ASSESSMENT OF FLOOD HAZARD AREAS IN THE CONGO RIVER BASIN IN THE DEMOCRATIC REPUBLIC OF CONGO: A CASE STUDY OF THE N'DJILI RIVER SUB-BASIN.

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A RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT FOR THE REQUIREMENTS OF THE AWARD OF THE DEGREE OF MASTER OF ART IN WATER RESOURCES MANAGEMENT IN THE DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES.

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DECLARATION

This research project is my original work and has not been presented for a degree in any other University.

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This research project has been submitted in partial fulfilment of the examination requirements with my approval as the University of Nairobi supervisor.

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To

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ACRONYMS

2D	Two Dimension
3D	Three Dimension
ADA	Altimetric Descent Algorithm
DEM	Digital Elevation Model
DRC	Democratic Republic of Congo
DZ	Depression Zone
FAO	Food and Agriculture Organization
FZ	Flat Zone
GIS	Geographic Information System
GPS	Global Positioning System
HRU	Hydrologic Response Unit
IDM	Inverse Distance Method
IFSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
LMSA	Local Minima Search Algorithm
LULC	Land Use/LandCover
OCHA	Office for the Coordination of Humanitarian Affairs
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tools
TIN	Triangular Irregular Networks
UN	United Nations
USDA	United States Department of Agriculture

ABSTRACT

The issue of natural hazard in general and flood in particular is a topical problem that marks a memorable action in the world and specifically in Democratic Republic of Congo, especially with regard to the latest catastrophic floods. In January 2017, the city of Kinshasa was flooded by a six-meter water-rise (a secular event) that left 48 dead and nearly 500 families displaced for about two weeks. This research aimed to locate the areas that are exposed to inundation within the city of Kinshasa. Indeed, the management of this risk is becoming more and more a necessity which must include all the actors.

In this report, the mapping of flood hazard areas has been exposed by a hydrological modelling approach through the example of the N'djili river which currently inundate the city of Kinshasa. The basin of the N'djili River is an area that by its topography and anthropogenic activities have caused it to be exposed to the hazard of flood.

This research project was carried out by a supporting contribution of geographic information system (ArcSWAT, ArcScene and ArcMap). ArcSWAT helped us to analyse the various factors such soils, land use and landcover, that influence flooding in the N'djili River catchment. The change in land use along the river is a triggering factor for the flooding process within the city. ArcScene allowed us to do a 3D simulation based on a secular and a quinquennial flood. By this we calibrated our simulations on these two different water levers corresponding to the floods taken into account, which gave us two risk zones (high and low risk). ArcMap is a component of ArcGIS that allowed us to represent our research findings in terms of maps.

This mapping appears to be one of the most effective ways to understand the link between the change on land-use/landcover and the hazards of flooding. It can serve as a basic document for the public authorities to define rules that can contribute to a better management of the city (for instance, the delineation of riverbeds can give an idea on the floodplains, the areas at high risk of inundation, these kinds of information can be useful for urban planners). The mapping of flood hazard zones is a way of alerting the population on the risks of inundation and areas likely to be flooded. It is also a planning tool for decision makers who are not necessarily technicians, and to whom come the final decision on the flood risk strategies.

CHAPTER ONE

1.0. INTRODUCTION

1.1. Background of the Study

Population growth, poverty, rapid and often uncontrolled urbanization are major factors of environment degradation in Africa (Beaujeu-Garnier *et al.*, 1963). Deterioration of the physical state of the globe is accelerating and there is no sign of a reversal of trends in the foreseeable future.

In 1981, experts estimated the world population at 4492 million with a growth rate of 1.7% per annum (Ramade, 1982) and 5.2 billion in 1991 (Sheila, 1995). Calculations thus indicate an average increase of about 5 million people per month (Riou, 1981). The estimates for the years 2025 and 2100 are respectively 8.5 billion and 10 billion (Wilches - Chaux, 1995). It is thought that 95% of population growth will occur in developing regions where resources have already reached their limits. For Africa, the projections indicated 587 million inhabitants in 1990, 768 million for the year 2000, 1.5 billion in 2030 and 3 billion in 2100 (World Bank, 1992). Currently, the African population accounts for only 10% of the world's population. However, its average annual growth rate is very high and represents 3% against agricultural growth of barely 1%. For the Democratic Republic of Congo, estimates indicate 78 million inhabitants {Anonymous, 2010}. The average density of the population is 29 inhabitants per km2 spread over a territory of 2,345,000 km^2.

This growing population is increasingly concentrated in cities that are growing at an exponential rate under the combined effect of natural growth and migratory phenomena. The strong appeal of cities in rural areas can be explained by the fact that urbanization is related to social and economic growth, the development of education, the increase in overall health conditions and accessibility to social services, culture or politics (UN, 1970). From 1990 to 1995, the world's urban population increased from 29% to 45% (Besse, 1998). The annual growth rate of the urban population is indicative of this dynamic: from 1950 to 1975, it rose to 3.3% in the world, 4% in the third world in general and 5% in Africa (Besse, 1998). In the Democratic Republic of Congo, the urban population is 40% with a growth rate of 7 to 8% {Anonymous, 2010} or 30,200,000 inhabitants of which one third reside in Kinshasa. Ngondo *et al* (1992) estimated the growth rate of the urban population of Kinshasa at 6.3% against 3.3% for the whole country.

Overcrowding coupled with insufficient resources and a lack of strong political will is the root of very serious problems in all areas: unemployment, increasing the number of homeless, proliferation of unplanned urbanization settlement, growth in poverty and expand gap among social classes, increase in insecurity, alienation of properties, infrastructure and service, inadequate land cover, catastrophic or dramatic erosions, saturation in transport sector, increased pollution, especially of water, shortage of green space and increased susceptibility to disasters and especially the regular occurrence of major disasters repeatedly such as floods and silting.

Kinshasa is an example of a tropical urban ecosystem facing complex problems. These are numerous and diverse as to their respective causes, of which poverty, explosive and uncontrolled population growth remain the most important.

The watershed of the N'djili River does not escape this sad reality. Explosive population growth, poverty and housing problems are the basis of a multifaceted and acute ecological crisis observed within this area. This results in heavy pressure on resources, particularly on land, resulting in an illegal and irrational occupation of all apparently available spaces including very critical marginal areas (river beds, flood zone and sensitive areas with steep slopes susceptible to erosion). Today, it is the part of Kinshasa that is threatened by more natural disasters: erosion, flooding, silting... Researchers have begun to look at different environmental, social, economic and even geological aspects of this part of the city. Unfortunately, the studies carried out to date are characterized by a very general approach which does not make it possible to apprehend the various problems as a whole and in their interrelations. This work is one of the first test of a systemic study applied to this watershed, which is of great importance for the city development, especially in a hydrological approach.

1.2. Statement of the Research Problem

River beds have always been coveted areas for their physical attractions, accessibility, and resources. Despite government policies aimed at protecting riparian ecosystems, these areas still subject to numerous anthropogenic pressures. The gradual occupation of the floodplains in recent decades has made them vulnerable for local populations and various infrastructures found there. In the context that floods are a major issue for the municipalities affected by this phenomenon, it becomes important to analyse in detail the risk zones in various sectors (urban, agricultural, etc.) subject to periodic floods. At the same time, natural or semi-natural areas along the river, more or less affected by human activities, are also vulnerable to the impacts of floods. For instance, it becomes interesting to delimit the extent of water bodies during major floods in order to assess sediment inputs along floodplains and better understand the fluvial dynamics associated with periodic floods.

In Democratic Republic of Congo, the N'djili River frequently overflows, due to steep slope and change on land use. Its basin is a system comprising two distinctly differentiated subsystems, it has its source in the rural area of Kongo-Central and flows through the urban part of Kinshasa. The rural or provincial part still has a certain vegetation cover which ensures the protection of the watershed despite the numerous attacks due to human activities, but the urban part, on the other hand, undergoes a very strong anthropic pressure as a result of the systematic occupation of all available spaces including critical areas and marginal lands which cause a certain rise of water that are sometimes disastrous and difficult to control. Population growth and lack of good urbanization policies in Kinshasa have caused the river to become a source of flooding within the city, people have built in floodplain and others flood-prone areas.

According to the Waterways Authority, observations on the water level in the port of Kinshasa indicate that the secular flood can exceed 5.9 meters, all the half-centuries 5.55 meters, every 25 years 5.25 meters, the decadal 4.9 meters, and the quinquennial 4.71 meters.

Flood management has to be a strategic requirement and each country should have a flood management plan and strategy. A good flood management plan and strategy, is subjected to several challenges that must be addressed in its process, such as securing lives, controlling rapid urbanization and effect of the change in climate on the water cycle. A quick and effective response to flood management and control would be first to identify areas that are the most exposed to inundation. Thus, we can even predict an upcoming flood or intervene more easily when we face it. In the plain of the N’djili river, one of the most flood prone regions of the city of Kinshasa, it has never been established a flood cartography that can facilitate interventions in case of overflowing or shows the areas likely to be flooded in times of any heavy rainfall, making river overflows its beds to cover areas not usually occupied by water. Intervention and prevention services should have tools that can enable them to intervene quickly or warn residents about the danger they could face in terms of urbanization. Unfortunately, it is a flood management handicap within the watershed of the N’djili river and it is one of multiple reasons that slow down the prevention and intervention processes in time of need. As we know, floods are likely to have potential negative consequences for health of human beings, environment and property, including recreational and economic activity. The vulnerability of a population is caused in particular by a location in a floodplain.

Flood management requires forecasting tools that can identify areas which may be flooded from observed (or expected) rainfall information and generate alerts, either punctually or spatially. Its tools are developed in order to support alert services. Among all these forecasting tools, mapping of flood hazard area is very important insofar as it allows us not only to have an eye on the river beds but also to assist the authorities in charge of urbanization to better do their work, especially in the context of protecting people and their property. It is in this perspective that our work will try to evaluate the possibilities of mapping the flood areas in the basin of the N'djili River based on Geographic Information System model.

Thus, this flood hazard mapping will offer as specific support for the optimization of emergency planning and implementation procedures aimed at reducing the impact of an on-going inundation on the population. Flood mapping is also of great benefit to riparian areas that are periodically affected by floods, as it can help reduce vulnerability or at least help in improving preparedness.

1.3. Research Question

In this study, each step in the methodology will be guided by the following questions:

- Does the use of geographic information system and remote sensing model improve the assessment of flood?
- What is the influence of spatial analysis on classification accuracy?
- How helpful is the study to the society?

1.4. Objectives of the Study

The key purpose of this research is to locate the flood hazard areas within the watershed of the N'djili river. In order to meet the main objective just stated, the following specific objectives have to be carried out:

(a) Delineation of the watershed of the N'djili river;

(b) Establishment of a hydrological study based on the catchment rainfall-runoff model;

(c) Inundation simulation model based on the water levels;

(d) Mapping of flood hazard areas.

1.5. Hypothesis of the Study

Null hypothesis

H_0: *There is no high risk of flooding during rainy season in low elevation areas under contour lines 350 metres on both side of the N'djili River and its tributaries.*

Alternative hypothesis

H_1: *There is high risk of flooding during rainy season in low elevation areas under contour lines 350 metres on both side of the N'djili River and its tributaries.*

1.6. Study Justification

The need for decision support tools for the assessment of major risks is no longer in doubt among planning officials, technicians or decision-makers. The increasingly common use of cartography, particularly in the field of natural hazards, seems to confirm this trend. In the field of so-called "natural" risks, synthetic cartography, synthetic mapping, which is expected to be associated with techniques such as computer science and remote sensing, is likely to draw attention to the risk itself, but also to anthropogenic attenuation factors, or more generally, aggravation of this risk, whatever it is (floods, movements of ground, avalanches snow, even earthquakes).

In urbanized areas, it is certain that these elements are particularly important, insofar as many people are concerned, especially because actors and victims of the aggravation of these natural risks are often the inhabitants themselves, particularly in developing countries. Even more than the consideration of the hazard itself, it is rather the forecasting methods which are being questioned, through the uncontrolled spatial growth of urban agglomerations and, correlatively, the modification of the natural balance such as: waterproofing of land, reduction or disappearance of water retention areas, modification of the profile along or across the watercourses, etc.

Flooding is one of the costliest causes of damage to property around the world as well as in several cities in our country, and the situation is steadily deteriorating due to change in climate, rapid demographic growth and settlement. This new tool will help authorities and companies in their decision-making. This watershed map of flood hazard will be a new, unique, reliable and consistent tool for quickly determining flood hazard at certain sites. This watershed assessment of flood hazards is based on physical data. It uses hydrological and hydraulic models and takes into account information such as flow accumulation, precipitation, land cover, geology, slope and topography.

Geographic Information System models allow us to develop a scientific tool that identifies areas exposed to flooding, even in areas where very little information was available at that time. Intuitive and easy to use, the map makes it possible to quickly determine if an installation is in a flood zone by entering the address (georeferenced) of the site to be analysed.

1.7. Scope and Limitation of the Study

The focus of this study is on the evaluation of flood hazard areas, and how to map them in a given watershed. To achieve the intended goal, this research is focused on how Geographic Information System and Remote Sensing can be used in order to predict and assess the magnitude of an inundation with limited data. The findings of this work will be useful to policy makers in sustainable settlement planning and flood management and mitigation. Primary data will be collected at weather stations located within the study area, followed by geospatial data on the terrain topography (DEM).

Due to the vastness of the country coupled with the financial and the time constraint, the research was confined to a limited area, the watershed of the N'djili River located in Kinshasa, the capital of the D. R. of Congo.

1.8. Operational Definition

Flood/inundation: it's an overflow of a large amount of water beyond its normal limits, especially over what is normally dry land.

Hazard: it's any agent that can cause harm or damage to humans, property, or the environment.

Risk: it can be defined as the probability that exposure to a hazard will lead to a negative consequence.

Map: it's a symbolic representation of selected characteristics of a place, usually drawn on a flat surface.

Flood hazard map: it's a map that contains details about the likelihood and/or magnitude occurrence of inundation.

Flood risk map: a flood hazard map can be converted into a flood risk map by adding some additional details about the damage (e.g. economical damage, housing, etc.).

Floodplains: there are land areas across a stream that can be subjected to flooding.

Watershed/catchment/basin: It is a geographic space drained by a watercourse and its tributaries.

Outlet: it refers to the lowest point of a river system.

Inlet: it's the entered point of a river system.

CHAPTER TWO

2.0. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

2.1. Introduction

In Democratic Republic of Congo and the rest of the world, floods have become a scourge in recent years, becoming more frequent and devastating. Even though Metelsat-Kinshasa has weather observation as well as 5- or 7-days forecasting models, precipitation is the most difficult weather variable to predict, it is difficult to accurately quantify the precipitation that falls on ground and locate the areas that will be most affected. In addition, there are no flood warning services that should be used to monitor the waterways in their geographical area (Ngondo *et al*, 1992).

The goal of flood hazard assessment is to determine the probability that a flood of a given intensity can arise over a long duration of time. The purpose of this assessment is to estimate this likelihood over so many years or decades so as the risk management activities can be reinforced. Intensity can be defined as the combination of depth and horizontal extent of the flood; however, there are other intensity measures that may be considered regarding the situation such as flow velocity and flood duration.

2.2. Inundation: an overview

Etymology: The word “inundation” comes from the Latin: “inundatio” which means submersion.

It can then be said that an inundation is a rapid or a slow flooding of an inhabited area usually out of water. Thus, the risk of flooding is the consequence of two components: the water that can overflow from its usual flow bed and/or man who settles in the alluvial space. The importance of an inundation depends on the water level, the speed of the current and its duration. These parameters are conditioned by rainfall, the state of the catchment and the characteristics of the watercourse (depth, width, etc.). These natural features may be aggravated by human activities (Cortes 2006, Merabet 2006).

2.2.1. Main Parameters Specifying "Flood Hazard"

Four main parameters are needed to characterize a flood hazard:

(a) Return Period (T): The notion of return period "T" is only another way of characterizing the frequency of occurrence of a phenomenon at a given moment. Statistically, it is defined as the inverse of the probability of occurrence "P" overrun of this phenomenon; T=1/P. A phenomenon with a return period of one hundred years (centennial phenomenon) has a one in hundred chance to occur or to be exceeded each year. This is verified if you consider a long period of time. But it can also, for short periods (a few years), repeat itself several times. In other words, in twenty years, an individual has a one in five chance of experiencing the hundred-year flood.

The notion of a flood is often associated with the notion of a return period (decadal, centennial, millennial flood, etc.). The longer this period is, the greater the flow and the intensity. The events most represented on the hazard map are the quinquennial flood (Q_5) and the secular flood (Q_{100}) (Merabet 2006).

(b) Height and Duration of Submersion: The submergence height can have a significant impact on the frame, especially when it exceeds the reference dimension. When the duration of submersion is important, health problems can arise, the water being often dirty, contaminated by the sewers or sometimes the oil escaped from the vats (Merabet 2006). For humans, water depths above 50 cm are generally considered to be dangerous. For example, a car starts to float from 30 cm of water.

(c) Flow Velocity: The flow velocity is conditioned by the slope of the bed and its roughness, the risk in case of flow depends on the height-velocity pair. For example, from 1m/s, the velocity of current becomes dangerous for humans, with a risk of being carried away by a watercourse or being injured by objects thrown into the watercourse at high speed (Merabet 2006).

(d) Volume of sediment: This volume is commonly called "*solid transportation*". These are materials (clays, silts, sands, gravel, pebbles, blocks, etc.) found in watercourses and which can be transported either by suspension in water or by displacement on bottom of a river bed, because of forces related to the current. The flood hazard of a torrential river will be essentially characterized by a high current speed and a strong solid transport (Merabet 2006).

2.2.2. Type of Floods

Depending on the event creating the disaster, we can distinguish several types of flood: floodplain inundation, flood by rising of water tables, torrential floods, flood due to runoff in urban or rural areas, flooding due to dam failure and marine flooding.

In the first four cases, the generating phenomenon is the rainfall, flood will start from the rivers. The classification consists in distinguishing if the inundations are caused by slow kinematics (floods of plain, rising of water table), or from those generated by with fast kinematics (torrential floods, runoff flood). While in the last two cases; the first generated by local circumstances that play to make a flood on a given sector due to a catastrophic event and the second is a result of an action of sea, that is the main factor determining the occurrence of disorders (Ledoux 2006).

2.3. Flood Hazard Mapping Tools

Three categories of tools allow the mapping of the flood hazard when it is in progress. These are field surveys, hydraulic modelling and remote sensing. However, despite their respective advantages, some of these tools have significant limitations, which reduce their interest in characterizing the flood hazard in a crisis management context.

2.3.1. Field Surveys

The acquisition of data directly in the field is a method widely used for the study of spatial and environmental phenomena, but is not adapted to the characterization of flood hazard in crisis management. Indeed, the spatial sampling carried out in the field is often low and poorly distributed, which makes it impossible to obtain precise information on the limits of the flooded areas and on the submersion heights at any point in these areas (Townsend and Walsh, 1998). In addition, there are often logistical problems of access to flooded areas and high data acquisition costs (Hess *et al*., 1995, Lang *et al*., 2008). Finally, and this is an important limitation, the time required to acquire data on the area, to process them and then to produce a map of the flood hazard is often too long to be adapted to the phase of crisis management, especially when the extent of affected areas is important.

2.3.2. Hydrological Modelling

Hydrological models are used mainly to predict flood extents corresponding to different return periods in a given territory. While the hydraulic models have the main attraction to numerically simulate hypothetical or real flood which allows to characterize the hazard in space and time (water level, flow rate, submersion time). They thus make it possible to predict the potential consequences of a flood and to provide information that is very useful to decision-makers, both in a crisis context and for forecasting and prevention. In addition, they need real flood observations to get rid of the real river, confirm the hypotheses and validate the numerical simulation (Hostache 2006).

Hydrological modelling is used to numerically simulate and predict the spatio-temporal evolution of the hydrological characteristics of a river during a flood, such as flow, water depth, flooded surfaces or velocities. water (Hostache *et al.*, 2005). It is a widely used tool for flood management, both for flood forecasting and for prevention and crisis management. Hydrological models, however, remain a schematic representation of a complex real system and require the understanding and integration of each process of the water cycle, using specific data (Estupina, 2004). This represents a large volume of data, which can sometimes be difficult and expensive to obtain because of an unavoidable lack of measurement stations, both in rural and urban areas (Mason *et al.*, 2012). In fact, data from remote sensing are sometimes used during the calibration and validation phases of hydrological models (Giustarini *et al.*, 2011).

2.3.3. Remote Sensing

According to Raclot 2003, remote sensing is defined as the set of knowledge and techniques used to determine the physical and biological characteristics of objects by measurements from a distance without physical contact with them. Cameras are the oldest and most widely used sensors in aerial remote sensing to map flood risk. However, they have undergone a very marked advance over time. In fact, to the traditional campaigns of systematic coverage by aerial photographs are added more and more commercial offers allowing to choose the type of sensors (aerial photography, scanner, laser, etc.) and the type of platforms (planes, helicopters, etc.).

Different remote sensing tools can be used to characterize the flood hazard. Aerial photography, which provides high resolution images of the flooded area, is considered a source of quality data for the delineation and analysis of flooded areas (Schumann *et al.*, 2009). However, its use for the generation of flood hazard maps is often limited by the high cost of airborne acquisitions and the time required for data acquisition, which is often too long when flooding is extensive (Mallinis *et al.*, 2011). To this can be added weather conditions preventing overflight of the flooded area and finally the difficulties of detection of the flooded areas under a dense canopy or through a thick cloud cover

Satellite optical sensors operating in the visible and infrared rang (from 0.4 µm to 100 µm) have improved access to data needed for flood mapping at a lower cost than aerial photography (Brivio *et al.*, 2002). The very high spatial resolution of the order of one meter by the most recent sensors (Ikonos, WorldView, Geoeye, etc.) now allows the precise identification of the water line and flooded urban and sub-urban objects. This is an interesting advance compared to older optical sensors (Spot, Landsat, etc.) whose spatial resolution is or was often of the order of several ten meters (Van der Sande *et al*., 2003). However, the acquisition of quality data is often greatly reduced by the presence of recurrent cloud cover during floods, with wavelengths of visible and infrared unable to penetrate clouds (Horritt *et al.*, 2003). Optical imaging also fails to detect flooded areas under dense vegetation cover, which excludes some of the information sought in some areas (Hess *et al.*, 1995, Sanyal and Lu, 2004).

2.3.4. Hazard Map

The creation of the vulnerability map is very often limited to a cartography based on a distinction of the different land use modes according to their greater or less tolerance to floods. Two main types of problem can be identified: the zonal approach and the entity-by-property approach. The first is to map the floodplain according to a typology of land use and then to assign to each homogeneous area an average density of goods. The second, less common approach is to identify each issue. It is rather well adapted for the weakly urbanized areas and for the small territories (Ledoux 2006).

2.4. GIS in Flood Hazard Mapping

2.4.1. Definition of GIS

It is a geographically located set of digital data structured within a computer processing system that includes hardware, software, and processes designed to allow, from a variety of sources, to gather, combine, analyse, model, manage, develop and represent the database according to semantic and spatial criteria in order to solve a complex problem (Zerouali 2005).

2.4.2. Flood Hazard Cartography

Cartography of flood hazard is a key element of the proper organisation of land use in areas susceptible (in regions vulnerable to flooding) to flooding. It creates tables and maps easy to read and quickly accessible to smooth the estimation of flood-prone regions and help the mitigation and corrective measures to be prioritised (Bapulu, 2005). Urban planner may use flood maps to determine if an area is exposed to floods.

Inundation cartography is designed to create an awareness of a likely overflowing to the habitants, NGOs, local authorities, etc. They push those who live and work in flooding regions to understand the risk of regional inundation and to undertake necessary measures. It is capital to understand that the change in climate requires to be cautiously taken into account regarding of the risk of inundation. Mapping the flood hazard usually anticipates a" snapshot" of the risk of flooding at a specific period of time. However, it is useful to consider the variation in nature of flood risk concerning the effects of climate change.

Nowadays, Geographic Information Systems (GIS) are extremely utilize to map inundation risk areas. According to Sanyal *et al*, (2003), GIS is a successful way to gather data from various cartography and Digital Elevation Model (DEM). By using Geographic Information Systems, flood extent may be delineated by contrasting local altitudes to ultimate water depth through rainfall-runoff model.

2.4.3. Digital Elevation Model

GIS provide excellent tools for analysing and displaying spatial information (Pitman, 2003) and at the same time reducing working time. Geographic information systems are often used either to create a digital elevation model (DEM) or to integrate variables into a hydrological model, for example. More precisely, their contribution to the creation of DEM becomes almost inevitable. Remain that a digital elevation model can be defined as a "representation of the topography of the Earth in a digital format, that is to say by means of coordinates and numerical descriptions of the altitude". Relief is a determining factor for many environmental phenomena and processes. In order to represent the relief and thus better understand the natural phenomena and processes that surround us, representations of topography in the form of digital elevation models are, since the mid-1980s, increasingly used. DEM is now almost always done using a Geographic Information System. Indeed, GIS allows the rapid creation of DEM since they integrate a large amount of data. DEM can be used, among other things, for road planning, for military applications, for hydrological modelling, for flood mapping, etc. With the progress in research on DEM, the quality of topographic representation achieved has become a major concern. It is not enough to simply represent the topography, but this representation must be as faithful as possible to the reality on the ground, and this correspondence between the terrain and the representation performed must also be able to be evaluated. The realization of a DEM can be done from many software and requires the choice and use of different variables. It is therefore essential for researchers to compare the different choices available to them. In addition, the quality of DEM is based on many factors that are important to know and master before a topographic matrix is made.

2.4.4. Factors Influencing the Quality of DEM

In order to obtain elevation values for all locations of the analysed surface, an interpolation of the known values is required. Interpolation using a GIS allows the creation of a continuous surface from sampled point values. Indeed, collecting data from anywhere in a territory is difficult and expensive, so interpolation is useful because it provides values at unsampled locations (McCoy and Johnston, 2001). The use of this technique is possible because the elements distributed in space are also spatially correlated. There are different types of interpolations each with their own particularities and therefore, more appropriate for certain situations and types of data. Inverse distance weighting (IDW), spline, and triangular irregular networks (TIN) are types of interpolation often used in geomatics and for the representation of relief (Chaplot *et al.,* 2006).

The inverse distance method (IDW) is based on a basic principle in geography in which the elements brought closer to each other are more similar. It is a deterministic weighted average method by which values are estimated by averaging the values of sampled points in the neighbourhood. Thus, the closer a point is to the value to be estimated, the more influence or weight it has in the interpolation process (McCoy and Johnston, 2001). However, this method may have drawbacks, such as the creation of "ox-bull", that is to say circles around certain values, and also the limitation of the interpolated values to the interval of sampled values (Arnaud and Emery, 2000).

The spline function, on the other hand, estimates the values using a mathematical function that minimizes the overall curvature of the surface giving a smooth surface passing exactly or very close to the sampled points (McCoy and Johnston, 2001). The interpolation splines pass exactly through the sampled points, while the smoothing splines pass close to them. With this method, however, the estimated values may be lower or higher than the sampled values (Arnaud and Emery, 2000).

Finally, another interpolation method mentioned above is that of the Triangulated Irregular Network (TIN). It consists of subdividing the geographical space into triangles and then interpolating at each place, by a weighted linear combination, neighbouring values (Arnaud and Emery, 2000). The TIN represents a surface composed of a set of contiguous but non-overlapping triangles. The main advantage of TINs is that they incorporate the original sample points, that is, the sampled points keep their position in the model, thus preserving the accuracy of the input data. Also, TINs are effective in interpolating elevation data irregularly distributed in space (Pedrini, 2001). However, this interpolation method is less efficient when there is little sampled data. TIN is the most commonly used interpolation method (Bates and De Roo 2000, Dempsey *et al.*, 2000, Lang and Erickson 2003, Marks and Bates 2000, Wise 2000). Finally, another interpolation method mentioned above is that of the Triangulated Irregular Network (TIN). It consists of subdividing the geographical space into triangles and then interpolating at each place, by a weighted linear combination, neighbouring values (Arnaud and Emery, 2000). The TIN represents a surface composed of a set of contiguous but non-overlapping triangles. The main advantage of TINs is that they incorporate the original sample points, that is, the sampled points keep their position in the model, thus preserving the accuracy of the input data. Also, TINs are effective in interpolating elevation data irregularly distributed in space (Pedrini, 2001). However, this interpolation method is less efficient when there is little sampled data. TIN is the most commonly used interpolation method (Bates and De Roo 2000, Dempsey *et al.*, 2000, Lang and Erickson 2003, Marks and Bates 2000, Wise 2000).

In light of the different comparisons made between the interpolation methods, none of them consistently outperforms the others. They each have their advantages depending on the type of data, their distribution, the scale of the phenomenon studied, the characteristics of the terrain, etc. In many cases, it is best to test the different methods before making a final choice. However, the realization of a numerical model of elevation does not depend only on the interpolation method used, as it might seem at first glance. Indeed, as mentioned by MacEachren and Davidson (1987), the accuracy of the estimated values depends on five interrelated factors. The first factor is the accuracy of the measured values. "There are different methods and instruments for obtaining topographic information such as curves level, aerial photographs, satellite images, LIDAR, IFSAR, GPS, total station, etc. These different methods and instruments make it possible to obtain topographic information of variable precision. The total station, for example, provides millimetre-accurate data, while LiDAR provides elevation data of about 15 cm accuracy, while the use of curves level usually implies a precision beyond the meter. The accuracy of the basic data will obviously affect the accuracy of the estimated values. If the accuracy of the basic values is 15 cm, it will be impossible to provide estimated values with a precision greater than 15 cm. In addition, the extent of the study area also varies according to the methods of data collection, some instruments provide highly accurate data, however the territory they cover is much smaller.

The second factor influencing the accuracy of a DEM is the "intensity" of the data or the size of the sample. For MacEachren and Davidson (1987), data intensity is the most important factor in the accuracy of the estimates. The size of the sample would be larger in the estimation of intermediate values than the location of the sampled points and the interpolation methods. Indeed, the precision of the estimated values can vary with the intensity of the sampling since it determines the proximity of the sampled points. The accuracy of the estimated values is therefore inversely related to the distance between the sampled points and positively related to the density of the data. As shown by MacEachren and Davidson (1987), the precision of the estimates increases at a decreasing rate with increasing sample size.

The third factor is the location of the sampled data. Depending on the method and instrument used in the data collection, the sampling pattern may be different. There are, indeed, different models of elevation data collection. The data can be sampled in a totally random (independent) way, along transects, or in a non-independent way by taking points in particular areas of the territory such as a slope break, hollows or vertices. These different sampling models make it possible to distribute the sampled points differently, which may have an effect on the estimates. Several studies have been conducted using these models (Ayeni 1982, Peucker 1979) and there is no consensus on the use of an independent or specific (non-independent) sample.

Finally, the fourth factor concerns the variability of the surface represented by the spatial autocorrelation and the magnitude of change of the surface per unit of distance. In fact, the different terrains have an influence on the estimation of the data because of the variation of their topographic surface. For example, in some places topographic variations may be important over short distances, while elsewhere variations are minimal. These variations can greatly influence the accuracy of the estimated values. Therefore, it is very difficult to establish which is the most appropriate interpolation method. In several works, the effects of different terrains are compared with interpolation methods. Generally, uncertainty tends to cluster in hilly places where elevation changes rapidly (Weng, 2002). This is why rugged terrain usually requires a larger number of sampling points to adequately represent these topographic variations. Although some studies have shown that interpolation methods are not the most influential factor in DEM accuracy, the fact remains that it is possible to make a wise choice to reduce the error of a DEM and thus improve its quality.

2.5. Spatial Prediction of Flood Areas

The management of flood is usually composed of four different steps: predictions, planning based on those predictions, corrective actions and an evaluation of damage (Fosu, 2009). According to Youssef *et al.* (2016), evolution geographic information system and remote sensiong have forged the management of flood mitigation in order to smooth the execution of every step. Different analyses can be performed before, during and after the flood. New self-operating or prediction methods have taken into account to assess flood models and demonstrated the effectiveness results (Hostache *et al.* 2013). Thus, the risks of inundation and susceptible flooded regions can be forecasted.

Several methods have been developed over the years for the application of the flood susceptibility mapping. SWAT model has been used to assess inundation and forecasting (Jayakrishnan *et al.* 2005). This hydrological model is incorporated with geographic information system and remote sensing to gather information and to analyse spatial parameters.

The effects on properties can be categorized into both direct and indirect effects. For instance, inundation can immediately harm infrastructure segments such as electricity substations or railway links. Study on the susceptibility of infrastructure relatively restricted even though there is an increase of literature regarding this topic. The elements of infrastructure are generally extremely specialised while the infrastructure systems are complex.

2.6. Research Gaps

Ngongo *et al.* (1992) has worked on an environmental impact assessment caused by the N'djili river within the catchment, but his study was only based on a general point of view. He had just spread his study on the assessment of environmental damage. Floods and erosions were cited as major consequences of environmental degradation in cities. This study did not take into account each case in the neighbourhood in order to develop preventive methods in the long and short term.

This work notified that on ground in Kinshasa, the issue of flooding remains hypothetical. Crisis management teams are just focused on interventions in case of a water rise event but never in prevention because of a lack of information and tools that can facilitate them a quick response in case of an on-coming flood event. The rate of urban population growth still increasing but there has never been a tool that can guide people in term of soil occupation and conservation.

The mapping of flood zones from spatial analyses remains hypothetical in the countries of sub-Saharan Africa, hence the lack of literature on this subject. The use of GIS in urban and rural planning remains a challenge in the developing country, perhaps due to a lack of equipment, information or technology.

2.7. Conceptual Framework

According to Linsey (1997) each natural flood is influenced by five including:

- Meteorological elements: there are some examples of meteorological elements such as temperature, precipitation, evaporation, sunlight, breeze and so on;
- Soil information such as the type of soil, the hydraulic transmission, the filed volume;
- Topographical elements including the slope of the land surface, the profile of the longitudinal profile, the section of the river cross;
- The land use such as agricultural region, settlement region and land cover;
- Network elements.

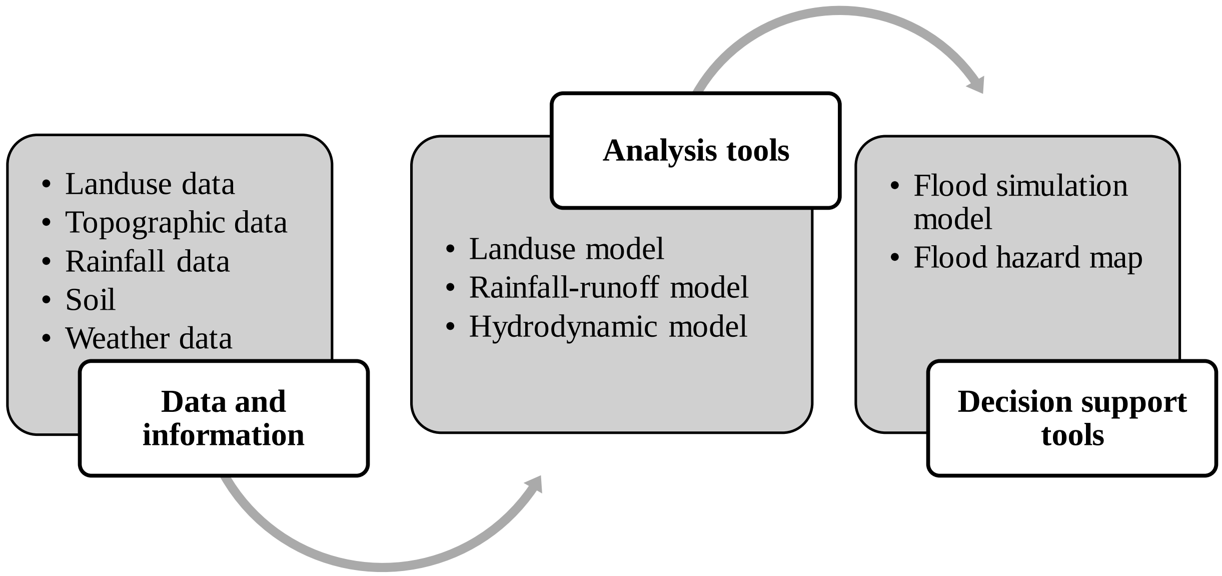

Figure 1: Conceptual framework

Source: Researcher

It is crucial to understand the land use and landcover since they are the consequence of high flood frequency and severity. There are some procedures such as decreased infiltration capacity, reduced evapotranspiration, forest opening, loss of vegetation, reduced porosity of soil. Probably the change in land use influences the floods since human beings have considerably altered the environment. The soil moisture and erosion have increased or reduced by the deforestation and drainage of large regions.

The elements of landscape have an effect on land use and drainage network components. For example, the agricultural area and the settlement regions are most of the time situated on low land surface slopes whereas the catchments of mountains possess sharp land surface slope and more shortened drainage system. The GIS rainfall-runoff model demonstrates the overall impact of changes of landscape on flood parameters.

The flood hydrograph is measured by the rainfall-runoff model. This model is dispersed and it is concretely based on a hydrological model for a durable isolated event simulation. The interrelation of rainfall-runoff model is usually employed as a mathematical approach in order to manage the planning of water resource, the prediction of flood and the alert schemes. The mechanism of developing a unit hydrograph was described by Sherman in 1932 and suggested that the unit hydrograph for watersheds should be 5000 km^2 or less.

The prediction of flood and modelling are the stages of modifying the rainfall into flood hydrograph and the transfer of that hydrograph through a watershed of any other hydrologic network.

A suitable flood evaluation plan relies on the effectiveness and quantity of the data and information gathered or accessible to conduct a particular study.

CHAPTER THREE

3.0. METHODOLOGY AND DATA ANALYSIS

3.1. Introduction

This chapter comprises the methodology applied in the study to achieve intended objectives. It thus includes the research design, presentation and analysis of data, area of study and study approaches/strategies.

3.2. Study Matrix

3.2.1. Geographic Location

The catchment area of the N'djili River extends from the Kongo-Central Province to the city of Kinshasa over an area of nearly 2,000 square kilometres between 15°9' and 15°39' east longitude and 4°22' and 4°59' South latitude. It is a complex system comprising two distinctly distinct sets:

- The upper course (rural areas) part of the Kasangulu and Madimba territories (District of Lukaya) located in Kongo-Central Province;
- The lower course (urban part) located in the city of Kinshasa.

The urban part of the N'djili River watershed, located in the city of Kinshasa, extends between 15°9'and 15°18' east longitude and 4°22' and 4°37' south latitude representing an area of about 625km^2, or 31.2% of the entire watershed.

The watershed of the N'djili River is a system comprising two distinctly differentiated subsystems, it has its source in the rural area of Lukaya (Kongo-Central) and flows through the urban part of Kinshasa (the potential flooded zone), the Congolese capital city which is the geographically deemed the largest in the whole country, with a population estimate beyond 12 million people over 9,965 km^2 area

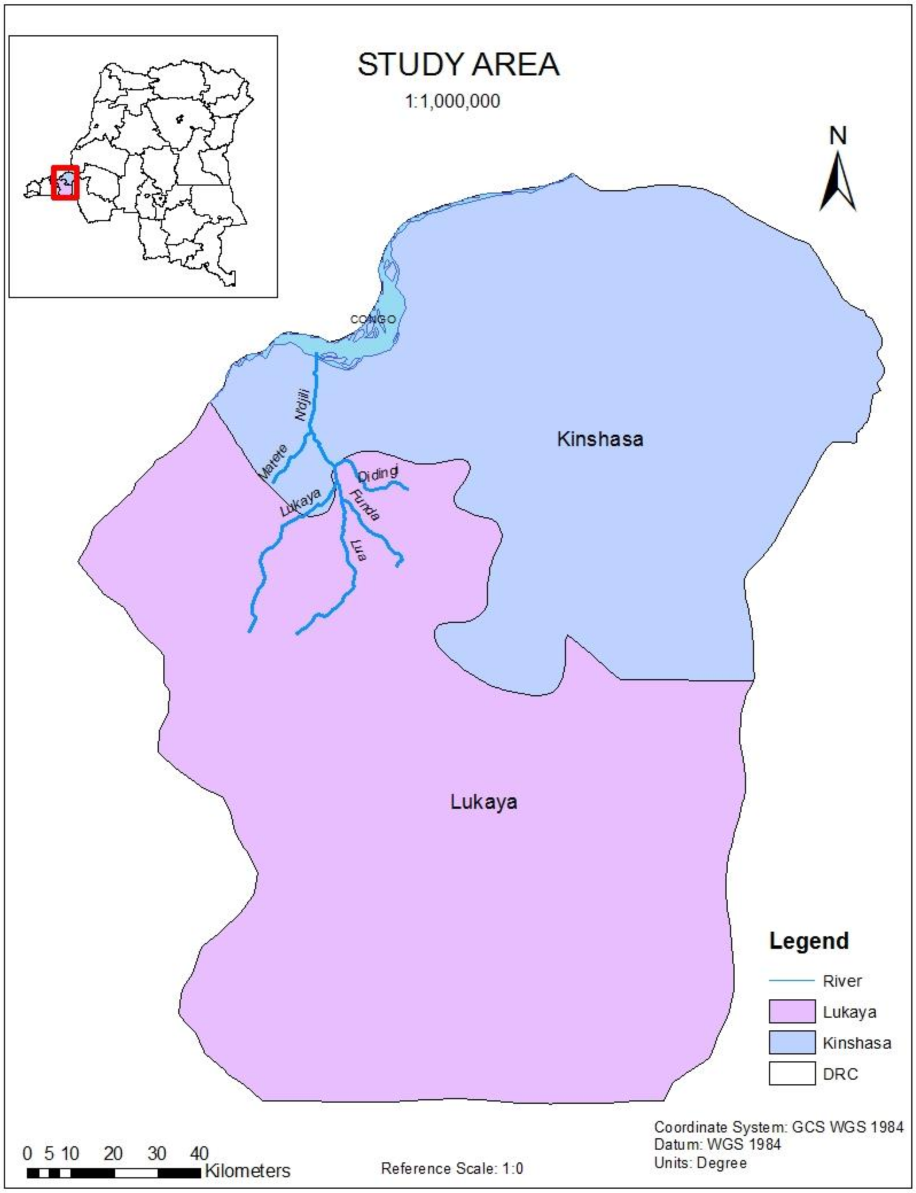

Figure 2: Study Area Map

Source: OCHA DRC/Administrative boundaries

3.2.2. Climate

Since our study zone is in the city of Kinshasa, I referred to its climate. The annual temperature variations in Kinshasa are about 13 degrees Celsius. Temperatures vary between 21°C and 30°C at dawn.

Kinshasa is located in a tropical climate zone, hot and humid. It is composed of a rainy season of 8 months and 4 months of dry season, that is to say, May to August. The rest of the year is relatively rainy especially around the months of December to March.

It rains on average 110 days a year with an average rainfall of 1500 mm/year. These precipitations are very disproportionate in their annual distribution with a rainy season concentrating 93 to 97 % and a dry season receiving only less than 10 % of total annual rainfall volume.

3.2.3. Wind

Winds play a major role in triggering rain. The urban part of the N'djili river watershed being located in the climatic context of Kinshasa, has the same wind regime as the whole of the city. Kinshasa is located near the marine current of Benguela and the influence of the pseudo monsoons of the Gulf of Guinea.

It is characterized by low winds south-westerly. Their speed rarely approaches 10 km/h. The average wind speed is 4 km/h in the rainy season and 5 km/h in the dry season. The normal direction of the winds observed at the wind vane at the Binza station is 250 to 270 °. Calms are the most frequent: more than 60% of the observations in the rainy season but the nights 50% of the observations in the dry season.

3.2.4. Hydrography

The city of Kinshasa is located on the banks of the Congo River. It is crossed by several local and local rivers, the most important of which are: Funa, Lukunga, Binza, Kalamu, N’djili and N'sele, although the N'sele has a basin of about 6.000 km² and N’djili a basin of almost 2,000 km², these two rivers are comparable.

The N'djili, almost 30 km long, is one of the tributaries of the Congo River. It has its source in the hills of the province of Bas-Congo and crosses the city of Kinshasa from South to North, and flows into the Congo River by a delta with anastomosed arms. Its course constitutes the boundary of separation between the city East and the rest of the city (Kinshasa-West, North, Center and South-West). It delimits with the N'sele river a part of the site called "*Plaine entre N'djili et N'sele*". Its beds are today colonized by the current city: one thus finds their dwellings, spaces occupied by market gardening and many farms for the breeding. In this respect, the economic role of the alluvial valleys of the hydrographic network N'djili river (valleys of Lukaya, Matete, Kwambila, Imbu river, Bimunsaka, Kimbasala ...) is very important. In addition, it can be noted that the N'djili Valley is a portion of the urban space of massive occupation.

The N'djili River marks deeply the sites where it is flowing. It flows and snakes in wide valleys of Kinshasa and thus plays an important role in the physiognomy and the economy of those areas (market gardening). Its mouth builds a delta where its alluviums mix with those of the Congo River.

Our study area is hydrographically characterized by the different erosional heads that surround it. It is one of the most vulnerable environments in case of erosions and floods in the capital.

3.2.5. Geomorphology

The topographic profile of the N'djili river watershed has two morphological groups:

(a) **Plain area:** It is located between 275 and 350 meters of average altitude (Luboya 2002). It extends to the north of the catchment area downstream and the N'djili outlet, going southward beyond the vicinity of Riflaert and N'djili Brasserie. There are lower areas, swamps and terraces that originate from rain erosion. To the east of N'djili, the alluvial terraces are presented as a succession of small compartments of some well-individualized square kilometres. In the West, the alluvial plain forms a single entity of about 70 square kilometres in area.

(b) **Hill area:** The hilly area extends upstream of the N'djili River beyond Riflaert, encompassing in some places the Kimbanseke Hills, from Kisenso to the vicinity of Dingi-Dingi. Slopes less than 12.5% are the most represented. However, slopes between 12.5% and 20% are found. Those of 20% and more are rare and clearly localized. In general, the slopes of over 20% and those associated with them are characterized by a phenomenon undermines the basis of catchment. This happens when the slope ends with an embankment. In this case, erosive activity is less when the foot of the slope is concave, and more intense when the foot of the slope is convex. This is the case of the eastern slope of Kisenso Hill.

The different landforms are result of erosive action caused by brutal runoff and heavy rain that attacked the soil since the late Cenozoic. Serious dangers threaten the lower reaches of the Kinshasa river basins, including the N'djili river basin. These are the erosions caused by the sudden runoff of the hills where they arise and of which they are the natural drains or hillsides that delimit their valleys. In the first case, these are the local rivers such as Makelele and Yolo, and in the second case they are the non-indigenous rivers represented by N'djili and N'sele. Their geological landscape has been shaped by weak rocks, composed mainly of soft sandstones and sands covered with a thick and easily removable weathering mantle. They shape topographic forms in the watershed resulting from slope and erosion in a poorly coherent material. As Kabala (1994) says, African soils are both poor and fragile for paedogenetic and climatic reasons. They are vulnerable and exposed to all forms of degradation: rain and wind erosion, physicochemical and biological degradation. The same is true of the N'djili river valley. However, it should be noted that the massive occupation of the N'djili, Lukaya and other major tributaries of the N'djili River has changed the natural physical properties of the watershed. This occupation has transformed the pedological context, the vegetation, the topography.

3.3. Research Design

The study design depicted that of a spatial analysis in answering any of the study questions. According to O'Sullivan et al. (2010), spatial analysis focus on the statistical analysis of patterns and underlying processes or more generally, spatial analysis addresses the question "what could have been the genesis of the observed spatial pattern?" It's an exploratory process whereby we attempt to quantify the observed pattern then explore the processes that may have generated the pattern. It aimed at identification of the areas exposed to flooding within the watershed of the N'djili River and the parameters that are taking into account in the inundation process.

This research was conducted through hydrological models and simulations in forecasting the level of flooding and its extent. The hydrological models were applied in this study by using remote sensing and geographic information systems since it provides specific and accurate responses; it also enhances explanations, counting there is also involvement of the collection of prediction, and phenomenon of interest is controllable since data presented is numeric.

3.4. Data Acquisition

The data used in a GIS are directly measured on ground (topographic surveys) or captured at distances (aerial or satellite photos) or entered from existing maps. Then, to integrate this heterogeneous data of quality, reliability, accuracy and spatial extension quite different in a GIS, different acquisition methods can occur (Zerouali 2005).

3.4.1. Digitization (Scan)

This mode is used to retrieve the geometry of objects on a pre-existing map. It consists of changing a cursor on a map placed on a digitizing table and previously calibrated in coordinates. The table is receptive to the electrical signals emitted by the cursor to locate them on the plane of the table. This method was used in the collection of geospatial data from the N'djili River in order to minimize scale errors.

3.4.2. Air Photogrammetry

This method is used to build medium-scale maps in countries with poor cartographic coverage or for large-scale mapping at a low cost.

3.4.3. Remote Sensing (Satellite Images)

This involves using either aerial photographs or recorded and transmitted satellite images; most often in digital form whose geometric processing also calculates the position of any point visible on the images (Zerouali 2005).

3.4.4. Import of Shapefile

This is a way to reduce the cost of data capture by retrieving existing data and converting it to the desired format, drive system, and projection system. For this, we use interfaces that allow to directly transform these data in the internal format of the GIS receiver through conversion libraries, or to go through an exchange format recognized by an import feature of the GIS data receiver.

It is through this method that we imported the Digital Elevation Model from the USGS site (Earth Explorer) and the data on soil, land use and landcover to those of FAO. At this stage of collecting digital data, it is important to pay attention to the format and coding of data. For example, soil, land use and landcover data is digitized in numerical form (represented by numbers).

3.5. Data Set

3.5.1. SRTM (Shuttle Radar Topography Mission) DEM of the Watershed

SRTM is a digital elevation model (DEM) provided by NASA with 30 meters resolution and vertical variable accuracy according to the continent. In February 2000, the spatial shuttle ENDEAVOR collected altimetry data using radar interferometry. This observation campaign allowed to establish numerous field models for nearly 80% of emerging lands. SRTM-DEM can be used for extraction of field parameters, plotting of topographic profiles, modelling of water flow or mass movement (e.g. for avalanches and landslides), creation of relief maps, etc.

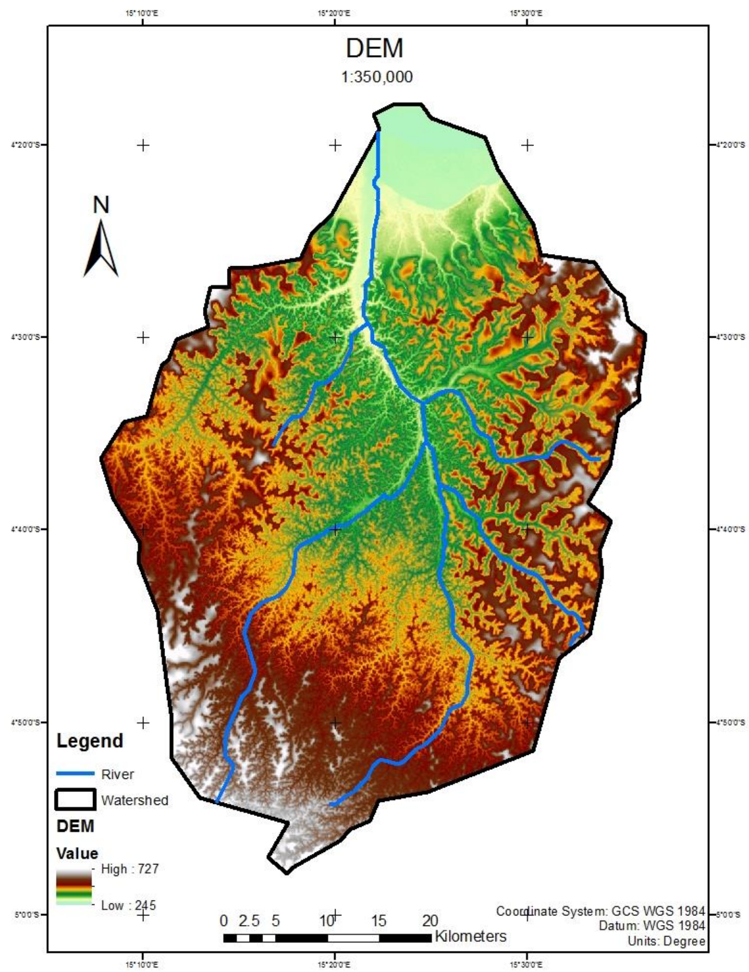

Figure 3: Digital Elevation Model of the Study Area
Source: Earth Explorer (SRTM)

3.5.2. Rainfall Data

SWAT software allows the integration of several weather stations in modelling. As a first step, the location of these stations, their altitude as well as the monthly average of each climatic parameter should be entered in the database. In a second step the daily data of these various parameters can be indicated during the simulation. In the case where some parameters would be missing, or a data gap period appears, SWAT allows to perform a simulation of these from the monthly data of references of the station. A weather station is available for the simulation, that of Kinshasa-BINZA (445 meter of altitude). Due to lack of information on daily rainfall data, we used the monthly rainfall data (attached in appendix).

3.5.3. Land Use and Landcover Data

Land use and landcover were spatialised from FAO's LULC classification. The spatial resolution is 1 km. The initial units have been reclassified within our watershed to constitute the following units:

- Rainfed croplands
- Mosaic Croplands/Vegetation
- Mosaic Vegetation/Croplands
- Semi-deciduous forest
- Closed broadleaved deciduous forest
- Open broadleaved deciduous forest
- Open needleleaved deciduous or evergreen forest
- Closed to open mixed broadleaved
- Mosaic Forest-Shrubland/Grassland
- Mosaic Grassland/Forest-Shrubland
- Closed to open shrubland
- Closed to open grassland
- Sparse vegetation
- Closed to open broadleaved forest regularly flooded (fresh-brackish water)
- Closed to open vegetation regularly flooded
- Bare areas
- Water bodies

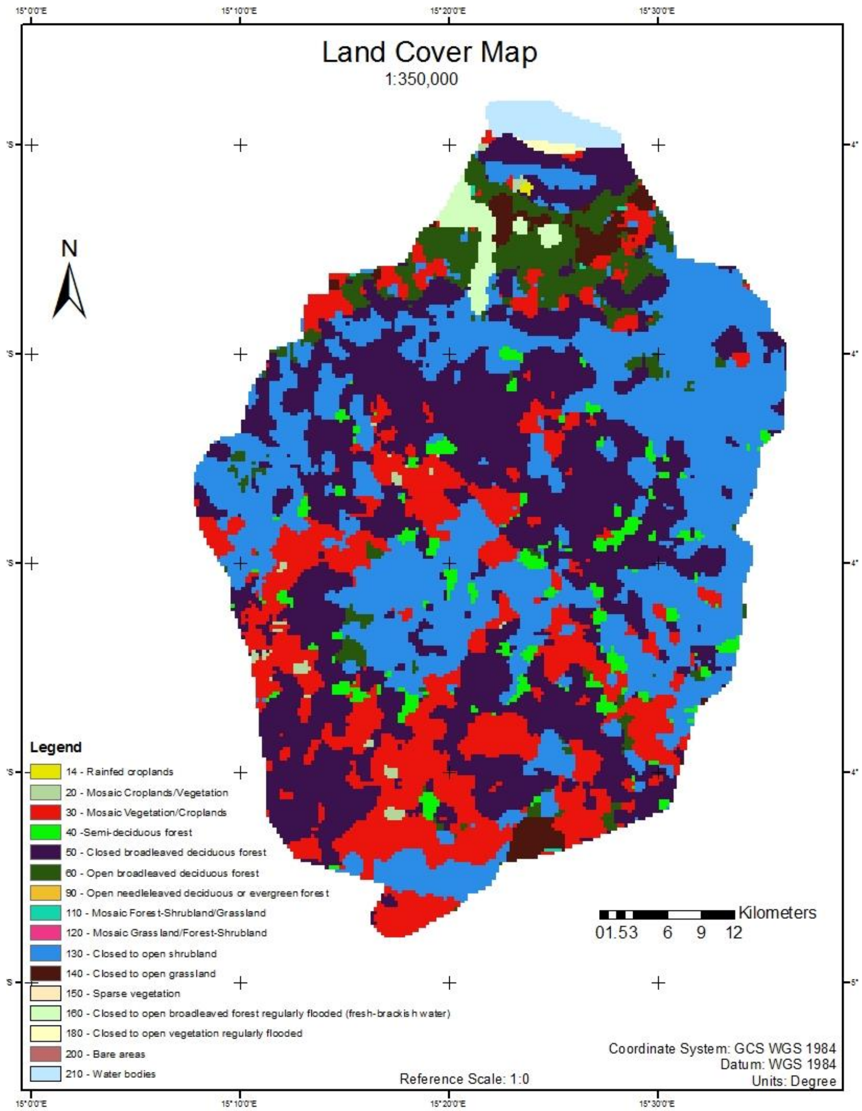

Figure 4: Land Use/ Landcover Map
Source: FAO's LULC Classification System

3.5.4. Soil Data

Soils were also spatialised from FAO's soils map (scale 1:5 000 000). Such a resolution greatly reduces the spatial variability of this determining factor but no other map is available over the entire watershed extent. That's why we clipped our soil map from the one of FAO. The main soils represented on this map are thus organized from south to north:

- Dystric Regosols: is a soil having a base saturation (by NH4OAc) of less than 50 percent, at least in some part of the soil between 20 and 50 cm from the surface.

- Ferralic Arenosols: soils of coarse texture consisting of albic material occurring over a depth of at least 50 cm from the surface, or showing characteristics of argillic, cambic or oxide B horizons which, however, do not qualify as diagnostic horizons because of the textural requirements; having no diagnostic horizons other than (unless buried by 50 cm or more new material) an ochric A horizon.
- Orthic ferralsols: soil defined by a fine-textured subsurface layer of low silt-to-clay ratio, high contents of kaolinitic clay and iron and aluminium oxides, and low amounts of available calcium or magnesium ions.

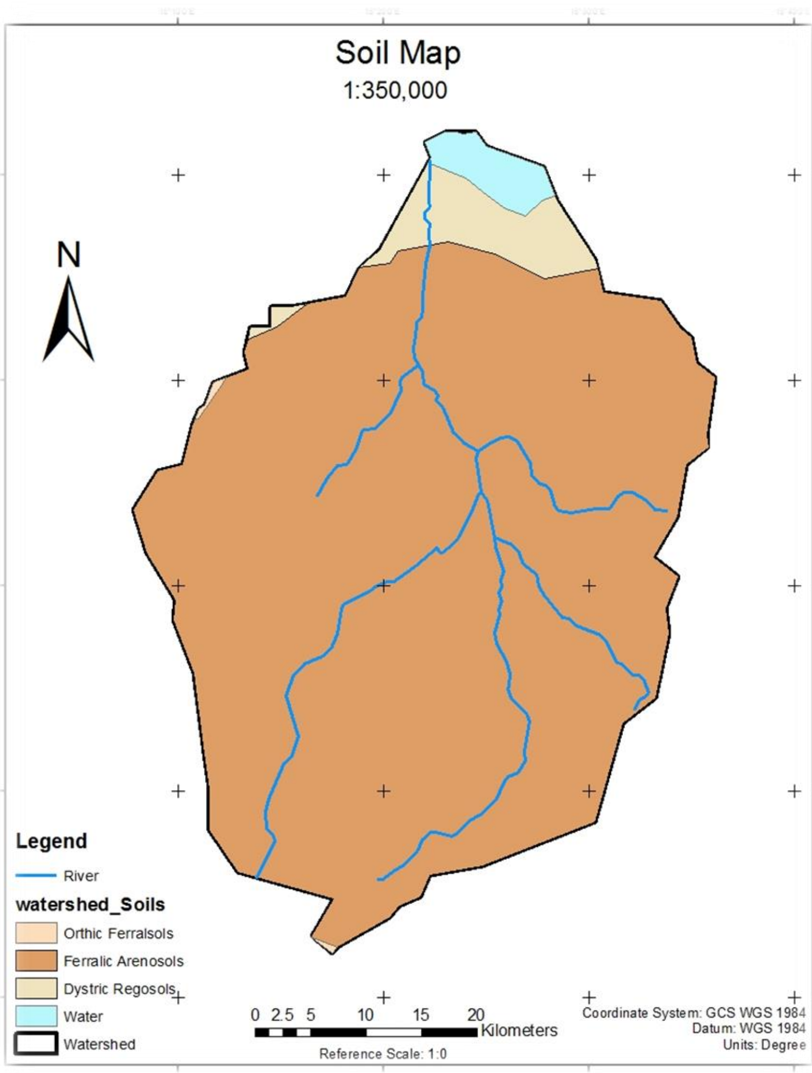

Figure 5: Soil Map
Source: FAO's Soil Classification System

3.6. Research Instrument

This study will be carried out using a Geographic Information System model (ArcGIS) and a Soil & Water Assessment tool (SWAT), the idea is to link our flood inundation model to a GIS package, this would allow us to create a flood hazard map. It's useful to specify that a flood hazard map contains details about the likelihood and/or magnitude occurrence. In the long run, this flood hazard map can be converted into a flood risk map by adding some additional details about the damage (e.g. economical damage, housing, etc.).

A reliable and efficient floodplain assessment require on the one hand some compulsory spatial datasets such as a Digital Elevation Map (DEM), a landcover and soil data, and on the other some optional spatial datasets like weather parameters, daily rainfall and streamflow data.

3.6.1. SWAT Model

SWAT is a hydrological model developed by the USDA Agricultural Research Service (Arnold et al., 1998). It is designed for watersheds from a few hundred to several thousand km². The model is semi-distributed: some parameters are spatialized while others are global. It is used to analyse the impacts of climate, soil, vegetation and agricultural activities on the flows. The basic spatial unit is the Hydrologic Response Unit (HRU), which represents a spatial combination of soil, landcover and rainfall. Any identical combination of these three elements is assumed to produce a similar hydrological response. It operates at a daily time step.

Some processes are represented by physical laws such as water transfer and soil storage, with an approach based on the EPIC model. However, SWAT is not a fully physical model. Thus, outflows are modelled by the Curve Number method for runoff and by an empirical equation based on the dry-out coefficient for subsurface flow (Arnold et al., 1998). The accessibility to variables and parameters is facilitated by coupling the model with a GIS (ArcGIS in this case). The hydrographic network is parameterized particularly in terms of roughness and permeability of the banks or geometry of the channel. The model makes it possible to follow the flows between the different stages of the water cycle with a display of the results in the form of tables or maps (Tripathi et al., 2003).

It has been validated in multiple regions around the world, in different climatic and geological contexts and for watersheds of varying size (Santhi et al., 2001, Vaché et al., 2002). In particular, it has been applied in the study area in all the watersheds of Niger, Volta and Senegal (Schuol & Abbaspour, 2006).

3.6.2. ArcGIS Desktop

ArcGIS Desktop includes a suite of integrated applications: ArcMap, ArcCatalog, and ArcToolbox. Using these three applications, you can perform all GIS tasks, from the simplest to the most advanced, including mapping, data management, geographic analysis, data update and geoprocessing. In addition, it gives you access to an abundance of spatial data and resources through ArcIMS services on the internet.

3.6.2.1. ArcMap

ArcMap represents the central application in ArcGIS Desktop. This is the GIS application used for all map tasks, including mapping, map analysis, and update. In this application, you work with maps. Maps have a layout containing a geographic window (or view) with a set of layers, legends, scale bars, Northern Arrows and other elements. ArcMap offers different ways to analyse a map, insert geographic data and layout mode in which you can perform many GIS tasks such watershed delineation, flow direction, flow accumulation, flood extent, etc.

3.7. Flood Mapping and Analysis

3.7.1. Flow Direction

ArcGIS help us to better understand where did water come from by using “hydrology tools” like flow accumulation and direction. Hydrologists utilize flow direction map to model the surface runoff that contributes to inundation. It shows the path that water will follow based on slope from neighbouring cell.

3.7.2. Flow Accumulation

Once you have a raster that indicates flow direction, a number of other interesting and useful calculations are possible. In particular, you can determine the locations of all the linear bodies of water, and you can determine, from slope and elevation, those areas where water may accumulate during times of intense precipitation. This is accomplished with the ArcToolbox Flow Accumulation tool.

3.7.3. Flood Mapping

The flood map was created from flow accumulation via a 3D simulation with “ArcScene”. In ArcScene you can simulate floods to know which parts would be affected if a flood were to occur. Although it is only visual, it gives you a general idea of how the event would affect you.

CHAPTER FOUR

4.0. RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the study findings and analysis of the data collected from different sources. It aimed at providing insights on the watershed delineation, the clipped watershed DEM, the basin slope map, the watershed flow direction and accumulation map, and the flood hazard map.

The approach is applied as an example in the watershed of the N'djili River, and carried out using ArcScene software as a hydrodynamic simulation tool and ArcMap as a tool for mapping exposed areas. This choice is well argued since the city of Kinshasa is continually confronted to floods generated by overflowing of the N'djili River, the model (3D) ArcScene will show well its capacity in terms of representation of the extent of the flood and ArcGIS via ArcMap will make it possible to spatialize the elements exposed to this risk and consequently to lead to a better decision for their management.

The simulation will be based on two different water-rise observed in situ by the Waterways Authorities.

4.2. Watershed Delineation

The extraction and delineation of a watershed is the first important step in hydrological modelling. A watershed that can be considered as a "system" is a hydrologically closed surface, ie no outflow from the outside and all excess precipitation evaporates or flows through a single section at the outlet.

The delineation of the watershed (Figure 6) is one of the most important parts of our study because it allows us to focus our research to the flows that directly affect the river N'djili. The spatial delimitation of our watershed allowed us to determine its area, which is **2410 km^2**.

The boundaries of the watershed are obtained by detecting and locating the ridges (water divide lines) in a multidirectional profile.

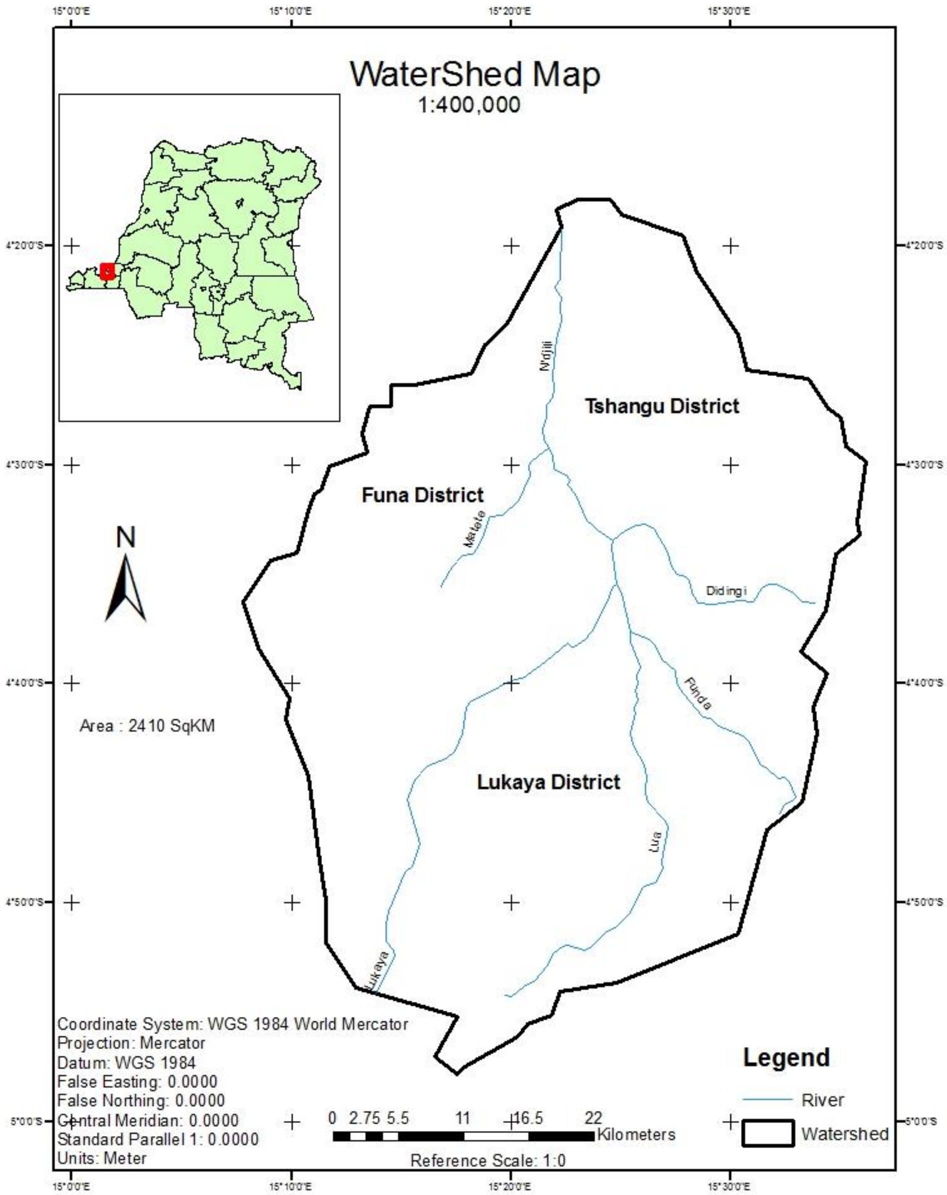

Figure 6: N'djili Watershed Map
Source: Researcher

The N'djili River system consists of a large number of tributaries and countless other small, permanent or seasonal streams. Their flow varies according to the seasons becoming more important during the rainy season. The table below gives the main tributaries of the N'djili River and the districts they drain.

Table 1: Main tributaries of the N'djili River

Course	Side	Tributaries	Length (km)	District
Upper	Left	Lukaya	44	LUKAYA
		Lua	31	
	Right	Funda	22	
		Didingi	22	
Lower	Left	Lukaya	-	FUNA
		Matete	3.5	

Source: Researcher

4.3. Slope Classification

Slopes in a watershed affects the runoff velocity while its length promotes high flow rates and concentration of water.

The slope is an important feature that provides information on the basin topography. It is considered as an independent variable. It gives a good indication of the surface runoff, the time of concentration (t_c) and directly influences the peak flow during a torrential rainfall. Several methods have been developed to estimate the average slope of a basin. All are based on a reading of a real or approximate topographic map.

Digital Elevation Model is a 3-dimensional representation of a surface obtained from altitude data that does not take into account the physical elements present in the field. Different slopes were extracted from the DEM via ArcToolbox (Spatial Analyst).

A Digital Terrain Model is a digital representation of the terrain in terms of altitude. It provides information not only about terrain shapes but also their position. Slope and orientation are obtained from the first derivatives of the DEM. The second derivatives tell us about the curvature of the terrain. All of this information represents the plans derived from the DTM. The slope is one of the fundamental data from which the hydrographic network will be determined.

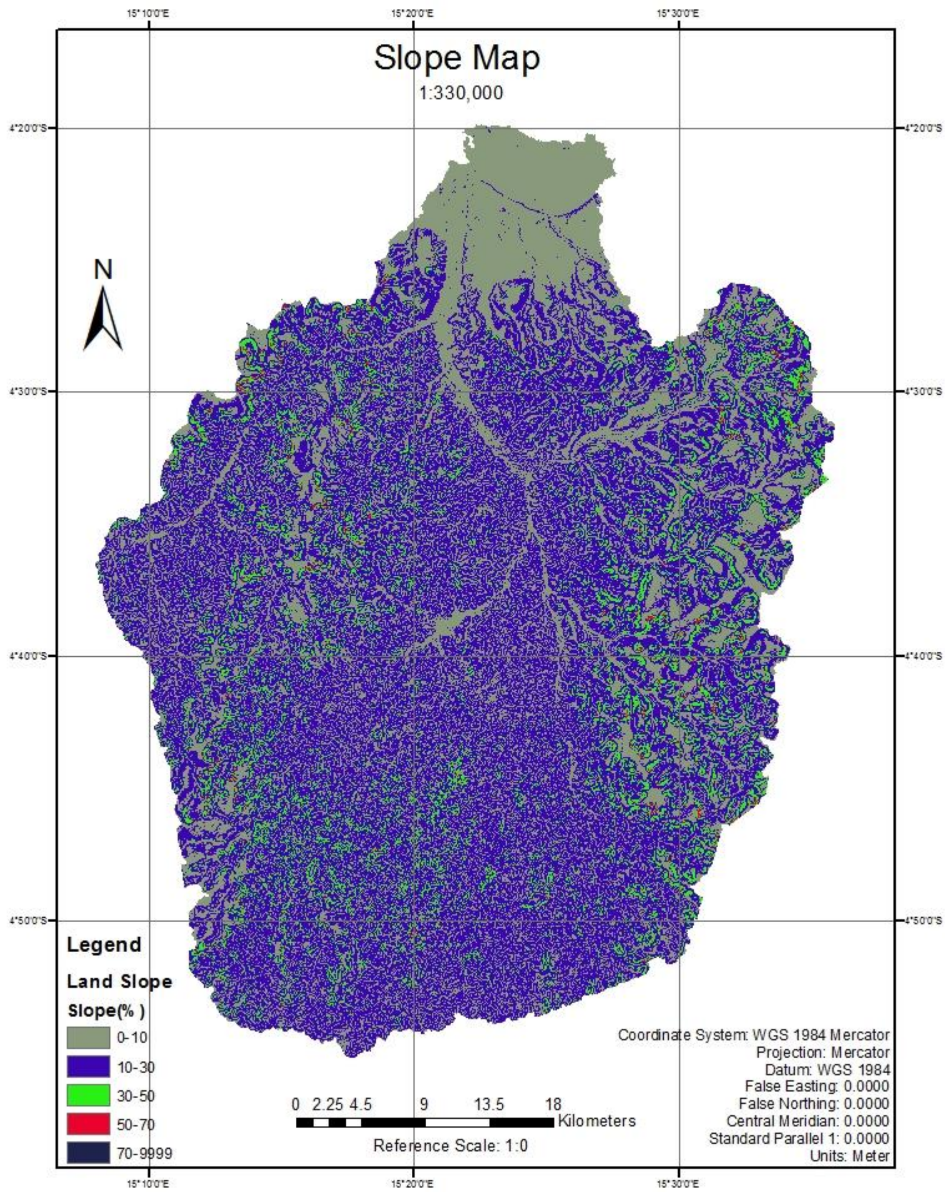

Figure 7: Slope Map
Source: Researcher

In Figure 7, it can be seen that the slope range reaches 10 percent in the river channel and 30 percent when it comes to the surface runoff; these information can already give us an idea of the flow velocities and disasters that can come from them (for instance, flooding in urban area and erosions in rural zone).

4.4. Flow Direction

This step in the process of flood hazard mapping consists of extracting the directions of flow. For this, we developed a procedure based on the exploration of the immediate neighborhood corresponding to 8-connexities (Jenson S.K and Resenfled E.G., 1988), which we reduced to two parameters. The Altimetric Descent Algorithm (ADA) calculates the difference in altitudes between the higher point (peaks) and its neighbouring pixels and thus locates the channel (or resolution cell) corresponding to the maximum descent. The flow directions that point to these corresponding cells are identified by the Freeman code and form the image of the flow planes. This image is coded between 0 and 2 where, the code zero (0) is assigned to a cell that has no direction (isolated cell).

Algorithm: $Min[Z(x,y) - z(x_i, y_i)]\ where,\ x_i = (x-1, x, x+1)\ ;\ y_j = (y-1, y, y+1)$

Z(x,y) corresponds to the altitude of peak and z(xi,yj) corresponds to the altitude of 2 neighbours.

As for the local drainage algorithm, it allows to calculate, at the level of each cell, the number of neighbouring cells flowing inside the central cell (channel). The result is coded between 1 and 2.

Measurement of river flows is based on a principle that, at a given stable point in the catchment, and under precise flow conditions, there is an unequivocal relationship between rainfall and flow through the prevailing conditions on the ground such as altitude difference, permeability, soil type, etc. Spatial analyst makes it possible to know the direction of flow on the ground. The result is visible and explained in Figure 8, the algorithm cuts the raster as a grid and assigns each cell created a higher or lower value depending on its altitude. This treatment makes it possible to visualize with a colour for each direction what will be the "path" of the waters contained in this surface.

The map of the flow direction is given in the form of image in the figure 8.

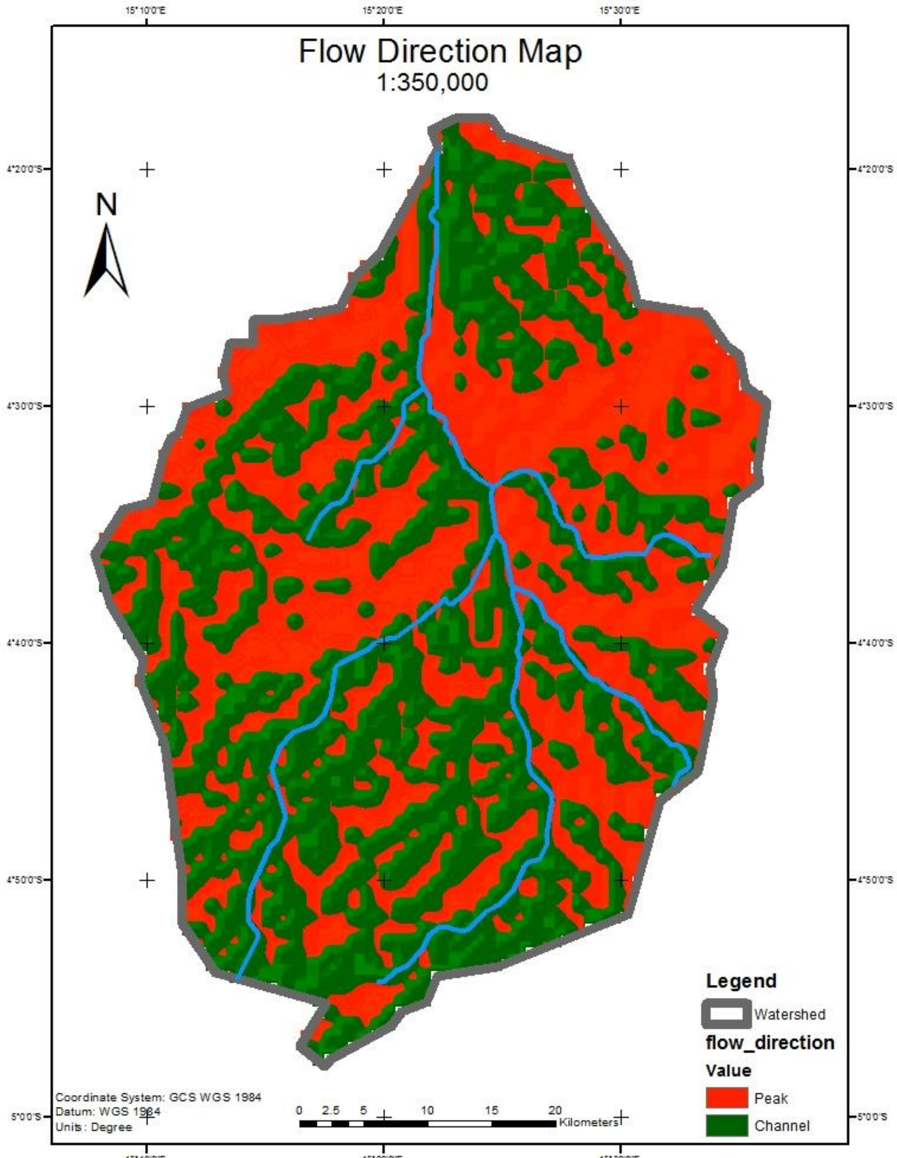

Figure 8: Flow Direction Map
Source: Researcher

To have a clear flow direction map, the processing parameters were subdivided into only two values, the peaks and the channel, thus it will be easy for us to determine from what high-altitude water comes to form an active or seasonal channel at low-altitude. A channel is said to be active when it is still drained even in dry season and it is said to be seasonal if it is only drained in the event of heavy rain. We have added arrows to this map for a better understanding of the flow direction phenomenon.

4.5. Flow Accumulation

Hydrological Network extraction techniques from a raster DEM are essentially divided into two approaches: those based on a geomorphological analysis by local characterization of the altimetric variations and those with hydrological inspiration based on the monitoring of the runoff of the water. In the first approach, several methods have been developed (Charleux-Demargne J, 2001) based on the morphology of the terrain, the descriptor parameters of the neighbourhood geometry, the study of the profiles, etc. A major disadvantage of these methods is the relative representativeness of local maxima and minima. The hydrological network extracted by these methods is fragmented and has discontinuities rendering it unusable for later applications. As for the methods related to the second approach, they retain the principle of a natural flow of water driven by gravity and guided by the topography. They rely on the determination of the flow directions of the water in each resolution cell or pixel from the altimetric values of the DEM, knowing that the water takes the path defined by the line of greatest slope. Thus, the cells pour into each other depending on the local slope, a coherent set of main thalwegs can be deduced. The extraction approach of the developed hydrological network is based on a hydrological analysis that uses the Digital Elevation Model.

Typically, DEM have areas of depression, formed by isolated cells whose neighbouring cells have higher altitudes and flat areas where the neighbouring altitudes are equal to the elevation of the channel. The presence of these zones poses a problem of discontinuity of the network, the water stagnates in the zones of depression and disperses in the flat zones (Lawrence W.M. and Jurgen G. 1998). For this purpose, we integrated in the process of extraction of the hydrological network, a Local Minima Search Algorithm (LMSA) which consists in locating the cells of depressions (Depression Zone=DZ) and the adjacent cells with equal altitudes (Flat Zone=FZ).

In order to overcome the problems of the discontinuities of water flow paths caused by depressions and flat areas, we treated the DEM by filling the depressions that trap water and forcing it to flow in the same direction inside the flat areas.

Indeed, this treatment is a simulation of the filling by water and the presence of an outlet allows water to follow its path according to the maximum slope. The algorithm will generate the formation of new artificial FZs that will be processed with the natural flat areas. As for the DZs treatment, the algorithm scans the contours of the flat areas and affects flow directions along the line joining the upstream to the presumed downstream of each zone, then it forces all the cells of the zone to flow in the same direction. It should be noted that the flow direction attributed to a flat zone depends on its size and the rate of runoff.

The map of the flow accumulation and local drainage is given in the form of image in the figure 9.

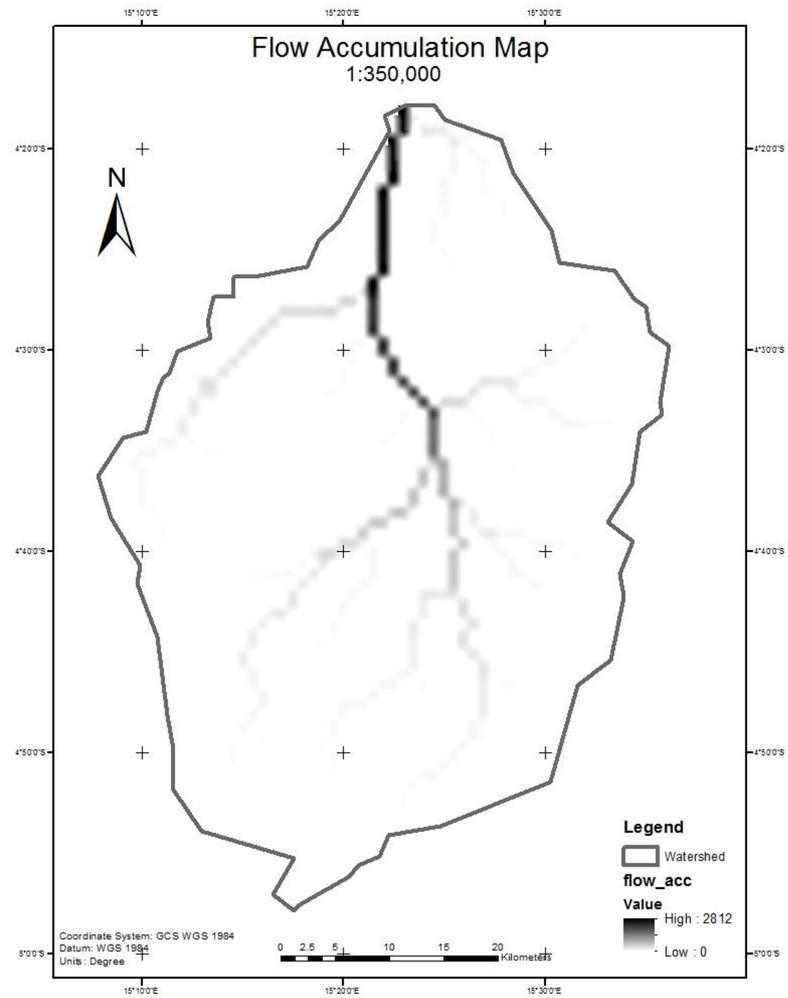

Figure 9: Flow Accumulation Map
Source: Researcher

This module requires only a flow direction map to calculate the weighted flow accumulation.

This treatment makes it possible to obtain a raster at the output of cumulated flows relating to each cell. It is then possible to see the accumulation of water; the flow channels correspond to areas where high flows are concentrated. Figure 9 is an example of viewing channels after increasing the contrast of the image to distinguish each tributary. It also gives us an idea about the flow evolution up to the outlet.

4.6. Flood Hazard Mapping

The model of simulation of the extent of floods require besides the DEM, the use of hydrological data. This type of simulation can be done with ArcGIS either on the flow rates or on the water level. In our case study, we simulated our flood event with water level recorded by the Waterways Authorities at the outlet of the River (port of Kinshasa).

Table 2: Water level (port of Kinshasa)

Flood	Water level (meter)
Quinquennial	**4.71**
Decadal	4.9
Every 25 years	5.25
Half-century	5.55
Secular	**5.9**

Source: Waterways Authorities (Democratic Republic of Congo)

ArcScene allowed us to do a 3D simulation based on a secular and a quinquennial flood. The results of our simulation on this basis of two water levels, subdivided our flood zone into two regions. A high-risk area that is completely submerged by water in both cases and another at low risk that is eventually inundated in case of a secular flood.

After the simulation was carried out by ArcScene, we have exported the simulation results to the ArcMap in order to delimit the flood zones. The following figure shows the final delineation of the flood zone after exporting the simulation file.

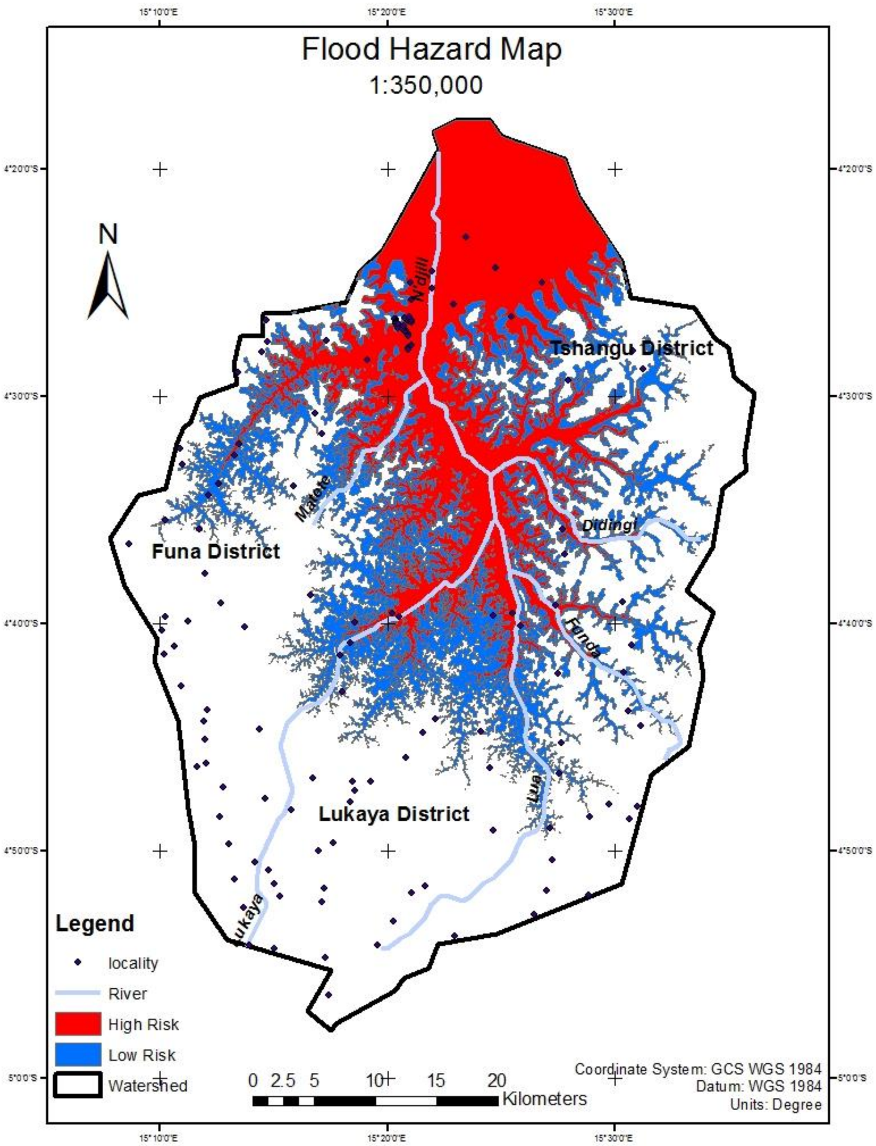

Figure 10: Flood Hazard Map
Source: Researcher

In red, the area at high risk, the one that is flooded in case of any rise of water (secular and quinquennial). In blue, the low risk area, which is flooded in the event of a hundred-year water rise.

4.7. Hypothesis Testing

To test our null hypothesis, we had to draw a contour map delineating the flood zones. By this, we can see how the rise of water is distributed in relation to the altitudes. In figure11, we found that contrary to our null hypothesis, there is indeed a great risk of flooding at altitudes less or equal to

350 meters. Each risk zone was grouped according to different colours with corresponding altitudes (red for high-risk areas and yellow for low-risk areas). It can thus be noted that between the altitude range 275-350 lies the area at high risk of flooding. This zone results from the simulation of a five-year water rise (the lowest water-rise observed). *Therefore, we reject our null hypothesis*.

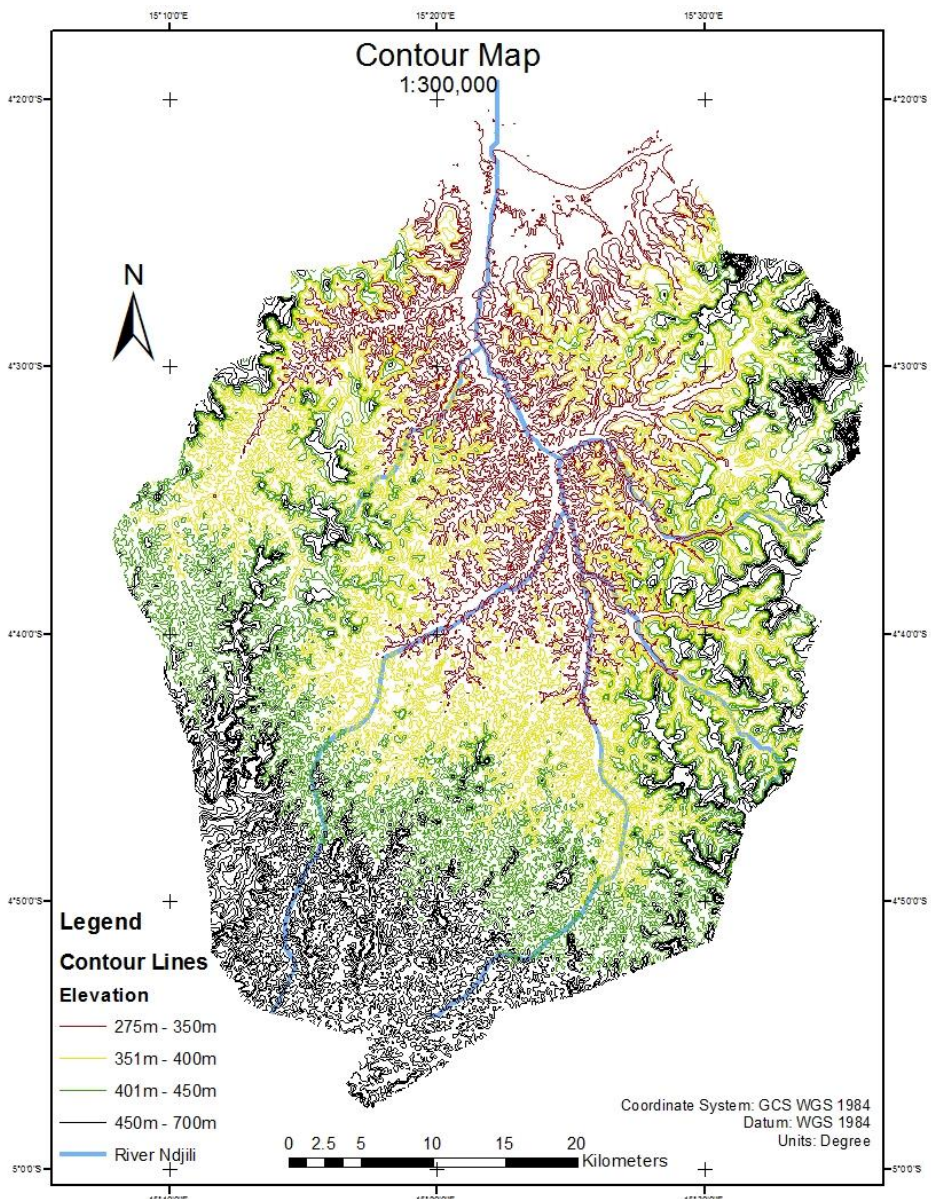

Figure 11: Contour Map
Source: Researcher

This hypothesis testing was made using an altimetric map that groups in block of colours, areas at the same risk of flooding. The altimetric representation of these flood zones allows validation of the spatial testing of the hypothesis, since, for some of these floods, the data on their extent were already hypothetically known. Indeed, the results of the simulation model (Flood Hazard Map) have been coupled with those of the altimetric cartography in order to delimit flood zones in terms of corresponding altitudes and thus, to highlight the most exposed places in case of any water rise.

By analysing the altimetry data, on the one hand, it can be seen that the five-year flood is also of great importance, since it is already a few meters away from the high-altitude zone; and on the other hand, the secular flood has been much more significant, since in several places it exceeds the limit of recurrence of floods in the catchment of N'djili River (350 meters above sea level as described by Luboya 2002), this type of flood was observed in January 2017. This model of simulating flood according to its altitudes enabled us to delimit each waterbody during the flooding process within the concerned watershed, it also gives us a concrete view on the level of inundation in all districts, thereby it’s observed that the District of Lukaya is just exposed to flood in case of one-hundred water-rise. The results provided by this comparison model are particularly interesting because of the precision obtained in the representation of different risk zones, it therefore makes it possible to better geolocate the extent of waterbody during an inundation, thus improving the mapping of flood hazards.

As part of an emergency measure plan, the flood level simulation model could be used by municipalities to implement an effective population evacuation, a land use planning and a flood zones delineation program (MSP, et al., 1998).

CHAPTER FIVE

5.0. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary

Perfect protection against the risk of flooding is actually estimated at an infinite cost. Whatever the device adopted for this purpose, only the understanding of the functioning of this risk makes it possible to better prevent it. Hence the need to adopt effective management ensuring optimal protection. This understanding must go through the identification of sites exposed to this kind of phenomena.

In this sense, our work represented by flood hazard mapping through a hydrological modelling approach in the watershed of N’djili, offers to policy-makers who are not always specialists, a clear and simple vision to compare different projects and scenarios. As a result, it implements a consistent and validated methodology for integrated flood risk management.

5.2. Conclusions

The traditional flood risk management method has become increasingly inadequate because of the pace of changes in indicators (land use, rainfall, etc.). To fill this gap, the use of GIS has provided new methodologies that can provide reliable results in modelling and mapping of hazard.

The city of Kinshasa has experienced an urbanization that today is at the root of many problems including floods. The present study on this phenomenon in particular, overflowing of the River N'djili led to the following conclusions:

(a) Floods in the city of Kinshasa are result of both natural and anthropogenic factors. The natural factors involved, namely topography, hydrography, include the presence of the N'djili River, rainfall and the nature of soil. The notable anthropogenic factor is related to land use;

(b) Overflowing of the River N'djili significantly influences flooding in Kinshasa during the rainy season;

(c) Floodplains have been occupied over years by people who increase the vulnerability to inundation;

(d) Flood hazard mapping is an effective management tool for inundation within the catchment of the River N’djili as it is very practical in terms of prevention. They are synthetic and easy to understand and can be used for public awareness.

Beyond awareness, which is a short-term measure, flood hazard maps can also help in long-term planning because in addition to helping to understand the phenomenon and improve knowledge about the characteristics of the city, these maps are a real support for integrating environmental constraints into all planning projects within the city.

The results of this mapping are schematized in a simple way allowing the various actors, in a flood risk management framework, to use them to decide (it is a decision support tool). GIS can help to develop a better decision-support tool if the necessary data and time are available.

The most serious problem encountered during the preparation of this work was the lack of reliable real data and the difficulty of accessing existing ones. This constraint forced us to choose simple models and to simplify other models, the topographic data were of modest precision while the modern techniques reach millimetric accuracies at the altimetric scale.

5.3. Recommendations

5.3.1. Flood Hazard Management

At the end of this study on the influence of the N'djili River on floods in the city of Kinshasa, some recommendations are needed:

a. To the parliament

- Update existing regulations on urbanization and human settlements.
- Ensure the effective implementation of these laws.

b. To the governmental authorities

- Reflect and seek with the provincial authorities, the financing for a long-term project of general containment of the river N'djili.

c. To the municipal authorities of the city of Kinshasa (short term)

- Focus on risk forecasting in term of flood management within the watershed. To do this, they can use the results of this document or set up a GIS dedicated to flooding in the city in order to control all the contours of the phenomenon;
- Remove all obstacles that prevent a natural flow of water in the river channel;
- Proceed to desensitize the watercourse and maintain sanitation facilities;
- Build sanitation facilities of greater capacity for the drainage of rainwater from the city to the N'djili River.

5.3.2. Future Research

Although the study has reached its aforementioned objectives, it mainly focused on the delineation of flood hazard areas based the water levels to collected by the Waterways Authorities at the outlet of the River N'djili. For further research, we suggest that it can be done a flood frequency analysis based on monthly high-flows in order to better understand the flow regime of the N’djili River and a flood hazard areas mapping based on rainfall data, so that we can do a comparative study.

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APPENDICES

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RAINFALL DATA
Source: Metelsat/Kinshasa-BINZA Station
Longitude: 15° 15' E
Latitude: 04° 22' S
Altitude: 445 m

Années	J	F	M	A	M	J	J	A	S	O	N	D	Total Ann
1961	115.0	107.5	108.9	393.9	170.0	0.0	2.0	0.1	83.9	95.3	268.7	91.3	**1436.6**
1962	147.7	143.7	260.6	55.6	166.2	0.6	0.0	0.1	49.4	100.8	286.7	233.7	**1445.1**
1963	53.8	171.9	244.6	212.7	118.1	0.8	10.9	0.0	13.1	87.7	283.4	260.9	**1457.9**
1964	127.9	94.7	133.1	193.5	175.7	0.0	0.0	11.1	6.4	80.3	289.1	124.3	**1236.1**
1965	114.5	84.2	301.3	110.5	120.0	0.0	0.0	2.2	36.5	123.3	221.2	113.6	**1227.3**
1966	100.6	121.9	346.5	289.0	71.8	23.6	0.0	0.0	20.2	103.4	205.4	111.9	**1394.3**
1967	250.7	163.2	224.0	77.5	127.0	21.0	0.0	0.0	9.9	72.2	276.2	22.7	**1244.4**
1968	86.7	77.9	178.9	160.9	182.4	0.0	0.0	0.0	32.1	118.8	170.5	63.6	**1071.8**
1969	148.7	117.7	117.7	350.7	171.4	2.0	7.9	0.2	4.2	160.5	337.2	77.2	**1495.4**
1970	177.1	102.1	204.6	232.2	134.2	0.0	8.6	0.0	48.6	83.3	339.4	116.8	**1446.9**
1971	157.4	67.7	148.9	182.7	65.2	6.4	1.0	1.2	43.9	14.9	185.6	176.8	**1051.7**
1972	181.2	7.2	175.0	120.2	81.5	0.0	0.0	16.8	19.5	42.3	265.2	158.6	**1067.5**
1973	176.9	139.2	160.0	338.5	193.6	0.0	1.2	1.0	43.7	187.6	304.8	172.0	**1718.5**
1974	501.5	199.9	287.5	294.0	99.7	0.0	5.7	0.0	1.5	107.1	193.8	186.3	**1877.0**
1975	98.7	92.4	251.7	104.9	167.2	0.0	0.0	1.7	4.7	123.1	140.0	281.9	**1266.3**
1976	77.6	244.9	101.9	236.1	35.5	17.3	0.0	1.5	25.4	174.5	216.8	193.5	**1325.0**
1977	163.9	101.4	288.8	232.3	245.4	39.2	0.0	0.0	23.8	157.8	189.7	201.7	**1644.0**
1978	171.4	65.7	33.2	166.4	49.1	0.0	0.0	0.0	47.3	48.1	227.2	177.1	**985.5**
1979	240.0	85.0	68.8	234.7	93.1	0.0	0.1	0.0	19.6	65.3	361.5	177.1	**1345.2**
1980	131.5	287.1	90.4	275.3	154.1	18.8	0.0	18.6	24.1	121.2	286.2	374.5	**1781.8**
1981	189.8	240.1	374.4	276.4	5.1	0.2	0.0	10.0	34.4	147.4	259.0	177.4	**1714.2**
1982	138.8	65.8	248.6	121.9	137.2	0.0	0.0	0.0	20.2	137.7	369.6	147.2	**1387.0**
1983	159.4	256.7	143.3	301.3	103.2	0.1	3.8	0.0	0.2	142.3	350.3	141.8	**1602.4**
1984	83.7	90.1	234.4	97.2	65.3	0.2	9.0	12.4	32.5	47.3	228.0	111.2	**1011.3**
1985	188.4	15.1	315.3	363.3	195.3	0.0	18.9	0.7	41.6	172.3	343.3	285.2	**1939.4**
1986	105.2	50.5	142.7	247.5	248.7	24.7	0.0	0.0	111.3	153.6	161.0	119.7	**1364.9**
1987	61.4	299.1	355.2	250.7	44.7	0.0	3.3	1.3	35.8	102.5	162.4	100.3	**1416.7**
1988	199.0	269.4	166.8	167.0	12.4	2.4	11.4	8.4	6.5	167.8	399.8	283.5	**1694.4**
1989	232.4	167.2	128.2	200.7	118.3	1.4	0.0	2.5	17.4	262.0	320.4	146.3	**1596.8**
1990	175.3	181.0	145.8	106.8	392.8	0.0	0.0	0.1	28.8	228.0	236.9	191.7	**1687.2**
1991	200.1	112.6	78.6	233.5	170.8	0.4	0.0	7.6	17.0	77.0	212.9	132.2	**1242.7**
1992	229.5	179.8	159.7	164.7	169.1	0.0	0.0	0.0	46.0	90.8	362.9	131.8	**1534.3**
1993	295.2	127.6	199.2	152.4	137.6	0.5	0.0	0.0	15.3	241.9	162.2	132.4	**1464.3**
1994	14.1	61.9	202.9	190.8	116.3	0.0	0.0	39.0	16.8	236.8	345.0	280.5	**1504.1**
1995	145.7	131.5	210.8	119.3	269.7	0.0	0.0	56.2	73.8	120.7	268.7	182.0	**1578.4**
1996	154.7	74.8	248.6	179.8	264.9	0.2	0.0	0.0	20.0	69.4	118.8	115.6	**1246.8**

1997	220.8	88.3	243.5	220.3	108.1	0.0	0.0	2.8	4.3	275.4	273.1	252.8	**1689.4**
1998	330.4	168.8	388.1	435.9	75.8	19.8	0.0	0.0	61.7	129.9	206.0	203.9	**2020.3**
1999	182.8	126.3	229.0	133.1	146.0	21.6	1.4	1.1	54.2	98.9	325.6	282.4	**1602.4**
2000	234.8	298.8	61.9	222.4	94.7	0.0	0.0	0.0	81.2	137.4	271.4	222.5	**1625.1**
2001	103.1	130.8	332.4	156.6	543.3	2.6	1.1	0.0	28.8	73.2	162.4	112.4	**1646.7**
2002	209.0	257.8	74.3	225.1	215.4	44.4	4.7	0.8	73.4	117.4	311.8	298.1	**1832.2**
2003	318.5	201.8	112.7	188.7	21.8	3.0	1.0	0.0	33.6	129.0	202.2	108.9	**1321.2**
2004	172.2	205.8	242.4	152.0	1.4	0.4	0.1	8.4	10.2	143.3	145.1	188.7	**1270.0**
2005	92.4	57.2	144.4	171.4	86.0	2.7	0.0	0	25.4	126.9	257.8	248.2	**1212.4**
2006	110.5	137.1	239.2	260.8	107.1	3.2	0.0	10.6	19.1	353.2	334.2	283.8	**1858.8**
2007	159.9	125.3	245.0	271.7	102.2	0.0	0.0	56.4	29.2	371.7	220.9	102.2	**1684.5**
2008	101.5	207.9	164.0	139.8	150.8	0.0	0.0	1.6	15	255.8	375.4	171.2	**1583.0**
2009	203.3	204.0	108.7	266.9	199.7	0.0	0.0	2.6	17.4	92.5	235.8	280.2	**1611.1**
2010	85.2	72.4	260.3	250.8	45.3	0.0	0.0	0	15.8	103.0	225.1	232.8	**1290.7**
2011	286.4	98.0	31.1	380.9	187.1	0.0	0.0	0	73.9	318.1	535.1	227.4	**2138.0**
2012	9.6	114.2	101.7	119.4	184.0	0.0	0.0	4.2	54.6	229.1	274.0	292.8	**1383.6**
2013	204.1	212.0	216.7	385.5	249.2	0.0	0.0	0.0	25.8	180.7	262.4	339.0	**2075.4**
2014	197.8	33.8	182.4	196.8	214.6	0.0	1.2	6.8	20.9	172.8	245.4	118.4	**1390.9**
2015	48.8	87.0	189.9	192.7	97.7	0.0	0.0	0.0	13.2	74.4	389.3	351.1	**1444.1**
2016	100.2	251.6	419.0	229.4	358.0	2.8	0.0	63.8	15.8	107.4	311.6	218.5	**2078.1**
2017	153.2	228.5	55.1	166.4	226.8	21.2	0.0	0	56.4	103.4	127.3	382.8	**1521.1**
2018	259.1	180.3	79.0	180	191.7	5.9	0.0	0	2	139.1	250.0	510.5	**1797.6**
Normale	**165.2**	**142.9**	**193.1**	**213.5**	**149.6**	**5.0**	**1.6**	**6.1**	**31.2**	**141.3**	**263.7**	**196.9**	**1510.0**