maximum water depth and maximum flow velocity were reached and the time at which pixel started being flooded.

The analysis of these output was discussed in the next chapter (chapter 5) and consists of two phases:
The first phase only focuses on how the flood simulation results can be post processed and used to calculate the derivative maps that have been requested by different stakeholders. The second phase is classical flood hazard assessment where maximum water depths of different scenarios i.e. return period were combined into a map giving annual probability of inundation.

5. RESULTS AND DISCUSSION

5.1. User groups of flood hazard maps

The results obtained from interview of specific target map users was that different user or target group have different needs with regards to flood hazard maps and that these requirements do not necessary understood by those producing the maps. It was found out that, even though different groups of stakeholders are discussing the same flood but all are perhaps not interpreting the contents in the same way. One may relate high flood hazard zones to shorter warning time, others to flood long duration or simply water depth. This shows how end-users have their own priorities to different flood hazard maps. Such differences may require the construction of different hazard zones for use by different stakeholders for the same flood. In this chapter an overview of flood hazard content requirement from different stakeholder was mentioned and how 1D2D SOBEK model together with GIS environment was used to prepare flood hazard maps that should in principle satisfy those requirements.

The following are potential end-users of flood hazard maps in Kigali city and the recommendations/requirements they stated with regard to flood hazard maps and the reason behind those needs in the context of use. These requirements were used to prepare flood hazard maps that should in principle satisfy those requirements.

5.1.1. Water resource agencies.

Water management agencies of Kigali can use flood maps as basis for planning for reactivation of water retention areas (dams etc…), developing and prioritizing flood protection plans, formulating relevant policies and identification of flood plains areas. Although, the flooding is sole responsibility of this field, users of this group are expert by professionals in using flood maps but they are not developing flood maps themselves. Even though this target group doesn't produce hazard maps, this research revealed that, users of this group are able to deal with technical content such as exceedance probability, return period etc…Therefore, based on the context of use of flood hazard maps described above, this agency highlighted that flood depth and flood velocity would be their potential needs with regard to flood hazard information.

5.1.2. City planning agencies

This agency is responsible to manage and monitor the demands on the use of space. Flood hazard plays a role as a natural factor that matter in spatial planning. Therefore city planners manage the space by finding out workable and sustainable land use equilibrium between built-up areas and open space. It is in this regard that this agency uses flood hazard maps purposely for preservation and recovery of natural flood plains, best practices for urban development, land use management, relocation of citizens in flood prone areas. It was found out that this group like water agency is able to deal with technical content. Even though this institution don't have any flood hazard maps to guide them to do what it was designed for, when asked the flood hazard maps content they think would be more helpful to them, This agency pointed out that flood extents and flood depths with different probabilities would satisfy their needs.

5.1.3. Disaster management and emergency control agencies

This agency is the main user of the flood hazard maps in the event of flooding. They are responsible for the victims of flooding. Therefore they use flood hazard maps to raise awareness among the people at risk and decision makers and preparation of emergency situation. The main purpose of flood hazard maps in this group is to provide quick access to information about affected areas in the event of emergency, such as people to be evacuated, infrastructure to be protected or evacuation routes. Within this agency, different entities (local municipalities, districts, fire brigades and armed forces) are involved in using flood hazard maps. Flooding or water are not their sole responsibility, user from this group (Army and fire brigade) may have less experience and familiarity with flood hazard maps and are not able to deal with technical content. The main aim of flood maps in this field is to enable quick access to information in an event of flooding. This information might include those areas likely to be flooded, people to be evacuated, planning tool for emergency response, the critical infrastructure to be protected and evacuation routes. According to the findings in this group, warning time, duration are the most important parameters with regard to hazard information that can in principle satisfy their needs.

5.1.4. Insurance companies

This group of stakeholders plays a role in this research where they have been interviewed to express their preferences as far as hazard information is concerned. Risk flood map is the most important to identify structural damages in this field but since this research is not intended to do flood risk assessment which could be a subject to further research but the production of flood hazard to this group is the first step towards flood risk assessment. Insurers need precise and accurate flood hazard information in order to define realistic premiums for flood damages and to identify who needs flood insurance. The hazard maps can be most important to this if it is displayed with some elements exposed to risk to further assess its risks. Users from this group are not familiar to deal with high density information and not able to comprehend with technical content in flood maps. According to the findings of this group during face to face interview, content requirements of insurance companies are in particular the following. Maps for insurance companies should include information of event specific damages displayed on the map therefore different events need to be produced. In order to satisfy their demands events of maximum flood depth, velocity, and impulse can be useful. The results were specific purpose map based on the mentioned parameters that will help them to estimate damages.

5.1.5. City Engineers agencies.

Engineers use flood hazard maps for designing new buildings and infrastructure to avoid flooding. This target group are not involved in producing hazard maps and therefore are less familiar with the general content of flood maps. Even though engineers do not use flood hazard maps in daily basis, this group are able to deal with the technical content of flood maps. According to the findings from different engineers during participatory approach, content requirement of engineers with regard to hazard information are maximum depths, flow velocity and impulse and duration may be of high valuables, the output were the map that shows where to put concrete structure to avoid collapse during flooding. And to redesign the material to be used during road construction in case road flooded with prolonged duration.

5.1.6. Citizens affected by flooding

Citizens are affected by floods on regular basis but they are neither directly involved in producing the maps nor do they deal with them on professional basis. However flood maps are often directed towards them with the aim of raising awareness. This research revealed that their use of flood maps are generally infrequent and hence may have such experience with such maps. As such this group is likely to be unfamiliar with concepts of technical languages such as exceedance probabilities/ return periods.

Interestingly, on the other hand members of this group are more likely to rely on detailed knowledge gained from history or previous experience of flooding. Therefore they provide valuable information and knowledge during mapping process which could enhance the map content. This group may therefore contain local residents who may have local knowledge of flooding and expertise about history of flooding in their neighborhood. Many maps are directed towards public to raise awareness of flood risk and provide information for flood risk preparation. In contrast to the previously mentioned groups, public users do not use flood maps very frequently and therefore often have different needs and requirements in terms of mapped content. The findings showed that flood maps for the public should be less complex and should contain the following basic information. Inundation extent and depth information for different specific events considered critical by public users and should be presented in the flood maps as the most important hazard information. As many citizens are not necessarily familiar with the concept of technical languages like return periods or exceedance probabilities, such expression and other technical languages should be avoided and rather terms like small, medium or extreme events should be adopted.

Table 5.1: Summary of different stakeholder's requirements/needs on the content of flood hazard maps.

Requirements / Stakeholder /End-user	Flood extent	Flood depth	Flood velocity	Flood impulse	Flood duration	Warnin g time	Purpose/context of use
Water resource agency		✓	✓				Water retention areas, Flood action plan, identification of flood plains...etc.
City planning agency	✓	✓					Regional planning, Construction planning…etc.
Disaster and response agency					✓	✓	Set up disaster management plan, evacuation planning…etc.
Insurance company		✓	✓	✓			Flood insurance rates, identify who needs insurance…etc.
Engineers agency		✓	✓	✓	✓		Protection of buildings and infrastructure,
Citizens prone to flooding	✓						Public awareness, Better flood protection

5.2. Combining end-users/stakeholders requirements with flood modelling outputs

As explained in the previous sections that different end-users of flood hazard maps have different needs and requirements. These requirement were used to prepare flood hazard maps that should in principle satisfy those requirement. The table 5.1 above is an overview of different stakeholder's with their different needs and the purpose of which their needs (flood hazard content) are intended to be used for. As mentioned in chapter four of this study, modelling outputs does not satisfy all user's requirements, but the output of the model was post- processed to fit each user's demand.

5.3. Modelling output

The output data of the model consists of series of water depth and velocity maps at predefined time step. Even though 2D flood propagation modelling is useful in simulating the behaviour flood especially over a complex urban terrain, but the output of the model is not ready for interpretation. These series of maps were transformed into different parameters requested by various stakeholders based on three return periods. Therefore post processing in ILWIS software was needed for further analysis. The analysis of these output was discussed in the next section and consists of two phases:

The first phase only focuses on how the flood simulation results can be post processed and used to calculate the derivative maps that have been requested by different stakeholders. The second phase is classical flood hazard assessment where maximum water depths of different scenarios i.e. return period were combined into a map giving annual probability of inundation.

5.3.1. Maximum inundation depth:

This is the flood hazard indicator that was requested by various stakeholders contacted in Kigali city. This output was derived from the model. The model simulation was carried out for 10, 20 and 50 year return periods. These ASCII maximum flood depth files was converted to GIS grid file format using arc tool box and it was georeferenced in order to overlay it with any other topographical features of downstream flood plain area as shown in fig 5.1 below. The flood depth map provides information about the water depths in different locations for a given recurrence interval that was recorded by history stations. Based on the local conditions, the water depth is given in centimetres or water depth (EXCIMAP, 2007). The water depth class in this study was based on the mapping procedure from different countries like Ireland and Netherlands as cited by (EXCIMAP, 2007). Ireland produces the flood depths with particular probabilities with water depth of 0.2m increment while in Netherlands, they use small scale flood depths covering large parts of the country. They use depths increment of 1m (0-8 m). This study uses mapping procedure developed by Ireland to classify water depths ranges with different probabilities based to several aspects like end requirements of the maps and individual perspectives as well as study area. The areas with deep water are considered to be dangerous to people and can be a potential damaging flood hazard parameter to objects like houses and cars. According to the literature (EMA, 1999) wading by able bodied adult person becomes more difficult and dangerous when the depths of still water exceed 1.2m when a velocity of shallow water exceeds 0.8m/s where by small and light vehicles crossing rapidly flowing cause ways can be become unstable when the water depth exceed 0.3-0.4m.

Cut off inundation depth that was given by US department of land and soil conservation cited by (Tennakoon, 2004) was realistic in urban flood applications where by the upper limit of low hazard zone was selected as 0.8m and low limit for high hazard zone was selected as 1.2m. But in this study, inundation depths of 0.1m and 0.5m was considered as upper limits for low and medium flood hazard class respectively as shown in figure 5.1 below. This cut-offs for defining hazard class is based to several aspects like end requirements of the maps and individual perspectives as well as study area. The maximum flood depth was highest on 50 year return event. This hazard parameter indicator was requested by various stakeholders (refer table5.1) like insurance companies and engineers to define realistic premiums for flood damages and to design new buildings and infrastructure against flooding.

Literatures highlighted that, an important factor that tends to increase the depths of flooding and hence the overall degree of flood damage is the presence of obstruction to movement (Penning-Rowsell, Floyd, Ramsbottom, & Surendran, 2005). Such obstructions includes buildings, embankment, culverts and bridges etc. The increase in flood level depends on the velocity of flood waters and the degree to which they are obstructed. This is the case for the area under study where high depths are found on critical infrastructure like bridges and culverts respectively.

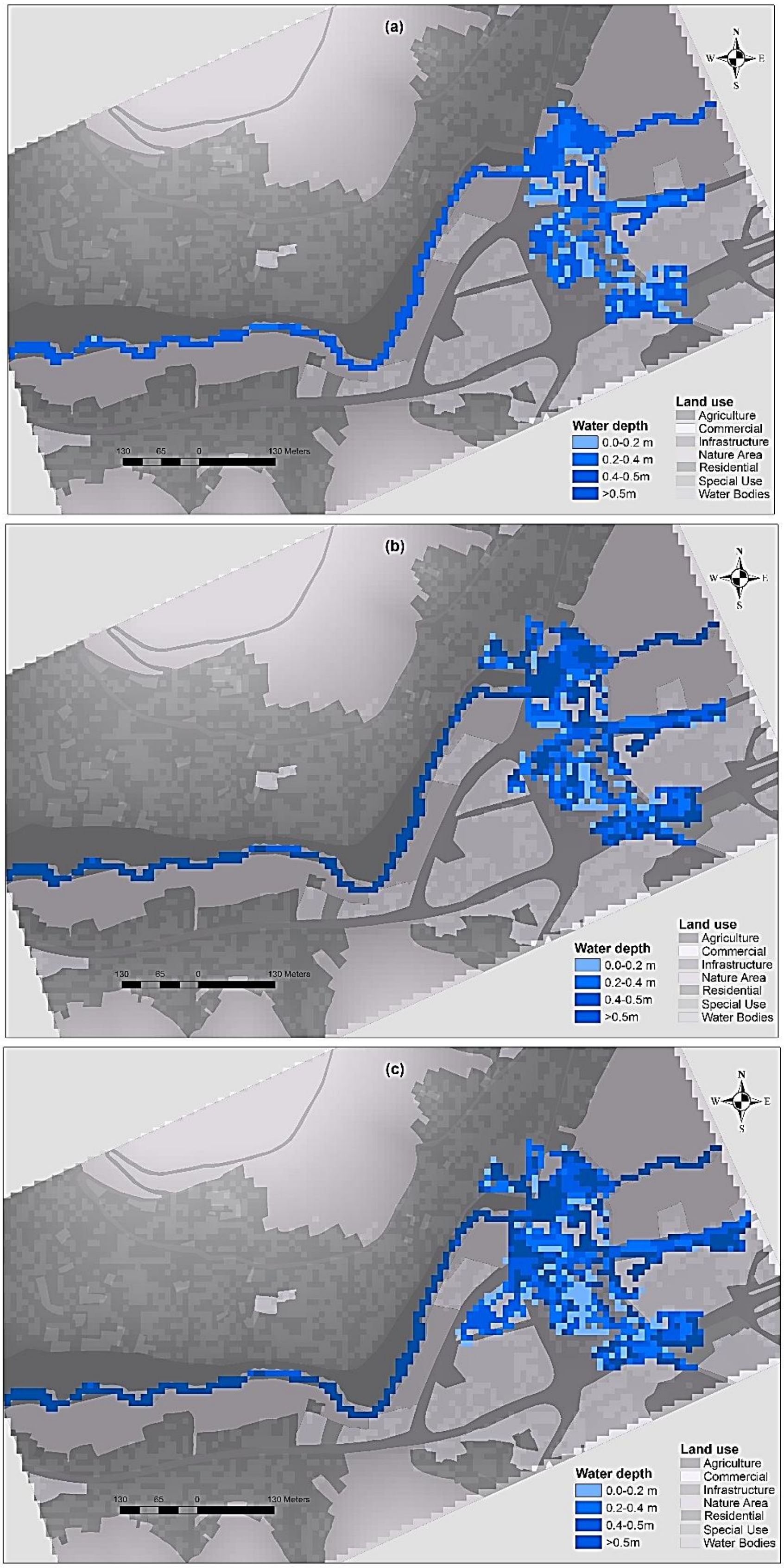

Figure 5.1: The spatial distribution of maximum water depth of the three different return periods (a) 10 year return period (b) 20 year return period and (c) 50 year return period.

Comparison of different return periods on flood depth characteristics

It is clearly shown in fig 5.1 that, for different return periods, it results in different flood hazard characteristics. For example for a storm with a return period of 10yr, an average flood depth was 0.36m but some places a maximum of 0.78m was reached while for other storms maximum flood depths of 1.12m and 1.47 was reached for an event of 20 and 50 years return period respectively apart from river and channel which can be even higher. Surface area in percentages for different depths classes of different return period are shown in table 5.2 below.

For the case of flooded area, the extent of flood with 10 year return period is less compared to other storms with return periods of 20 and 50 years. In general inundated area is much less than not inundated area for all types of storm events refer to fig.5.2. The largest inundated area was caused by an event of 50yr return period and is covered less than 10% of the study area. The extents of flooded area goes increasing with an increase of return periods and tend to follow south west direction of the study area. This is because the sloppiness and land cover (paved surface) in that direction favors the flow of water compared to other directions where shrubs and high slope are predominant.

Table 5.2: Maximum flood depth - surface area (% of flooded area) per depth class of different return periods

Flood depths class (m)	10yr return period	20yr return period	50yr return period
0.0-0.2	29.8	24.4	17.9
0.2-0.4	41.0	31.1	14.4
0.4-0.5	19.7	28.5	31.3
>0.5	9.5	16	36.4
Total (x 104 m2)	(6.1)100	(7.4)100	(8.3)100

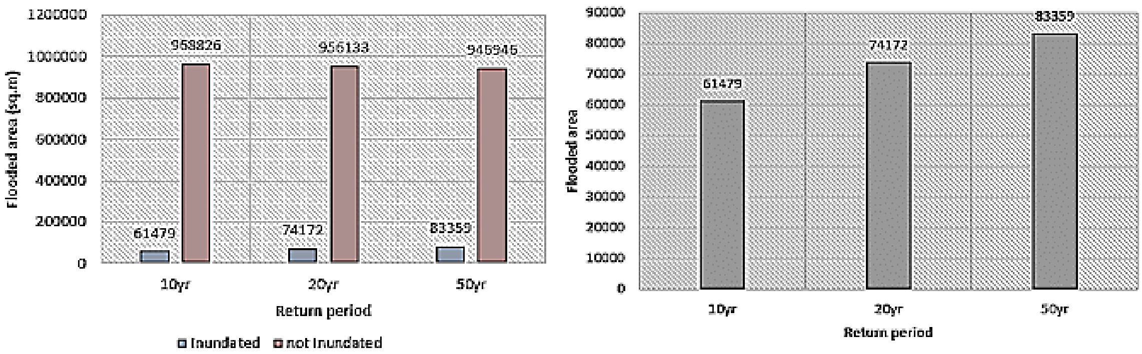

Figure 5.2: Comparison of inundated & not inundated (left) and flooded surface area (m2) with an event of different return period

5.3.2. Maximum flow velocity

Similarly to depths of inundation described above, the flood velocity indicator is derived from direct model output. This hazard indicator was requested by different stakeholders in Kigali city (refer to table 5.1). The flood velocity map was simulated for 10, 20 and 50 year return period. This parameter is a component of flood water that can make objects like cars to float and can sweep off our feet. This parameter alone doesn't estimate the potential damage but when combined to depth can easily estimate the objects that can be potentially damaged see figure 5.4. Combination of both flood velocity and flood depth will give another parameter called impulse which will be discussed in the next section.

The flow velocity maps for different return periods are shown in figure 5.4 below. It is clearly shown in the figure 5.4 that a maximum velocity of about 1.45m/s was reached to some places in the study area. As the depth of flood water increases, buildings of light construction will began to flood, in this circumstances, buildings can be severely damaged when they settle unevenly in receding flood water. If the velocity is significant, buildings can be totally destroyed and cars can be swept away (EMA, 1999).This factor is important to insurance and engineers due to the fact that, flood velocity leads to structural damages and these damages increases as velocity increases. According to (Penning-Rowsell et al., 2005) at a velocity exceeding 2m/sec, the stability of foundations and poles can become affected by scour. Those higher velocities are found on the critical infrastructure such as roads, culverts and bridges. This is probably due to the fact that some culverts surface area may not be enough to hold all incoming mass of water and caused some turbulence on its mouth. The velocity is a bit high in the roads because the road is pervious surface which can favour high moving water. Different scholars mentioned that a persons may be swept away when velocity is above 0.5m/s Marco, 1994 cited by (B Merz, AH Thieken, 2007). However better indicator for human instability is the product of flow velocity and water depth.

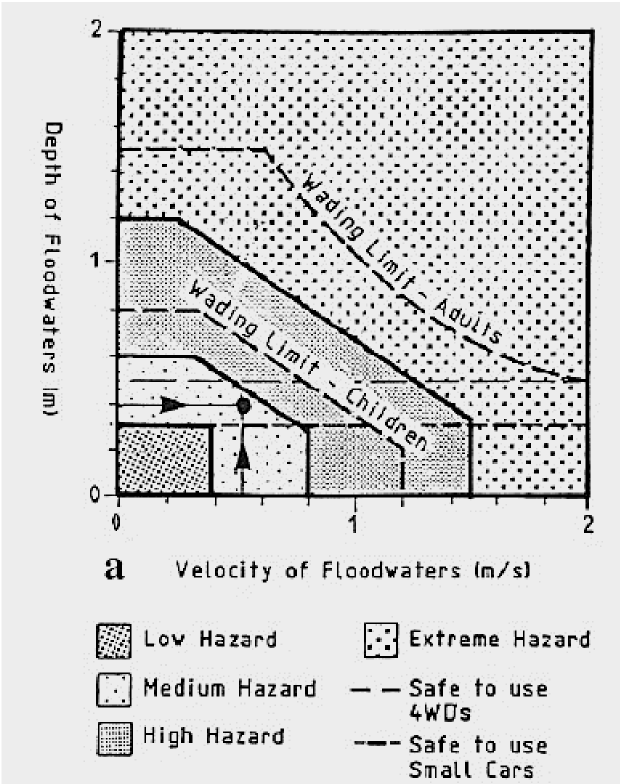

Fig 5.3: Graph that combine both velocity and depths to define initial level of hazards

Source: (Ramsbottom, Floyd, & Penning-Rowsell 2003)

According to the literature (EMA, 1999) wading by able bodied adult person becomes more difficult and dangerous when the depths of still water exceed 1.2m when a velocity of shallow water exceeds 0.8m/s where by small and light vehicles crossing rapidly flowing cause ways can be become unstable when the water depth exceed 0.3-0.4m. See fig 5.3 above.

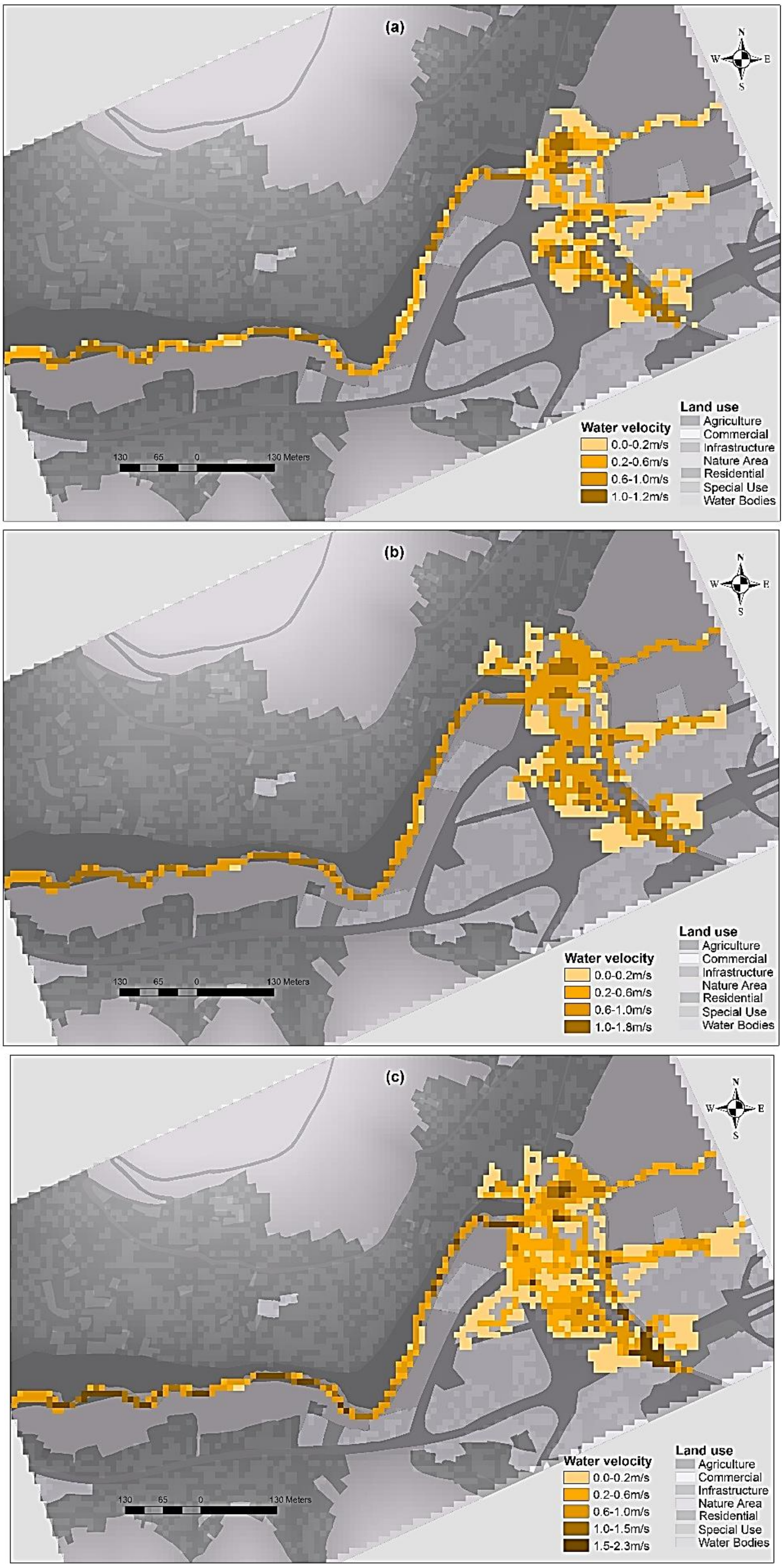

Figure 5.4: The spatial distribution of the maximum flow velocity of the three different return periods (a) 10 year return period (b) 20 year return period (c) 50 year return period.

Comparison of different return periods on flood velocity characteristics

Different storm events gives different flow velocity flood characteristics. For a storm with an event of 10yr return period a maximum of 1.33 m/s was reached compared to a maximum of 1.86m/s and 2.32m/s for an event with 20 and 50 year return period respectively. This is due to the fact that, a storm of 20 and 50yrs is higher compared to a storm of 10yr event can probably cause the high moving water and high discharges (hydrographs) which is the input of the model. Different flow velocity classes and the surface area in percentage occupied by each class is shown in the table 5.3 below.

Table 5.3: Flow velocity- surface area (% of flooded area) per velocity class of different return periods

Velocity class (m^2/s)	10yr return period	20yr return period	50yr return period
0.0-0.2	42.3	35.1	32.8
0.2-0.4	30.6	25.4	26.6
0.6-1.0	16.2	26.3	26.4
>1.0	10.9	13.2	14.2
Total (x 10^4 m^2)	**(6.1)100**	**(7.4)100**	**(8.3)100**

5.3.3. Maximum impulse (m2/s) (Potential damage)

This hazard map is the most important when estimating damages. Damages can be explained in different forms, damages due to floods occurs on one side due to the fact that things get wet like carpets, pedestrians and cars etc... And on the other side due to physical destruction because of the water flow. These destruction potential of the water flow depends on both flow velocity and water depth. This means that deep water with high flow velocity has more damaging potential than shallow water with zero or slow flow velocity.

The map of maximum impulse was highly demanded by insurance company and engineers to determine who needs insurance and critical infrastructure to be protected or upgraded respectively. This parameter is calculated at each time step by multiplying flow velocity with water depth. This means that for each pixel, this values demonstrates the amount of movement of water mass. This is because neither flow velocity nor flood depth alone can estimate the amount of potential damage. For example shallow water with high velocity doesn't have a lot of kinetic energy or momentum but deep, fast flowing water have a lot of kinetic energy and can be potential threat for people and vehicles and can damage objects like houses too. The maximum impulse of 1.45m2/s are found on the map of storm with 50 return period. Different impulse map for different return periods was depicted in the figure 5.5 below. The observation that are made on flood velocity can be applicable on flood impulse. The high impulse are found on the roads and culverts which can probably danger vehicles and pedestrians. Available studies showed that people lose stability in flows in relatively low depth-velocity products. According to (Jonkman, 2009) on test experiment done on the person and vehicles instability done in Japan, he showed that people may experience difficulties in walking through water when the depth-velocity product (Impulse) exceeds 0.5m2/s. and cars may lose stability when depth-velocity products exceeds1.0m2/s depending on the size of car of course.

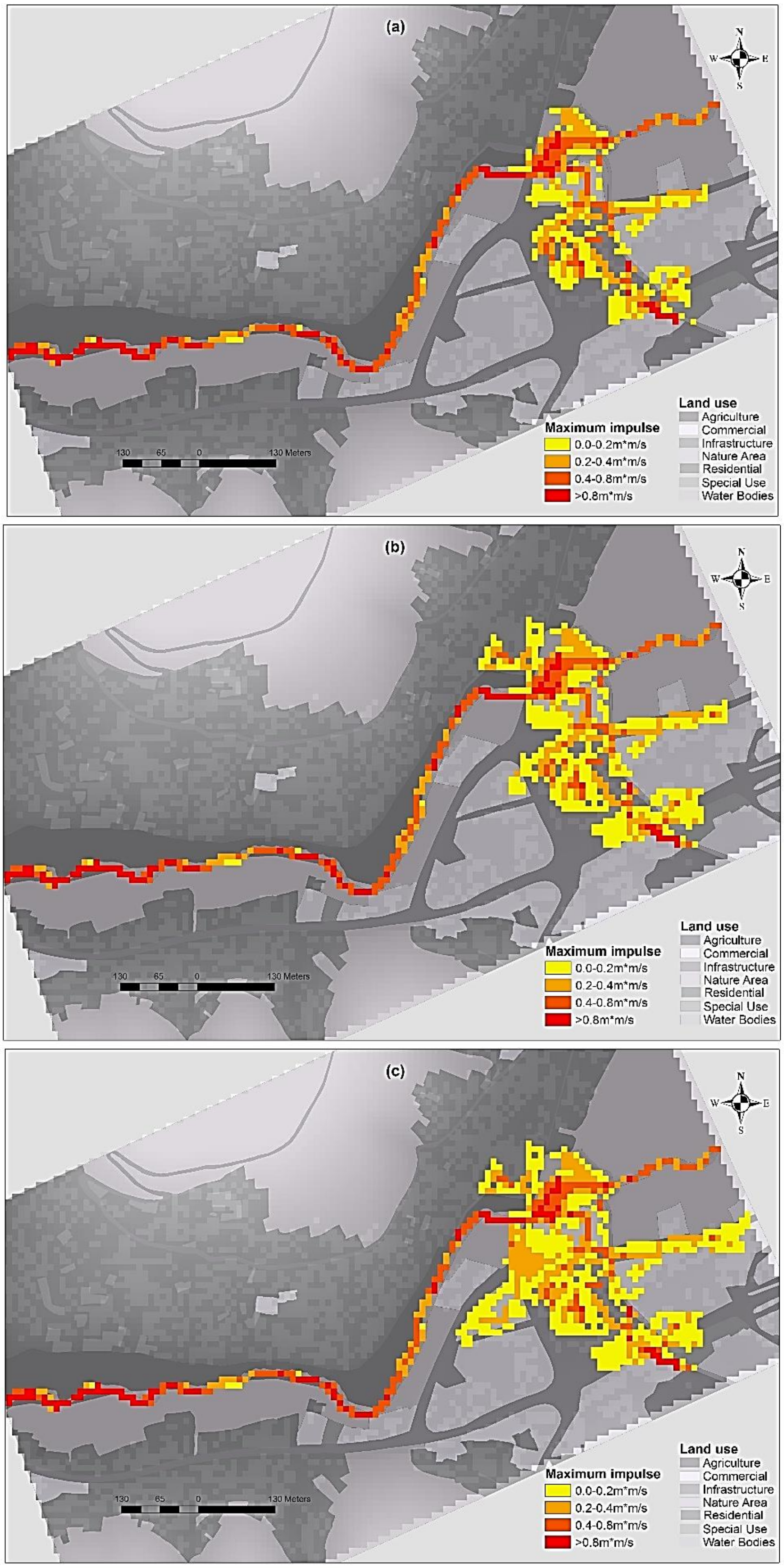

Figure 5.5: The spatial distribution of the quantity of moving (impulse) in the three different return periods (a) 10 year return period (b) 20 year return period (c) 50 year return period.

Comparison of different return periods on maximum impulse characteristics

Different return period results to different impulse values and extents areas. For an event of 10yr return period, maximum of 0.89m2/s was reached while for other events with 20yr and 50yr return periods, a maximum of 0.95m2/s and 1.34m2/s was reached respectively. The following table gives an overview of maximum impulse class and their corresponding flooded surface area (%).

Table 5.4: Maximum impulse (m^2/s) - surface area (% of flooded area) per impulse class of different return periods

Impulse (m^2/s)	10yr return period	20yr return period	50yr return period
0.0-0.2	48.2	39.9	36.4
0.2-0.4	22.9	23.9	26.2
0.4-0.6	15.5	16.7	16.4
>0.6	13.4	19.5	21
Total (x 10^4 m^2)	**(6.1)100**	**(7.4)100**	**(8.3)100**

Available studies showed that people lose stability in flows in relatively low depth-velocity products. According to (Jonkman, 2009) on test experiment done on the person and vehicles instability done in Japan, he showed that people may experience difficulties in walking through water when the depth-velocity product (Impulse) exceeds 0.5m2/s. and cars may lose stability when depth-velocity products exceeds1.0m2/s depending on the size of car of course.

According to the literature US department of land and soil conservation cited by (Tennakoon, 2004) shows the hazard class in combination of both velocity and depths. The wading was unable when the depth of inundation and water velocity is in range 0.4-0.8m and 2.0-0.0 m/s respectively (See fig 5.6). And damage of the light structure are possible when both depths and velocity increases.

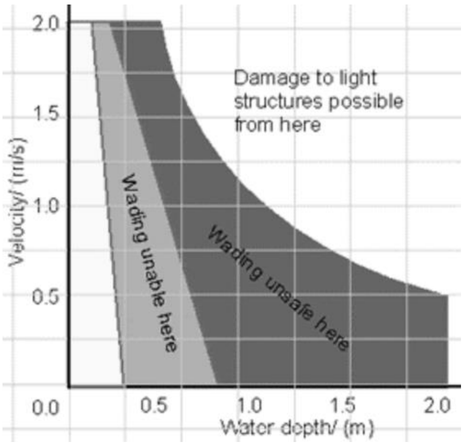

Figure 5.6: Flood hazard class

Source: (US department of land and soil conservation)

5.3.4. Warning time (hr.)

Disaster management and emergency control agency in Kigali demanded warning time as their first priority. They wanted map that shows how much warning time people have before the coming of the flood and the moment it arrives at their home and prepare themselves. In order to produce this flood parameter which is not derived directly from the model, the maps with water depth at various time steps offers a good opportunity to create a map that shows the propagation characteristics of the flood. For example if we want to observe the flow propagation of flood that starts after 30min hour, we have to look on depth map at t=60min. The flood propagation (warning time) of Kigali with different return periods are described in figure 5.7 below. It is clearly shown that, flash floods of Kigali have short warning time i.e. large surface area receives water less than 30 minutes time of simulation in all floods with different events and people in those areas may have to prepare themselves before 30minutes time. These location with short warning time are found near river Nyabugogo, culverts and bridges because water fails to pass through the culverts and overtops on the surface immediately. The areas that is flooded less than 1hour time for an event of 10 year return period have been increased in 20 and 50 year return period respectively. According to (EMA, 1999) warning time is determined largely by watershed characteristics. The larger the catchment area, the longer available warning time. However in small steep catchment, there is short warning time as the catchment responds quickly. This is the case of the area under study where by the catchment is very steep, urbanized and small in size hence responding very quickly. If there is enough time available, flood hazard can be reduced by evacuation. Nevertheless, even if people and their belongings are fully rescued, a flood will still cause a significant damage to static infrastructures and still cause disruptions of substantial community.

Looking carefully at figure 5.7, the short warning time are found on upper part. This is due to the fact that there is obstruction to flow by elevated infrastructure like culverts which reduces the flow to the lower part (south direction) but increases the water depth and reduces the warning time in the upper part.

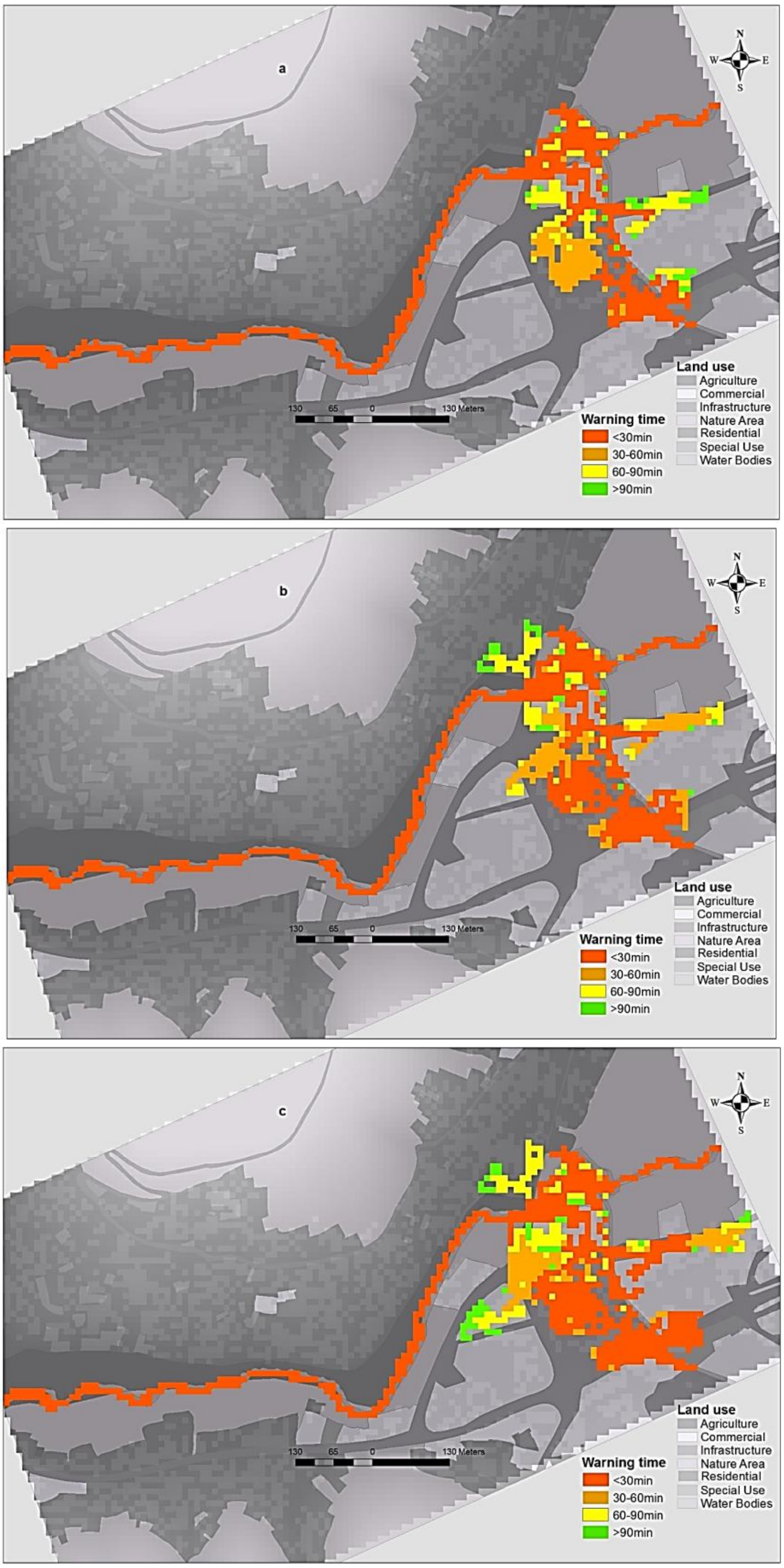

Figure 5.7: The spatial distribution of the arrival time of the first flood water (Warning time) with event of different return period of (a) 10 year return period (b) 20 year return period (c) 50 year return period.

Comparison of different return periods on flood velocity characteristics.

Different return periods due to different storms shows different warning time. For a storm of 10 year return period, surface area that receives short warning time(<1hr) was less than those areas that receive the same warning time for different events of 20 and 50 years respectively. The overview of the area flooded by different warning time classes for different events is shown in table below.

Table 5.5: Warning time (min) - surface area (% of flooded area) per warning time class of different return periods

Warning time (min.)	10yr return period	20yr return period	50yr return period
<30min	49.0	56.0	62.3
30-60min	29.5	26.5	23.9
60-90min	20.0	16.1	13.0
>90min	1.5	1.4	0.8
Total (x 10^4 m^2)	**(6.1)100**	**(7.4)100**	**(8.3)100**

5.3.5. Estimated flood duration (hr.)

Different stakeholders contacted in Kigali requested this hazard parameter. This parameter gives rough estimates of how long the flood water remains at certain location. This parameter is based on various assumptions such as drainage of the flood water from the flooded area (Alkema, 2007). Therefore, this study assumes that there is free drainage at lowest point of inundated area. The duration of inundation is an important parameter for flood risk assessment especially engineers need such parameter in evaluation of transport blockages. This parameter can influence the extent of damage and loss to properties. Although the relation between duration and threat to human life is not as strong as flood depth, but prolonged inundation can cause diseases like malaria which can be a threat to human being. Although different health agencies in Kigali was not contacted, it is unlikely that this parameter can be disagreed by this agency.

1D2D modelling in SOBEK cannot generate flood duration on pixel basis automatically, This study uses the methodology used by different author like (Alkema, 2007) and (Tennakoon, 2004) to derive flood duration. This parameter were derived using time integration of inundation depth files created at each time step of simulation. First of all 18 ASCII flood depth map for each time step 10 minutes interval for three hours were reclassified into binary raster map with value zero for pixels which did not undergo flood and value one for inundated cells. All 18 classified maps were summed up to get inundation duration. The final map represents pixel value of 0 to 18. This means that pixel value of 18 represents pixel inundated through out of the simulation period (3hrs) while pixel value of 6 represent areas inundated only 60 minutes (1hour) though out inundation. Finally flood duration was classified to be useful for flood hazard assessment. This classification shows that almost all overland areas have short flood duration (3hrs) which reflects the reality of the Kigali city flash floods which last at most 3hrs. It was decided to use T/3 and 2T/3 as a cut off of flood duration which correspond to higher and lower hazard class limit. In this case T= 3hrs therefore upper limit is equal to 1hr and lower limit corresponds to 3hrs. The inundation duration maps for different return period are shown in figure 5.9 below. Large surface area in the study area will be submerged for a period of 3hrs. In lower parts within and near by the river, flood duration could be even more than 3 hours because of those parts are naturally difficult to drain because of its low elevation. Also there are areas not nearby rivers that takes quite long time 3hrs to drain (bus park area). This is due to probably/possibly limited capacity of the drainage channel to discharge off water in that area.

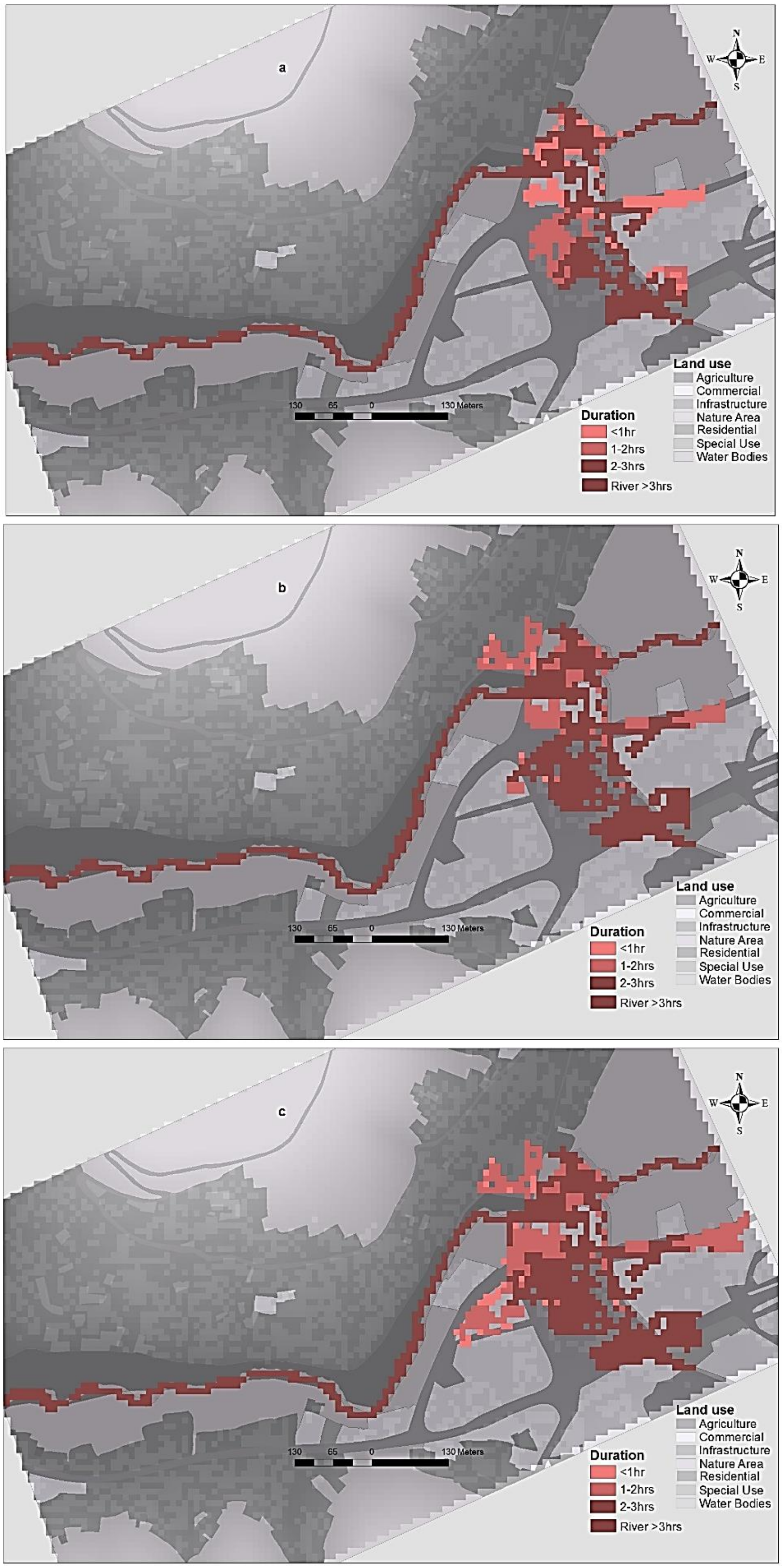

Figure 5.8: Spatial distribution of estimated duration of flash floods in hrs for different return periods (a) 10 year return period (b) 20 year return period (c) 50 year return period.

Comparison of different return periods on flood velocity characteristics.

The extent and surface area that takes long to submerge increases as the storm size increases refer to fig 5.8 above. Most of parts of Kigali will be submerged for a period of 3 hours which can even be higher depending on the elevation. Surface area for long submerged location increases as the flood storm size increase. The overview of submerged area with their corresponding events are shown in the table 12 below.

Table 5.6: Flood duration (hrs.) - Surface area (% of flooded area) per duration class of different return periods

Duration (hrs.)	10yr return period	20yr return period	50yr return period
<1hr	2.4	2.0	3.0
1-2hr	24.9	20.6	25.1
2-3hr	72.7	77.4	71.9
Total (x 10^4 m^2)	**(6.1)100**	**(7.4)100**	**(8.3)100**

N.B: In 10 year flood event, the flood extent is less compared to flood extent of other events of higher magnitude. This means there low level of exposure in this event and the impact might me less. For the event of higher magnitude like 20 or 50 years return period, the flood extent increases and the level of exposure is likely to be higher due to possibility of higher density development like economic activities taking place in the area of study are more exposed in 50 year even hence the higher the impact.

5.4. Flood hazard mapping

Hazard can be defined as the probability that an event of certain magnitude occurs in a given area within a specified period of time. Since this research the user play's an important role, therefore the product shown in this research are the needs of different stakeholders. The findings showed that flood maps for the public should be less complex and should contain the following basic information. Inundation extent for different specific events considered critical by public users and should be presented in the flood maps as the most important hazard information. As many citizens are not necessarily familiar with the concept of technical languages like return periods or exceedance probabilities, such expression and other technical languages should be avoided and rather terms like small, medium or extreme events should be adopted. In doing so, flood extents of different return period10, 20, and 50 years were combined to generate the simplified hazard map shown in figure 5.9.

In order to generate the hazard maps, we need to know the flood propagation of different events such flood depths and velocity. If we want to calculate the annual probability i.e. the chance that a certain magnitude occurs in the next coming year we have to divide 1 by return period. This study, an event of 10, 20 and 50 year return period was simulated by 1D2D SOBEK and their flood extents was combined to generate flood hazard maps. The return periods and their calculated annual probability is shown in the table 5.7 below.

Table 5.7: Probability values for different return period

Return period	Annual probability
10	0.10
20	0.05
50	0.02

Finally these annual probability was assigned to each flood extent of each event (10, 20, and 50) and these maps were integrated to get flood hazard maps of study area which can be easily understood by citizens at risk. The flood extent that has highest chance to occur i.e. 10% chance (10 year return period) was classified as high flood hazard and that of 5% chance to occur (20 year return period) was classified as medium while 2% (50 year return period) chance was classified as low flood hazard as can be seen in the table 5.8 and integrated flood hazard map are shown in figure 5.9 below.

Table 5.8: Probability range values for hazard class.

Hazard class	Probability values	Return period
Low hazard	0.02	50year
Medium hazard	0.05	20 year
High hazard	0.1	10 year

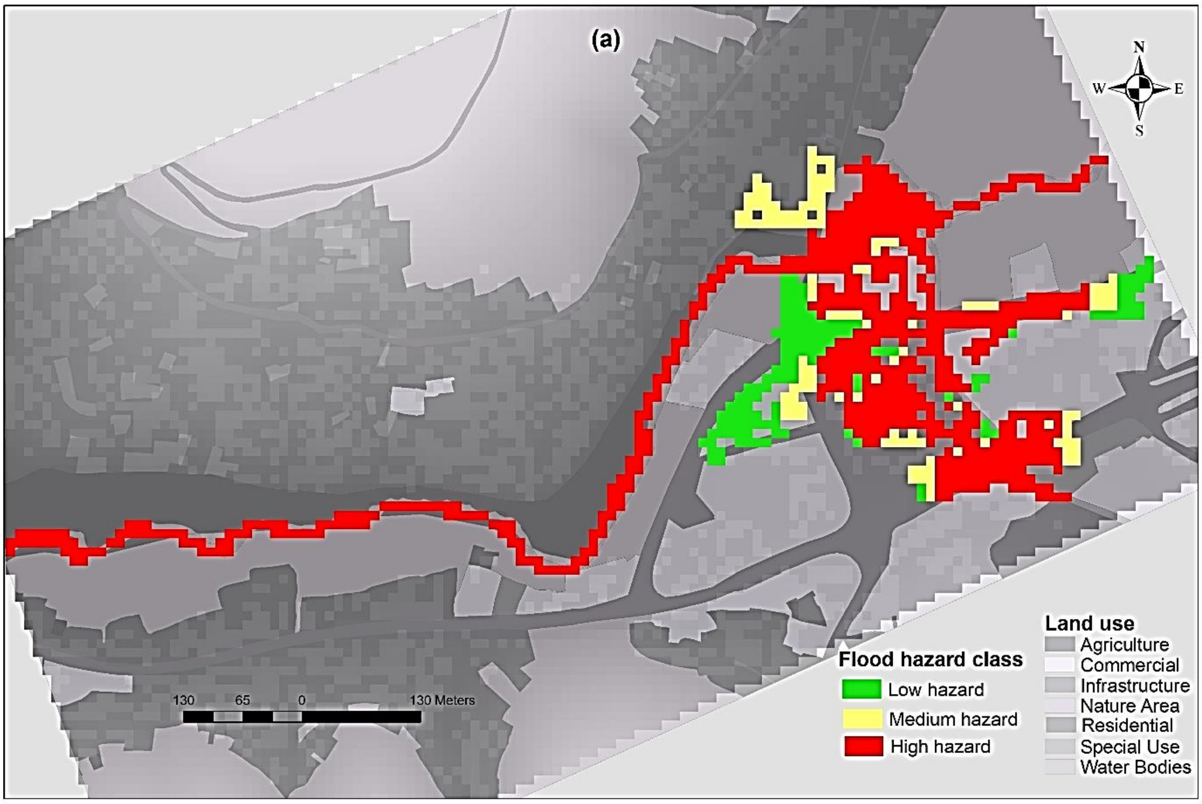

Figure 5.9: Hazard class in the downstream of Mpazi catchment, Kigali city

These hazard classes are distributed in different area sizes as depicted in figure 5.10 below

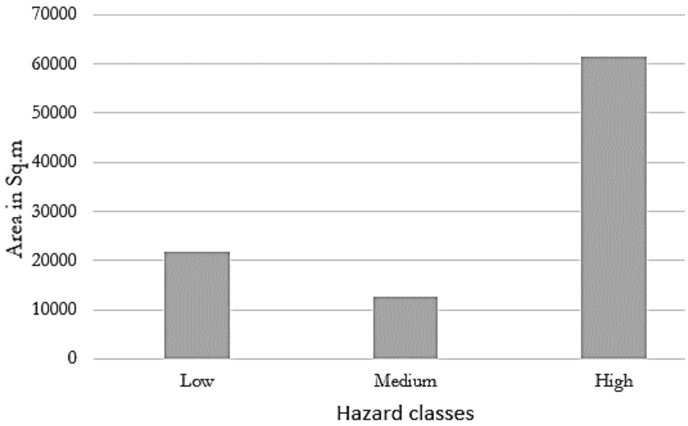

Figure 5.10: Area distribution for different hazard classes

Based on the fig.5.10 above, it is explicitly shows that, the area of high hazard class is greater compared to low and medium classes. When blocks of building footprints were overlaid on the above hazard map, 22 buildings were estimated to be in high hazard class; 7 and 14 estimated buildings were found to be in medium and low class respectively. The function of the building exposed to hazard zones are of commercial type. Therefore the maximum number of commercial buildings are located in high hazard class area as shown in table 5.9 below.

Table 5.9: Estimated number of buildings located in different hazard class

Hazard class	Estimated number of buildings	Cumulative counts	Percentage
High	22	22	51.2
Medium	7	29	16.3
Low	14	43	32.5
Total	43		100

Hazard mapping as basis for land use planning

City planning agency requested flood hazard maps as basis for land use planning strategy. But further they requested an advice on the implications of product produced. It is in this regard that, this research tried to find out some scholars/literatures that describes the guidance of how to flood maps as basis of land use planning.

Merz &Thieken, (2007) highlighted that some countries are adopted the strategies for flood hazard mapping. This is because these initiatives provide and increase communicative power on flood risk over time. For example, in the article of BUWAL, 1998 cited by (Merz et al, 2007) Spain, UK, Germany, Netherlands and Switzerland are heavily engaged in mapping activities to identify zones which are prone to natural hazards taking into consideration flood depth, impulse and exceedence probability in land use planning. And according to author report, this mapping activities arise awareness of the citizen.

Therefore, the government of Rwanda are also obliged to consider the above mentioned maps (depth velocity and impulse) in land use planning because these maps contain information about intensity of dangerous process and about its probability. The intensity and exceedence probability are combined to quantify the hazard. Figure 5.11 shows standard intensity-probability matrix and different hazard levels. By means of this matrix, areas are characterized as zones of land use bans, restriction and recommendations. These zones can be a basis for land use planning as cited by (Merz et al, 2007)

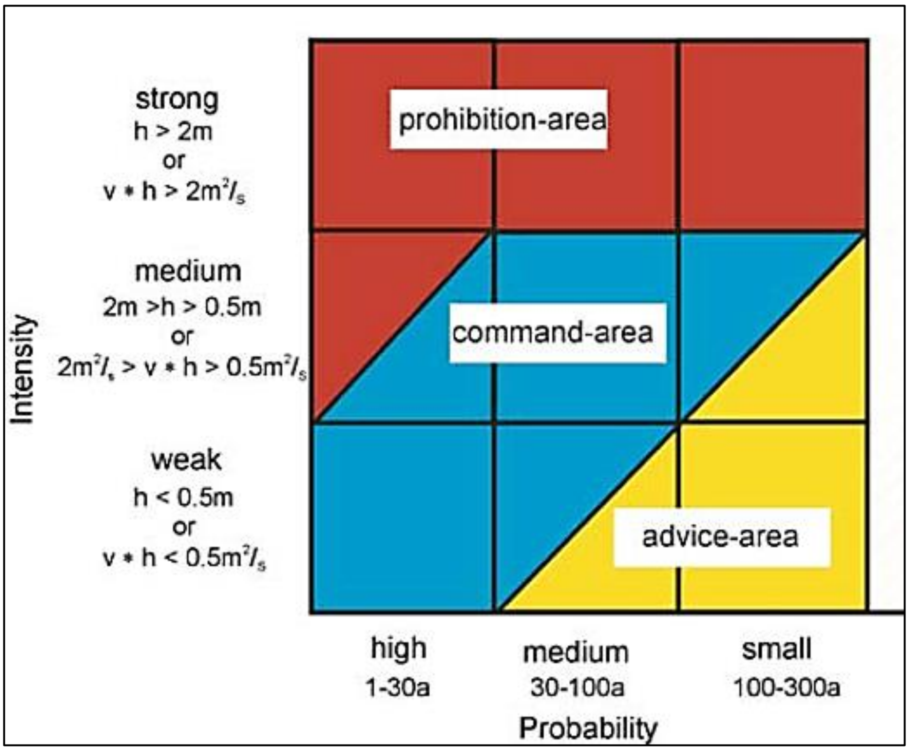

Figure 5.11: Intensity-probability matrix for the assessment of hazard prone areas (danger zones) as a basis of land use planning in Switzerland modified by BUWAL, 1998 cited by (Merz et al, 2007)

The explanation of the above zone is that, in prohibition areas, construction are generally not allowed whatsoever in the zones that has water depths greater than 0.5m with high probability of occurrence (1-30 years). In command areas, construction is possible under certain restrictions refer to figure 5.11. In advice areas, constructions is possible but recommendations are given. For the case of this study, based on standard matrix above 10 and 20 year return period corresponds to high probability while 50 year corresponds to medium probability.

Taking assumptions that, city planners of Kigali uses the above intensity probability matrix as basis for land use planning, the following table shows numbers of buildings in each land use restricted zones.

Table 5.10: Estimated number of buildings in area of study exposed in land use bans based on probability matrix cited by (Merz et al, 2007)

Land use bans	Estimated number of building exposed
Prohibition area	9
Command area	29
Advice area	5

N.B: Sensitive objects like schools, hospitals, etc… should not be built in such zones

5.5. Assessment of usefulness of the product

Finally, assessment of usefulness of the product produced have to be assessed by various stakeholders. The appropriate way to assess the usefulness of the flood hazard maps produced was to deliver them to the interviewed stakeholders. The stakeholders have to assess if the product produced satisfy their requirements. This procedure was used by (BIRARO, 2014) while assessing the designed requirement for

land information updating. In this study also, in order to assess the usefulness of the product in context of use, a survey monkey questionnaire (Internet questionnaire) was designed which intends to determine if the stakeholder's requirements are met with the product produced or not.
Each stakeholder (city planning agencies, disaster emergency response, engineers, water management agencies, insurance institution and citizen in flood prone areas) received the product. Initially before submitting product to target group, the product was designed in such way that the spatial location can be understood by different stakeholders concerned. And the following was one of the guiding questions.
Do you think the flood hazard maps produced will support in the following activities? (See table 18 below)
Are you satisfied with the information provided on flood hazard maps according to your institutional requirements?
Three out of Six stakeholders (Water resource agency, Disaster and emergency response, and insurance company) replied to the questionnaire and the following table gives an overview of the answers of those guiding questions.

Table 5.11: Over view of response of interviewed stakeholders

Activities	Flood extent	Flood depth	Flood velocity	Flood impulse	Flood duration	Warning time
Regional planning						
Construction planning						
Evacuation planning					X	X
Re-activation of water retention areas	X	X				
Insurance rates		X	X	X	X	
Disaster management plan	X					X
Public awareness	X	X				
Protection of building and infrastructure						
Formulating relevant policies	X	X				X
Identify who needs flood insurance				X	X	
Safe construction in industry						

Legend: X= Water resource; X= Disaster and emergency response; X= Insurance company

Are you satisfied with the information provided on the flood hazard maps shown according to your institutional requirement?
By linking this questions to different requirements of replied stakeholders analysed in previous section 5.1 where by warning time and duration was the requirement product for disaster and emergency response, water depth, water velocity and impulse were the map requirement from insurance company and water department agency. From the above question, all stakeholder replied and agreed that they are now satisfied with the product produced and are useful to their institutions. However, they are some suggestions for improvement and recommendations from these stakeholders that are discussed in analysis of their feedback below.

Feedback analysis and recommendation

Based on their replies on the guiding questions above and based on table 5.10, one can draw a conclusion that, Stakeholders are now contented with the flood hazard map information because their requirements are met. This can possibly cause an increase in communicative power of the flood hazard maps produced. This can possibly solve the initial situation which leads to a problem that the maps are not effective in

promoting the public to take actions in reducing their vulnerability because of disagreement of the contents in maps. However, there are some recommendations suggested by stakeholder for further improvements listed below.
It seems (feedback) from different stakeholders that this product produced is the intermediate product but of course the final product for the study point of view. This is because when giving the stakeholder the room to comment on the product and suggest further improvement, they pointed out that they are satisfied by the current state of the product since it is effective in communicating the risk areas but they want to be free from floods hence emphasizing on the solution of mitigating such floods. Therefore, it is this regard that water resource agency emphasized on the strategies to reduce the flooding. From study point of view, this shows that at least product produced gives rough impression that it has some impact on different user since it raises awareness to them since they are now know where to take actions from institution requirement point of view. Therefore map alone might not help sufficiently to overcome the entire problem but it can be the part of problem solving strategy.

In terms of visualisation, disaster management and emergency response agency suggested that, it's good and interesting to see types of economic activities affected but displaying number of potentially affected inhabitants will be added advantage for raising awareness but for this research, population data was missing since it was beyond the context of this study.

6. CONCLUSION AND RECOMMENDATION

The previous chapters describes in detail the research objective and the methodology used to accomplish those objectives. This chapter concludes the research by describing briefly how these objectives were achieved and both conclusion and recommendation drawn from the results.

6.1. Summary of conclusion

This study was aimed to assess the usefulness of flood hazards in Kigali. In order to assess the usefulness of flood hazard maps, it was necessary to look at user requirements from different users in Kigali. Therefore this was achieved by setting out four sub objectives with their research questions along the way.

Sub-objective1: To identify the specific needs and requirements of specific end user groups of flood hazard maps

This sub-objective was achieved during data collection done in Kigali as discussed in section. One of the guiding research questions that helped to achieve this sub objective was *"who is the focus (target) group or end user of flood hazard maps?"* And "*what are the specific needs do those users need with regard to hazard map?"* During field work, different users of flood hazard maps were identified. These ranges from government institution to private sectors. The potential active users of flood hazard map in Kigali were City planning agency, water resource agency, Disaster and Emergency response agency, insurance companies, engineers and citizens affected by flooding. Based on the empirical findings from participatory approaches that incorporates interviews conducted in Kigali city with these stakeholders, it was found out that these stakeholders have different needs and requirements refer to table 9. This was proved by the fact that one user relate high hazard zones to shorter warning time, others to simply water depth or duration. Such differences may require the construction of different flood risk zones for use by different stakeholders for the same flood. These requirements were used to prepare outputs that should in principle satisfy these requirement.

Sub-objective 2: To define an appropriate method to generate user requirements on flood hazard maps

User's flood hazard map preferences can be satisfied through application of various methods. In order to define appropriate method to deliver stakeholders needs, the guiding research question was *"Which is the appropriate tool to generate specific user needs?"* And *"What are necessary parameters to be integrated in method described and the needed resolutions of those defined parameters?"* This study further revealed that application of coupled 1D2D hydrodynamic models (SOBEK) for flood simulation together with ILWIS software can contribute better understanding and quantification of floods in urban areas of complex terrain like Kigali city. Four main types of input data were needed for this modelling suit: 1)The digital surface model to represent both natural and manmade topography (roads and buildings); 2) river or cross sections to represent the shape of the river; 3) boundary conditions, which includes the incoming discharge at the upstream and water levels or rating curve at the downstream boundary; and 4) surface roughness data, which represents the resistance of the flow by different land cover types along the flood plain and the river channel. 10m pixel size was selected which is assumed to preserve urban features, maximize study area and optimize computation time

Sub-objective 3: To develop the flood hazard maps by considering user specific needs.

The potential active users of flood hazard maps in Kigali have different needs. Some of these requirements contains flood hazard maps with different events. These requirements were used to prepare outputs that should in principle satisfy these requirement. Consequently, research questions like *"Which areas are likely to be inundated in different return periods?"* And *"What is the significant change of flood behavior with* *changing return period?"* This study found out that, the areas near by the critical infrastructure like culverts and bridges were flooded firsts due to possibility of its small sizes which cannot handle the mass of water entering hence overtopped. It was revealed that the extent of flooding increases as the return period increases where it increases from 5.0% for 10 year return period to 8.7% for 50 year return period. The velocity and flood depth are increasing with the increase of return period too.

Sub-objective 4: To assess the usefulness of flood hazard maps developed.

Finally, since this study was aimed to assess the usefulness of the flood hazard maps developed, it was necessary to check how useful the products are. This was done by delivering the flood hazard maps to different stakeholders to cross check if their requirements are satisfied or not. The monkey questionnaire was designed which intends to determine if different stakeholders are satisfied. Three out of six stakeholders replied to the questionnaire. The needs of these stakeholders were warning time and duration for Disaster and emergency response agency, water depth, velocity and impulse for insurance company and flood depth and velocity for water resource agencies. Their replies indicates that, they are now happy with the flood hazard map information which can possibly cause an increase to attain their potential to fulfil the needs of different users, to raise awareness and provide a clear and understandable source of information for planning. This can possibly solve the initial situation which leads to a problem that the maps are not effective in promoting the public to take actions in reducing their vulnerability because of disagreement of the contents in maps. However, maps alone might not help sufficiently to overcome the entire problem but it can be the part of problem solving strategy.

6.2. Recommendations

- ✓ In general this research was intended to produce the flood hazard map characteristics based on the requirements of end-users. A topic that was not discussed in detail as requirements was the issue of resolution both spatial and temporal resolution of flood hazards maps which can be a subject to further research. The issue of uncertainty was not discussed in detail with different stakeholders. Modellers for flood hazards are aware that the results of their model are at certain degree of uncertainty but such uncertainty for example in flood extent are not shown in the maps which can suggest a non-existing precision to the user. Therefore this can be a subject to further research to find out how to visualize such uncertainties to be easily understood by the users.

- ✓ In this study, some boundary conditions used like river discharges and water levels were of less accurate, or was non-existent. It is therefore recommended that monitoring of rivers must be paid more attention.

- ✓ This research was only limited on assessing flood hazards and to characterize and quantify the hazard. This research didn't tackle the risk assessment phase which was also the need for different users like insurance company. This research recommends further studies to transform the hazard assessment produced into the risk. This will require additional information on the vulnerability of all exposed elements and their value. This was pointed out by different users during validation phase of the products.

- ✓ Model results shows that, the dimensions of critical infrastructure may possibly be the root cause of flooding. It is recommended that the infrastructure like drainage system and culverts size should be improved to allow the mass of water to pass through.

- ✓ It was found out that the amount of discharge coming from upstream Mpazi catchment is too much which can possibly be caused by developments (existing land cover) in upstream which decreases infiltration hence increases runoff. It is recommended that, another study is needed to run different scenarios of changing upstream different land covers to slow down the discharge entering the downstream which causes regular flooding.

- ✓ This research was only limited to only one catchment in Kigali city, it is advisable to do hazard assessment of the entire country.

6.3. Limitation of the study

The main limitation of this study was the available data for the model. For example no longer records of historical data of river discharges to establish properly the return period. This study was based on the estimation of maximum recorded discharge from 2011 to 2014 measured by the data logger.

This research uses the upstream boundary conditions for Mpazi watershed performed by the consultants of which the Author has no clue if rainfall-runoff model used was calibrated or not.

Model calibration in the downstream stream flood plain was based on the flood depth from interview that could lead to biasness. More data for calibration and validation such as flood extent and discharge recorded at downstream area was not available. Finally there is limitations on modelling in general since both hydrological and hydrodynamic models have some degree of uncertainty. This is due to insufficient data and data quality.

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Appendix 1: Data preparation for the Gumbel method as explained by (Parodi G, 2009)

Sort the annual maximum daily rainfall data values 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-1

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-2

Calculate the plotting position for each observation as:

Y = -LN (-LN (PL))………………………………………..EqA-3

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-4

Finally return period is calculated as:

PL = EXP (-EXP (-Y))……………………………………...EqA-5

Calculation of rainfall return period using Gumbel Method

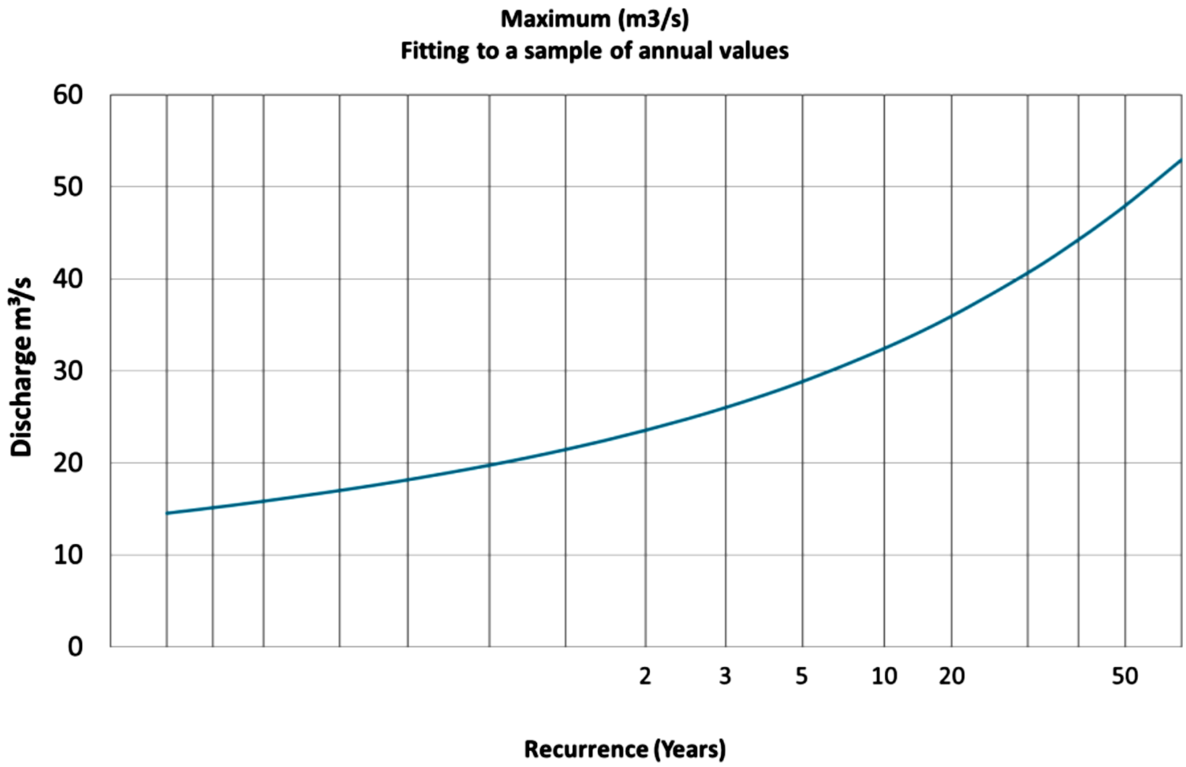
Daily rainfall	Rank(R)	Left probability (PR)=R/N+1	Right probability 1-(R/N-1)	Return period (T)	Y=-LN(-LN(PL))
27.4	1	0.032258	0.967742	1.033333	-1.23372204
31	2	0.064516	0.935484	1.068966	-1.00826445
31.3	3	0.096774	0.903226	1.107143	-0.84817244
33.6	4	0.129032	0.870968	1.148148	-0.71671372
36.9	5	0.16129	0.83871	1.192308	-0.60133299
39.3	6	0.193548	0.806452	1.24	-0.4960537
42.3	7	0.225806	0.774194	1.291667	-0.39748472
42.7	8	0.258065	0.741935	1.347826	-0.30346609
43.2	9	0.290323	0.709677	1.409091	-0.21249718
43.5	10	0.322581	0.677419	1.47619	-0.12345767
45.2	11	0.354839	0.645161	1.55	-0.03545588
45.9	12	0.387097	0.612903	1.631579	0.0522616
48	13	0.419355	0.580645	1.722222	0.140368602
50.4	14	0.451613	0.548387	1.823529	0.229501376
52.5	15	0.483871	0.516129	1.9375	0.32029204
52.6	16	0.516129	0.483871	2.066667	0.413398773
53.6	17	0.548387	0.451613	2.214286	0.509536687
54.8	18	0.580645	0.419355	2.384615	0.609513182
55.1	19	0.612903	0.387097	2.583333	0.714272302
57	20	0.645161	0.354839	2.818182	0.824954504
59.3	21	0.677419	0.322581	3.1	0.942981875
59.9	22	0.709677	0.290323	3.444444	1.07018592

63.9	23	0.741935	0.258065	3.875	1.209008835
64.6	24	0.774194	0.225806	4.428571	1.362838126
68.7	25	0.806452	0.193548	5.166667	1.53659934
74.3	26	0.83871	0.16129	6.2	1.73789269
76.6	27	0.870968	0.129032	7.75	1.979412778
78.5	28	0.903226	0.096774	10.33333	2.284915186
89.2	29	0.935484	0.064516	15.5	2.707679652
106	30	0.967742	0.032258	31	3.417637092

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

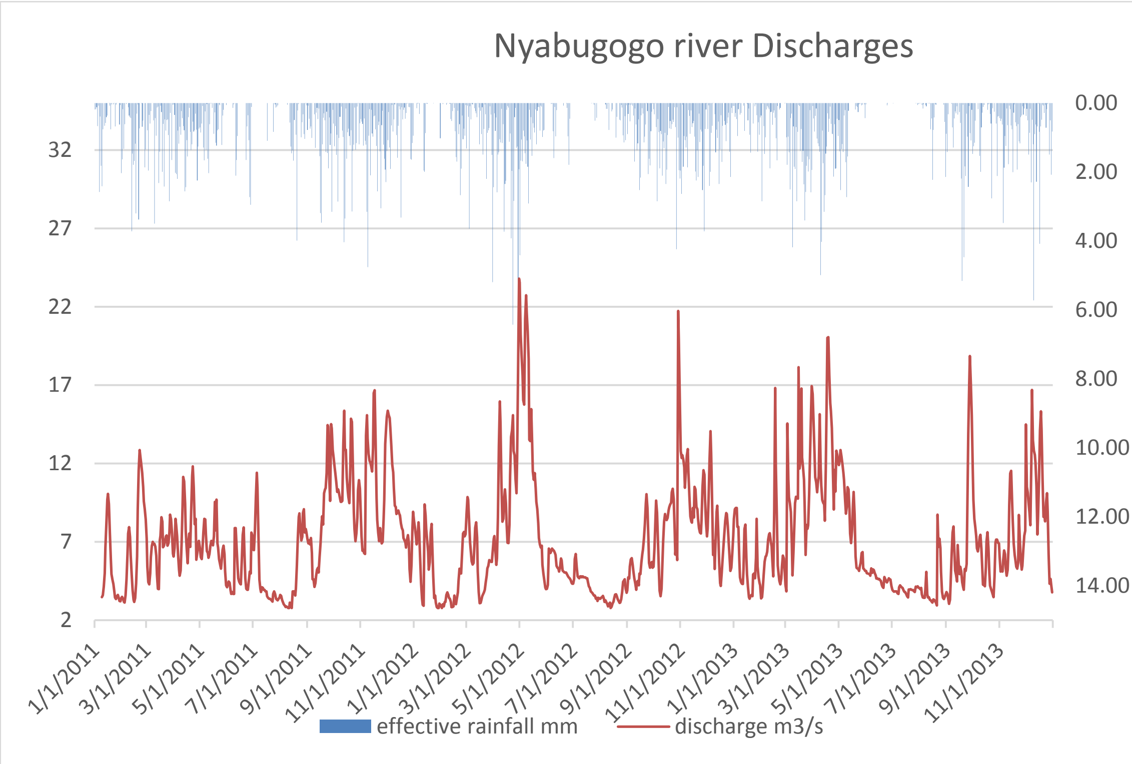
Return period (T) for rainfall (mm)	Y=0.0625x-2.8585	PL= EXP(-EXP(-Y)	Return period T=1/(1-PL)
79	**2.079**	**0.9**	**10**

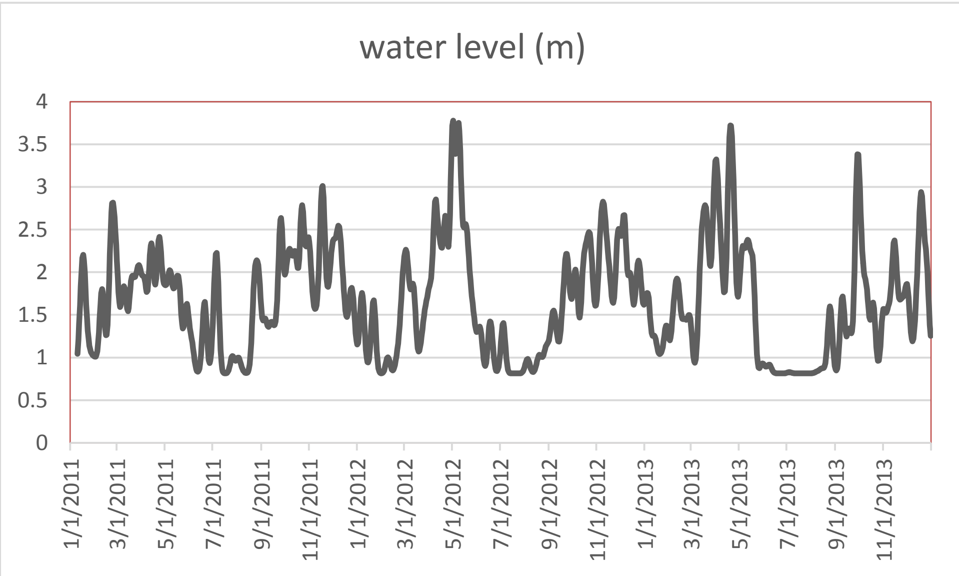
Appendix 2: Discharge values for Mpazi catchment developed by consultants



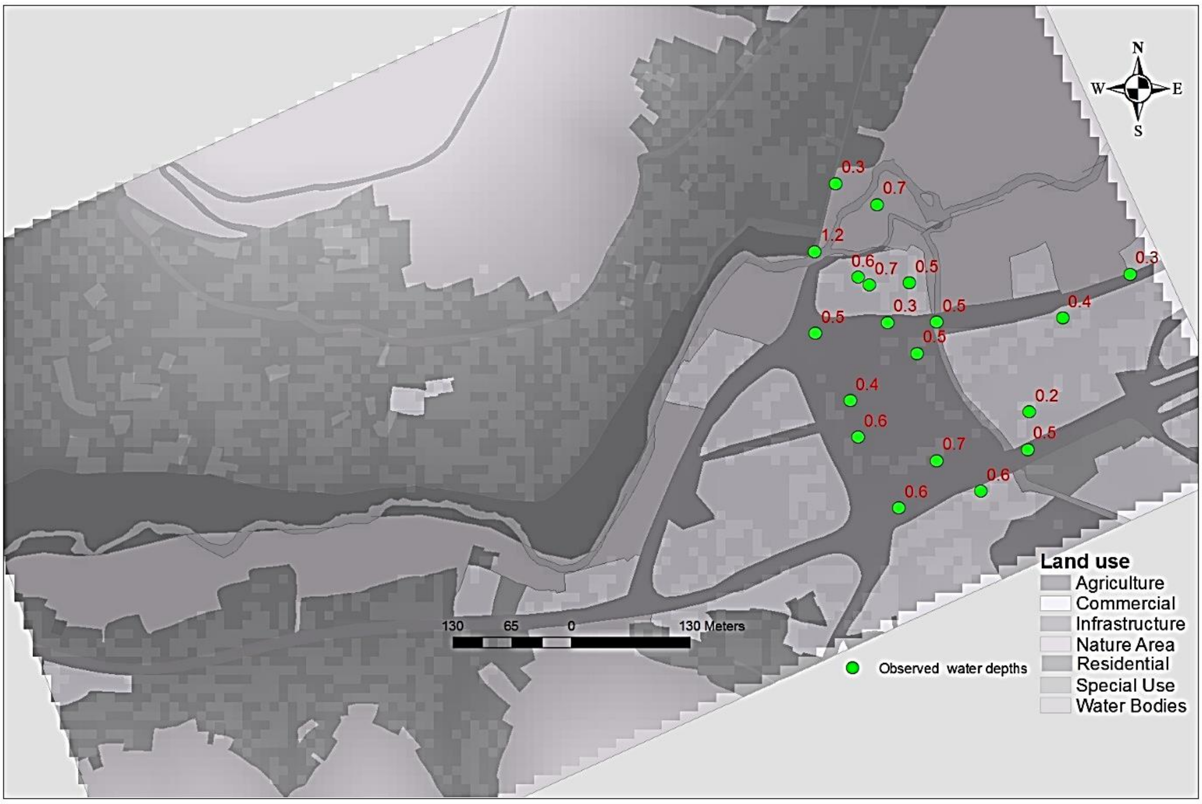
Annual peak discharge values for the Mpazi catchment. Source: (SHER-Ingénieurs-conseils, 2013)

Appendix 3: Nyabugogo river discharges and water levels recorded in Nemba gauging station





Appendix 4: Locations of recorded water levels in the downstream of study area used in calibration



Appendix 5: Fieldwork questionnaire

ITC: Faculty of Geo-Information Science and Earth Observation of the University of Twente, Netherlands

Researcher: Fred MUGISHA
Contact: f.mugisha@student.utwente.nl

Research Title: Modelling and assessing urban flood hazards based on the end-user requirements in Mpazi catchment. Kigali-Rwanda

Questionnaire Number: ……………..
Date: …………………………………
Time of Interview: …………………..
Location: …………………………

Purpose of the questionnaire

This questionnaire is organized within the frame of the stakeholder's consultation activities. It specifically addresses the flood hazard mapping (assessment) to identify user's preferences each designed for various end users. To ensure a common understanding, the questionnaire uses a standardized terminology, which is explained in the next sections.

Definitions:

'**Flood**' is defined as a temporary covering of land by water, '**Hazard**' is defined as a physical event, phenomenon or human activity with a certain probability and the potential to result in harm to people and properties ,'**Flood hazard map**' is defined as a map showing the areas that have flooded, could be flooded with an indication of the probability, and if appropriate the water depth and flow velocity, apart from maximum water depth and velocity, other four flood hazard parameter maps can describe the different aspects of flood event, Maximum impulse, maximum raising of water level, flood propagation characteristics (warning time) and duration. The following are definition of each parameter as described by (Alkema, 2007) see example attached.

1. **Maximum water depth (unit: m):**

This map shows the maximum water depth that occurred during inundation. The rationale behind this parameter map is that areas with deep water are more dangerous to people and potentially more damaging to objects like houses and cars.

2. **Maximum flow velocity (unit: m/s);**

This map shows the maximum flow velocity that occurred during the inundation. The rationale behind this parameter is that velocity is a component of the floodwater that can sweep people off their feet and make cars float away. This map shows where preferential flow paths may develop that could be dangerous for Children, adults and cars.

3. **Maximum impulse (unit: m2/s);**

This map shows the maximum impulse that occurred during the inundation. The impulse is calculated at each time step by multiplying water depth and flow velocity. For each pixel this value represents the amount of movement of the water mass (per pixel the mass only depends on the water depth, since the surface area of the pixel and volume weight of water are constant). The rationale behind this parameter is that flow velocity alone does not suffice to estimate the amount of potential damage or danger to humans and cars to be swept away. Shallow water with a high flow velocity does not have a lot of kinetic energy or momentum and neither has deep, but practically still-standing water. Deep, fast flowing water however is potentially dangerous for people and vehicles and is potentially damaging to objects like houses and crops.

4. **Maximum rising of the water level (unit: m/h);**

This map shows the maximum speed at which the water level rose at some point during the inundation. It is calculated by taking the difference between two successive water depth maps, divided by the time interval between the two maps. The result is an increase in water depth per hour. The rationale behind this parameter map is that a quick rising of the water level is potentially dangerous for people who may not have sufficient time to seek higher ground or elevated structures.

5. **Flood propagation characteristics (unit: h);**

This map shows how the flood propagates through the area. After each time interval the flooded area is identified and compared with the situation at the previous time interval. It records the time at which a cell is inundated for the first time. The rationale behind this parameter map is that it shows how much time it takes for the first floodwater to reach a certain location and thus how much warning time people have to prepare themselves. Areas that are flooded quickly are potentially more dangerous than areas further away.

6. **Duration (unit: h**).

This map estimates the time the floodwater remains at a certain location. It is based on several assumptions regarding the drainage of the floodwater from the flooded area.

Section 1: Contact information:

This section asks for contact details of the person responsible for the flood risk mapping survey and for contact information for other relevant institutions in the country.

Contact name: ……………………………………..

Organization: ……………………………………..

Position: ……………………………………………

E-mail: ………………………………………………..

Telephone: …………………………………………….

Address: ……………………………………………….

Section 2: The general mapping formats options and information provided.

This section asks for information on the type of flood maps existing in the area of competence of the institution completing the questionnaire.

1. Does your institution play a role before, during and after flood ev☐ YES ☐ NO
2. 1f so what? ………………………………………………………………………………………… ………………………………………………………………………………………… ………………………………………………………………………………………… …………………………………………………………………………………………
3. Does your institution have any hazard information about urban floods? YES ☐ NO ☐

   If no, skip to question ……………………………………………………….15 &16

4. If yes, did you make it yourself or has it generated by another organization?

5. What type of flood information do you have in you institution?

   Hazard map ☐ Risk map ☐ other ☐ Specify………………………

6. Where from, does your institution get information about flood hazards? ...………… ………………………………………………………………………………………… …………………………………………………………………………………………

7. How often do you get this information? ....
………………………………………………………………………………………
………………………………………………………………………………………
…………………
8. Are you satisfied with this frequency? YES ☐ NO ☐

9. If not, how often do you need it?
………………………………………………………………………………………
………………………………………………………………………………………
……………………………………………………………………………………..
10. Is the information/contents in the flood hazard maps useful for you? YES ☐ NO ☐

11. Explain what and how? ………… …… ……… ……… ……… ………
………………………………………………………………………………………
………………………………………………………………………………………
12. Does your institution pay for data/ flood hazard maps? .... …… …………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………
13. Does your institution pay for updating and dissemination of flood hazard maps? .... …….
………………………………………………………………………………………
………………………………………………………………………………………
14. Does your institution have sufficient staff capable of producing and using capable flood hazard maps? YES ☐ NO ☐

Answer 15 & 16, if question 2 was 'NO"

15. Would your institution like to get flood information? YES ☐ NO ☐

16. What sort of information does your institution need? ………………..
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………

Section 3: Representation of flood hazard parameters on the map

This section addresses options to visualize the specific hazard parameters on the maps based on user preferences.

17. What are the most important information/ contents to be shown on the flood hazard map (Rank according to your needs)? 1most important to 6 least important. 0 = not important

Type of flood hazard parameter	**Unit**	**User preference**
Maximum water depth	(m)	
Maximum flow velocity	(m/s)	
Maximum impulse	(m^2/s)	
Maximum rising of the water level	(m/h)	
Duration.	(h)	
Flood propagation characteristics	(h)	

18. What is the above flood hazard parameter maps (information) used for in your institution?
    ………………………………………………………………………………………
    ………………………………………………………………………………………
19. For which activities/tasks in your institution are flood hazard parameter maps (information) required?
    ....
    ....
20. Which organizations you collaborate with may also use of flood hazard maps (information)?
    ………………………………………………………………………………………
    ………………………………………………………………………………………
    Would you like to receive the feedback on the results of this survey?
    ………………………………………………………………………………………
    ………………………………………………………………………………………