USE OF DIGITAL ELEVATION MODEL IN A GIS FOR FLOOD SUSCEPTIBILITY MAPPING: CASE OF BUJUMBURA CITY

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Abstract
In many parts of the world, flood is one of the most expensive and devastating natural hazards especially in urban areas. A significant and violent rain fell down on Bujumbura city and its surroundings in the night of 9th-10th February 2014 during less than three hours where rivers crossing the city overflowed and flooded the plain bordering the Tanganyika Lake. This study aims to exploit morphologic properties of Tanganyika Lake watershed to detect and map areas that are most vulnerable to flooding during extreme precipitation events. A Digital Elevation Model (DEM) was integrated in a Geographic Information System to compute morphometric factors influencing susceptibility to flooding. A weighted overlay analysis was carried out on these causal factors to distinguish areas according to their susceptibility to flooding. Main damages of February 2014 were located and superimposed to the resulting map of flood prone areas in order to validate the results.

Keywords: *DEM, GIS, flood susceptibility, overlay weighted analysis, Tanganyika Lake watershed, Bujumbura city*

INTRODUCTION

Flash floods are rapid surface water responses to rainfall, produced by extreme precipitation events of short duration affecting a limited area. The potential for flash flood casualties and damages is increasing in many regions of the world due to the social and economic development bringing pressure on land use (Marchi et al., 2010). They cause extensive disruptions to a diverse range of living, working, societal, and spatial environments, the raison why they are reported to be one of the deadliest and most expensive natural hazards worldwide. Flood damages do not only depend on precipitation amounts but are also a consequence of geomorphological factors and human influences (Maruša et al., 2014) and in this study, the main attention is particularly concentrated on geomorphological factors to flooding. Flash flood events can be characterized by the amount of rain responsible to their occurrences and their duration. For some authors, floods happen when accumulated precipitation are larger than 100 mm in few hours of the triggering rainfall (Gaume et al., 2009; Llasat et al., 2008), but for some other authors, flood episodes can last up to 34 h (Marchi et al., 2010). Hydrological response-time to extreme precipitation is usually smaller than 6 h (Georgakakos and Hudlow, 1984), but it can be up to 16 h (Marchi et al., 2010).

According to the national contingency plan of Burundi, flood risk is considered as the most threatening compared to other natural hazards. For example, in 2007, two million people affected by heavy rains and floods were in need of emergency assistance, 50-80% of crops were destroyed and seven provinces out of seventeen were declared at disaster. Historically, national strategic places such as the international airport, the port of Bujumbura, the industrial zones as well as divers infrastructures have been subject to floods. Flooding also proliferates epidemics of waterborne diseases such as cholera or dysentery. In our area of interest, Bujumbura city, the municipalities along Lake Tanganyika are the most at risk due to their location in floodplain. In this study, we focus on the damages of the 9th to 10th of February 2014 event where the cost in infrastructures was evaluated around 4 million dollars. Indeed, this episode affected national roads, bridges, schools, markets and agricutural infrastructures, water supply and electrical networks and caused several households destruction. Furthermore, this event made about 20,000 people homeless, 77 deaths and important infrastructure damages.

The identification of flood prone areas is becoming a more challenging and pressing issue around the world (Di Baldassarre et al., 2013a,b ; Sivapalan et al., 2012). Obviously, both public decision-makers and private leaders are in need of the development of new tools and strategies not only for prompt risk identification but also for mapping over large regions. The scientific community made significant efforts to improve techniques for the detection of areas exposed to the flood hazard. In particular, several hydrologic and hydraulic modelling approaches are regularly developed and used for practical applications (Grimaldi et al., 2013; Merz et al., 2007). In recent studies (Barbara Theilen-Willige et al., 2015; Bates et al., 2003; Brandt, 2005; Cook and Merwade, 2009; Tate et al., 2002), topography data in the form of a Digital Elevation Model (DEM) are used in hydraulic, hydrologic or hydrodynamic modelling, and in mapping flood-prone areas or flood inundation extent. DEMs can be derived from contour surveys, cartography, photogrammetry, interferometry and radar imaging and their horizontal resolution and vertical accuracy (Siddharth and Merwade, 2015) are important parameters when chosing a convenient DEM product. Nowadays, the United States and other developed regions of the world have resources to collect LiDAR (Light Detection and Ranging) data with horizontal resolution of as high as 0.5 m, and vertical accuracy in the range of 0.15–0.25 m (Aguilar et al., 2010; Giglierano, 2010; Smith, 2010). However, many parts of the world are still relying on coarser resolution, less accurate DEMs derived from Shuttle Radar Topography Mission (SRTM) and Interferometric Synthetic Aperture Radar (IfSAR) to make flood inundation maps (Sanders, 2007). A considerable number of studies in the past have emphased on the importance of DEM resolution in flood inundation mapping, concluding that higher resolution DEMs produce more accurate flood maps (Brandt, 2005; Marks and Bates, 2000; Omer et al., 2003; Werner, 2001). Furthermore, the vertical accuracy of a DEM doesn't influence the results at its own but is affected by its source, sampling techniques and interpolation techniques (Bater and Coops, 2009; Burrough, 1986; Chaplot et al., 2006; Heritage et al., 2009; Merwade, 2009). The DEM used in this study is described in the data section.

This study used DEM data to exploit morphologic properties of Tanganyika Lake watershed in order to detect and map areas prone to flooding during extreme precipitation events. Thus, an orthophotograph dataset of the study area and an existing topographic map were used to locate infrastructures such as bridges, roads, settlements that may be affected by flooding occurrences. The findings show that DEM analysis allows getting satisfactory results for flash flood hazard assessment.

STUDY AREA AND DATASET

Description of the studied area

Bujumbura city is located at 3° 22′ 32″ South 29° 21′ 33″ East, around the North-East corner of Lake Tanganyika in the West of Burundi. Seeing its location is a floodplain of Imbo region, flood hazard can not be studied without considering its surrounding topographic environment and hydrologic regime. In fact, the borders of the city are eastwardly limited by foothills of Congo-Nile crest which is a mountainous chain. In addition, rivers crossing the city originate from the mountains and have to go a long distance to and through the floodplain. The figure below illustrates that Bujumbura city elevation is inferior to 1000 meters while the top of the surrounding areas can reach 2500 meters. An example of topographic profile from A to B (see Figure 1) depicts that natural reality caracterised by rugged terrain. Furthermore, the distribution of relief faithfully reflects the climatic diversity. The wettest area is this Congo-Nile Ridge where annual rainfall average varies between 1600 and 2000 mm while lowlands of Imbo receive annual rainfall less than 1200 mm and often even less than 1000 mm. Similarly, average temperatures in Congo-Nile Ridge hover around 15°C with temperatures as low as 0°C but 23°C in the plain.

Flood events have been occuring inside the city where are established most of the economic and administrative activities of the country. Seeing that the eastern high regions are the rainiest in Burundi, heavy precipitations are accompagnied by land degration by soil erosion and land slides in the steepest slopes.

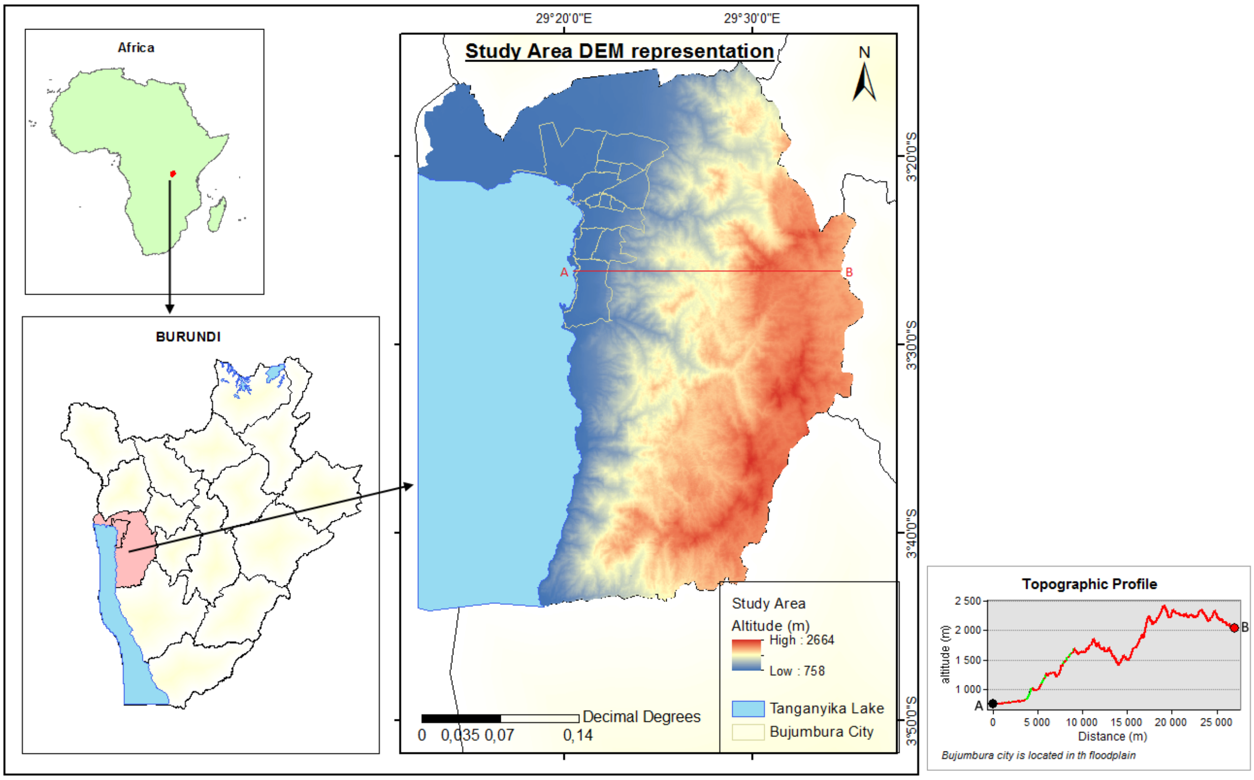

Figure 1. Location of the study area and topographic profile

Data

We exploited a Digital Elevation Model (DEM) from BCG (Bureau de Centralisation Géomatique) which is a National Center of Geographic Information of Burundi. This DEM was acquired in 2012 and underwent a stereoscopic rectification with Socet Set Software by Fit Conseil. Although there are data such as ASTER DEM available for free download, this one was chosen for its spatial resolution of 10 meters. While this product covers the whole country, the portion we are using was clipped according to the extent of the study area with ArcGIS. In addition, apart from an existing topographic map, an orthophotograph with 50 cm of resolution was used for the validation of the results. Both topographic map and orthophotograph helped to locate the main damages of February 2014 event to check whether the affected areas are found in the mapped flood prone areas.

METHODOLOGY

There are many causative factors of flash flood and their use varies from one study area to another (Pedzisai, 2010; Pramojanee et al., 2001 and Yalcin and Akyurek, 2004). Sometimes, data availability determines the factors to consider in a certain study. The present work aims to extract morphologic properties that can play a role in influencing flash flood occurerences under certain triggering factors such as extreme precipitation events. We focus our attention to natural geomorphologic preparatory factors to flooding. From the DEM, slope gradient, drop raster, height level and aspect maps are derived. These allow to determine areas which relatively receive more quantities of water input than the surrounding environment during precipitation period in general and flood event in a particular. These areas likely to be affected by flooding are located in flat surfaces, areas with slope inferior to 10 degree, and altitude inferior to 920m (the lowest altitude being 758 m) in our study zone. These potential causative factors are aggregated and weighted to derive the map of susceptibility to flash floods represented in lowest to highest classes. In order to compute the map, weights are determined where every weight is a percentage of influence from each factor. The most important criterion is given the highest percentage as arbitrary weight. Furthermore, inside each parameter, rating values representing degrees of influence are considered (e.g.: within slope gradient criterion, areas with slope egal to 0 degree are distinguished from those with 0.1 to 5 degrees for example: their influence depends on these rating values). This approach is summed up in the flowchart of Figure 2.

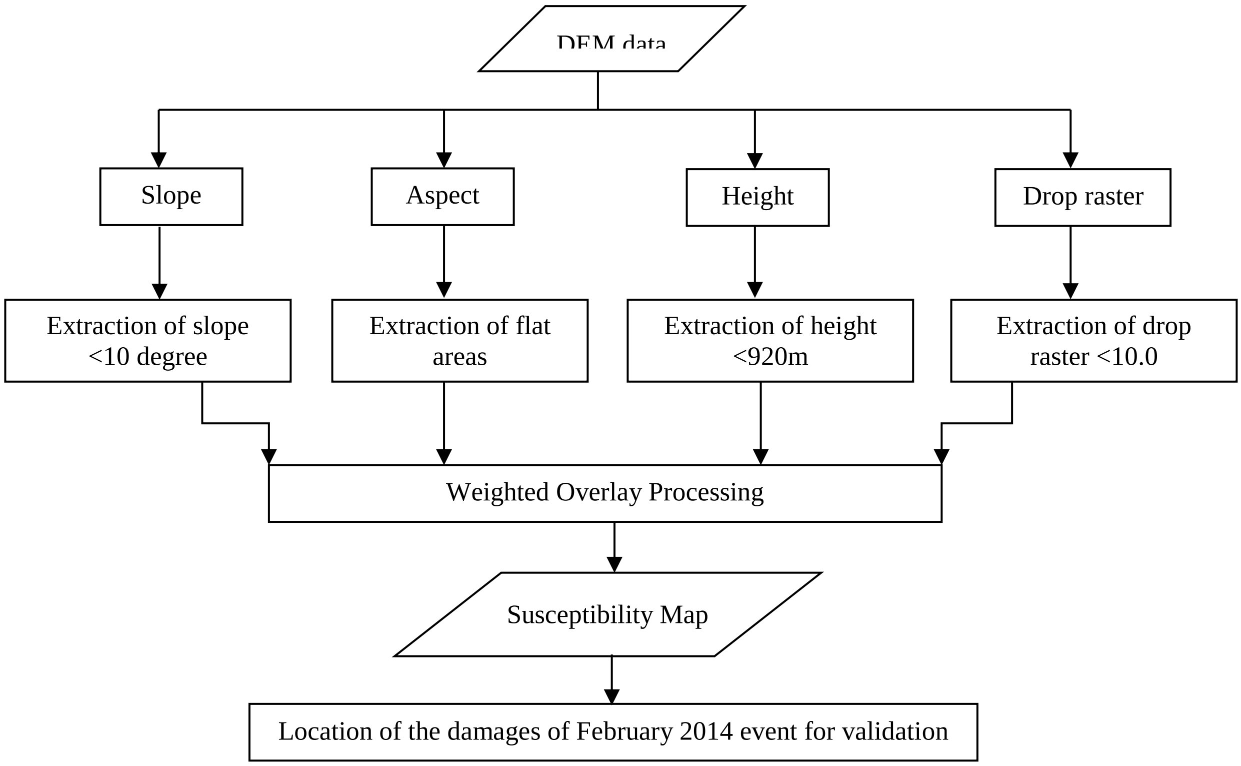

Figure 2. Methodology flowchart

RESULTS AND DISCUSSION

In order to detect flood-prone areas with causal morphometric factors superimposing over each other, a weighted overlay processing was carried out.The resulting map (Figure 3) shows classes of susceptibility to flash floods. The North-East of the city is the most susceptible to flooding: this is due to the fact that it is characterized by flat areas with slopes inferior to 3°. The drop raster factor shows a ratio of the maximum change in elevation from each cell along the direction of flow. Its values in these areas revolve around 0, which indicates that the change in elevation is almost null. The extracted aspect from the DEM helps us to explain why that zone is more susceptible to flooding: its value -1 indicating flat areas dominates in that zone. These most prone-areas cover residential areas and farm lands. This reveals also the vulnerability of economic infrastructures such as roads, bridges and other public and private settlements. As it can be observed on the map the susceptibility varies from higher in the West to lower in the East. Thus, the susceptibility to flooding decreases as the elevation increases eastwardly.

This map helps us to explain historical meteorological events that have been reported to be devastating in the city. Here are some exemples. In 1983 and 1986, severe floods around the main river crossing the city, Ntahangwa, caused huge losses valued at over one billion Burundian francs. Damages included:

- the destruction of homes in neighborhoods Buyenzi in 1983 leaving many families homeless;
- and in 1986, the deterioration of machinery and equipment of the industrial zone and destruction of factories like COGERCO (cotton factory), RAFINA (oil factory), BRARUDI (brewery), the port of Bujumbura and others companies were affected;

In 1991, floods were recorded at Kajaga and caused significant exodus of the affected population. In the years 2006 and 2007, severe floods have severely affected most of the country. Muha and Kanyosha rivers also regularly cause flooding but less catastrophic than the previous.

All these locations are found in the mapped flood prone areas. However, this study used some located damages of the February 2014. These have been collected by the governement of Burundi and reported in document that not only presents the economic losses but also maps and describes the most affected areas during the event.

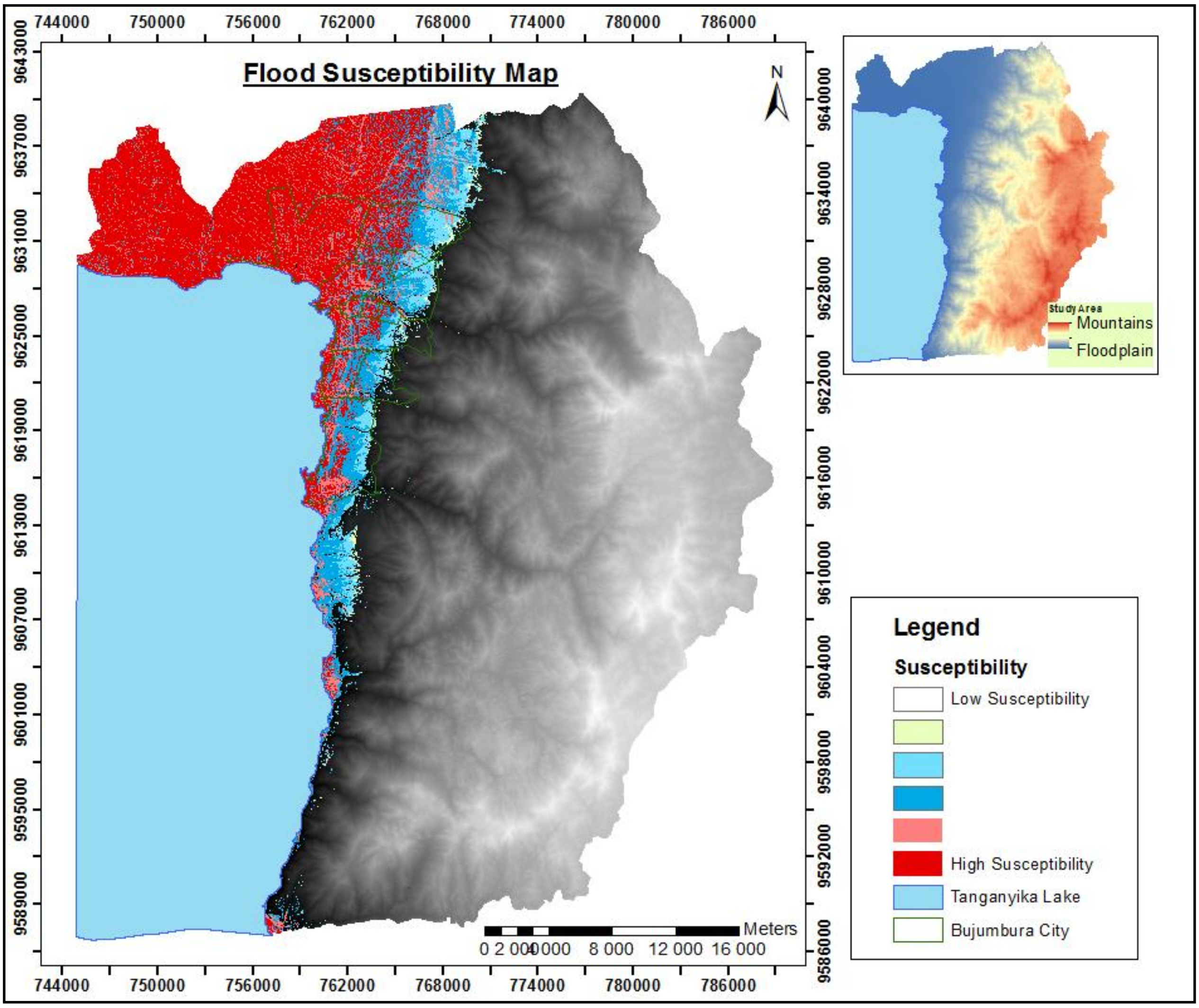

Figure 3. Flash flood susceptibility map: detection of prone-areas

In order to validate this map, a layer of reported damages of the February 2014 flood event was superimposed on the susceptility map to locate them. As mentioned in the introduction, this meteorological event caused important economic losses and was the consequence of 80 mm of rainfall during 2 hours and half (from 8h to 9h30 PM). In some part of the world such as arid and semi-arid regions, this precipitation would have caused less harm. But the violence of the flood was aggravated by soil saturation and thus the low infiltration due to previous rain occurrences. Thoughout the country, the precipitation of February 2014 were clearly above average, particularly at Bujumbura with 153 mm compared to an average of 100 mm. In addition, more than the half of February 2014 precipitation fell down the same day in less than 3 hours.

Figure 4 locates the damages categoried in roads/bridges, schools, markets, farm lands and drinking water supply. This map reveals that most of road/bridge damages were not located in the floodplain. This was due to the sediment loads from the Congo-Nile Ridge and land slide occurrences during the episode. However, other damages were related to flooding. For example, Table 1 shows selected schools and markets affected by the flood. It is also obvious that the triggering heavy rain was concentrated in the North and North-East of of the city. It is not usual that the flash flood occurs in the whole city at the same due spatial variability of the rainfall distribution in time.

The intensity or frequency of hazards, exposure and relative vulnerability accentuate the consequences of floods. Seeing that some natural factors such as topography, rainfall rate are difficult or even impossible to prevent, there are other human influences such as constructions in floodplains or too near to roads, lack of maintenance that can be easily addressed. Significant impacts of the February 2014 flood are associated with areas that are known as having a deficit in rainwater drainage. Therefore, this natural predisposition to flood hazard can be overcome purposeful actions in order to build a sustainable and resilient city.

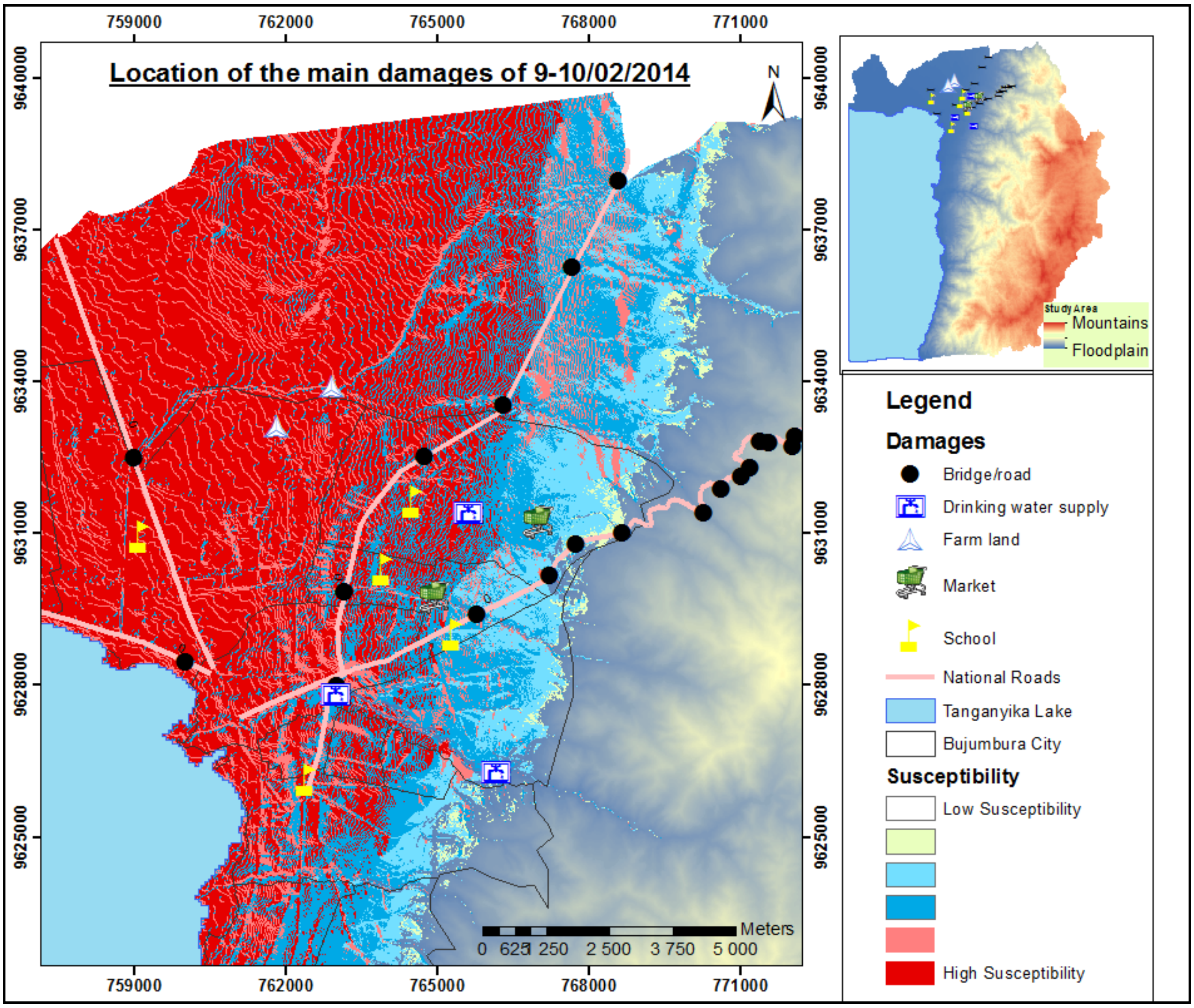

Figure 4. Location of main damages of the 9th – 10th February 2014 event

This following table reveals the fact that these locations are definitely inside the flood prone areas.

Table 1. Examples of the affected locations(markets and schools) and the flood impact

Entity	Flood level	Sediment deposit	Nature of impact
Kamenge market	Less than 50 cm	10 to 50cm	Some constructions destruction
Gatunguru market	More than 1 m	More than 50cm	More than 100 stands destroyed
EP Kinama III	Less than 50 cm	10 to 50cm	Classrooms damaged
Gasenyi III	Less than 50 cm	10 to 50cm	6 classrooms flooded, mud
Kamemge II	More than 1 m	Less than 50 cm	11 classrooms affected
Kinama IV	Less than 50 cm	10 to 50cm	5 classrooms flooded, mud

In this study, we were interested in the main damages with significant economic impacts. About 1,000 houses collapsed and population was forced to leave certain localities.

CONCLUSION

This study evaluates the contribution of morphometric causal factors of flash floods. It is an overview of the impact of the terrain properties on susceptibility to flood occurrences in urban areas. The advancement in remote sensing data acquisition and their integration in a Geographic Information Systems contribute to specific studies in flood researches. Digital Elevation Model allowed us to compute the morphometric analysis resulting in mapping the susceptibility to flash flood. By aggregating causal factors, the weighted overlay procedure presented the ability to distinguish areas with higher, medium and lower susceptibility to flash floods. The lowest and flattest areas are the most affected by the flash floods in Bujumbura city. These are located along the Lake Tanganyika and in the floodplain towards the North of the city. The lack of data about real time observation of flash floods constitutes a hindrance from disaster monitoring and model validation. Some studies have used satellite images like LandSat dataset to detect surface water during flood episode. But because of the cloud over the study area preventing us from acquisition of useful images, the results were validated according to the field investigation of the impacts of the February 2014 event. Prevention of damage to human life and infrastructure related to extreme rainfall and resulting flash floods requires preparedness and mitigation measurements that should be based on a regularly updated GIS data mining.

This study provides important information to the decision-makers, helping them to develop appropriate adaptation strategies and flood prediction. Local authorities have to conduct activities for the rehabilitation of infrastructures after abnormal excessive rainfall but also need to consider a resilient reconstruction. The challenges of Bujumbura urban development, water drainage, sustainable land management are to be truly addressed in the long-term period through land use policies and plans. A futher study for the same area will integrate other parameters such as soil influence, run-off, drainage density, distance to main channel and land cover to enhance the flash flood hazard mapping.

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