Master of Science in Engineering

Decision Support Framework Integrating Spatial Information for Building Flood Retrofit

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February 2017

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A thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Engineering

Seoul National University

2016

Decision support framework integrating spatial Information for building flood retrofit

December 2016

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Decision support framework integrating spatial analysis for building flood retrofit

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이 논문을 공학석사 학위논문으로 제출함

2016年 12月

서울대학교 대학원

건축 학 과 건축공학전공

멜리사

멜리사의 공학석사 학위논문을 인준함

2016年 12月

위 원 장	박 문 서	(인)
부 위 원 장	이 현 수	(인)
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Abstract

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As the climate changes, raising the frequency of stronger thunderstorms, the flood risk that metropolitan cities face will only intensify. With ongoing informal settlements and ever-increasing changes in the land use, building assets that are not exposed to flooding will eventually find themselves within floodplains.
As an attempt to adapt buildings to withstand future events and decrease their vulnerability, researchers and government agencies have developed various flood retrofit strategies. However, the implementation in urban areas is not always

feasible or appropriate due to insufficient geospatial consideration in the decision-making process.

The present research aims to provide a decision support framework combining spatial aspects, along with all influencing factors to derive suitable retrofit solutions for homeowners.

Through Geographic Information Systems (GIS), spatial characteristics are first extracted as data prerequisite, then inserted into the analytic hierarchy process (AHP) for an efficient evaluation of appropriate structural measures against flood.

To ensure the effectiveness of the framework process, a study of a residential house is conducted in Kinshasa, the capital city of Democratic Republic of Congo, which regularly endures severe inundation.

As research results, digital maps of exposed buildings are provided, as well as recommendations of most suitable retrofitting options for the case study.

Not only the simplified GIS-based calculation approach can be used to generate flood impacts without specialist knowledge, but also government authorities and managers can take advantage of the framework process to suggest tailored solutions for homeowners, actively involved in the process.

Keywords: Flood impact, risk level, Spatial data, GIS-based, Residential buildings

Student Number: 2015-22139

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1.1. Research Motivation

Flood, a natural part of the hydrological cycle, is very beneficial to the ecosystem by supplying for instance freshwater to the ground or irrigating farmlands. However, in contact with vulnerable built obstacles, floodwaters can become catastrophic and leave thousands homeless, especially when they overflow populated lowlands without proper drainage systems.

In 2008, the United Nations estimated that almost 40% of the world urban population was living about 100 km from the coast. The proximity to rivers makes cities along coastal regions the most vulnerable due to high-density of built structures and reduced surfaces to absorb or retain floodwaters.
Flash flood, one of the most frequent storm types during warmer months of the year, usually falls in less than 6 hours with little or no alarm, causing considerable damage to buildings. The sudden occurrence of the hazard along with the destructive power only reinforces the need to adapt structures and protect them from potential future risk.

The risk of flood equals to the probability of being flooded coupled with the vulnerability of the area. To clearly understand the connection between the two terms risk and vulnerability, it is important to consider the commonly adopted Source-Pathway-Receptor-Consequence (S-P-R-C) flood model illustrated in figure 1.1, picturing the process that leads to building damage.

For a flooding to occur, there must be a hazard trigger such a high rainfall that abundantly reaches receptors including vulnerable buildings through flood pathways (lowlands). At building scale, the biggest consequence is the failure of built structures and critical systems inside them.

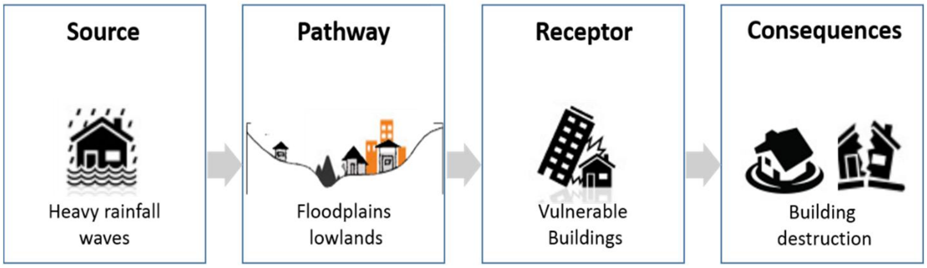

Figure 1. 1 Source-Pathway-Receptor-Consequences Conceptual model

To cope with the increasing flood threat, Decision makers have developed various strategies at every response level to prevent or reduce flood damage (see picture 1.2), particularly for residential buildings that are the most vulnerable within floodplains along coastal areas (Sanyal & Lu, 2005).

With the world shifting towards adaptive measures, governments have developed various national policies to regulate constructions within flood prone areas and have created financial mechanisms to assist victims after severe events. In developing countries, however, there is only desolation after a flood event (Bolia, 2014). The assistance tends to be meager if not nearly inexistent.

Also, national and private insurance institutions have enhanced the enforcement of building codes by setting prior conditions to request flood insurance services. For instance, a residential property with a basement nearby river banks or constructed with combustible materials cannot claim expenses coverage, as the inundation risk has clearly been underestimated during construction.

Federal agencies also allow people living within declared disaster areas to apply for loans, with an interest rate depending on their country. In this way, those experiencing severe flooding damage may quickly recover.

At the community level, flood control actions have always been the way through which people try to protect their neighborhood from being flooded.

The scope of this research lies on the structural responses at the individual level where homeowners have two choices. They can either be reactive by repairing their homes every time after a flood occurs or be proactive by retrofitting their properties to resist upcoming events.

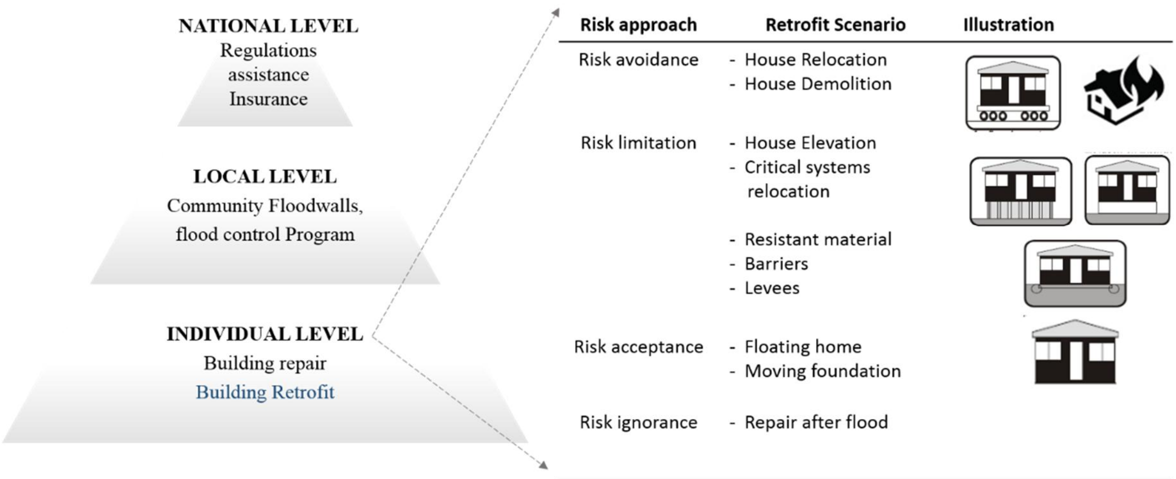

Figure 1. 2 City responses to urban flash flooding at property level

Flood retrofit refers to the adaptation of a building to recover quickly after a flood impact or withstand hazards in the future (Harper, 2015). Although daily repair works always seem affordable, precedent studies have sufficiently proved that the life cycle cost of retrofitting allows property owners to save a considerable amount of money from not fixing after years.

Four types of risk management approaches described in figure 1.2, hold unique to building retrofitting measures. The two extremes are the risk avoidance, involving a homeowner to relocate his property to higher grounds or demolish it according to urbanism regulations and the risk ignorance approach which consists of repairing after inundation has occurred. Between the two mentioned strategies, there are risk limitation measures including house elevation above flood depth; relocation of exposed equipment; flood-proofing remodeling and risk acceptance alternatives such as the floating home or movable foundation concept.

The selection and implementation of these measures involve the consideration of various parameters. Decision support frameworks have been developed to help an individual make practical choices. However, their application present considerable limits, as introduced in the next section.

1.2. Problem Statement

Preventing flood disaster and securing sustainable national development have always been a major concern of planners and government authorities. Decision makers, all over the world, are struggling to respond effectively to the increasing flood threat mainly because of the mono-sectoral approach through suggested decision support frameworks. Precedent researchers tend to focus on engineering, socio-economic and environmental aspects of the hazard while neglecting its spatial characteristics, which reside at the source of the event. The gap in the knowledge seems to weaken management efforts, often proved to be less productive (Generino, et al., 2014).

In the risk mitigation phase of floodplains, management activities require detailed information of the event including hazard features, characteristics of vulnerable buildings and the risk extent so that resulting impacts can be evaluated (Vaghani, 2005).

Spatial data is a prerequisite to any natural disaster analysis aiming to suggest proper land use management against floods. However, spatial information is not always within easy reach, especially in developing countries, where inadequate policies in place do not promote studies and tools related to climate change adaptation (Olowu, 2010).

The weakness of existing methodologies resides in the fact that they require the input of more than available data to retrieve desired information. The lack of a simplified calculation approach considering the deficiency of data has often forced researchers to conduct analysis with little or without spatial characteristics.

Given the above context, most precedent researchers proposing decision support frameworks have limited themselves by using the little spatial information they dispose of as a primary database by assessing features related to the building location and eventually the risk of flood. But the spatial knowledge does more than just providing data. It gives the opportunity to transform information obtained from the unique location of the building into criteria to evaluate appropriate measures. There is an urgent need to explore how extracted geospatial characteristics influence the decision of flood retrofitting once they are converted into evaluation metrics.

1.3. Research Objectives and Scope

The shift of floodplain management approaches towards resilient strategies demands not only for all experts of different fields such as spatial planning, architects, construction managers or geology to interact but more importantly, for citizens (homeowners in particular) to be actively involved in the process. This is where the research is heading.

In an effort to answer the question of 'how to bridge the spatial knowledge gap in the process of choosing the most appropriate flood retrofitting solution?', the primary goal of the present research is to provide an expert decision support framework which considers geospatial characteristics of buildings and flood along with other influencing aspects.

As data prerequisite, a GIS-based simplified calculation approach of flood impact is created, enabling the extraction of geospatial characteristics of flood and building despite data deficiency.

To ensure the effectiveness of the framework process, an actual case study of a chosen building within floodplain will be carried out to provide a practice guideline for decision makers.

The focus study area of the research is the plain of Kinshasa, the Capital City of Republic Democratic of Congo, which regularly endures heavy thunderstorm and considerable damage to residential buildings. The

plain, surrounded by the Congo River on the North side, receive a copious amount of rain waters from Hills on Southside before they flow into the River (figure 3.1).
This phenomenon, coupled with the rapid urbanization and the ongoing informal settlement within the region, creates a permanent dangerous condition for buildings, reinforcing the need to adapt them quickly so that they can resist future events.

The focus of this study is flash flood particularly at the scale of residential buildings. The force of floodwaters is very destructive, especially because of all debris that is often swept up in the flow. Exposed residential buildings are the most vulnerable particularly for unprepared homeowners.

1.4. Research Process and Methodology

The present research begins with the definition of the problem stated and objectives to be achieved. Then, it is extending to the preliminary study of the research two components, representing the second chapter.

The first part focuses on GIS as a prerequisite to obtaining spatial information for the evaluation of retrofit measures. To fill the gap of data in the decision process, a simplified approach to calculate the risk of flood is created through Quantum GIS (QGIS), known for his effectiveness of assembling and analyzing information from different sources (Sanyal & Lu, 2005).

In the second part, a review of multi-criteria decision analysis methods is conducted to choose the research corresponding methodology. After that, a screening of current flood retrofit strategies at building level as well as existing frameworks is made to ensure that the research is filling a gap of spatial knowledge. Next comes the development of the decision support framework, along with the efficiency discussion and the establishment of the process.

The research lands at the application part with a case study to check the effectiveness of the DSF process. Starting with the study area context, the GIS calculation approach is implemented to obtain geospatial information. Then, through AHP, retrofit alternatives are ranked and submitted to a sensitive analysis to check the final evaluation. The process is illustrated in the figure below.

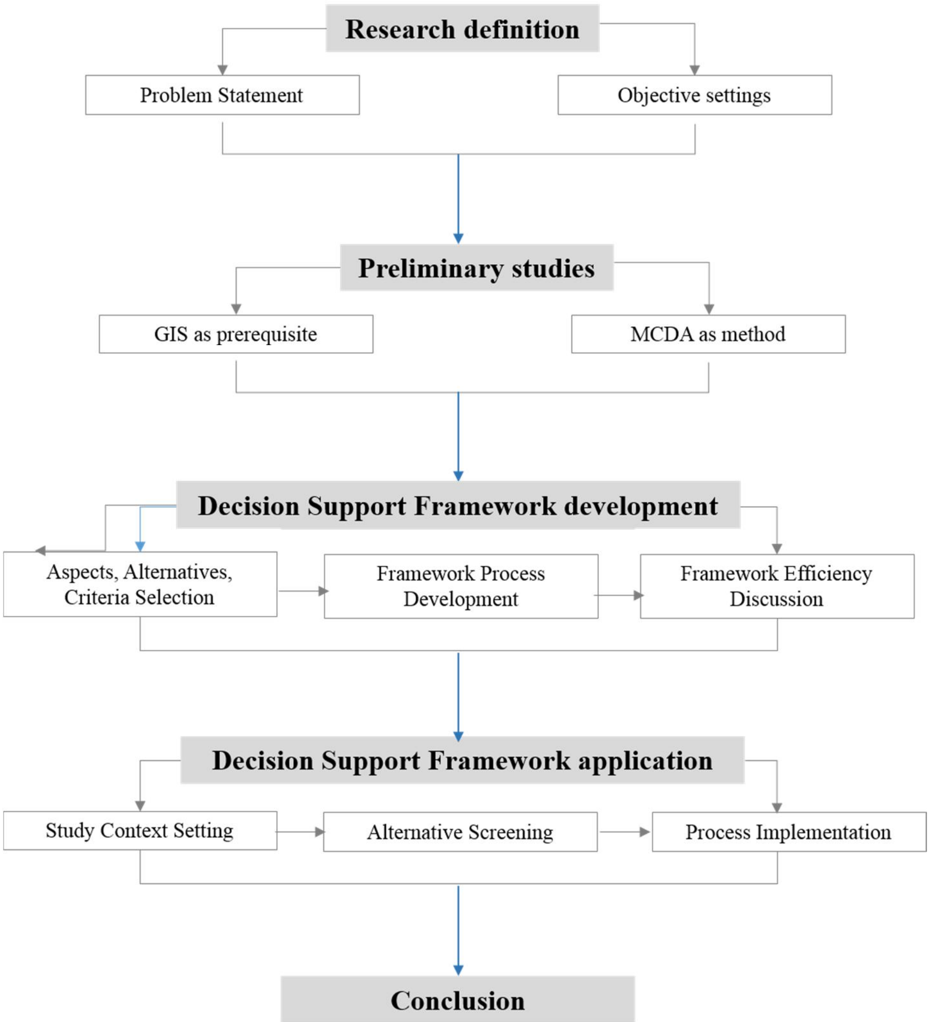

Figure 1. 3 Research Process Diagram

1.5. Summary

Flash flood, coupled with the ongoing population within floodplains, is an permanent threat to built structures. Government authorities and planners have suggested various structural measures so that exposed buildings can withstand flood impacts and cope with future events. Furthermore, Precedent researchers have developed frameworks to evaluate flood retrofit alternatives. However, the question of 'how to choose the most appropriate solution for an owner' remains incomplete due to the lack of geospatial information about buildings themselves and related flood characteristics.

The purpose of this research is to fill the gap of spatial consideration in the evaluation process. The study area is the plain of Kinshasa City, the capital of DR Congo, which has been home to the severe flooding events over the past decades.

As for the research process, the knowledge gap is first identified, and objectives are set. Then, a preliminary study on GIS as data prerequisite and existing multi-criteria decision analysis methods is conducted to ease the development of a new framework considering Spatial Information in the following section.

Finally, a case study is carried out to ensure the process effectiveness, from the application of a simple approach to extract metrics to the evaluation of retrofitting measures through the Analytic Hierarchical process (AHP).

Chapter 2. Preliminary Studies

2.1 GIS as research prerequisite

2.2 Multi-criteria decision support as Method

2.3 Summary

In its first part, the present chapter underlines the need to integrate spatial information into the flood management before developing a simplified calculation approach primarily to fill up the gap of data lack encountered in the management of floodplains. Then, a case study is conducted to ensure the effectiveness of the method. In the last part, multi-criteria decision analysis methods are screened along with current retrofitting measures and existing decision approaches to draw a pathway for the development of a new decision framework.

2.1. GIS as prerequisite

2.1.1. The need of Spatial Consideration

Flooding as well as other natural disasters are nothing but spatial features and they must be understood under this perspective to be well managed. According to Curtis Andrew & W. Mills Jacqueline (2010), most natural hazards have patterns that have leave spatial footprints and within these patterns are built structures, cultures and social interactions. This underlines that there is a clear tie between geographic location and human settlements.

Disaster management cycle comprises four phases: planning or preparedness, mitigation, response, and recovery. At the flood mitigation phase, before deciding how to cope with inundation at building level and what appropriate retrofit measure to apply, evaluating the risk of flood and quantifying resulting impacts is one of the priority in the top priorities (Albano et al, 2014).

Flood mapping is therefore an essential component of flood risk management because it does not only provide accurate geospatial information about the extent floods on a given building, but also, when coupled with geographic information systems (GIS), it helps extracting useful information to evaluate retrofitting alternatives for future adaptation (Younghun Jung, 2014).
As flood risk analysis requires the manipulation of various resources from

different data layers to obtain a desired outcome. The digital knowledge through Geographic information Systems is indispensable as they provide effective ways of assembling data and visualizing results. (Aronoff, 1995).

In addition to the capabilities for data input, storage and retrieval; GIS enable the output of data 'Georefencing' which refers to the process of assigning geographic coordinates to data with a specific reference system. In easy words, it is about digitizing locations of 2D objects into the 3D GIS model so that it can be analyzed.

Georeferencing can thus be used, to fill the data deficiency in the calculation process by transforming existing data into desired information.

2.1.2. Simplified Calculation Approach Development

2.1.2.1. Data manipulation in QGIS

Every modeling in QGIS starts with the need to collect all necessary data and prepare layers to put into the processing interface. The simplified method priorities only crucial information needed to calculate the flood risk level within an area. When they are not available, datasets are generated from existing raster files or through the overlay operation, resulting in an information gain.

Among the broad range of GIS tools for determining areas affected by flood, Quantum GIS (QGIS) is being increasingly used for its advantage to be user friendly, intuitive, free and open-source software (FOSS). Another great feature of QGIS is the capability of running calculations on any platform (Windows, Mac, Linux, etc.) which makes it more favorable over other GIS-based FOSS for this research.

Over the years, QGIS has gained many disaster management plugins developed to support the flood consequences estimation (Mancusi, Leonardo et al. 2015; Albano, Raphaele et al. 2014). However, as they require specific database input such as the hazard warning time, the building inventory or the depth-damage curve before calculation, they cannot be used in the context of data deficiency.

Fortunately, a key advantage of geographic information systems (GIS) is its capability to apply spatial operators to GIS data in order to identify spatial relationships between layers and derive new information, especially when it comes to the modeling and production of hazard risk cartographies. QGIS has a wide variety of built-in processing operations, easily accessible via the Processing Toolbox.

Overlaying, probably the best-known operation is intensively used all along the process. It implies the data integration by superimposing two or more map layers to produce a new map layer (Nigel Trodd, 2005). While being the simplest procedure, it is quite powerful and requires more efforts to put at the same coordinate system different sources of layers to retrieve the desired information.

There are two methods to perform an overlay operation—feature overlay from vector data and raster overlay within QGIS. The flood risk calculation in this research is mostly carried out through the feature overlay operation, implying the three fundamental processing algorithms (Escobar, 1998):

1. 'Point-in-Polygon': point features of one input layer are overlaid on polygon features of another layer to obtain set of points polygon attributes

2. 'Line-in-Polygon': lines or arcs features of one input layer overlap polygon features of another layer resulting in a new layer, which contains lines with additional attributes from the polygon within which they fall.

3. 'Polygon-on-Polygon': Polygons from two input layers merge to create new polygons with jointed attributes in an output layer.

During the flood calculation, overlay tool functions such as union, clip, intersect, dissolve, difference, symmetrical difference and join attributes are used to draw spatial relationship between layers of separate data and obtain the information needed. The table 2.1 below describes their operations as well as the related input-output data.

Previous paper-based maps collected analogically several years back are a primary source of datasets. Although they might have been digitalized, they are not always available. Most of the time, ordinary people and even researchers are left with image versions of data inventory. They necessitate to be scanned and then georeferenced through GIS to become digitalized and easily to handle. Real world coordinates for geo-referencing can be obtained from a field surveys- collected with a Global positioning system (GPS) device for few identifiable features in the image or map paper.

Luckily, in this research, most of coordinates also called Ground Control Points (GCPs) have been fund marked on the image itself. After inserting it in the model, the image is warped and made to fit within the chosen coordinate system. Available paper maps such as such the relief, land use, flood-prone zones can be geo-refenced through flood mapping process.

Table 2. 1 Feature Overlay Tool functions

Function	Operation	Overlay type	Input data	Overlay data	Output
Clip	Cuts a layer based on boundaries of another layer	Binary	Any	Polygon	Only common features to input layer
intersect	Combines data where the input layer meets two or more others	Multiple	Any	N/A	common features to all layers
union	Melds two layers into one while keeping their attributes	Multiple	Polygon	N/A	All input and overlay features
Dissolve	Merges features with a single layer based on common attributes in the attribute table	Binary	Polygon	Polygon	New layer with common attributes
Difference	Subtracts areas of one layer based on the overlap of the other	Binary	Polygon	Polygon	Only Features of input layer
Symmetrical difference	Creates new layer based on areas of two layers that don't overlap	Binary	Polygon	Polygon	Features of either input or overlay layer
Join attributes	Creates a layer with common attributes of two layers	Binary	Any	Any	New attributes table of both layers

2.1.2.2. Simplified calculation process

The figure 2.1 explains the three main modules of the calculation approach and actions that a user needs to take during the process. It is later completed with the 'how and what to proceed with' at the application section of the third chapter.

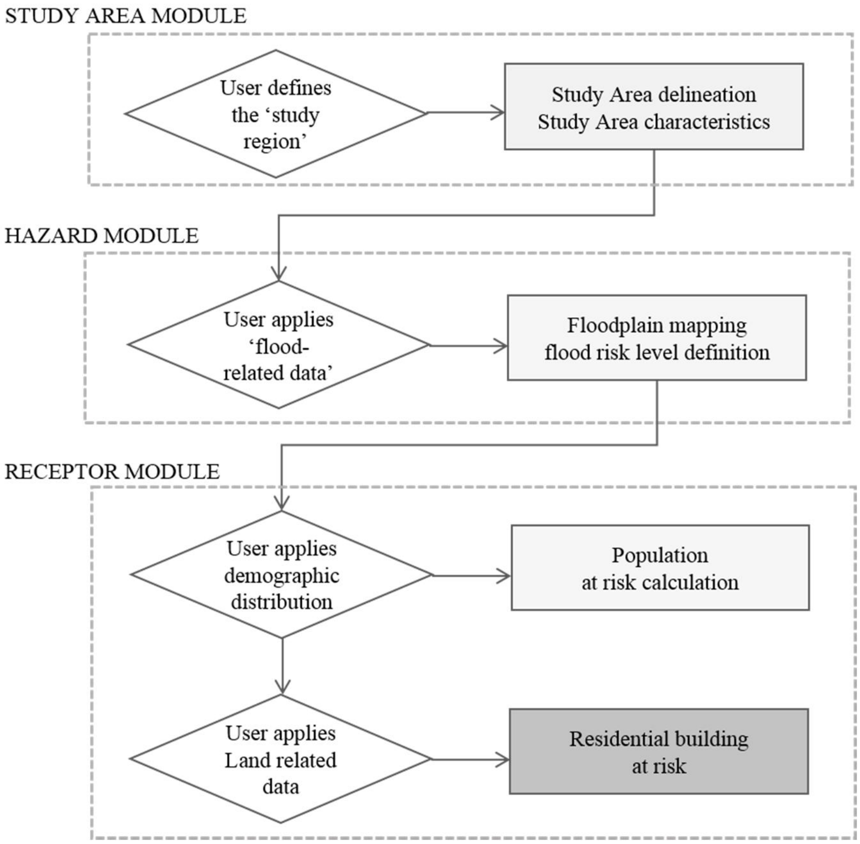

Figure 2. 1 Simplified flood risk calculation at building scale

The first step of the method is related to the Study area module. It consists of preparing layers related to the area delimitation and physical conditions such as the administrative boundary map and the topographic map. These layers are essential, informing about the area bounder lines and the terrain conditions. At this stage, the user creates the base map of the study region.

The second step, concerning the Hazard Module, is the key feature of the simplified calculation method. All 'available' data of the region, capable of providing any flood information is load into the model to delineate floodplains with their risk level.

Several approaches have been developed to obtain the flood spatial extents. The most primitive yet most accurate method consists of integrating flood elevation data from high watermarks observed at various locations (Wang, et al., 2002; Centry & Lopez-Parodi, 1980). Although it has been proved to be a logical process due to empirical evidences, it does not represent the nature of the flood, which varies over time and space.

Lately, with the increasing accessibility to computing technologies, many numerical models have been widely applied to the floodplain mapping (Grayson, et al., 1992). The recent advance of remote sensing within GIS environment has been helpful, enabling the estimation of floodplain boundaries based on satellite imagery.

After reviewing the application of GIS and satellite images in flood risk management, many researchers acknowledged the lack of remote sensing data accessibility for flood boundaries delineation in developing countries. (Sanyal & Lu, 2004; Qi, et al., 2009).

With the non-availability of data, the digital elevation map (DEM) serves as the base map from which other hydrological layers are extracted from using raster operators in QGIS.

The Contour map in the figure 4.2 is an excellent example of the 'Contour' function tool. Likewise, the catchment basin and the entire stream network can be accurately estimated from the simple DEM-based process of the area drainage basins as they are strongly influenced by elevation (S.Pike, 2006). The catchment is a significant factor determining the time taken for rain to reach the river by its shape and the amount of water to reach the river by its size.

To predict areas that are going to be flooded under a certain depth of water, a simple interpolation technique of extracted contour map nodes is conducted. The spatial interpolation is usually used in cartography and geography for the need of predicting and generating the complete surface data of an area based on a set of given data either in the form of discrete points or subareas. (Siu-NganLam, 1983). Areas with depth greater than zero are considered to be potentially floodplains (Noman, 2001; Merwade, 2009; Tate, 2002). Thus, they constitute the study area 'potential' flood extents.

Historical flood maps recorded over past years represent another primary source of data for the Hazard Module. Being paper-based data, historical maps in urgent need of update not only benefit from the digitalization process of geo-referencing in QGIS but also serve as a comparative guide during the floodplain derivation through the hydrological modeling.

The last step concerning the flood receptor Module, requires the user to input demographic statistics and land related data to obtain respectively the population exposed to the flood risk and retrieve residential buildings within flood-prone areas which is the final goal of the spatial analysis. The provided map, couple with socio-economic and environmental factors would be a great asset for decision makers in the management of floodplains.

With a clear picture of the location of buildings at risk, specific ‘adaptation’ measures can be taken to cope with inundation events. It would enable an easy identification of shelters for the exposed population and better elaboration of preventive actions against the environmental degradation. On the other hand, an economic analysis for a given house can only be conducted based on an empirical case study, which is clearly a limitation of the calculation approach.

2.1.3. Calculation Approach Implementation

2.1.3.1. Study Area Context

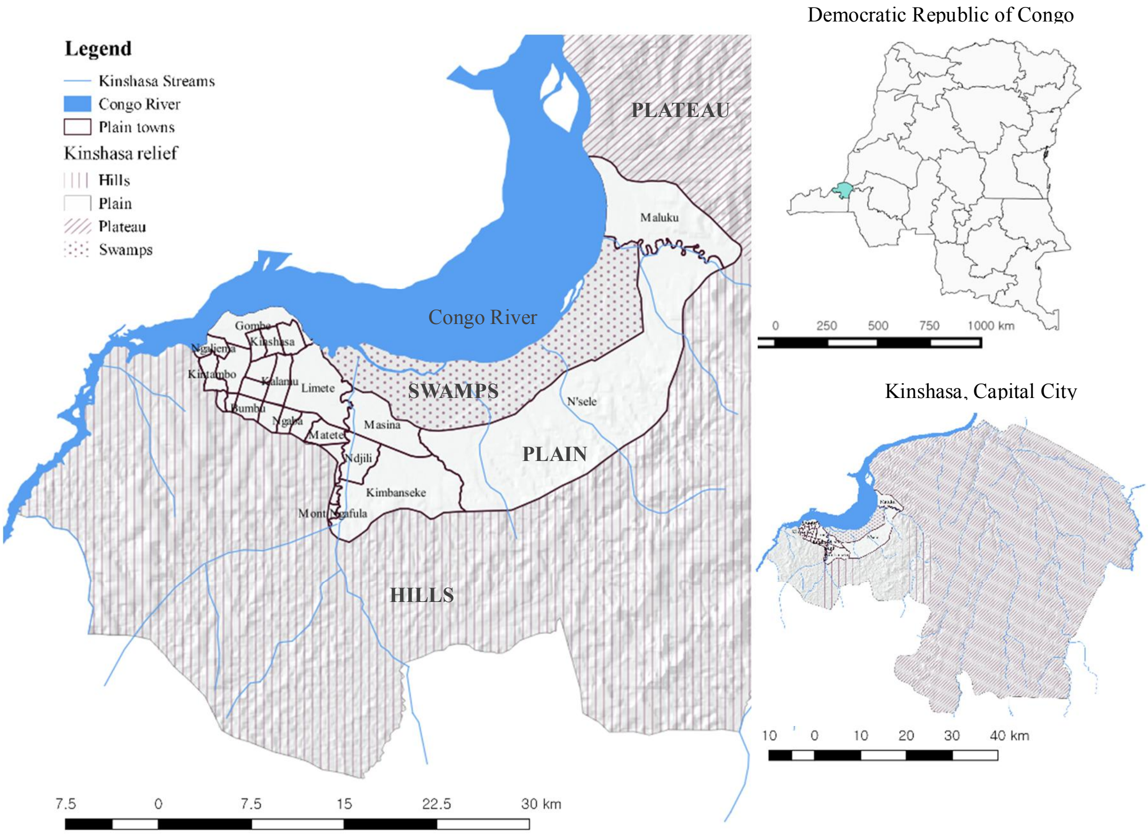

Figure 2. 2 Research Study Area, the Plain of Kinshasa City

The above picture delimits the focus area of the research study, the plain of Kinshasa City lying on the left bank of the Congo River in a wide crescent shape. It is a lowland (279 ~320m of elevation) bound north by swamps along the river, east by a vast plateau (flat land above the sea level), South and west by a chain of hills where all streams draining the city flow from. The plain area, home to the city business center and government institutions, was the favorite place for habitants to settle before the country independency. Soon after 1960, it quickly became saturated with informal settlements, primarily due to the rapid urbanization and migration from rural areas. The most important portion of the population is concentrated in the urbanized part of the city, located within the plain area. In 2014, an estimated 12million of the population was covering only 5,8 % of the total city surface, that is to say 583km² out of 9,965km², making the plain extremely dense (Bolia, 2014). Seeking to easily access some of the city major facilities, transportation or cultivable lands near stream banks, people are forced to live within non-buildable zones and wetlands inside the plain, exposing themselves to the risk of getting flooded.

Flash flood is nothing but a regular stress for Kinshasa citizens. Lying not far from the equator, the city receives copious amounts of rainfall which, when coupled with the soil saturation and drainage network inadequacy, often exceed the infiltration capacity, the rainfall is mostly in the form of heavy torrential downpours (79% of rain kind), observed during height months of the year particularly in November, March and April. Flooding in the plain usually mainly occurs because of the Congo River and tributary streams. Over the years, the average level of the River has not stopped to vacillate, sometimes bringing strong floods to riverine habitats. Until 1940, the maximum rise of the river level was 5.6m.the unusual flood of 1961 had a high-water mark of 5.20m, whereas the most severe of 1999 brought the mark to 5.44m (Lateef et al, 2010). This takes the current average level of the river to 298m above the sea level, exposing lands within the plain with lower elevation to groundwater flooding (picture 3.2). In addition to the river overflow, the most frequent hazard comes from sheet floods and tributary streams with the highest record of 222mm/m² in 2007. With abundant rainfall, streams usually overflow their banks and cause considerable damage to nearby population and building assets. The climate simulations indicate that rainfall will become more intense and more destructive over the coming years bringing floods within the plain area along with landslides and soil erosion of surrounding sloped planes. This highlights the urgent need to portray the risk level of flooding so that exposed residences particularly private properties located can prepare to adapt for upcoming events.

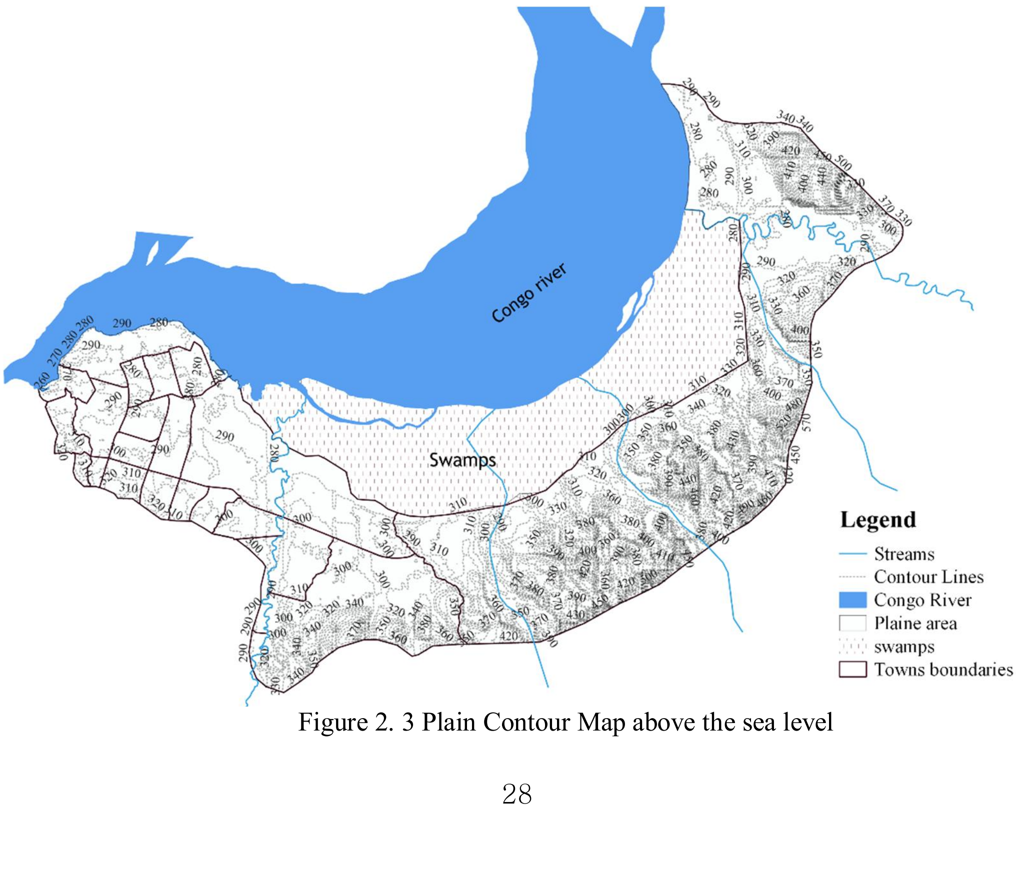

Figure 2. 3 Plain Contour Map above the sea level

2.1.3.2. Simplified method implementation

2.1.3.2.1. Flood risk Calculation

The implementation process is entirely carried out through the QGIS 2.18.0 tool as illustrated by the interface screenshots of the three main Calculation modules. The data used for the case study were obtained from various sources (table 3.1). Maps such as the city topography, the administration boundaries and the land use came from the Congo geographic institute based in Kinshasa. Statistical data were from the World Bank and the World Resources Institute online. One of the data found without much effort was the digital elevation map, easily accessible online in different resolutions. Flood historical maps were retrieving from past events recorded by the Congo bureau of Statistics. All data were projected in WGS 1984 EPSG: 54004 Geographic Coordinate System.

	Data	Data type	Data Source and Year
1	City topography Map	Raster file	Congo geographic institute, 2012
2	City administrative Map	Shape file	Congo geographic institute, 2015
3	Digital Elevation Map	TIFF	Consortium for spatial Information, 2015
4	River and Stream Map	Shape File	Congo geographic institute, 2012
5	Flood Historical Maps	Raster Files	Congo bureau of Statistics; 1990,1998,2001,2008, 2012
6	Population Statistics	Excel Files	World Resources Institute online
7	Land use Map; Land statistics	Shape file; Excel Files	Congo geographic institute, 2012; World Resources Institute online, 2013

Table 2. 2 Research study Data types and sources

The process starts with the creation of the study area. The City topographic map is first loaded into the GIS model to be georeferenced and then overlaid to the administrative map. The study area borders are denoted after being clipped consecutively from both layers, as well as the neighborhoods boundaries within it.

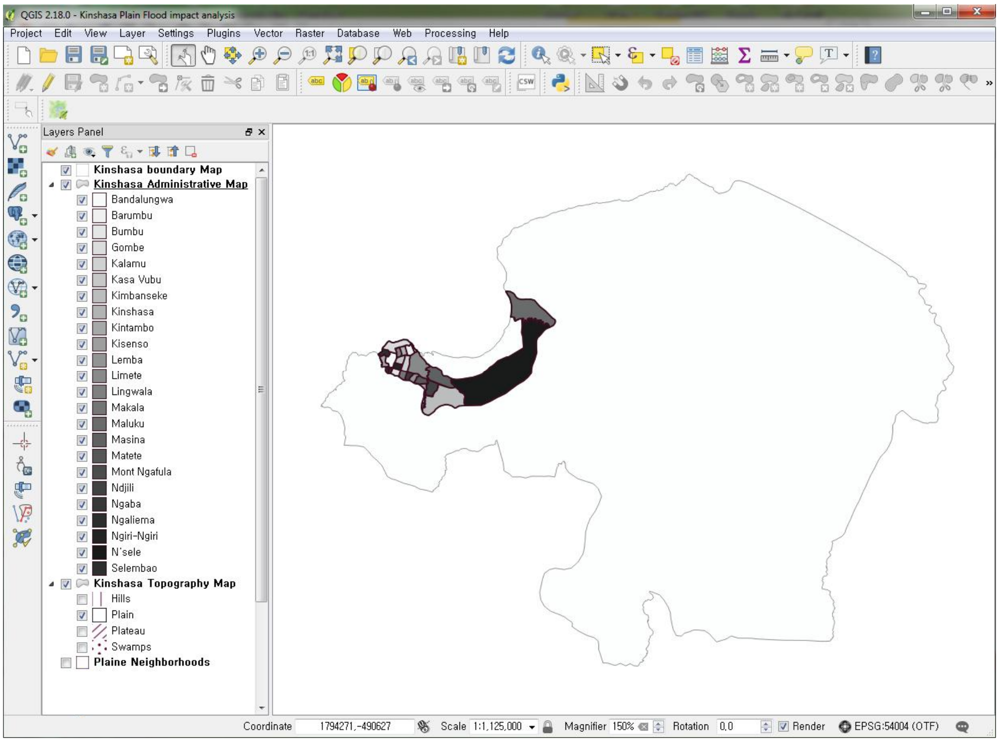

Figure 2. 4 Study area creation (QGIS screenshot No. 1)

At the second phase related to the Flood Hazard Module, the river and streams map followed by the digital elevation map are loaded into the model. A clip of the elevation within the plain leads to the generation of the contour lines layer, the catchment basin as well as the entire stream network. The cross-section elevations extracted from topographic datasets are in turn used to produce water surface elevations. The flood extents are then obtained by subtracting the topography from the interpolated water surface obtained through hydraulic modeling. Areas with depth greater than zero are considered to be potential floodplains. Finally, after georeferenced historical maps, there are converted to vector files to extract past recorded floodplains within the plain. A comparative analysis is conducted with potential flood-prone areas to update historical records. Then the risk level is defined, based on the inundation depth within a zone.

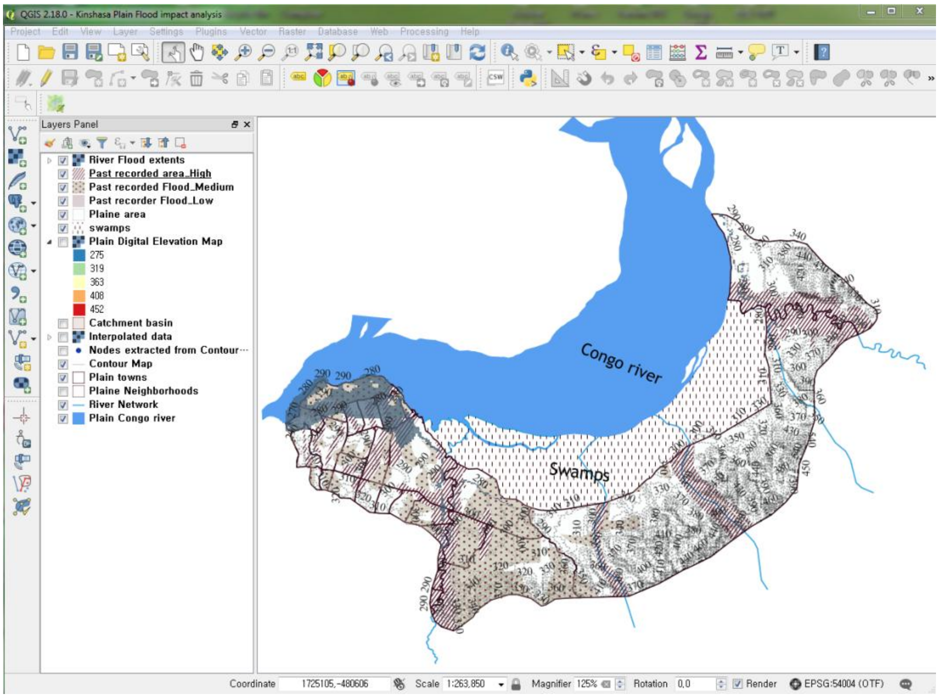

Figure 2. 5 Floodplain modeling (QGIS screenshot No. 2)

The last step aims to calculate the risk level of flood receptors such as the population and building assets within a flood-prone area. To begin, the demographic distribution data and land occupation data originally in excel file are saved in comma-separated values format (CVS) format to be processed in

GIS. A first Join of attributes table between the population statistics and the neighborhood boundaries provides the population at risk layer once extracted from the floodplain map created earlier. A second join, between the land occupation statistics and the land use datasets gives the possibility to retrieve residential buildings within the flood-prone areas.

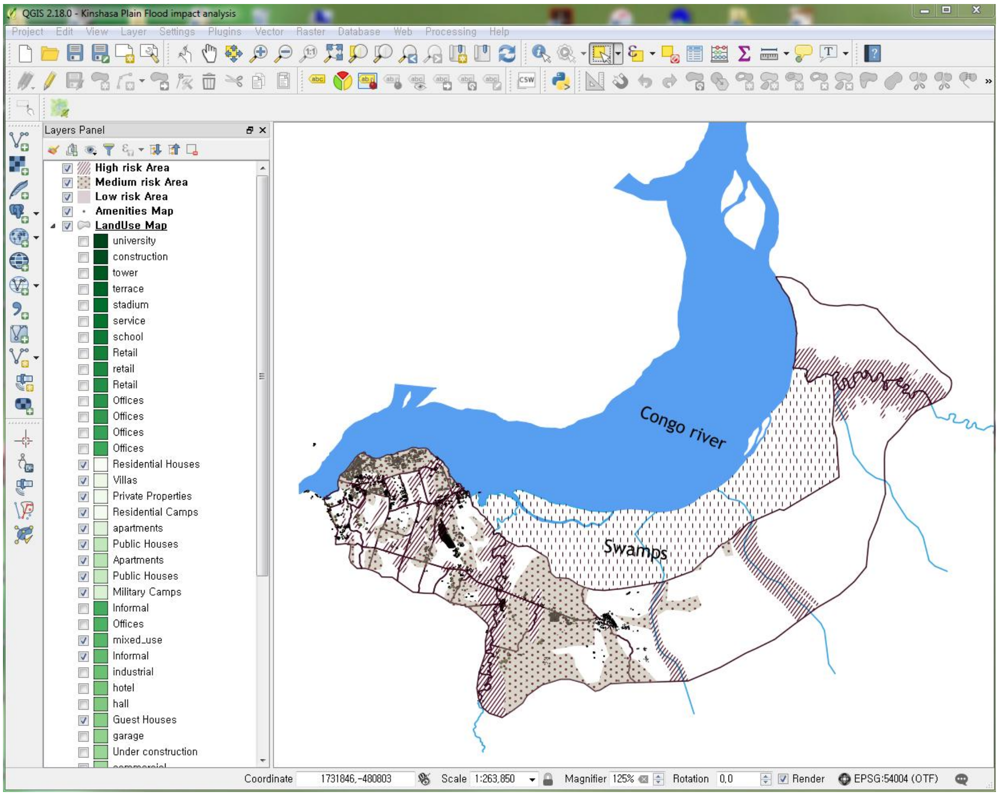

Figure 2. 6 Residential buildings Calculation (QGIS screenshot No 3)

Besides the interface screenshots provided, the implementation process is better understood in terms of input and output diagram illustrated in the figure 3.6 below.

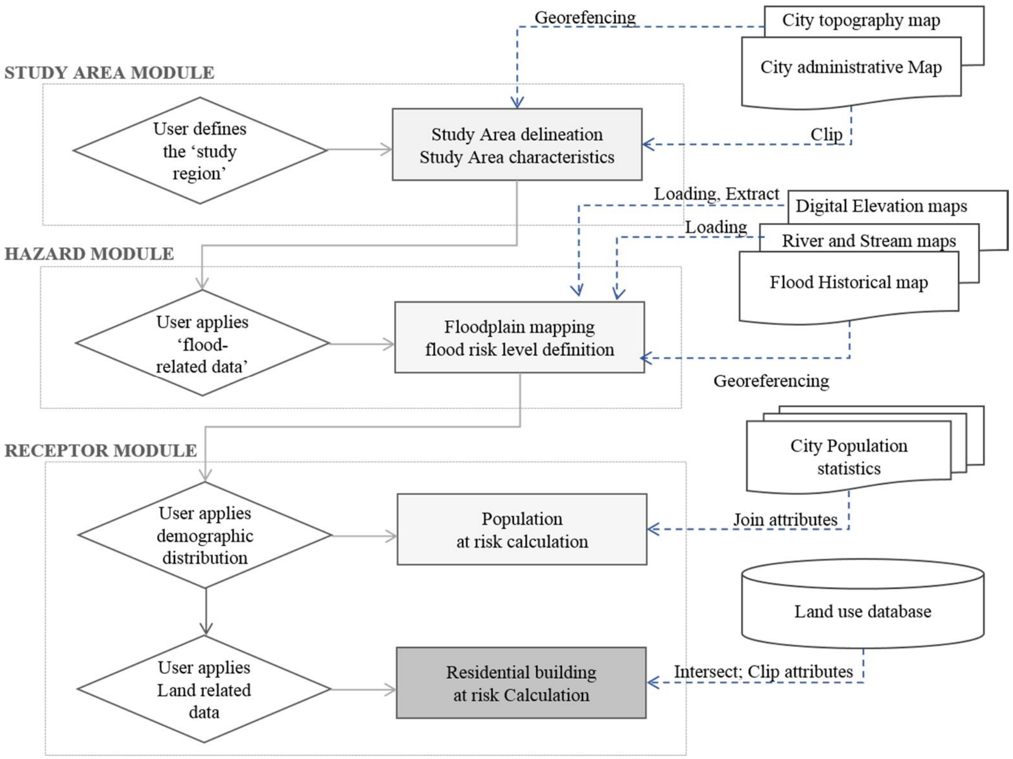

Figure 2. 7 Calculation Method Input-Output Diagram

2.1.3.2.2. Findings and Recommendations

With abundant rainfall and the presence of the Congo River as well as tributary streams, Kinshasa City has plenty of water resources. However, the availability of areas free from flood is increasingly becoming a challenge, particularly in the plain where the chaotic population density as shown in the figure 3.7 expands human activities nearby water bodies (streams, Congo River, and swamps) which don't take long to overflow and exceed the soil absorption capacity during strong thunderstorms.

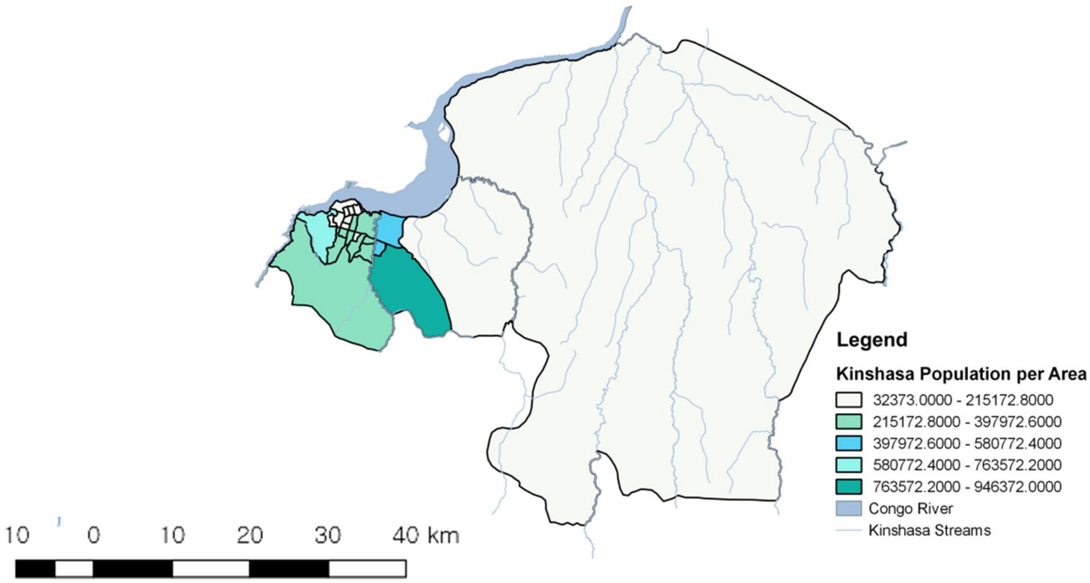

Figure 2. 8 7 Kinshasa Population Map

The calculated map of the population at flood risk revealed that although the plain surface represents only 4% of the total city area, it accommodates 75% of Kinshasa population based on 2013 statistics. The strong desire to quickly reach work places and city institutions explains largely the increasing tendency to settle within the plain. But, the lack of constructible lands drives high informal settlements within wetlands and nearby stream banks.

Flood-prone areas have been portrayed in the figure 3.8 which indicates that almost every town in the city, whether it is located in the low, medium or high risk zones, is exposed to flooding.

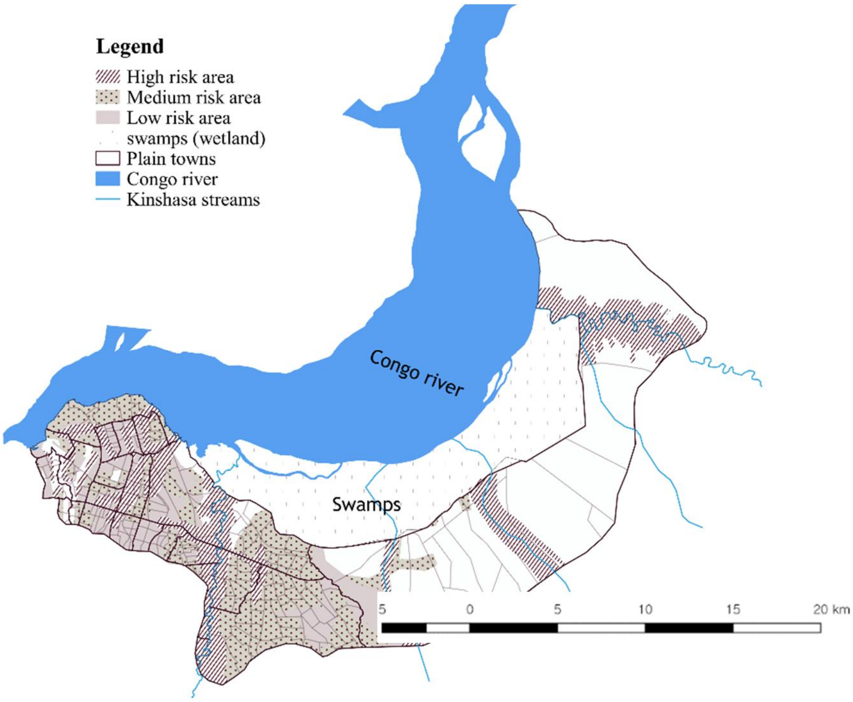

Figure 2. 9 Floodplains in the plain area of Kinshasa

The most common causes among those rising the flood in the region are the over spilling on tributary streams and the lack of adequate collectors for runoff.

The calculation of residential buildings pointed out that 50.5% of properties face a permanent threat of flood, with different risk levels depending on their location. Flood risk levels are classified in the table 3.2 after screening past researches, principally the guide of the bureau de reclamation of 1988.

The fact that the plain area is frequently saturated with floodwaters reinforces the urgent need to adapt vulnerable buildings. Properties in low risk zones require minor improvement of openings such as windows, doors, or more rarely air vents, sewer outlets, and drains located below 0.9 meter. The installation of temporary protection devices would be a great asset to prevent water from entering inside the house.

Buildings within medium and high risk level zones require permanent retrofit measures as they are highly exposed. With the climate change predicting stronger flood events, the 28.8% of buildings within high risk zones will only become desolation if they are not already.

Since now, all attempted strategies by individuals with little if not any help of local authorities to mitigate flood impacts within the region have not been successful. In long term, there are incredibly expensive compared to the cost of investing in resilient measures.

Table 2. 3 Flood risk level classification

Classification of Flood Risk Level	Low	Medium	High
Flood depth	< 0.91m	0.91 to 1.5m	> 1.5m
Ratio of Residential Buildings at risk	7,68%	14%	28,82%
Recommendation for decision makers	Minor building improvement	Permanent flood retrofit measures	

The provided flood risk map of residential buildings can serve as a detailed informative tool that urban planners and homeowners to undertake measures to cope with floods. An adaptation strategy calls for more appropriate flood retrofit solutions for buildings at risk to be found so that they can resist extreme events. This is where the research is heading to, in the next section.

2.2. Multi-criteria Decision Support Methods

2.2.1. Multi-criteria Decision Analysis Overview

Many problems that we handle every day are resolved intuitively. But, when they become too large and involve conflicting objectives, the desire for a formal procedure to make the decision-making process transparent, that is to say, clear and fair enough, comes out.

Multicriteria decision analysis (MCDA) methods are suitable for the purpose, particularly if the problem involves several alternatives with criteria that can be analyzed against each other. Providing techniques to find a compromise solution between diverging parameters, they have been developed to support the decision maker in their unique and personal decision process. The best example is the cost or price, which is easily in conflict with the quality or safety. For instance, a cheap car is rarely the most comfortable or safest one. But with a consideration of various criteria, MCDA methods can reconcile different parameters through the evaluation of their criteria to meet decision maker predispositions.

The key advantage of MCDA is the incorporation of subjective information also known as preference information of stakeholders to any problem where an important decision needs to be made (Ishizaka & Nemery, 2013). This fact brings the user to the center of the process, which matches the research goal.

MCDA methods have evolved with time since the 1960s. The steady increase of academic publications has fostered the development of specific methods for different types of problems in the decision-making process. The broad availability of free software, spreadsheets containing method computations, *ad hoc* implementations and Smartphone applications has made MCDA more accessible in an array of disciplines, ranging from environment management and geography to informatics and mathematics.

A poor problem definition often leads to a poorly structured decision to be made (Mabin & Beattie, 2006). On the other hand, the decision problem needs to be clearly identified to meet an effective solution.

The nature of a decision is complex. Roy (1981) defines four main types of decision problems people face in daily life. The first one is the choice problem, implying the selection of a ‘single' best option out of many alternatives. Then comes the sorting problem which categorizes options into ordered and predefined groups to regroup similar behaviors or characteristics. The third one is the description problem, describing options and their consequences. It is usually conducted at the beginning of a decision analysis for a better problem definition. Finally, it comes the one we are interested in, the ranking problem. It orders options from best to worst as a result of scores or pairwise comparisons, and few several other techniques (Itami & Cotter, 2012).

Additional decision types proposed by other researchers are often variants of the four decision problems if not a combination of them. The elimination problem introduced by Bana e Costa (1996) for instance is a particularity of the sorting problem and the elicitation problem, a variation of the description decision problem.

Considering a large number of decision problems, several methods have been developed to help policy makers to achieve their goals rapidly. There is not a perfect way to solve a decision problem. Each method has its limitations, particularities, and perspectives. Guitouni, et al.(1999) supported by Ishizaka et al. (2013) suggested that one way for choosing the right method is to look at the required input information and the outcomes. They drew the following table, which mostly focuses on ranking and choice problems.

Table 2. 4 Require inputs for MCDA ranking and Choice methods

Inputs	**Effort Input**	**MCDA method**	**Output**
Utility function	Very HIGH	MAUT	Complete ranking with scores
Pairwise comparison on a ratio scale,	↑	ANP	Complete ranking with scores
Pairwise comparison on a ratio scale		AHP	Complete ranking with scores
Pairwise comparison on an interval scale		MACBETH	Complete ranking with scores
Indifference, preference, veto		ELECTRE	Partial and complete ranking
Indifference and preference thresholds		PROMETHEE	Pairwise preference degrees and scores
Ideal option and constraints	↓	Goal programming	Feasible solution with deviation score
Ideal and anti-ideal option		TOPSIS	Complete ranking with closeness score
No subjective inputs required	VERY LOW	EA	Partial ranking with effectiveness score

The analytic hierarchy process (AHP) highlighted in Table 2 is the MCDA method we are going to use to derive most suitable solutions for a given house based on multi-criteria factors. Developed by Saaty (1970, 1980), AHP is a structured technique to organize complex problems related to ranking decisions. The following are the three basic steps that need to be implemented through the process.

1. Problem structuring
2. Priorities calculation
3. Consistency check

As all MCDA methods, the problem is structured according to the hierarchy where the top element is the goal. The second and the third levels represent the position of criteria and alternatives successively. Within a four levels problem structuring, the second tier comprises categories or aspects of criteria. Then come sub-criteria at the third level and retrofit options at the lowest level.

There exist three types of priorities in AHP. Criteria priorities related to the importance of each criterion, local alternative priorities concerning the importance of an alternative according to one particular criterion and the alternative global priorities, intermediate results between local and criteria priorities. (Ishizaka & Nemery, 2013).

Priorities are calculated based on the pairwise comparison, a technique consisting of comparing a criterion or an alternative to other measures or alternatives including it. The comparison relies on the linear 1-9 scale illustrated in Table 2.3. It has been the most applied, as many researchers have argued in its favor.

Table 2. 5 Saaty's 1-9 fundamental Scale

Linear Scale	Degree definition
1	Equal importance
2	Weak
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong importance
8	Very strong plus
9	Extreme importance

AHP has been applied to various studies related to flood risk management, mostly to delineate flood zones at risk through the evaluation of criteria related to flood factors such as land-use, drainage, density, soil type, precipitation or rainfall, slope, and elevation. (M.Kordi, 2008; Harrison & Qureshi, 2003; Lawal, et al., 2012; Yahaya, 2008).

AHP has also been associated with the generation of decision support systems (DSS) on natural resources and environmental management. A decision support system or matrix acts as a robust tool for decision makers by providing qualitative aspects of the alternatives along with quantitative criteria to derive priorities. In 1982, Saaty et al. used AHP to compare options for managing high-level nuclear waste which is a complex problem requiring more than one criteria to be evaluated. Similarly, recent researchers have applied AHP for ranking issues, construction projects and sites (Itami & Cotter, 2012; Montgomery, et al., 2012).

Although many researchers have focused on the land use planning and conservation of floodplains, few efforts have been made regarding building protection alternatives. This can be explained by the world primeval focus on mitigation approaches rather than adaptive solutions for buildings.

For a long time, the first approach to reducing or eliminate the flood threat to buildings was to reinforce the protection of surroundings, by constructing floodwalls or dams. More studies were driven towards flood impacts reduction, thus excluding strategies for building retrofitting. With the recent shift towards adaptation approaches to cope with the climate change, efforts are rising to develop proper DSS for flood retrofit alternatives at building scale (Harper, 2015).

2.2.2. Flood Retrofit Measures Screening

Willis (2014) stated that "Ideally, the best approach to flood risk mitigation is to simply not build in a flood zone or occupy an existing structure in a flood-prone area” (p.2). Indeed, this tends to be easier said than done. People lives within floodplains, it is a fact. Moreover, they are aware of the flood risk involved and try to protect themselves. The way to cope with flood disaster highly depends on society differences. Capacities to fight against flood impacts and efforts to implement retrofitting measures are related to social groups, whether they are poor or wealthy, men or woman, young or old, autochthonous or not, etc. While some homeowners struggle to relocate out of their neighborhoods and escape from floods, others are trying to find ways to live with the water.

There are multiple ways to prevent the risk of flooding. Community responses usually involve constructing defense walls or levees to inundation pathways. Meanwhile, individuals have the possibility to undertake many structural and non-structural measures to mitigate floods at building scale.

Many researchers have constructed an umbrella of several measures for buildings regardless of their function. The US Federal management agency has listed six groups of retrofitting methods for homeowners to consider in rebuilding or preventing floods (FEMA, 2014). The six measures are Elevation, relocation, demolition, wet flood-proofing, dry flood-proofing and barrier systems. ‘Elevation’ involves not only raising the building lowest floor above the flood depth, but also relocating critical systems to higher positions. Eventually, the first floor of the building and the basement if there is any, are filled or left to serve as the house storage. ‘Relocation' basically refers to moving the house to a free flood area.

Within high-risk zones with heavy frequent floods, the cost to repair a building can sometimes exceed the value of the structure itself. In this case, FEMA (2014) argued that there is no better option than the ‘demolition' of the house or its abandon, particularly when it has been harshly destroyed from floods.

While ‘wet flood proofing’ consists of allowing water in the building with the use of water resistant materials at the floodwater level, ‘dry flood-proofing’ group comprises all measures to prevent floodwaters entering the building and damage it.

The use of membranes and sealants such as waterproof coatings, impermeable membrane, supplemental layers of masonry or simply the reinforcement of building envelope and foundation can make surfaces of the house impermeable to floodwaters.

Finally, ‘barriers', deployable or permanent, are used to prevent water damage to the building. Deployable barriers, also considered as a dry flood proofing technique, are positioned at vulnerable openings of the house (windows and doors).

Permanent barriers can be assimilated to levees in the sense that they protect the house from exterior, in a form of a floodwall. However, they require less space than levees while almost providing the same level of protection.

The use of equipment as flood retrofitting strategies has been mentioned by other researchers (YeonSunwoo, 2012; Yahaya, 2008). Water removal equipment such as sump-pump and back-up generator can be of a great utility in the basement during flood events. In addition, backflow valves can be used to protect potable water from contamination of septic or wastewater return in the pipe. Cost effective resilient measures such as the use of permeable paving or water-friendly concrete may help lowering flood impacts.

The table 2.6 below comprises the 12 most common retrofitting alternatives at residential property level from precedent studies. Measures such as relocation and demolition have been excluded from the research scope because they do not promote an adaptation effort against climate change impacts and future floods events. Another unsuitable alternative is the relocation of the structure. How can possibly a building be moved within a dense urban area? Also, levees are not viable options as it is not an easy task to gather the required amount of sand to form a consistent flood protection in metropolitan cities.

Remaining strategies have been grouped following two flood risk mitigation approaches. The risk avoidance and risk ignorance are not resilient options; thus, they are not included in the scope of recommended strategies.

Table 2. 6 Common retrofitting measures at building scale

Mitigation	Retrofit solution	Building element	Explanation
	1. Relocate house utilities	Equipment	Relocate to upper floors
	2. Elevate the house	Structure	Elevate the lowest floor above the flood level
	3. Flood damage-resistant materials 4. The use of membranes and sealants 5. Permeable surfaces	Material	Use flood-proofing materials, permeable paving, flood membranes and sealants
Risk limitation	6. Permanent Barriers 7. Temporary barriers	Structure	Flood walls outside the building
	8. Infill lowest floor such basement or 1st floor	Structure	Fill the floor permanently

	9. The use of Pump, back-up, backflow valves 10. The use of flood vents	Equipment	Use back-up generator and pumps in basements, use of vents at openings
Risk acceptance	11. Reinforce building envelop 12. Reinforce foundation	Structure	The reinforce building walls, windows and foundation

2.2.3. Existing Decision Support Frameworks

The growing awareness of the need for decision-makers to quickly choose appropriate measures without neglecting any flood related decisive aspect has encouraged researchers to develop comprehensive framework and decision tools.

At property-level, spatial information remains at the source of any flood analysis, from the estimation of flood impacts to the assessment of preventive actions to take. Within suggested frameworks, spatial data-sets have been increasingly used as external source to visualize the interrelationship between location characteristics and hazard consequences. However, exploring how spatial knowledge can be converted into MCDA metrics for retrofitting evaluation has not gained much attention among precedent studies, constituting a gap of knowledge for the academic corpus.

Two tendencies are arising among decision support approaches. The first framework method involves the use of MCDA within the GIS environment in order to calculate flood impacts associated with the risk level. (Generino, et al., 2014; Ouma & Tateishi, 2014; Imtiaz, et al., 2012; Fadlalla, et al., 2015). Many researchers have attempted to weight through GIS flood related criteria received from expert opinions or homeowners' preferences. Although they tend to use common data such as rainfall, digital elevation map, zoning map, soil, slope, population density, drainage or land-use maps for the weighting process, they differ in the choice of the MCDA methods contained in the table 2.2 to rank priorities and derive different risk levels of high scored factors. As the flood risk level has to be calculated through a simplified methodology, the first approach is not adequate given the research objective.

The second framework approach pushes the analysis scope beyond flood impacts by evaluating retrofit measures. Federal agencies around the world, especially the US federal management agency (FEMA), have provide owners with informative tools and flood-proofing techniques to help them decide appropriate measures for their properties. (FEMA, 1998; FEMA, 2001, FEMA, 2007). However, the big portion of the work remains to the owner to compare on his own different techniques given his the house location.

As an effort to remediate, New Zealand research centers (NIWA et al, 2012) developed various tools including flood impact reduction matrix form, which basically allows the owner, along with the help of experts in field to eliminate undesirable measures through yes or no applicability check. Another interesting tool is related to the preference such as aesthetics concern of the owner, accessibility, onsite and offsite flooding concerns. As much help these two forms can provide decision makers, the absence of quantifiable metrics makes the judgment consistency impossible to be assessed. Participants would have to rely on their own experience and ingenuity.

Few researchers went furthermore by using MCDA to obtain a ranking of resilient solutions for buildings within flood-prone areas. Harper (2015) for instance, used the FEMA decision making matrix (DSM) based on building, social, economic and environmental aspects to derive priorities among retrofitting alternatives. Then, after changing the DSM weights, he evaluated alternatives using a modified version of Saaty's AHP, highlighting the fact that analysis results closely depend on the ratio assigned to each aspect of the matrix.

Not the only there is a lack of spatial consideration in FEMA and Harper suggested frameworks, their problem structuring lead to a lot of uncertainties when assigning a preferred score to a particular criterion. For instance, if more than two criteria are assigned the same score based on the scale definition, their total average would probably be similar, which is actually an inaccurate priority derivation.

Furthermore, once the judgement matrix has been completed, a consistency check is performed to detect possible contradictions in the entries (Ishizaka & Nemery, 2013) as the human nature is often inconsistent. This is because a respondent of the questionnaire could have a vague definition of the problem, insufficient information or less concentration when comparing criteria. The lack of consistency check simply induces an uncompleted matrix and illogical judgement (Generino, et al., 2014).

2.3. Summary

Evaluating the extent of flood and determining potential impacts to buildings have always required the manipulation of information from different sources to extract useful metrics and assess retrofit alternatives. As spatial data are not always available, the use of GIS is, therefore, essential as it provides a way to assemble data and quickly visualize outcomes. Precedent researchers have suggested various approaches to calculating the risk of floods, but most of them require a considerable amount of input data that are not always within easy reach.

Throughout the first section of the chapter, a simplified methodology based on georeferencing has been suggested. The method, prioritizing only crucial information to obtain desired results, consists of assigning real world coordinates to paper-based maps. Then, by overlaying different datasets, the extent of flood impacts on residential buildings are calculated. An implementation of the process was carried out through the focus area case study, the plain of Kinshasa, to ensure the effectiveness of the suggested calculation method.

The second section of the chapter did a review of multi-criteria decision analysis methods as well as current retrofit measures at building level. Finally, a comparison of existing decision support frameworks was drawn, to emphasize the need to develop a new framework considering spatial information in the decision-making process.

Chapter 3. Decision Support Framework Development

3.1 Framework Aspect, Alternatives and Criteria selection

3.2 Retrofit decision support framework development

3.3 Framework Efficiency Discussion

3.3 Summary

The third chapter explores the development of a new framework given the lack of spatial consideration in precedent studies. Aspects, alternatives as well as criteria, derived from previous researchers are submitted to decision makers for a review. Then, the process to obtain priorities is drawn along with requirements prior the implementation of the framework.

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3.1. Retrofit Aspects, Alternatives and Criteria Selection

The selection of flood retrofitting aspects starts with a deep understanding of urban resilience factors to which they are related. Precedent studies have often defined resilience as the system ability to recover quickly from toughness or its capacity to cope with changes. It often explains how individuals, communities, and business manage to live (withstand and recover, adapt) with multiple shocks and stresses and how they realize opportunities to transform their environment development.

United Nations (UN Habitat, 2015) defines disaster resilience as the thinking that encourages a holistic view of the urban system, 'the one that seeks to understand the interconnected nature of a city's spatial plan, physical assets, socio-economic and environmental dimensions. A breakdown of individual part of the system would make a metropolitan area more vulnerable to the hazard.

Many disaster management agencies and researchers have suggested decision support matrices to weight flood aspects related to the urban system. (FEMA, 2014; YeonSunwoo, 2012; Harper, 2015). FEMA, for instance, applied ratio metrics to the building, social, economic and environmental aspects to be incorporated into a DSM for a practical alternatives evaluation. The spatial aspect left aside; the building aspect was weighed 60% more important than the three others (Economic-10%, Social-10%, and Environmental- 20%. It was justified as if the building is unable to withstand the flooding effects; then all retrofit efforts are veined. In a changing world where there is no unique solution for every building at flood risk, some people may wonder why the building aspect should be the most important while the cost of affording such structural modifications are their biggest concern.

As an effort to balance the weight based on the decision maker's preferences and to incorporate spatial characteristics, a survey was conducted to derive the priority of each aspect according to the flood retrofit goal. Six respondents completed the questionnaire (R_1-R_6), the homeowner of the house case study in chapter 3 and five engineers of Archi-Lab, an architecture firm of Kinshasa City, DRCongo. It came out that the economic aspects scored higher with 30%, followed by 23% for the spatial dimension and 22% for building characteristics. 14% was given to social and 12% to environmental aspects. There are represented in the following table.

Table 3. 1 Survey results of aspects weighting

	Owner	R 1	R 2	R 3	R4	R 5	sum	Average	Priority ranking
Spatial	25%	20%	25%	20%	30%	20%	140%	0,23	2
Building	10%	30%	20%	25%	20%	25%	130%	0,22	3
Social	20%	10%	15%	15%	10%	15%	85%	0,14	4
Economic	40%	30%	25%	30%	25%	25%	175%	0,29	1
Environment	5%	10%	15%	10%	15%	15%	70%	0,12	5
Total	100%	100%	100%	100%	100%	100%	600%	1	

After obtaining the weight of aspects, the next step is to derive from precedent studies, criteria related to suitable retrofit alternatives at the property level. The following question is the primary drive of the criteria screening process: is the criterion 'c' of the alternative 'n' effective for the particular aspect 'k'? Here, the effectiveness can switch to another degree definition according to the explanation in Table 2.6 below.

Table 3. 2 Alternative criteria definition and judgment scale

Aspects (k)	Criteria(c)	Explanation	Scale (1 to 9)
Geospatial aspect	Flood level and duration	Degree to which the flood level and duration impact on the measure	1= No impact 9= High
	Soil type	Performance degree of the measure given the soil type (permeable vs. nonpermeable)	1= Low 9= High
	Construction life	Degree to which the measure functions given structure age (existing vs. new building)	1= Low 9= High
	location design features	Degree to which the measure performs based on design elements (number of stories, columns, leveling, etc.)	1= Low 9= High
Building aspect	Debris Control (C_{11})	Degree of which the measure controls debris accumulation from flood waters	1=No at all 9= Full control
	Structural reinforcement(C_{12})	Degree to which the measure reinforces the building structure (Foundation)	1=No at all 9=Full reinforcement
	Envelope bearing capacity(C_{13})	Degree to which the measure protects walls, windows, and other openings	1=No at all 9=Full protection

	Utilities protection(C_{14})	Degree to which the measure protects critical systems during and after flood event	1=Not at all 9=Full protection
Social aspect	Recovery time (C_{21})	Time to recover after a flood Impact	1=Long 9=Less
	Aesthetics (C_{22})	Degree to which the measure integrates the surrounding landscape	1=Not at all 9=Full integration
	Accessibility (C_{23})	The accessibility into the building after implementing the measure	1=Age/ability limit 9=All users
	Impact on surrounding properties (C_{24})	The degree to which the measure impacts on nearby properties	1= High impact 9=No impact
Economic aspect	Space change (C_{31})	The degree of building space change impacts on the building value	1=Significant change 9=No change
	Cost Vs. value of building(C_{32})	The cost of the measure compared to the building value	1=Low 9=High
	Skill level(C_{33})	The skill level required to perform the work (Medium= Owner capability)	1=Highly skilled 9=Anyone
	Implementation duration Cost (C_{34})	Time required to implement the measure weeks=1~52; days=1~7, hours< 24 hours	1= Weeks 9=Hours
Environment aspect	Floodwater friendly(C_{41})	The degree to which the measure integrates floodwaters (works with water)	1=not at all 9=Complete integration
	Waste and Pollution contribution(C_{42})	The degree to which the measure contributes to the pollution and waste	1=High 9=No contribution
	Climate Change adaptation(C_{43})	The degree to which the measure adapts for future events (recovers quickly, withstands)	1=not at all 9=Complete adaptation

Spatial and building characteristics were extracted from information obtained through GIS, to constitute the geospatial group containing four main criteria. They consecutively express the degree at which the inundation risk level and duration impacts on the measure, the degree of the alternative performance given the soil type (permeable vs. non-permeable soil), the alternative applicability given building age (whether it is an existing or newly constructed house) and the building design elements to consider.

In the building aspect group, criteria express the degree to which the alternative would control debris of floodwaters; reinforce the structures, and protect the house openings (windows and doors) as well as utilities. They are all related to non-combustible buildings, the most dominant in urban areas.

In the Social group, criteria such as the time to recover after a flood event, the aesthetics of the measure, the accessibility to the building and impact on surrounding properties are all related to the way people interact with the building once the alternative is implemented.

The four most common flood retrofit factors associated with the economic aspects are the cost of the implementation compared to the building value; the cost of the implementation duration, the cost of the desired skill level and the cost of space lost after the measure is implemented.

Finally, Criteria in the environmental aspect group concern about the waste and pollution that floodwaters contribute to once the measure is carried out. Another important criterion is the degree to which the strategy integrates flood and function well with waters instead of fighting against them.

3.2. Retrofit Framework Process

From above, the framework has been shaped to obtain a more accurate result by going back to the roots of methodologies and calculate all over again. First, a spatial calculation of flood risk is processed separately through QGIS. Then, the spatial information obtained is integrated into the framework process to precisely define the problem, set suitable retrofitting alternatives and derive criteria along with socio-economic & environment considerations. By doing so, the generated flood risk map can be reutilized to address autonomously other community issues arising from floods. Also, the fact that flood-related criteria highly depend on the respondent subjectivity, they cannot serve as an informative tool for different building scenarios. On the other hand, the process would undoubtedly lead to a tailored solution.

The Multi-criteria analysis of alternatives and criteria is entirely conducted through Microsoft Excel spreadsheet based on Saaty AHP methodology as explained in the previous section. The consistency ratio of the matrix is checked, and alternatives are ranked.

Finally, a sensitive analysis is applied to the problem parameters to ensure the coherence of the final decision. Through the analysis, different "what-if" scenarios can be visualized which are helpful to observe the impact of variation on criteria to final alternative rank (Syamsuddin, 2013). System inputs that cause significant uncertainty in the output should, therefore, be the focus of attention to increasing the effectiveness of alternatives ranking.

The next figure just reiterates the explanation of the developed decision support framework and the process to get optimal retrofit solutions for a single house based on its spatial configuration.

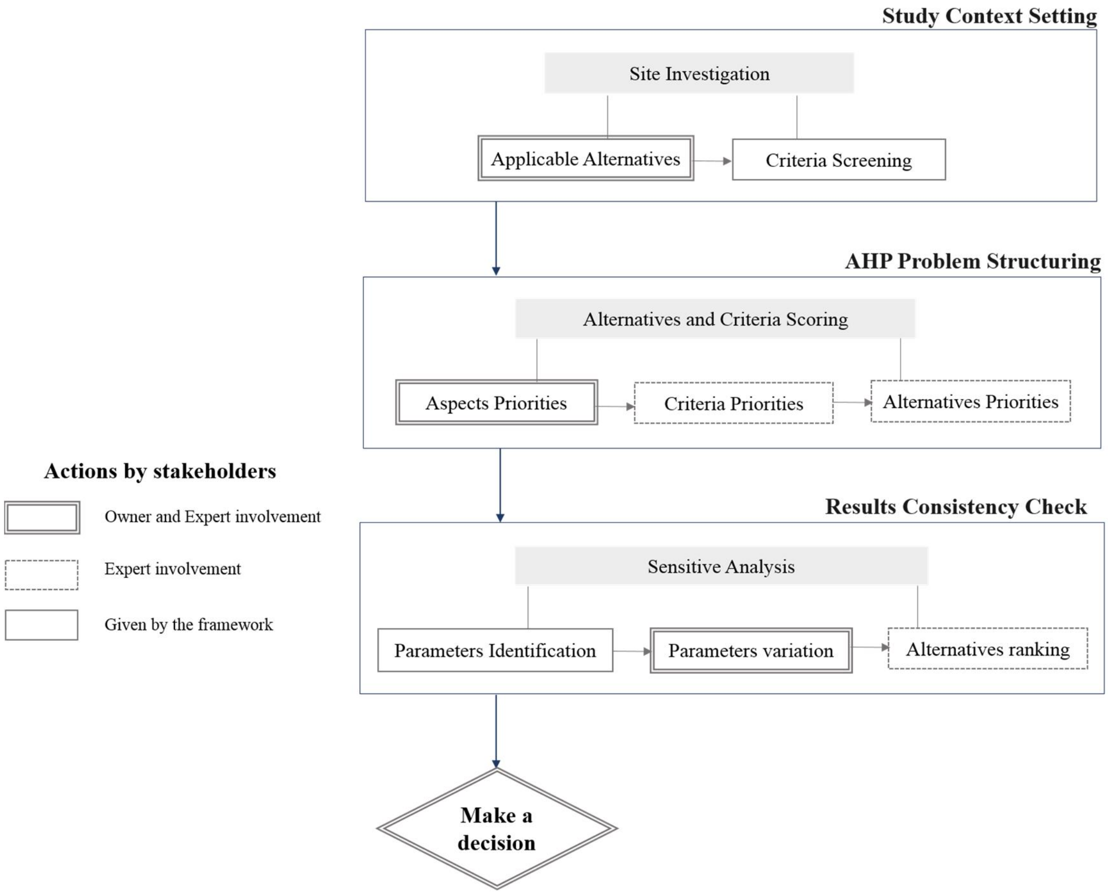

Figure 3. 1 Decision Support Framework Process

3.3. Framework Efficiency Discussion

As mentioned above, the framework implementation calls for the full involvement of the primary decision maker, the owner of the property. When working in collaboration with expert, the owner helps to eliminate uncertainties related to some measures and set applicability for others. The owner judgment, although subjective, must be taken into consideration to understand the relationship without the building and its users. Consequently, this relationship reflects itself into the measure performance.

As the analysis through AHP is mostly quantitative, previous researchers underlined the fact that experienced owners or experts in fields including construction managers, surveyors, and geotechnical engineers were required. However, the framework process, as explained in this research, is entirely conducted through Microsoft Excel spreadsheets, which suggests that no specialist knowledge is needed to carry out the evaluation. The fact that the framework process is easy to be implemented ease the integration of individuals in the decision-making process.

For the academic corpus, the use of spatial elements in the analysis is the great asset of the approach. Without this consideration, decision makers would spend much time gathering data, based on past events and site investigation. With a data inventory through GIS, the research goes fast and more accurate. Another fact is the conversion of obtained information into the multi-criteria decision matrix to evaluate retrofitting measures. The transformation approach relies on the fact that the more alternatives are analyzed under different perspectives, the better they can be understood. Geospatial elements are not only a gain of information from another aspect, but there are at the origin of any natural disaster.

Besides the comparison with previous methods, the framework efficiency analysis can also be conducted through the cost-benefit approach by comparing the damage of floods with a current measure or without any, to the implementation of alternatives suggested from this research. However, with data on the flood depth-damage curves and economic variables, such comparison is not within this research scope.

3.4. Summary

Although many researchers and federal agencies have suggested aspects to evaluate retrofit measures, the four typical drives among them remain the following: building, social, economic and environmental.

As the primary objective of this dissertation is the integration of spatial information in the decision-making process, spatial characteristics of the building and flood have been extracted through GIS and then, converted into metrics to assess suitable retrofit alternatives. The weight of each different aspect, along with criteria, were submitted to a panel of six experts for a consistency review.

Finally, a new decision support process was established along with a discussion on the efficiency. The efficiency analysis portrays the need for a spatial-based decision support framework as well as the process requirements for users.

Chapter 4. Decision Support Framework Application

The fourth chapter gives a clear picture of how to obtain appropriate flood measures for a given home, from its localization to the selection of suitable solutions through the AHP considering spatial, environment and socio-economic related factors.

4.1. Study Context Setting

From the obtained GIS flood risk map, a house case study has been chosen for a thorough understanding of the retrofit framework process. The property is located in the Mont- Ngafula town, within the plain area which has been regularly flooded at a medium risk level. An illustration is shown in the picture 4.1 below.

On November 12th, 2016, a strong thunderstorm coupled with the overflow of Kalamu stream was reported, causing nearly million in damage, electric power interruption for days and economic activity loss with many fatalities. As much destruction was attributed to the thunderstorm, other towns in the city had been exposed to similar if not stronger climatologically flood risk in the past.

Many urban policies have been suggested in the past to secure building assets in the region. However, the unstable socio-political environment of the country has provided little room for their implementation. With the consideration of global warming, housing conditions will only worsen.

A site investigation has been effectuated to apprehend flooding problems associated with the house. From observations, the saturation of soil in the region does not ease the filtration of rainwaters, particularly when impervious building surfaces (roofs and pavements) in upper elevated lands send runoff to the house soil that cannot absorb all of it.

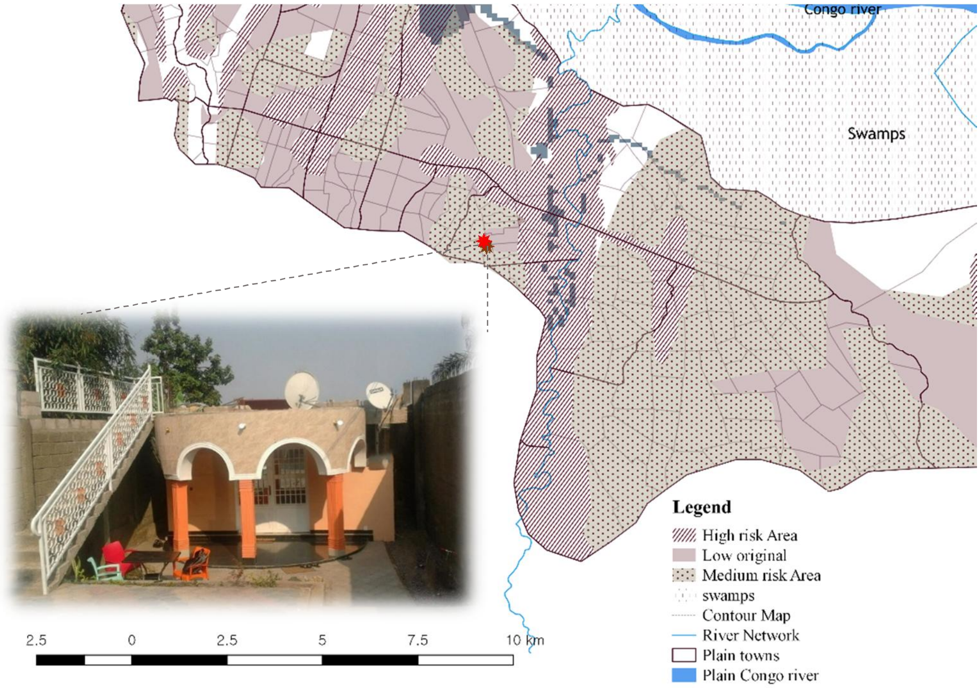

Figure 4. 1 Case Study localization

The house has been constructed with non-combustible materials, on a slightly sloped landscape. As the house is not directly accessible from the street, the ground leveling represents an obstacle for floodwaters to be adequately evacuated through the street water collectors.

Also, the enclosure prevents floodwaters flow at a certain level resulting in a "perfect bath tub" during heavy rain.

For a better understanding of flood impact on the building and a good visualization of applicable measures for the building based on surrounding, a 3D model was created from Sketch up Pro 2016.

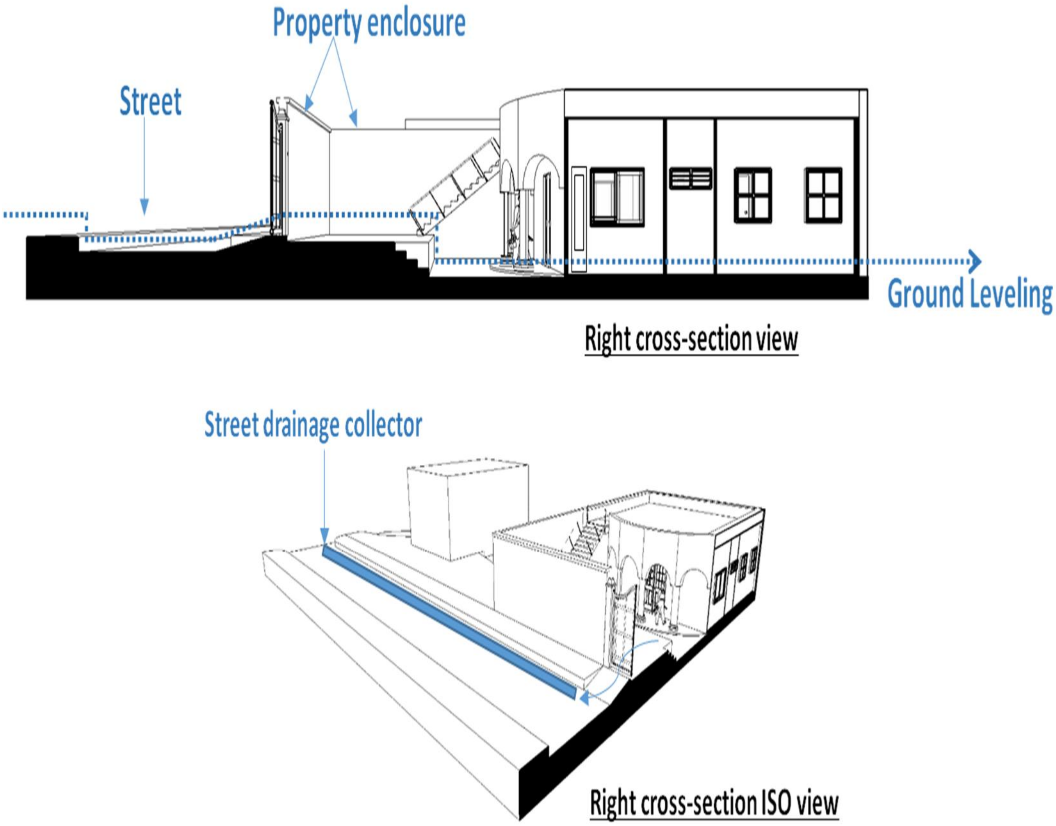

Figure 4. 2 House context 3D modeling

4.2. Retrofit Alternative selection

Given the building context, all current measures were screened by professionals based on aspects and criteria of the decision support framework. The selection of applicable measures is proceeded by elimination illustrated in the survey sheet below.

Table 4. 1 Survey sheet of measures applicability

Aspects	Criteria	Actual Situation/ Observations	Not applicable / concerns
Geospatial	Flood level and duration	1m<Level<2m; less than 6 hours	
	Soil type	Impermeable soil	Concerns for the use permeable surfaces
	Construction life	Newly constructed building	
	Location design features	one story; front columns, Enclosure, gently sloping landscape	Barriers, Pump, back-up, Flood vents are not applicable
Building	Structure reinforcement	Non-Combustible material	
	Building envelop Protection	Doors exposed	
	Utilities protection	Left side electrical cabinet	
	Waste accumulation control	Little to no amount of waste	
Social	Building accessibility	sloped ground, small children	
	Recovery time	Hours to 1 or 2 days	
	Building aesthetics		

	Impact on surroundings (Properties)	Properties on the left and right side	Concerns for House Elevation
Economic	Cost vs Building Value	Great concern about cost, different for each alternative	
	Cost of Skill level required	depending on the measure	
	Cost of time required	depending on the measure	
	Cost of space change and loss	depending on the measure	
Environmental	Climate change adaptation	depending on the measure	Concerns for other hazard types
	Floodwaters integration		
	flood waste and pollution Increase	depending on the measure	

In accordance with expert opinions, height alternatives were retained. There are grouped into three major scenarios.

- The elevate scenario comprises following retrofit alternatives:
  - relocate utilities - (A_1)
  - elevate the house - (A_2)
  - infill the lowest floor - (A_3)
- The flood-proofing material scenario includes:
  - the use of membranes and sealants - (A_4)
  - the use of permeable surfaces - (A_5) such as porous paving or concrete as well as
  - the use of resistant materials - (A_6)
- the structure reinforcement scenario consists of:
  - strengthening the buildings envelop-(A_7)
  - strengthening the building the foundation-(A_8)

4.3 AHP-based Alternative Evaluation

The second phase of the decision support framework consists of conducting an AHP analysis to derive priorities among retrofitting alternatives of the house case study. To begin the analysis, the problem has been structured as shown below into four levels respectively the goal, retrofitting aspects, criteria and alternatives.

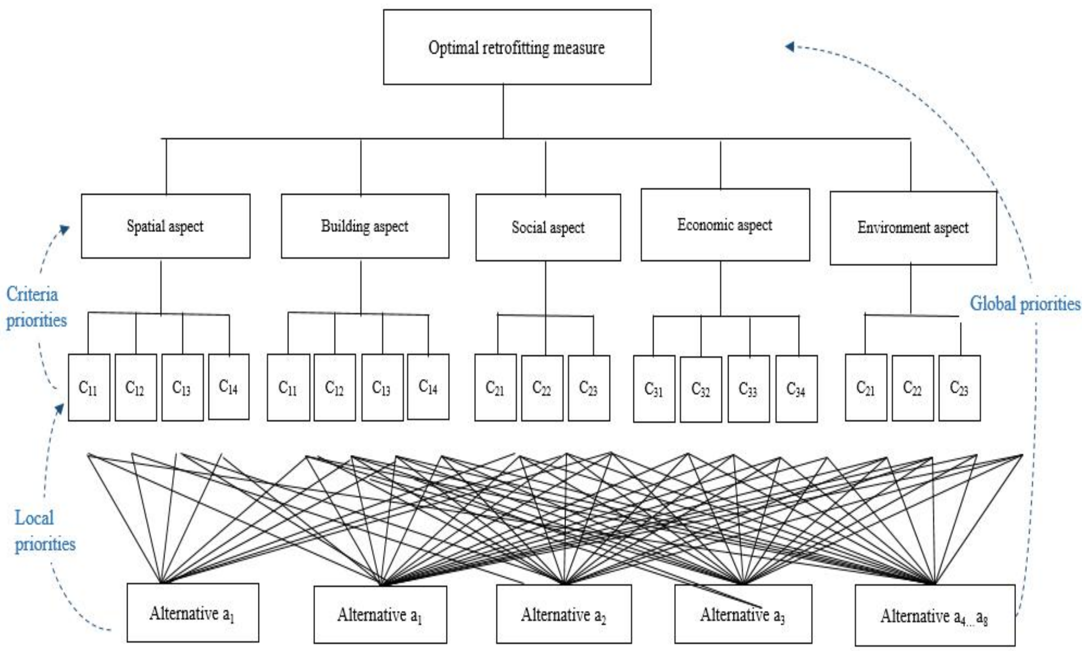

Figure 4. 3 AHP problem structuring

Then, criteria priorities have been derived based on experts' judgement. Compared one by one, criteria have been assigned a weight value within the range of 1 to 9 or the inverse, according to their importance with respect to the aspect group. Following matrices were obtained.

Table 4. 2 Priorities derivation matrices of Criteria according to each aspect

			Spatial aspects			
Criteria	C_{11}	C_{12}	C_{13}	C_{14}	Weight	Ranking
C_{11}	1	3	5	7	0.57	1
C_{12}	1/3	1	3	5	0.26	2
C_{13}	1/5	1/3	1	3	0.12	3
C_{14}	1/7	1/5	1/3	1	0.06	4
			Building aspects			
Criteria	C_{21}	C_{22}	C_{23}	C_{24}	Weight	Ranking
C_{21}	1	3	6	9	0.58	1
C_{22}	1/3	1	4	7	0.28	2
C_{23}	1/6	1/4	1	4	0.10	3
C_{24}	1/9	1/7	1/4	1	0.04	4
			Social aspects			
Criteria	C_{31}	C_{32}	C_{33}	C_{34}	Weight	Ranking
C_{31}	1	3	5	1	0.57	1
C_{32}	1/3	1	3	1/3	0.26	2
C_{33}	1/5	1/3	1	1/5	0.12	3
C_{34}	1/7	1/5	1/3	1/7	0.06	4
			Economic aspects			
Criteria	C_{41}	C_{42}	C_{43}	C_{44}	Weight	Ranking
C_{41}	1	3	5	9	0.57	1
C_{42}	1/3	1	3	7	0.27	2
C_{43}	1/5	1/3	1	5	0.13	3

C_{44}	1/9	1/7	1/5	1	0.04	4
Environmental aspects						
Criteria	C_{51}	C_{52}	C_{53}		Weight	Ranking
C_{51}	1	3	5		0.64	1
C_{52}	1/3	1	3		0.26	2
C_{53}	1/5	1/3	1		0.10	3

Once all matrices were completed, a consistency check is conducted to verify that there is not any contradiction in the provided judgment. With an average 0.02, that is to say less than 10%, the comparison is said to be consistent

After that, local priorities are derived, referring to the comparison between alternatives with respect to one specific criterion. When read vertically, the table below highlights the most effective alternatives given a single criterion and aspect.

Table 4. 3 Priorities derivation of retrofit alternatives according to each criterion

	Spatial				Building			
	c_{11}	c_{12}	c_{13}	c_{14}	c_{21}	c_{22}	c_{23}	c_{24}
a_1	0.157	0.157	0.157	0.231	0.071	0.024	0.331	0.023
a_2	0.231	0.231	0.033	0.033	0.033	0.331	0.231	0.047
a_3	0.331	0.331	0.024	0.024	0.048	0.231	0.157	0.032
a_4	0.033	0.071	0.331	0.331	0.106	0.157	0.048	0.070
a_5	0.024	0.024	0.231	0.157	0.024	0.033	0.024	0.105
a_6	0.048	0.106	0.048	0.106	0.157	0.106	0.106	0.222
a_7	0.106	0.048	0.071	0.048	0.331	0.071	0.071	0.163

a_8	0.071	0.033	0.106	0.071	0.231	0.048	0.033	0.336

	Social				Economic			
	c_{31}	c_{32}	c_{33}	c_{34}	c_{41}	c_{42}	c_{43}	c_{44}
a_1	0.231	0.048	0.048	0.048	0.157	0.157	0.157	0.045
a_2	0.033	0.071	0.033	0.024	0.033	0.024	0.033	0.036
a_3	0.024	0.331	0.024	0.033	0.024	0.033	0.024	0.024
a_4	0.329	0.106	0.071	0.331	0.331	0.231	0.231	0.331
a_5	0.158	0.033	0.106	0.231	0.231	0.331	0.331	0.230
a_6	0.071	0.231	0.231	0.157	0.071	0.106	0.071	0.106
a_7	0.048	0.157	0.331	0.071	0.048	0.071	0.106	0.071
a_8	0.106	0.024	0.157	0.106	0.106	0.048	0.048	0.157

	Environment		
	C_{51}	C_{52}	C_{53}
a_1	0.024	0.024	0.331
a_2	0.071	0.231	0.024
a_3	0.048	0.033	0.231
a_4	0.157	0.106	0.071
a_5	0.231	0.331	0.033
a_6	0.331	0.157	0.157
a_7	0.106	0.071	0.106
a_8	0.033	0.048	0.048

Finally, the global alternative priorities, intermediate values between the criteria priorities and the local priorities are calculated to obtain the ranking of alternatives with respect to the top goal. According to the result table 3.9, the relocation of critical systems is to the most applicable measure based on the importance degree of criteria as well as alternatives. However, it does not yet constitute the most retrofit solution as results may change under different scenarios.

4.4 Results Sensitive Analysis

The last phase of the framework process consists of conducting a sensitive analysis, to observe how the final ranking is likely to change. A gradual change is made on weight values of the problem variants, which happened to be the five aspects- spatial (Sp), building(B), social(So), economic(Ec) and environmental(En).

Previous weights obtained from the survey were as follows: Sp= 23%, B=22%, So=14%, Ec=29%, En=12%, based on the scenario where the cost is the most important aspect for the owner. Five more scenarios have been developed based on each aspect-driven analysis.

A mathematical model in the table below was created through simple operations in Excel spreadsheet to obtain a random distribution of weights over a scale of 100 once there is a variation of a single aspect ratio.

Table 4. 4 Random variation of Aspects weight

	Sp	B	So	Ec	En	Total
Input Weights	X1	X2	X3	X4	X5	
	$Y1 = \sum_{X=1}^{5}(X) - 100$ $Y2 = Y2/5$					$\sum_{X=1}^{5}(Xi - y2)$ =100
Output variables	X1-Y2	X2-Y2	X3-Y2	X4-Y2	X5-Y2	

- Spatial driven- scenario: Sp= 35%, B=20%, So=12%, Ec=27%, En=10%,
- Building driven- scenario: Sp= 20%, B=35%, So=11%, Ec=26%, En=9%,
- Social driven- scenario: Sp= 18%, B=17%, So=36%, Ec=24%, En=7%,
- Environmental driven-scenario: Sp= 17%, B=16%, So=8%, Ec=23%, En=34%,

The obtained results are presented in different charts of the next section.

Table 4. 5 Global priorities of retrofitting alternatives

	Spatial Aspects	**0.23**	**Building Aspects**	**0.22**	**Social Aspects**	**0.14**	**Economic Aspects**	**0.29**	**Environment Aspects**	**0.12**	**Global ranking**	
Alternatives	Weight	Average	Weight	Average	Weight	Average	Weight	Average	Weight	Average	Weight	Ranking
A_1	0.161	0.008	0.083	0.004	0.151	0.004	0.153	0.009	0.056	0.001	0.026	3
A_2	0.196	0.009	0.138	0.006	0.042	0.001	0.030	0.002	0.107	0.003	0.021	7
A_3	0.278	0.013	0.110	0.005	0.105	0.003	0.026	0.002	0.063	0.001	0.024	5
A_4	0.094	0.004	0.113	0.005	0.240	0.007	0.292	0.017	0.135	0.003	0.036	1
A_5	0.055	0.003	0.029	0.001	0.123	0.003	0.270	0.016	0.236	0.006	0.029	2
A_6	0.066	0.003	0.140	0.006	0.137	0.004	0.082	0.005	0.268	0.006	0.024	4
A_7	0.083	0.004	0.224	0.010	0.111	0.003	0.062	0.004	0.097	0.002	0.023	6
A_8	0.065	0.003	0.163	0.007	0.091	0.003	0.085	0.005	0.038	0.001	0.019	8

4.5 Findings and Discussion

The evaluation of height appropriate measures reveals that the use of membranes and sealants was the most efficient retrofitting alternative followed by the use of permeable surfaces and the relocation of utilities. The result is portrayed in the figure below.

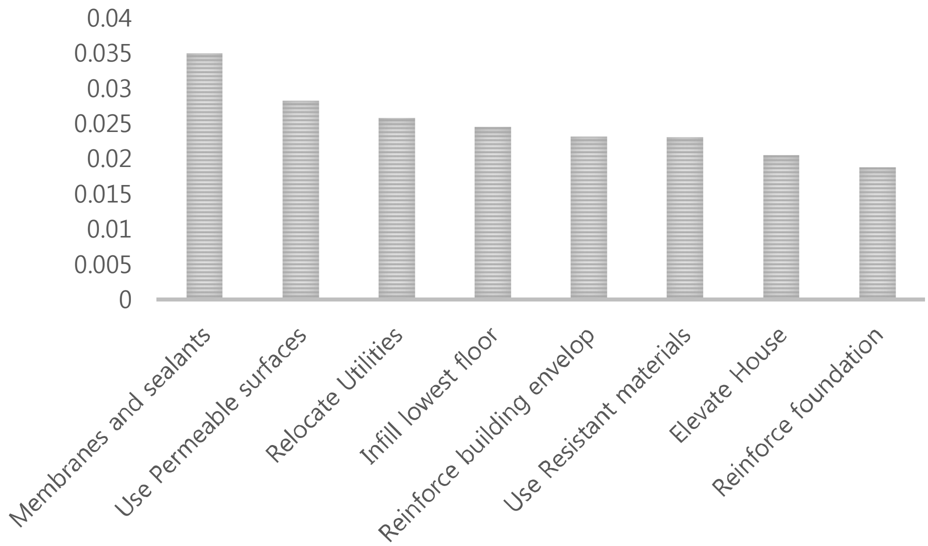

Figure 4. 4 Cost driven scenario results

Looking closely at the local priorities in Table 4.5, the use of membranes and sealants seems to be the most practical action to take as it provides full accessibility to the house with no additional cost for the space change and no impact on the surrounding properties. As the building is newly constructed, the alternative is the most cost-effective compared to the building value at the moment.

The use of permeable surfaces for pathways and areas lightly used was ranked second mainly because it is affordable given the implementation time and skill it requires. The most important criterion for this alternative is the integration of waters, coping entirely with flooding before, during and after the event. In Kinshasa, the cost of permeable brick pavers varies between 2 to 4% per m^2 that is 10 to 15% higher than ordinary pavers. With a life expectancy of 20 to 30 years, this measure would allow saving money saved from not treating surface runoff after floods.

The third-ranked alternative involves the relocation of the electrical system to an upper position to protect the house utilities completely. The alternative does not contribute to waste or pollution during severe events if the system is fully protected. Also, the cost of installation is relatively low compared to the benefit of safe energy use during and after flood events.

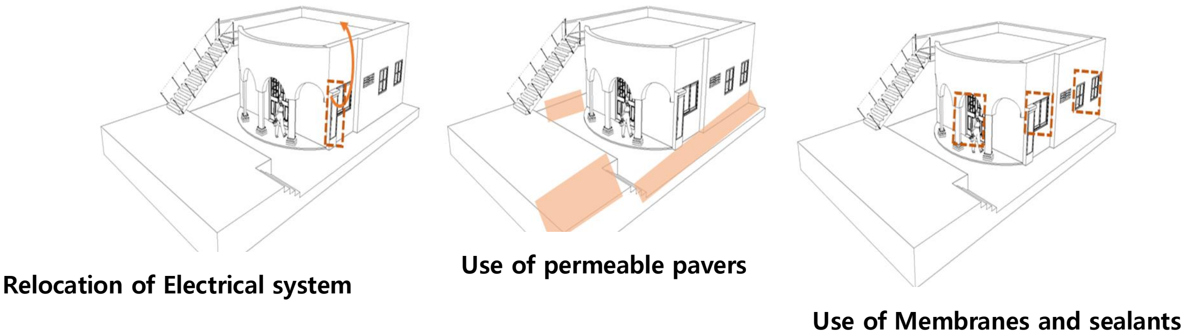

Figure 4. 5 Comprehensive proactive suggestions

The decision support matrix was cost-driven. More priority was given to the cost when assigning weights to each aspect according to the owner needs and available resources. An interesting fact in the comparison was to observe the alternative which involves the infill of the house lowest floor to be ranked in the fourth position.

Being located in the medium risk area with an impermeable soil, the impact associated with the level and duration of flood was one of the top priority of geospatial consideration for most of respondents. Also, the recovery time is immediate as the all house would be delocalized to upper grounds.

During sensitive analysis, an increase or a decrease in aspect ratio was expected to automatically change the ranking position of retrofit measures. Surprisingly, regardless of their orders, utilities relocation, the use of permeable surfaces and the use of membranes and sealants was always in the top four, while cost-prohibitive, time-consuming or aesthetically inappropriate strategies had low scores.

The use of membranes and sealants ranked higher in all scenario except in the environmental driven-scenario where instead, the use of permeable surfaces was the highest.

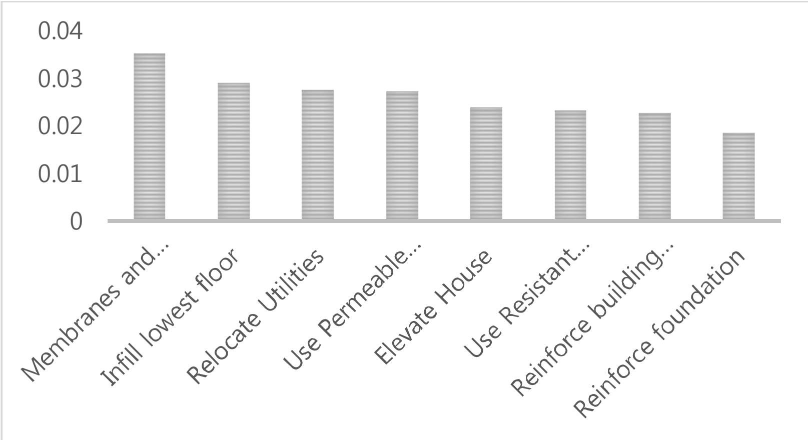

Figure 4. 6 Spatial-driven scenario results

The reinforcement of the building envelope ranked second in the building-driven scenario; which totally makes full of sense.

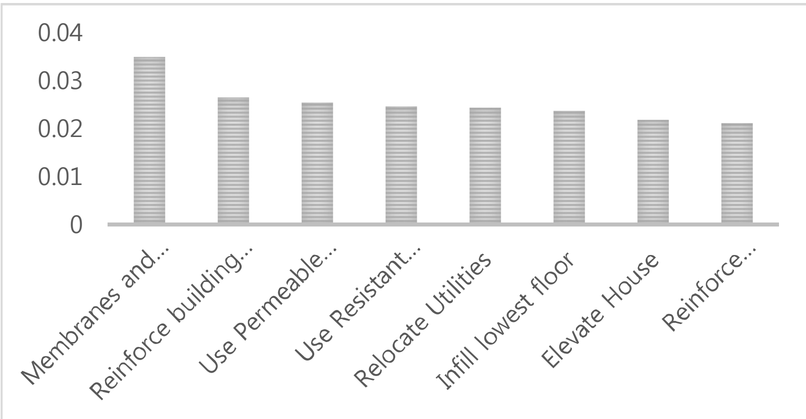

Figure 4. 7 Building driven scenario results

There was not any difference between social and cost-driven analysis, previously obtained. This fact only underlines the robustness of the framework.

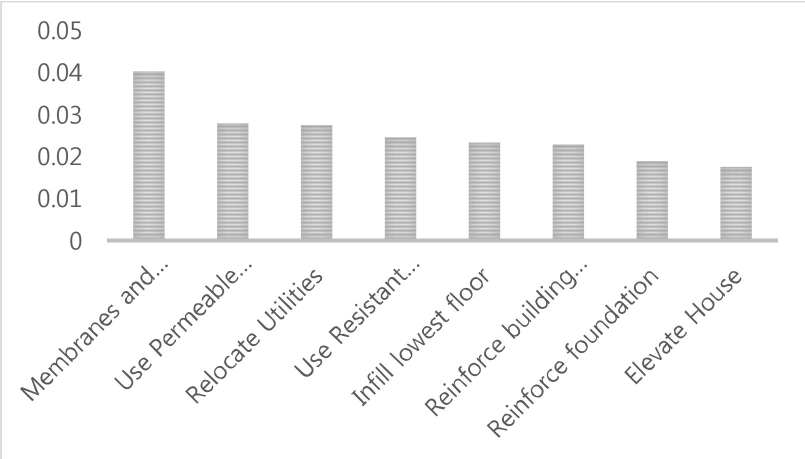

Figure 4. 8 Social-driven scenario results

Another alternative which requires attention is the use of resistant materials for the environmental driven-scenario. Followings figures illustrate results of the sensitive analysis based on each different scenario.

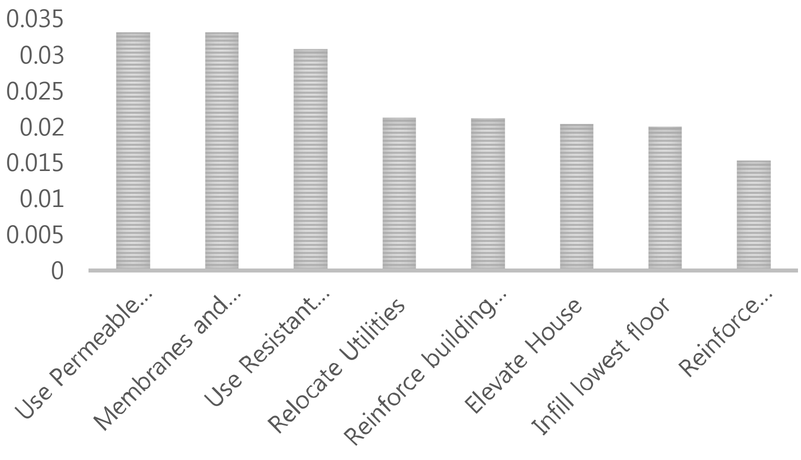

Figure 4. 9 Environmental- driven scenario results

The research has conducted a single case study, that is to say, one owner among

respondents. Although it is arguable that multiple case studies could have led to more informative outcomes for buildings with similar contexts, the geographic location being unique for any given building tends to suggest the contrary.
Perhaps, the question is not how many case studies have been conducted but rather how friendly the framework process has been to the respondent owner and experts.

It is evident that another owner would come up with a different ranking of aspects, and a building located elsewhere would certainly lead a different assessment of retrofit alternatives. This fact suggests that more efforts should be undertaken to improve the framework efficiency and reduce inconsistency in the judgment. Also, an extent of the variability should be limited to set the environment within which the framework is applicable.

4.6 Summary

The application of the decision support framework Process starts with the contextualization of the area to be studied. As much as the site investigation is essential at this phase, a screening of suitable alternatives along with the selection of criteria must be conducted with the help of experts before the evaluation of retrofit measures through AHP.

After obtaining AHP results, a sensitive analysis was carried out to test the analysis robustness. A final ranking was generated along with most appropriate solution given the case study. It has been suggested that the combination of the top three ranked measures namely use of membranes and sealants, permeable surfaces and the relocation of utilities would be the most appropriate solution based on a cost-driven scenario.

Chapter 5. Conclusion

5.1 Research Summary

5.2 Contributions

5.3 Research limitations and further studies

This last chapter of the research gives a brief summary of the all process from the problem definition to the application. Then it highlights valuable contributions of the research outcomes along with limitations encountered during the process. Finally, directions of further studies are given, to ensure a good continuation of academic progress.

5.1. Research Summary

Strategies on how to manage exposed buildings within populated floodplains are as old as the history of human settlement. Facing the challenges of climate change, urban cities are trying to take appropriate resilient measures to cope with stronger upcoming flood events with all available resources. However, it is far from being effective enough.

In an effort to adapt for the future, the main objective of the present research is to provide a decision support framework which connects spatial characteristics of buildings and flood with the AHP-based multi-criteria decision analysis in order to provide tailored retrofitting solutions for properties at risk.

The first step of the framework consists of creating a simplified flood impact calculation approach in Quantum GIS as a means to fill the gap of spatial data deficiency in the process.

Then, with enough spatial information of a given building within a flood-prone area, the site investigation is conducted in order evaluate all applicable retrofit measures. Through AHP, quantitative metrics of flood resilience aspects along with qualitative criteria of flood strategies are analyzed to rank the most appropriate alternative for the property.

At the last step, the final evaluation is subjected to a sensitive analysis to confirm its robustness and find out which variable causes the largest deviation in the analysis. Then the final ranking of retrofitting alternatives is provided.

The effectiveness of the DSF process is checked through a case study of a residential building at medium flood risk level within the plain of Kinshasa City. It has been found that relocating the critical system to an upper position of the house, along with the use of permeable pavers and resistant material for openings would be a perfect combination to combat flood risk and adapt the house for future events.

Additionally, the sensitive analysis has revealed that the change in aspect's ratio slightly introduced the strategy of reinforcing the building envelope, an alternative that imperatively needs to be considered in the decision-making process.

5.2. Contributions

The suggested decision support framework can serve as an expert tool in the decision-making process of flood retrofitting measures for buildings at risk. The consideration of Spatial information would help decision makers and practitioners to define more precisely feasible flood strategies and criteria for a given home. With the owner preferences at the center of the process, better perspectives can be explored during the analysis.

The simplified flood calculation approach through QGIS contributes to fill the gap of data availability, particularly in developing countries where it is still the case. The generated digital flood risk map can be used as a detailed informative tool for a good land-use management.

During strong flood events, shelters can be easily identified and proper measures quickly taken for exposed structures. Also, flood hazard zones depicted can help determine to what extent flood insurance is required for homes or buildings located near streams and rivers. Not only individuals and particularly homeowners are actively involved in the decision-making process of flood retrofitting measures of buildings, planners and managers would also be able to correspond site characteristics with flood appropriate solutions

As for the case study, various community programs have been developed to reduce flood consequences on buildings. Being inadequate, many of encouraged practices against flooding have failed to protect neighborhoods by becoming themselves part of the problem. (Rupture of Kinshasa water reservoir). This fact is mainly due to the lack of technology transfer after as majority of local projects have been conducted by official development assistances (ODA) as a mean to help developing countries.

With the quantitative framework, however, communities would have a tool to access the risk at which they are exposed to and become proactive in the floodplain management.

Measures are not always affordable, government in the country which has tried to address water stress, could take advantage of this framework to suggest incentives for owners and enhanced the city renovation, particularly for informal settlements.

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5.3. Research Further Studies

A major outcome of the simplified GIS calculation approach was the flood risk level of buildings within floodplains, mainly obtained from the digital elevation map and historical flood sources. However, with more input data such as the water velocity or river discharge, the digital flood risk map obtained would be more informative concerning the time and amount of floodwaters to reach exposed areas.

The building inventory data would also integrate buildings characteristics such material, structure, number of floors, making them accessible without necessarily a site investigation. This would allow an effective cost-damage analysis of flood impacts and an assimilation of the house case study results to other buildings with similarities.

On the other hand, most of applicable retrofitting strategies in urban areas have been proved by precedent studies to be efficient and some of them even cost-effective. However, there are still uncertainties about recent developed adaptive alternatives such as the use of amphibious or floating foundations, which are still cost-prohibitive for some regions of the world. The use of local resources could lower the cost and make the technology available for all.

Additionally, further researches on the cost-benefit of investing in the optimal retrofit measures are primordial.

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