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Flood risk mapping and an evacuation route planning: the case of Zomba, Malawi

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STUDENT REPORT

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Synopsis
For many years the lands of Malawi have dealt with the events of natural disasters such as the floods. The people have been suffering by hunger, disease and losing their properties due to the ravaging strength of the water flows from high intensity rainfalls. This study presents the methods that will allow us to understand and perceive the risk levels of flooding in the area and on how to plan an evacuation strategy for the city to areas with the lowest threat levels. It is with the purpose to help the affected population by assisting the humanitarian and government agents to improve decision making plans in order to better re-allocate their resources as to help the population in need.

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Abstract

Over several years the people of Malawi have been facing hazards from the floods caused by the torrential and heavy rains which have persisted in the country. Bursting the river's banks through several hours affecting more than hundred thousands of people and causing US $3 million worth of damage to households and infrastructures. From the 15 of 28 affected districts, the most vulnerable and worst hit are Chikwawa, Nsanje, Phalombe and Zomba. The reason for these hazards to merge in such times are due to the climate change, that the Northern and developed countries have contributed the most, but it is the Southern and undeveloped countries that are most vulnerable to its effects. It is with the utmost importance of this thesis to help the decision makers from the government and humanitarian agencies to evacuate the population away from the danger zones and to be able to re-allocate their resources, food and supplies to the affected population.

The study case scenario is Zomba, one of the largest districts from the mentioned list. A quick assessment will be made according to the choice of the study area between the Districts and a flood risk map will be drawn by using the tools of GIS in order to raise the awareness of the people to take better notice of the floods scale and impact. Different factors that are directly related to the creation of a flood will be calculated and combined through the GIS tools in order to estimate the flooding areas. These factors are: the slope, the flow accumulation, the elevation, the rainfall intensity, the soil type and land use. Once finished the flood risk map, a study will be performed to identify within the affected city, the most viable routes to evacuate from the floods. In this study we will present a total of five flood risk zones identified as lowest, low, middle, high and highest level flood zones. Afterwards, an urban evacuation plan is required to be calculated in order to find the most suitable paths to take, reaching to the lowest flood risk zones from within or outside the city. The objective of this is to minimize the total travel distance for the population to reach to higher grounds and to minimise the loss of lives during the storms and havoc. In the end, a final map will be made that identifies the scale of the flood as well its risk zones and the shortest paths to take for the lowest risk zones. Taking into consideration of the most critical types of infrastructures at risk such as schools, universities, hospitals and other buildings where mass of population might be gathered at. Giving these structures priority to evaluate the crisis situation, allowing them to evacuate in a sophisticated matter.

Table of Contents

List of Figures

1. Introduction

In this chapter we will reach upon the reasoning of why this paper is focused in the country Malawi and the hazards that have been occurring through several years. The struggles and actions taken part of by the humanitarian actors that have been present during the harsh times of which the population of Malawi have been facing during the storms. The problem statement will be introduced and explained as well the research question, divided into different sub-questions, providing with a much in-depth explanation of how to develop and approach the different aspects that this study brings. The study case scenario that has been chosen will be brought into this chapter and the reasoning behind its choice. The data sources will be specified as well their purposes in solving the problem presented in this thesis. Lastly, a literature review will be made to identify the methods to calculate the flood maps and the best evacuation routes by using GIS tools.

1.1 Malawi floods and the Humanitarian actors

The country has been facing heavy rain falls for several years but not all events had been registered, and only a few of them have caused a major impact to the country's population and economy. These events are demonstrated in the timeline bellow Figure 1 Malawi floods timeline.

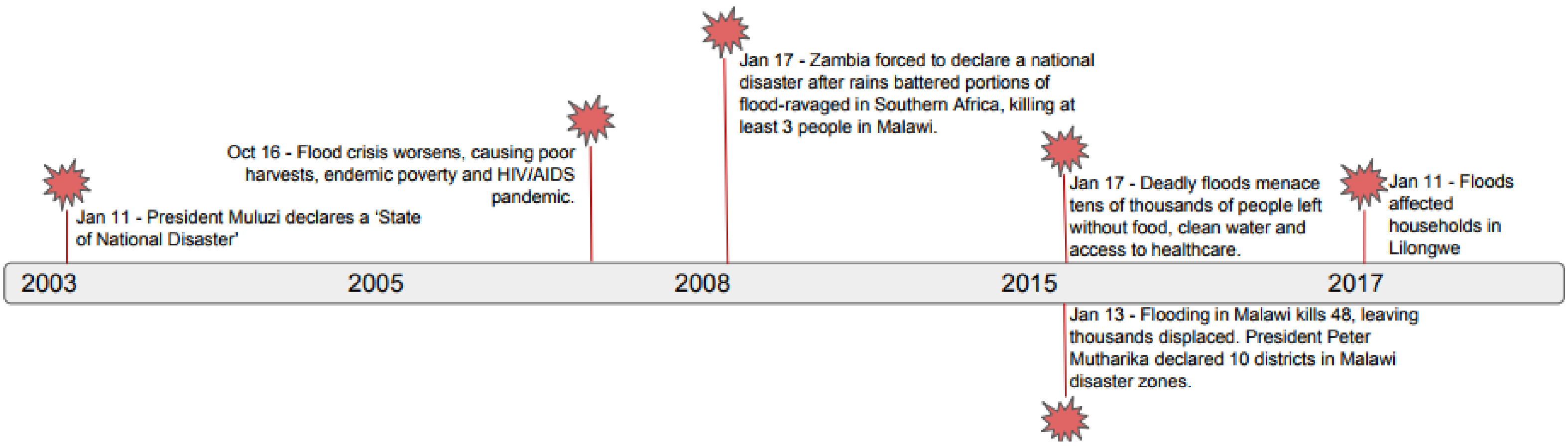


Figure 1 Malawi floods timeline

In the year 2003, the President Muluzi had declared a 'State of National Disaster' in the country, asking for international assistance to help the population that thousands had been displaced, facing with famine due to the droughts ("BBC NEWS | World | Africa | Malawi Declares Flood Emergency").

After two years the country keeps facing with droughts and floods resulting in the worst food crisis ever been faced in more than a decade. In addition to that, the people went across with the effects of the HIV and AIDS pandemics due to the lack of food from harvests and increasement of poverty (FAO - "Malawi Facing Serious Food Crisis").

Following in 2008 there aren't many records regarding to the event, however the affected country Zambia, that is geographically located to the west of Malawi, has declared a National

Disaster after suffering the effects of floods in South Africa with the fact that at least three Malawians have deceased. It becomes clear that during this event Malawi's population had also suffered with a high scale of displacement (Shacinda).

The highest on record of flood effects was in the year 2015, causing hazard and chaos to over a million Malawians from the southern regions (World Bank, 2017). The amount of displaced people had been increasing during the month of January to tens of thousands without access to food and clean water ("Flooding In Malawi Kills 48 People, Leaves 23,000 People Displaced, After Heavy Rains")(Laura Smith-Spark). The President Peter Mutharika has declared that the year 2015 had the highest disaster scale, when half of the country was affected, estimating around US $51 million of damage costs and approximately 230,000 people had been displaced from their homes (Chonghaile).

The most recent event in the year 2017, Malawi finds itself facing with a La Niña weather phenomenon, causing heavy rains and subsequently the worst floods in the District of Salima ("Malawi - Lilongwe - Floods Affected Households As Of 13Th Of February 2017").

During the years that have passed, the floods have caused large consequences for the communities and individuals, by traumatising the victims and their families on a long term due to the loss of loved ones and witnessing their homes and properties being destroyed Figure 2 Destroyed properties by the floods. Not only the people are affected by the floods but also the infrastructures such as the roads, bridges, farms, houses and vehicles, causing heavy damages to the economy of the country and the disruption of supplies such as clean water, electricity, transportation, communication, education and healthcare Figure 3 Destroyed infrastructures by the floods. Such tragedy takes years to be rebuilt ("What Are The Consequences Of Floods? | Office Of The Queensland Chief Scientist").

Figure 2 Destroyed properties by the floods

Figure 3 Destroyed infrastructures by the floods

The main cause for these floods to take form are due to the heavy rains during the raining season in Malawi that takes place between December and the end of March. The higher levels of precipitation the higher risk is for flooding. The following table shows the monthly average of rainfall in Malawi between the period of 1991 and 2015 ("Country Historical Climate - Malawi"):

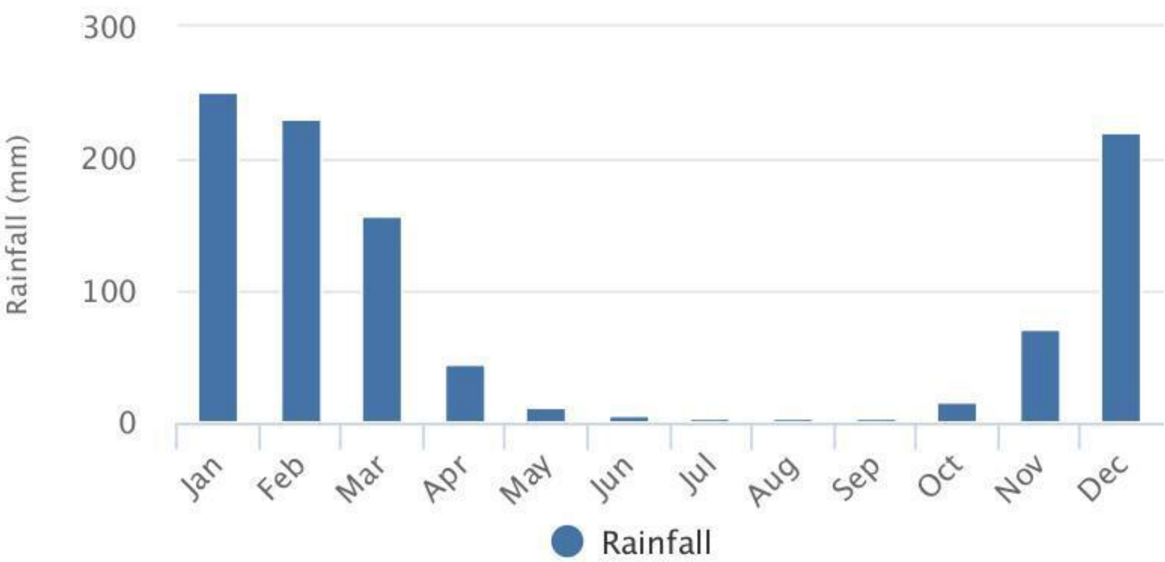


Figure 4 Average monthly Rainfall for Malawi from 1991-2015

According to the timeline above Figure 1 Malawi floods timeline, most of the floods that had been recorded as the most critical and notorious hazards, were taken place in the period around January, with the highest average level of being 243.2 mm of rainfall. While for the lowest average level, in September, was recorded of about 2.5 mm. If we look in the average monthly of rainfall in the capital District city of Zomba Figure 5 Average monthly Rainfall for Zomba from 1991-2015, we can see that in January the average monthly rainfall in the period of 1991 to 2015 is about 251.14 mm.

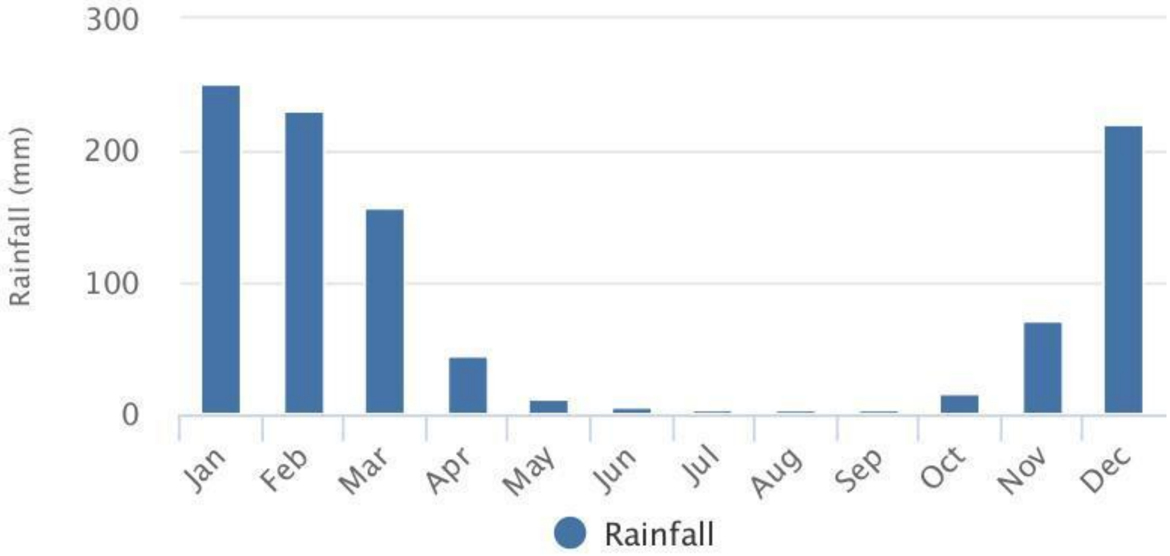


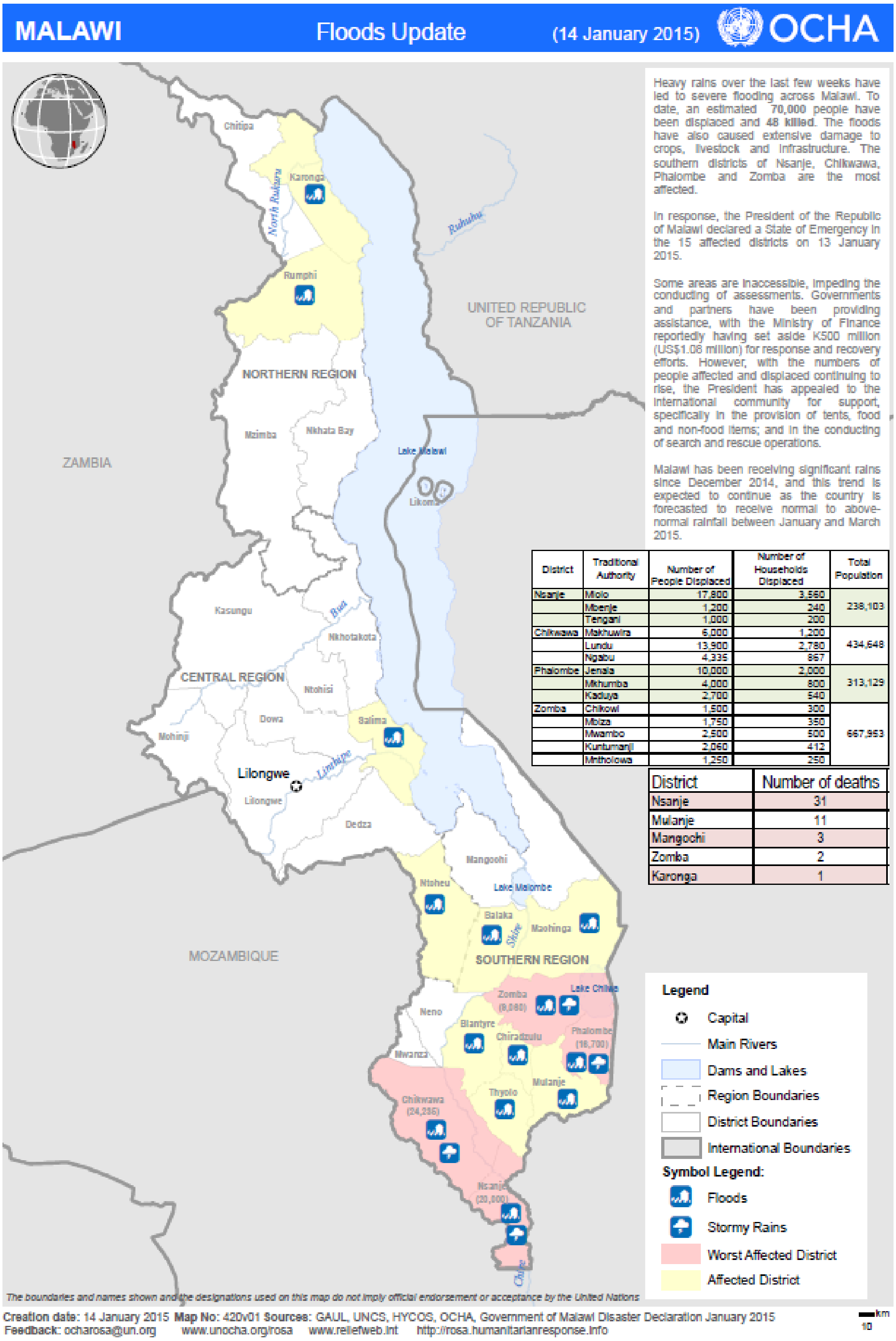
Figure 5 Average monthly Rainfall for Zomba from 1991-2015

In order to perceive the floods in an accurate manner we need to understand how many inches of height the precipitation can cause. According to the following image Figure 6 Average precipitation mm in Zomba. Source: ("Zomba, Malawi Travel Weather Averages (Weatherbase)"), the annual average precipitation for the month of January in Zomba is 307mm, of which it is the equivalent of 12.1 inches of water level.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C (°F)	27 (80)	27 (80)	26 (79)	26 (78)	24 (76)	22 (72)	22 (72)	24 (75)	27 (81)	29 (85)	29 (85)	27 (81)	26 (79)
Average low °C (°F)	18 (65)	18 (65)	18 (65)	17 (62)	14 (58)	12 (54)	12 (53)	13 (55)	15 (59)	18 (64)	19 (66)	18 (65)	16 (61)
Average precipitation mm (inches)	307 (12.1)	251 (9.9)	257 (10.1)	69 (2.7)	18 (0.7)	10 (0.4)	8 (0.3)	8 (0.3)	5 (0.2)	30 (1)	109 (4.3)	277 (10.9)	1,344 (52.9)

Figure 6 Average precipitation mm in Zomba. Source: ("Zomba, Malawi Travel Weather Averages (Weatherbase)")

The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) is one of the United Nations agencies that coordinates effective humanitarians' actions for the people in need. The next map Figure 7 Malawi: Floods Update (14 January 2015) is one of their products, that identifies the districts that are most affected and to what level, the changes in the weather through meteorology analysis in the area and the estimative figures of displaced, deceased, and total population in each affected district.



District	Traditional Authority	Number of People Displaced	Number of Households Displaced	Total Population
Nsanje	Mlolo	17,800	3,560	238,103
	Mbenje	1,200	240	
	Tengani	1,000	200	
Chikwawa	Makhuwira	6,000	1,200	434,648
	Lundu	13,900	2,780	
	Ngabu	4,335	867	
Phalombe	Jenala	10,000	2,000	313,129
	Mkhumba	4,000	800	
	Kaduya	2,700	540	
Zomba	Chikowi	1,500	300	667,953
	Mbiza	1,750	350	
	Mwambo	2,500	500	
	Kuntumanji	2,060	412	
	Mntholowa	1,250	250	

District	Number of deaths
Nsanje	31
Mulanje	11
Mangochi	3
Zomba	2
Karonga	1

Figure 7 Malawi: Floods Update (14 January 2015)

The United Nations High Commissioner for the Refugees (UNHCR) is yet another agency of the United Nations that has a mandate to protect refugees, internal displacement people and among other individuals that form the group People of Concern. The UNHCR also builds maps, the Reference maps Figure 8 Malawi Reference Map - UNHCR 2016 to show the presence of the humanitarian agents by field units, offices and the locations of the people of concern within refugee camps, centers and urban locations of communities that are hosting the refugees. These maps are used for helping the humanitarian officers with decision making for the different assessments over different needs for the people of concern.

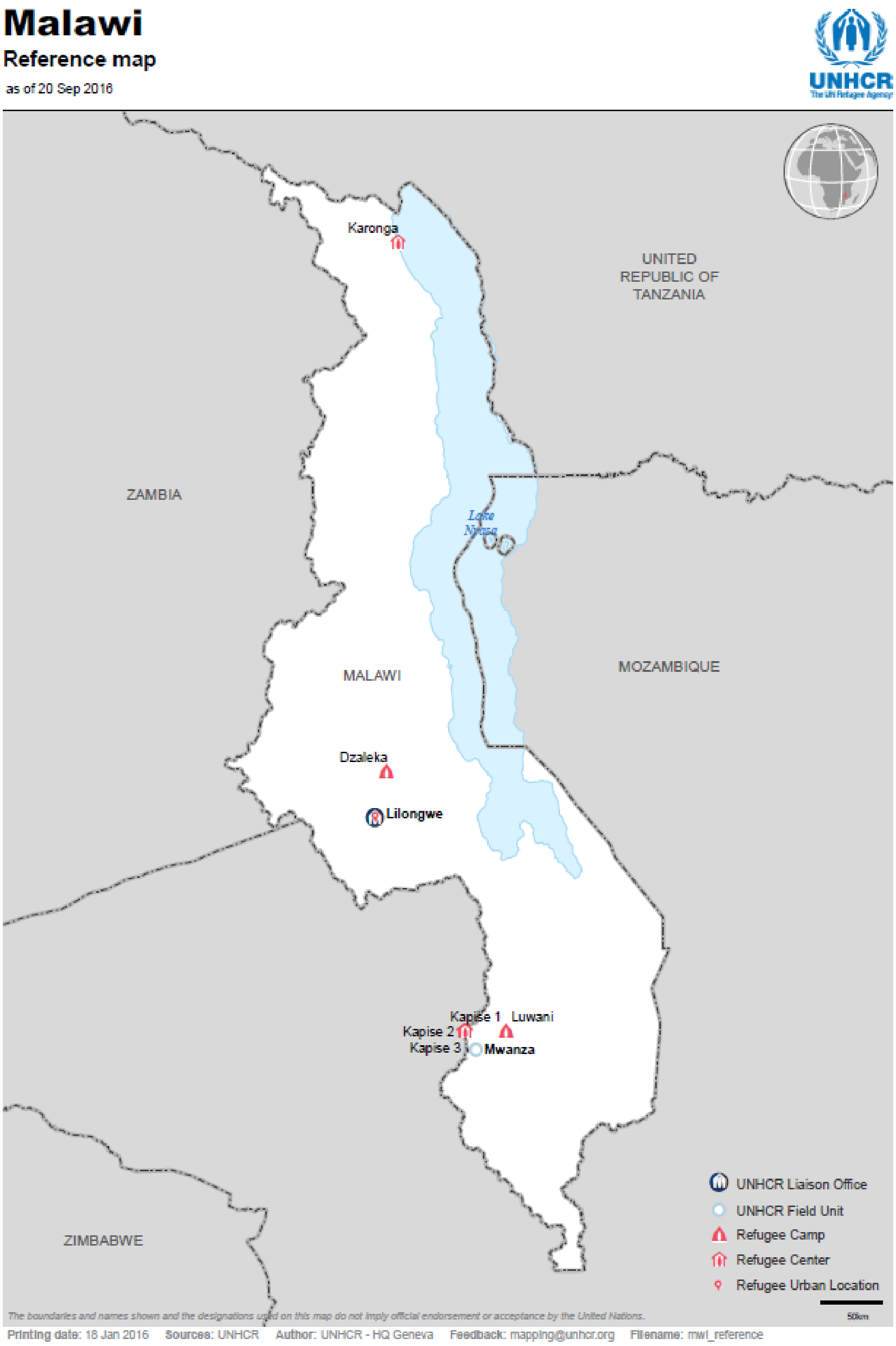


Figure 8 Malawi Reference Map - UNHCR 2016

For this study, the District of Zomba has been chosen as the area of study. Particularly the Capital city of the District that is called Zomba. Within the area of the city and its surroundings, the estimation of different danger levels zones and the evacuation routes will be made and the reasoning for choosing this area follows in the next sub-chapter.

1.2 Problem statement

In the year 2015, of which was the highest record of floods and damaged properties in Malawi, the most affected districts were Zomba, Chikwawa, Phalombe and Nsanje as the following image demonstrates Figure 9 Malawi Floods (as of January 2015).

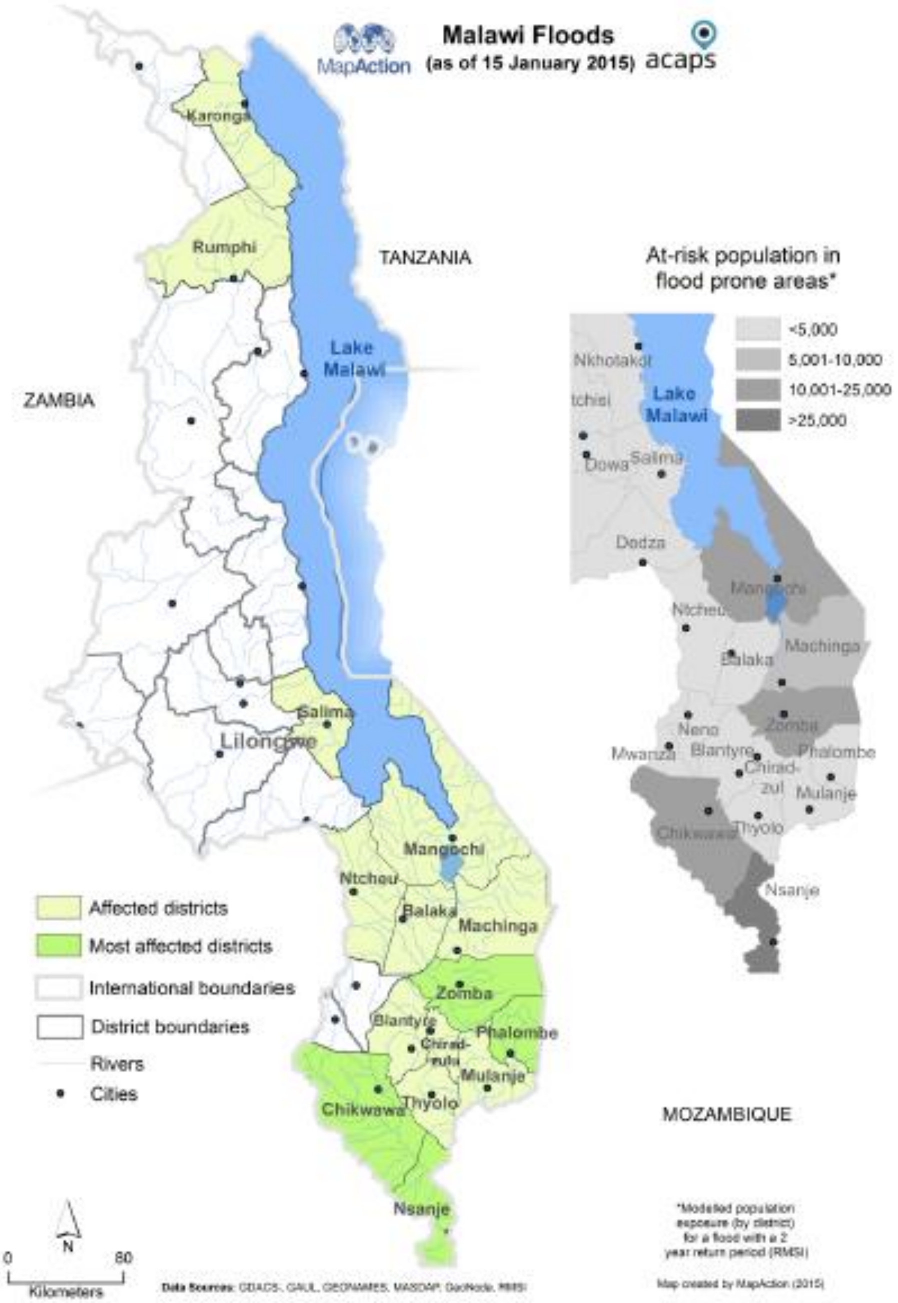


Figure 9 Malawi Floods (as of January 2015)

From these four districts, Zomba has been chosen as the study case scenario. For it has a considerable large amount of population at-risk, being around to 20 thousands individuals. In addition, it is the only district from the list above that is next to a large water body, a lake which is called Lake Chilwa. And where the capital district, city Zomba, we can find a larger number of buildings such as schools, universities and hospitals Figure 10 Study case scenario selection. These buildings are important to prioritise the assessment and analysis of the evacuation planning for people that more vulnerable to floods such as children and hospitalized patients.

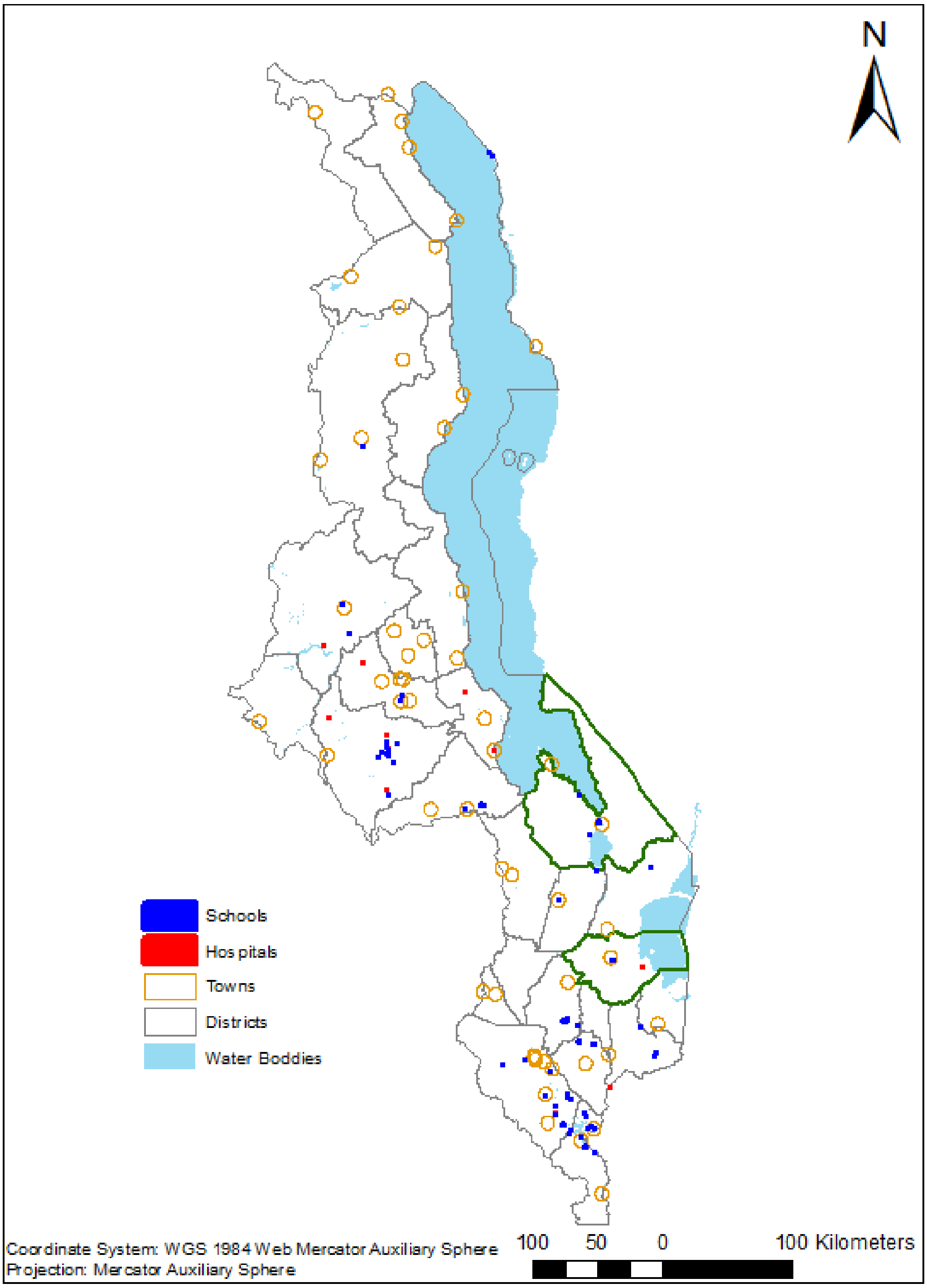


Figure 10 Study case scenario selection

The map above shows in green two potential Districts to be chosen as the case study scenario, Zomba and Machinga. The major towns are represented in yellow circles while the red marks are the boundaries of hospitals and in blue the schools. The city Zomba has two schools and one hospital, more than the remaining towns in Malawi while being nearest to a water body as previously mentioned.
Taking into consideration the problems that the people are facing and the efforts of the humanitarian actors to help, this paper has the purpose to provide with better detailed visualization for improving the decision making for resource allocation and for the population evacuation to areas where the possibility for a flood event is minor.

In order to do so, this thesis has been structured to answer the following research question:

How to assess the hazard and vulnerability of the land through a GIS developed flood risk map with a solved location-routing problem for the Capital District of Zomba in Malawi?

To answer this question it is required to divide it into three different sub-questions:

- **What are the methods to estimate different flood risk zones within the area of the city Zomba, Malawi?**
- **How to solve a location-routing problem to reach the less vulnerable flood risk area from the city?**
- **What are the merits of using GIS to support a flood risk decision making map?**

This paper will contain the methodology as in how to calculate and estimate the floods within the different levels of precipitation that have been measured in the country and how to establish the danger levels per zone limited by the boundaries of the city Zomba. And to plan and calculate the most shortest, fastest and yet safest routes for evacuation during a flood event, taking into account the priority of certain buildings such as the schools, universities and hospitals. According to the results and discussions there will be a conclusion as to what merits there are by using GIS tools to support a flood risk decision making map and how it could improve the humanitarian's decision making and their resources reallocation.

1.3 Data Sources

Many countries in Africa are hard to find data but Malawi has a Data Portal where we can find most of the required shapefiles apart from the digital elevation model. The following table shows the source, the date of the data that has been used, the name of each layer, the correspondent definition and the link from where the data has been collected.

Source	Date	Name	Definition	Link
Aster	2011	GDEM	The Aster Global Digital Elevation Model is a joint work between the Japan's Ministry of Economic, Trade and Industry (METI) and the U.S. National Aeronautics and Space Administration (NASA). The product has a 30 pixel size.	https://gdex.cr.usgs.gov/gdex/
Geonames	2011	Populated places	Population dataset of places/cities within the country	http://www.geonames.org/
Global Administrative Unit Layers (GAUL)	2015	Admin level 2 (Districts)	Administrative unit level 2 of Malawi. Represented by Districts.	http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691
Malawi Spatial Data Platform (MASDAP)	2014	Land Cover	Malawi Land Cover Map Scheme II represents classified land cover categories as preferred by the Malawi Government Representatives; who also assisted in the development of this map products.	http://www.masdap.mw/
	2013	Precipitation Average	Precipitation average that goes from 500mm to 2500mm in the country Malawi by location.	
OpenStreetMap (OSM)	2017	Buildings	Types of infrastructures (residences, industrials, etc.) within the whole country of Malawi.	http://download.geofabrik.de/africa/malawi.html
		Contours	Elevation lines of the land within Malawi.	
		Land soil	Description of the soil types in the country of Malawi	
		Land use	Land cover mapping of current land resources through thematic series such as forest, water, paved surfaces, etc.	
		Places	Locations of cities, towns, villages and hamlets within the country of Malawi	
		Rivers	Vector map of the rivers, streams and ditches in polylines.	
		Roads	Vector map of the primary, secondary and tertiary roads, paths and tracks in polylines.	
		Water bodies	Areas of lakes, seas and oceans represented in polygons within the country of Malawi.	

Table 1 Data Sources

The Global Digital Elevation Model from Aster will be used to calculate the slope, elevation and flow direction that will be needed to get the flow accumulation and among other data that is required. The geonames dataset are used to identify the amount of population in Zomba as well its location. The admin boundaries of GAUL are used to gather the limits of the chosen District so to clip the digital elevation model into a smaller area so to facilitate. The land cover from the data portal is one of the criterias to be used in predicting the flood risk zones. And the precipitation average would be as well one of the criterias but the low quality raster data would demise the estimative and therefore it is only for informative background. The

OpenStreetMap offers a big selection of data from infrastructures, buildings, land use and hydrology of the country.

1.4 Literature Review

During a rainfall, the precipitation is the point where the water falls onto the land and moves into a stream that later will follow through the river, ending then to the sea or lake (Oliveira et al.). If the precipitation level rises, the streams and rivers will be overflown of water, expanding through other ridges and open spaces that the landscape directs, originating then a flood. The flooding process includes several factors that depends on the landscape's nature such as the following: Slope - The steepness of a surface that can be measured in degrees from horizontal (90°), calculated by the rise divided by the run. Each cell in the slope raster file will have a value (in degrees or percentage) of the steepness of the land. The higher the value the steepest the terrain and the lower the value the flatter the terrain ("Slope | Definition - Esri Support GIS Dictionary"). In a low slope value surface there is more drainage of water from the rainfall, collecting for longer period and subsequently increasing the risk for flood (Gigovic et al.). Elevation - Is the vertical distance from a point or object that is situated above or below the mean sea level ("Elevation | Definition - Esri Support GIS Dictionary"). By knowing the height of the land we can perceive the altitude of areas that are flat and that are susceptible to be flooded or not. It has a role in determining the movement of the water flow and to what level of depth (Gigovic et al.). Rainfall Intensity - Once there is a rainfall, the intensity is measured by depth units per time (mm/h), in order to perceive the ratio of the total amount of rain that falls during a period. This is one of the most important factors for a flood to occur. Soil type - The different types of soil can have different behaviours for flood. Some types of soil and vegetation can absorb water. The size and shape of the rivers with the presence of structures and vegetation adjacent to the river may affect the level of the water that flows in the streams ("What Factors Contribute To Floods? | Office Of The Queensland Chief Scientist"). The presence of vegetation and structures adjacent to the river can also slow down the speed of the water flow and therefore allowing to absorb more water, increasing the risk of flood. Flow Accumulation - Measures the number of cells that flow into each cell once known the flow direction for each cell. This allows to visualize the rivers and streams that the water from rainfall shapes in the terrain and the direction of the water flow through the terrain until it reaches the sea or lake. Land Use - The urban development tends to change the land composition. The presence of trees and other types of dense vegetation, decreases the resistance of the water flows, allowing the water to spread more easily in higher quantities and to different directions. The development of urban areas along the rivers can change the capacity of a waterway to carry water and increase its volume, increasing the possibility for a flood to occur (Center). Catchment/Watershed - When rain falls on a surface area of land of which the type of its soil allows to collect and drain the water into the river or other waterways. The bigger the catchment the more water is collected, allowing for the water to be drained into the river in higher quantities and therefore increasing the risk of flooding. The criteria above are based on the available data and this study's methodology allows the incorporation for other potential criteria yet to be included, such as the rainfall intensity, flow direction, aspect, wetness index and the like.

According to the Federal Emergency Management Agency (FEMA) and the National Flood Insurance Program, there are several flood zones that are identified according to the risks in different parts of a country ("Floods: Flood Zone - Which One Are You In"). Each zone is assigned a character from the alphabet:

V Zones - is a Special Flood Hazard Area[1] (SFHA) that is lower than the Base Flood Elevation[2]. These zones are the most dangerous of the SFHA, generally situated alongside the coast line and originated mostly due to the wave velocity, hence the V letter.

A Zones - Among the SFHA these zones are the second most unsettled, being subject to rising waters due to close proximity to streams, rivers and lakes. Within the A-zones there are different named zones that reflect of the way the land might be flooded.

Other Zones - The X zones are not SFHA for they are the minimal risk areas with low chance for flooding occurrence. The D zones are the areas of which flooding might be possible. However these areas have not been studied in depth yet.

Upon making the research regarding to the different flooding danger zones, for this study the flood zones that FEMA and the National Flood Insurance Program have developed will be referenced as the following: V Zones as being the High Danger Zone (Red), the A Zones as Medium Danger Zones (Orange) and the Other Zones as the Low Danger Zone (Yellow) accordingly. The zones of where there is no flooding at all will be referenced as the Lowest Danger Zone (Green).

Once figured out the main factors for flooding development and the different flood zones that come into existence, the data collection comes next, and the appliance of methods through several tools that allows us to calculate and estimate the different danger level zones of flooding within the chosen watershed. All the flood's factors apart from the flow accumulation, are dependent from one another. If we take a look at the slope, the most dangerous areas are the ones with the lowest slope as well the highest slope, but if the area has a low slope at a higher altitude of elevation, then it would be considered as a safe area. Because the chances for a flood to occur would be minimum, since the water always finds its way downhill. Therefore the slope would depend on the elevation as well on the type of soil and the land use. The same applies for the soil type when it comes on the land use. For instance, where the highest particle size of the soil would prevent a flood insurgence by easily absorbing the water, if it is in a settlement area, where most of the land is covered in cement for roads and other infrastructures and buildings, then it would actually allow to generate a flood. At least all factors would depend greatly based on the elevation, no matter the circumstances, the water will always flow downwards until reaching the sea or lake.
In order to figure out how much weight each factor depends according to each other, a traditional method of Analytical Hierarchy Process (AHP) is required. It is a set of matrixes that would allow to identify the percentage of weight for each factor/criteria towards one another

[1] Area identified by FEMA as an land area that is at high risk for flooding where there is at least a 1 in 4 chance of flooding during a 30-year mortgage ("Special Flood Hazard Area").
[2] "Refers to the elevation associated with the "100-year flood", or a flood with a 1% chance of occurrence in any given year." ("Floods: BFE - Know Your Base Flood Elevation")

with the purpose of solving the same goal (Shanu), of which is to identify the different danger level zones in the area. It deals with the complexity of a decision making to set the priorities towards to the best decision. The ranking scale for the criteria's and alternative options are as follows in the Table 2 Table of relative scores:

Value of a_{jk}	***Interpretation***
1	j and k are equally important
3	j is slightly more important than k
5	j is more important than k
7	j is strongly more important than k
9	j is absolutely more important than k

Table 2 Table of relative scores

The first matrix is the *pairwise comparison matrix* A with the size $m^x m$, where the m is the number of criterias to be evaluated. "The j and k represent the options of which will be calculated the weight of influence between each and the value a_{jk} is the importance of the correspondent criteria relative to other. If the value of $a_{jk} = 1$, then both criterias are equally important, then if $a_{jk} > 1$, the *j*th criterion is more important than the *k*th criterion, while if $a_{kj} < 1$, the *j*th criterion is less important than the *k*th criterion…" (Saaty). The second matrix is the *option scores matrix* S with a size of $n^x m$, where the m is the number of criteria's to be evaluated and n is the number of m plus the calculated score of the weight for each criteria. "The entry S_{ij} represents the score of the *i*th option with respect to the *j*th criterion" (Saaty). Once finding out the scores, the goal can be achieved, in this case, the estimation for different levels of risk zones for flooding in the area.

The evacuation routing problem serves with the purpose of showing the authorities and the people the safest routes to take away from the crisis that is to happen during the event of a flood due to high intensity of rainfall. Its process requires to identify the different types of roads through the city and outwards to the places that are to be classified as safe areas. It is important to select the most viable roads, ignoring the low width sized roads for they can prove to be more harmful than safer to cross for a large mass of population. In case for Malawi, there aren't many roads that are capable to provide good conditions such as space or well pavement to travel. Therefore for this study, all the different types of roads will be used and different multichoice paths will be drawn. A straightforward method for calculating the shortest or fastest routes is available by using ArcMap extensions such as Network Analysis. With this extension it is possible to find the houses that are within five minutes of a fire station department, or which ambulances can deploy the quickest to an accident, or even how to improve the customer service through delivery service's vehicles while minimizing the transportation costs. These questions are answered by a system of interconnected elements, which are a network of lines and connecting points from different locations ("What Is The Arcgis Network Analyst Extension?—Help | Arcgis Desktop"), allowing to build a network dataset, able to conduct diverse analysis. Several routes might be calculated due to the obstacles that may be present such as low capacity bridges to support the road the passage over the river. In a case event where the river becomes flooded and does not have the means to support the flow of water in an efficient way, the bridge could prove too unsafe as means of travel. Therefore a set of multi choice route paths may be need to solve the evacuation plan towards the safe areas. Some zones of the city might require a different route that is quicker or shortest. Although the strategic buildings such as the schools and hospitals will have the priority focus for the evacuation, it would not mean that the rest of the population would not receive the same attention. So an evacuation route will be provided for the different zones of the city according to the possible obstacles people may find in the way.

2. Methodology

Through this chapter there will be an in-depth analysis of every aspect taken into consideration for flood risk such as the characteristics of the land that includes the watershed delineation of the area and it's flow accumulation, the different soil types that behave differently in the presence of water, the slope and elevation in the area of Zomba as well the land use and infrastructures that are present within the city. In the end a more sophisticated multi analysis will be done resulting into one final map of danger level zones for flooding from the different calculated influence weights of each criteria. Afterwards an evacuation route problem will be solved by selecting the best routes for the population of Zomba during the time of a flooding crisis, considering the width of the routes among other safety countermeasures.

2.1 Criteria Analysis

2.1.1 Watershed Delineation - Flow Accumulation

An important aspect to take into consideration is to determine the contributing areas for the water to flow and concentrate in different points, to what it is called watershed ("How Watershed Works—Help | Arcgis Desktop"). To obtain it we need to go through a few steps that consists of cleaning the Global Digital Elevation Model and calculate different outputs that will help analyse and choose the watershed delineation. The following models explain the process for this:

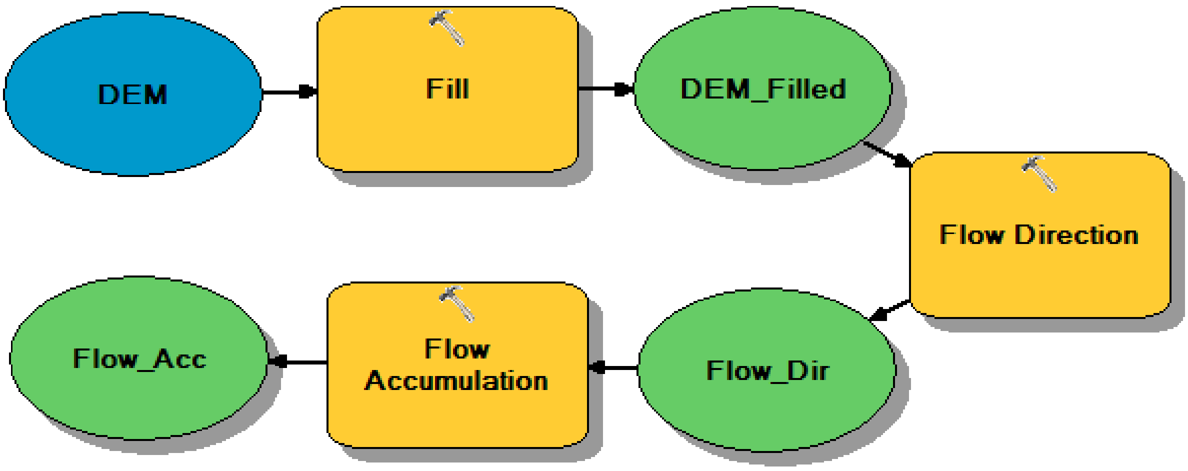


Figure 11 Flow Accumulation Model

As a first step we need to clean the raw data of the retrieved DEM. By using the function *Fill* we will fill all the sinks in the area so that the drainage network to be calculated needs to find the flow path of every cell in the raster. If it were not for this tool the cells would fail to drain off the edge resulting into an endless conversion. The following Figure 12 Fill function process Source:"Hydrologic Modeling And Watershed Delineation" shows the process of the function: The flow direction is a drainage network, composed of cells with a value assigned that

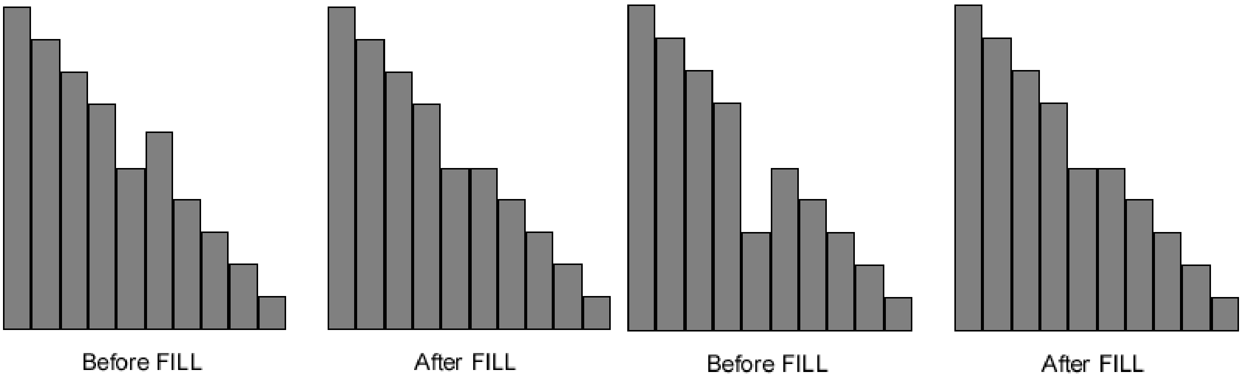


Figure 12 Fill function process Source:"Hydrologic Modeling And Watershed Delineation"

indicates the direction of which it will drain in the surface. Where at every 3x3 cell neighbourhood, the cell at the center will be determined of a value depending on the direction that flows.

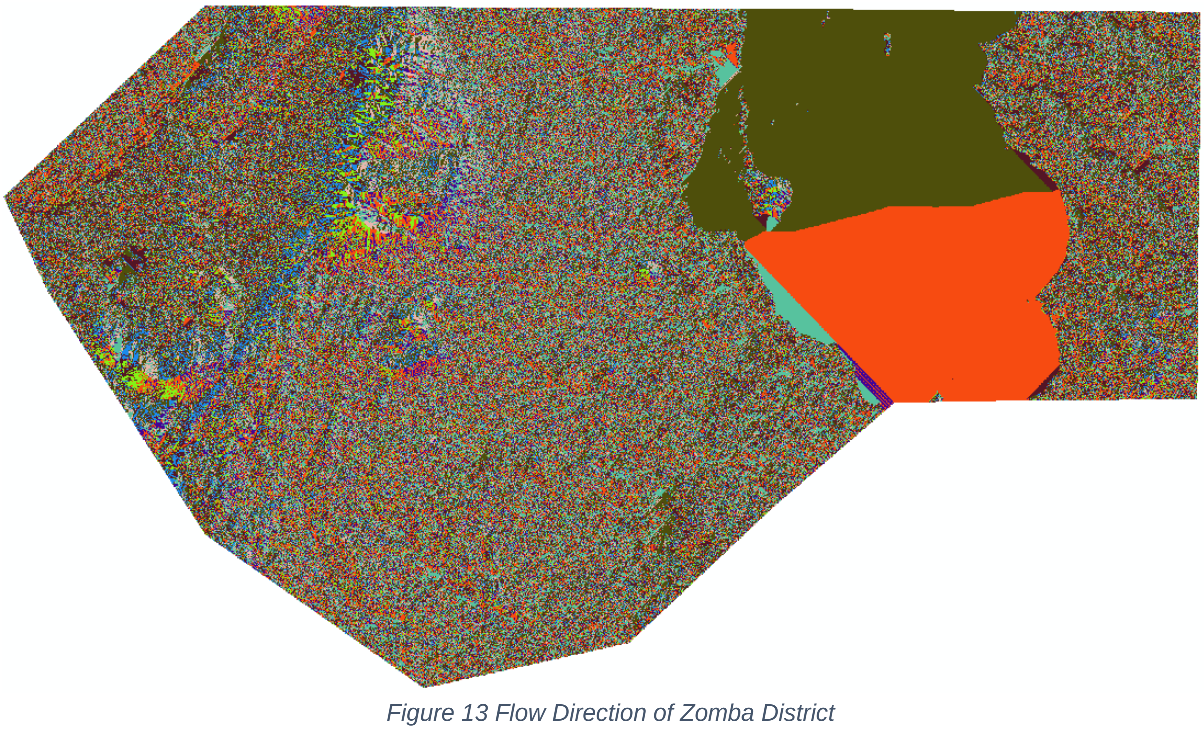


Figure 13 Flow Direction of Zomba District

The next step in the model is the flow accumulation, where the watersheds are spatially defined by the drainage in the surface. Based on the direction flow, each cell will be accumulated originating into an accumulated flow, creating a network of flow cells. The cells with a larger value have higher amount of flow cells. Once obtained it, the basin can be calculated by following the next steps:

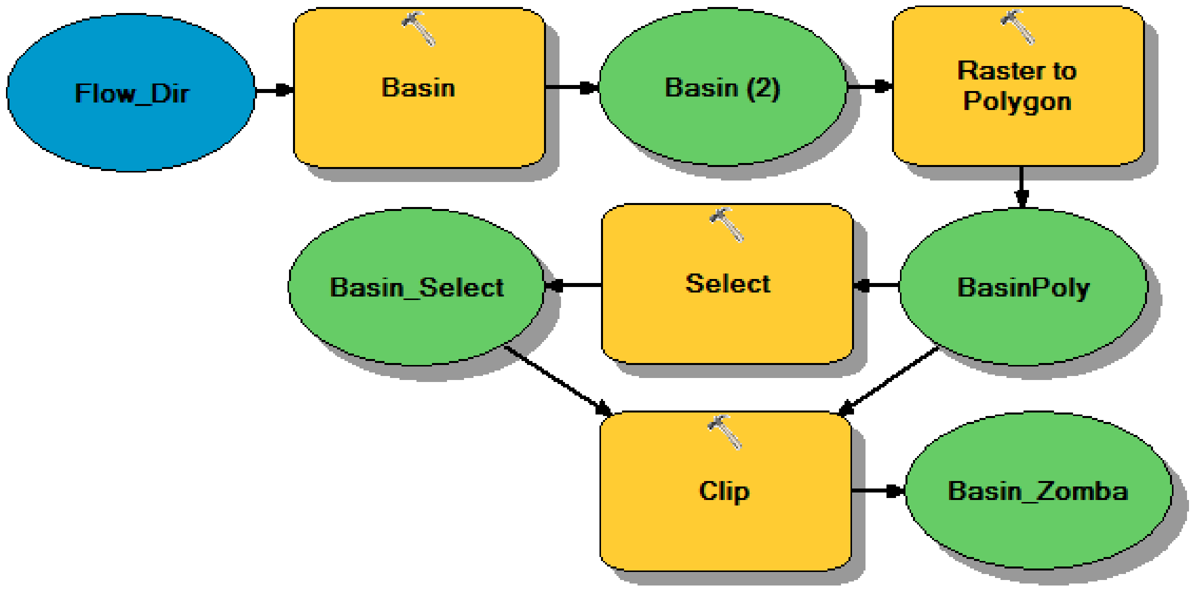


Figure 14 Basin Model

With the flow direction we can divide the raster into several basins according to the ridges of the raster. It uses the flow direction that automatically identifies the locations of where the flows would begin. This function is useful for large areas as such is the case scenario for this study. The basin of which the city of Zomba lies in will be chosen and exported. After converting the basin into a polygon it is easier to select the area (Figure 15 Basin and clipped buildings of Zomba) that we want to focus on and use it to clip all the raster's that will be determined later.

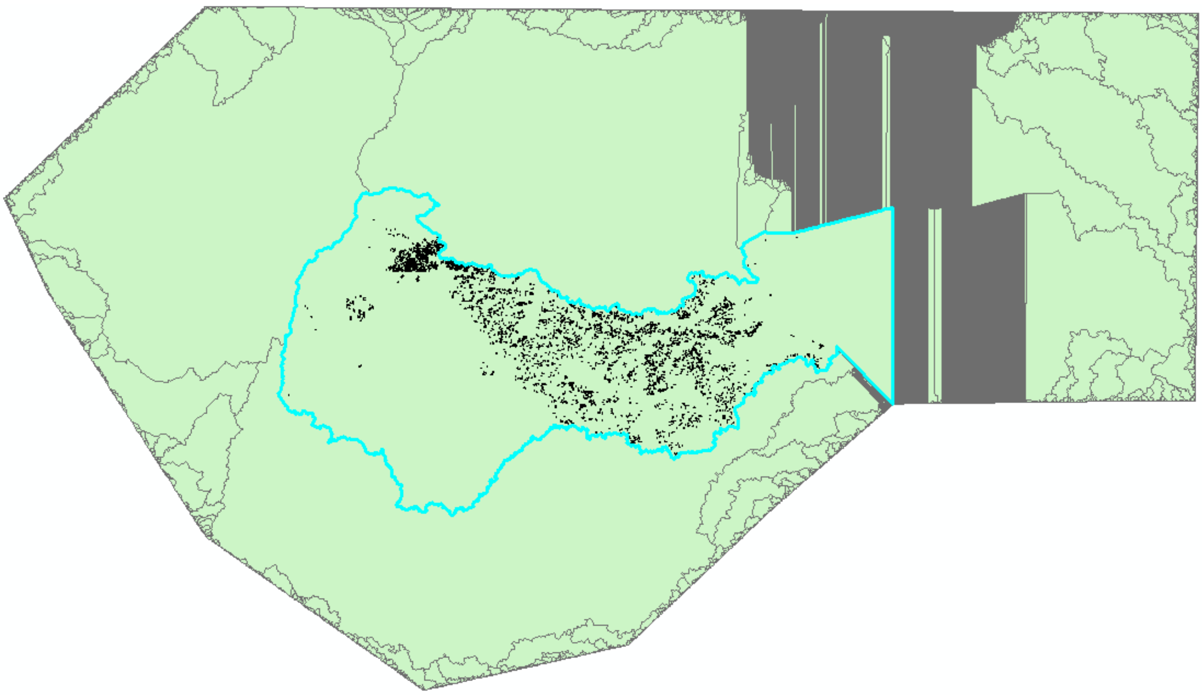


Figure 15 Basin and clipped buildings of Zomba

The selected basin has an area of 890 kilometres per square. It is a much smaller area from the original output, but even so, a small portion of the city is not included within this basin. For this study purposes the missing part of the city will be considered under the same category of danger level as the rest of the city.
Before going through the watershed delineation the following steps in the next figure are required to be determined:

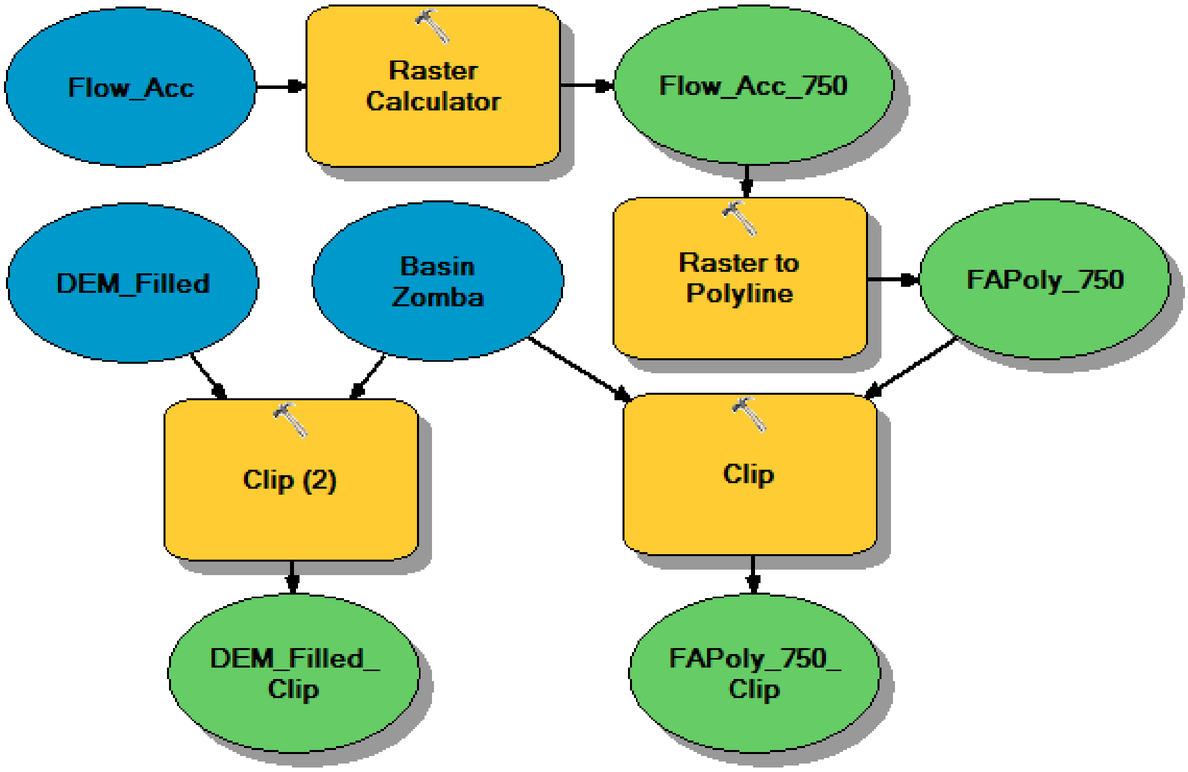


Figure 16 Watershed Delineation Model

By using the *Raster Calculator* function we retrieve the cells from the flow accumulation that have a value equal or higher than 20000[3]. After clipping it into the chosen basin the comparison between the hydrology from OpenStreetMap data and the calculated flow accumulation is visible in Figure 17 Calculated flow Accumulation, rivers and streams from OpenStreetMap.

[3] Instead of 750 mentioned in the model (Fig. X). The value has no units and the higher the value the more accumulated cells are in the area, defining the rivers that are more permanent in the area.

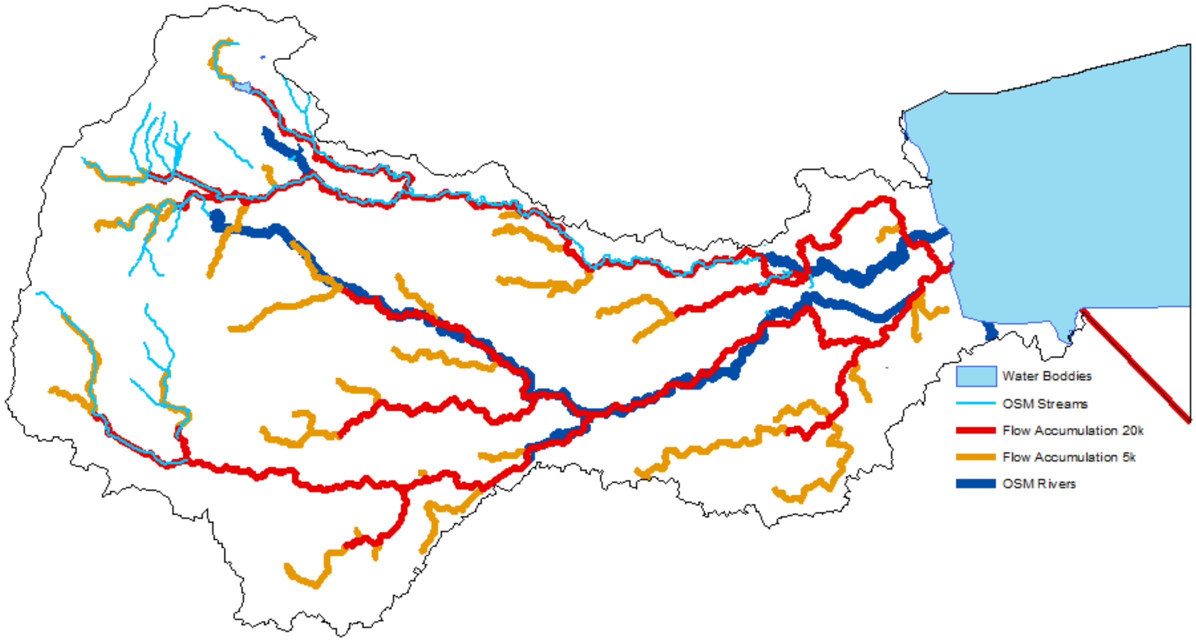


Figure 17 Calculated flow Accumulation, rivers and streams from OpenStreetMap

It is clear that the rivers from OpenStreetMap dataset is lacking data in between the northwest and northeast of the basin where the river flow is interrupted and then it continues towards the lake. The flow accumulation on the other hand seems to be precise and follows almost the same paths as the OpenStreetMap data. The final step is to clip the digital elevation model by the basin, representing then, the watershed delineation Figure 18 Watershed Delineation.

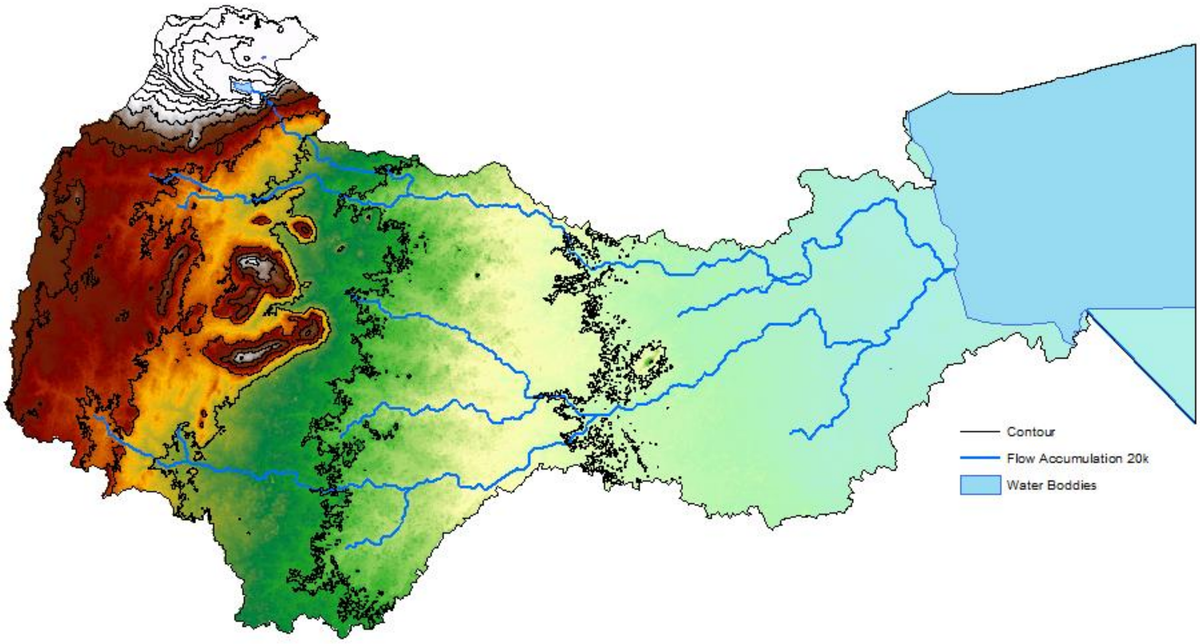


Figure 18 Watershed Delineation

From the image above we can see that the streams flow from the west, where the altitude is highest, to the east to where the lake is. The area of highest altitude is the mountain of which is next to the city of Zomba, it has a waterbody connected by an accumulated flow. This waterbody is the dam that provides clean water to the city. In the next image we can see a much closer point of view of the city. The city has one portion of a river from OpenStreetMap and one accumulated flow from the dam intersecting into the middle on the civic area. This accumulated flow acts as an obstacle for the people from the north zones of the city to evacuate towards south. The other accumulated flow in south of the city is also an obstacle for the whole city to cross towards south. But it is the flow from the dam that is most threatening, the high intensity rainfall can fill the dam to the limits flooding the area that will eventually flow downhill towards the city. The flow will then travel at high speed from such heights by such a short distance into the city with a brute force that could devastate the area.

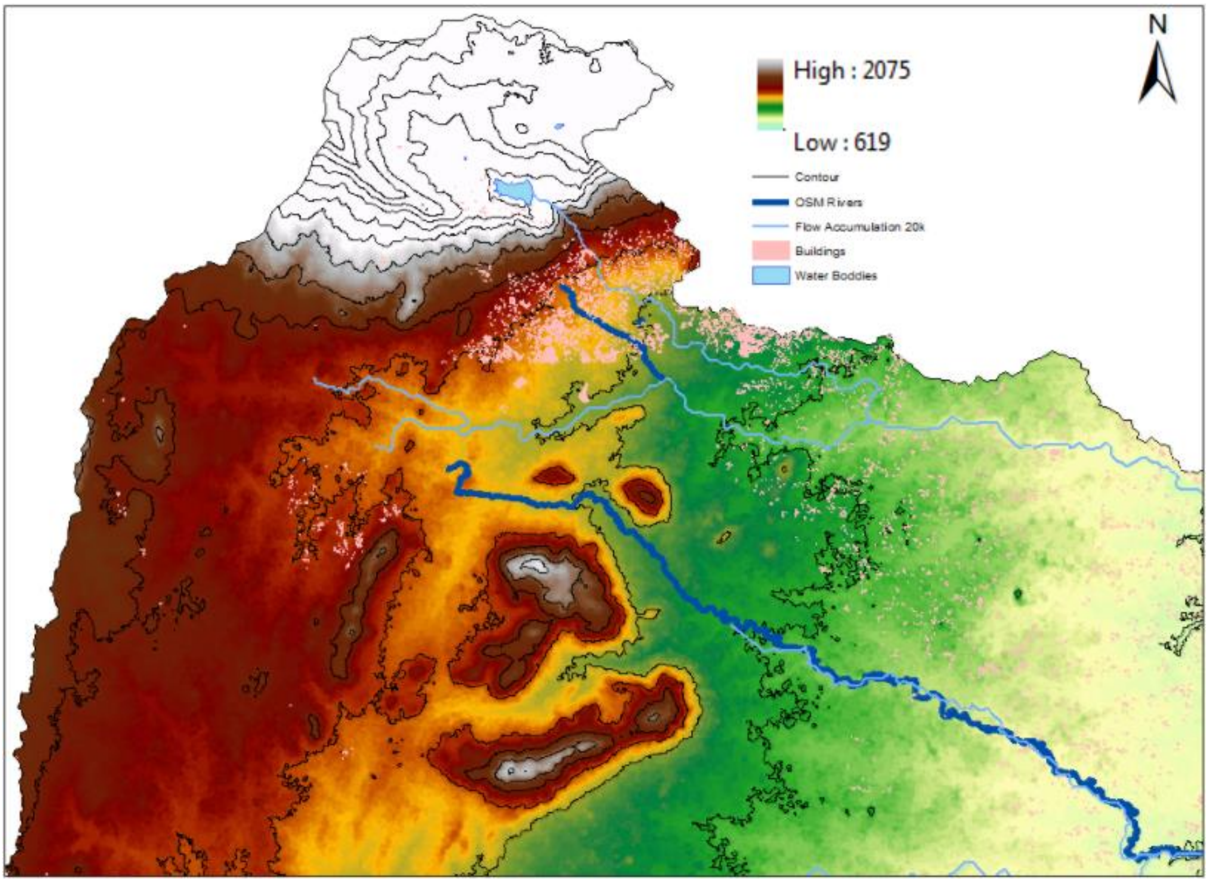


Figure 19 Rivers from OSM and calculated flow accumulation in Zomba Capital

It is also obvious in the Figure 19 Rivers from OSM and calculated flow accumulation in Zomba Capital that the calculated flow does not follow entirely the rivers of the OpenStreetMap. This could prove that either the determined flow accumulation are not accurate or the OpenStreetMap data lacks quality or it is simply outdated. The rivers from OpenStreetMap dataset are known to be permanent waterways, they are gathered and drawn through satellite imagery. But according to the accumulated flows methodology, the more accumulated cells the more it is subject to be a permanent waterway. After investigating the OpenStreetMap data through the satellite images we can see that in fact it is the OpenStreetMap data that is outdated. The following Figure 20 river (source OpenStreetMap) on the left and satellite image on right show precisely the previous statement:

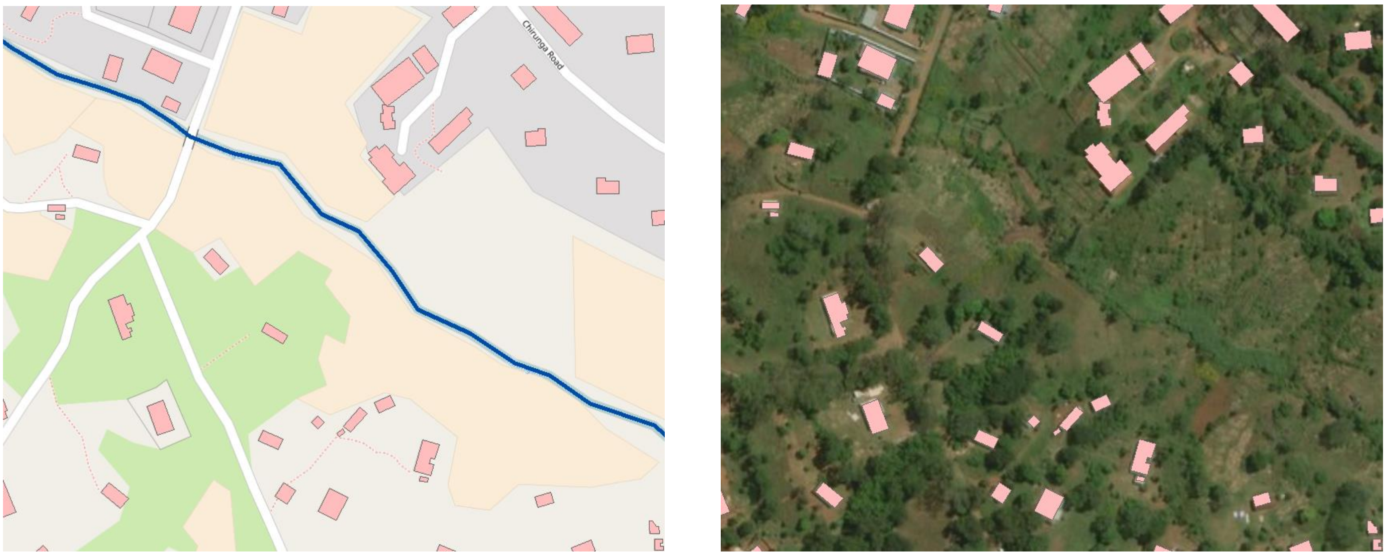


Figure 20 river (source OpenStreetMap) on the left and satellite image on right

In the OpenStreetMap data it is visible a bridge that goes over the permanent river. While in the satellite image we can see that the river is dried or it has a small flow but there is no evidence in the existence of a bridge. Other areas where there is only presence of rivers from OpenStreetMap but no presence of accumulated flows have also the same case scenario as the images above. While the areas where we can find presence of accumulated flow but no rivers from OpenStreetMap are indeed matching with the satellite images as the following Figure 21 Flow accumulation at left and satellite image.

Figure 21 Flow accumulation at left and satellite image on right

It is visible in the satellite image the lines of water that are followed by the line of dense vegetation and although not very accurate, it still is within the standards for this study's objective. The in-accuracy of the accumulated flow is also due to the fact that the global DEM used to determine has a pixel size of 30x30 meters. Nevertheless the size of the pixel is still approved for use in this sheer scale of an area to find the risk level zones and to identify the evacuation paths towards the yet to estimate the safe areas.

It is unclear of how much the rivers/flows can handle and drive the volume of water to come from the high intensity rainfall. And by measuring the rivers widths, there is an average of 7 meters of distance between the two land points of the rivers. Therefore for this thesis, we will consider the distances as a buffer from the accumulated flows for different danger level zones. It is always best to consider the worst case scenario for times of great catastrophes, so the distance for each danger level zones will be considered the double of the distance from the previous danger level buffer. So a distance of 10 meters from the polyline outwards will be considered as a high level danger zone (Red), of 20 meters as a medium danger level zone (Orange), and the 40 meters as low level danger zone (Yellow), any distance further would be then considered as a safe area (Green). By calculating the distances of the buffers from the flow accumulation, also add the averagely measured distance of 7 meters of width of the rivers. The following image Figure 22 Danger level zones buffer in Zomba Capital shows an example of an area of the city with the accumulated flow danger level zones, affecting the hospital building.

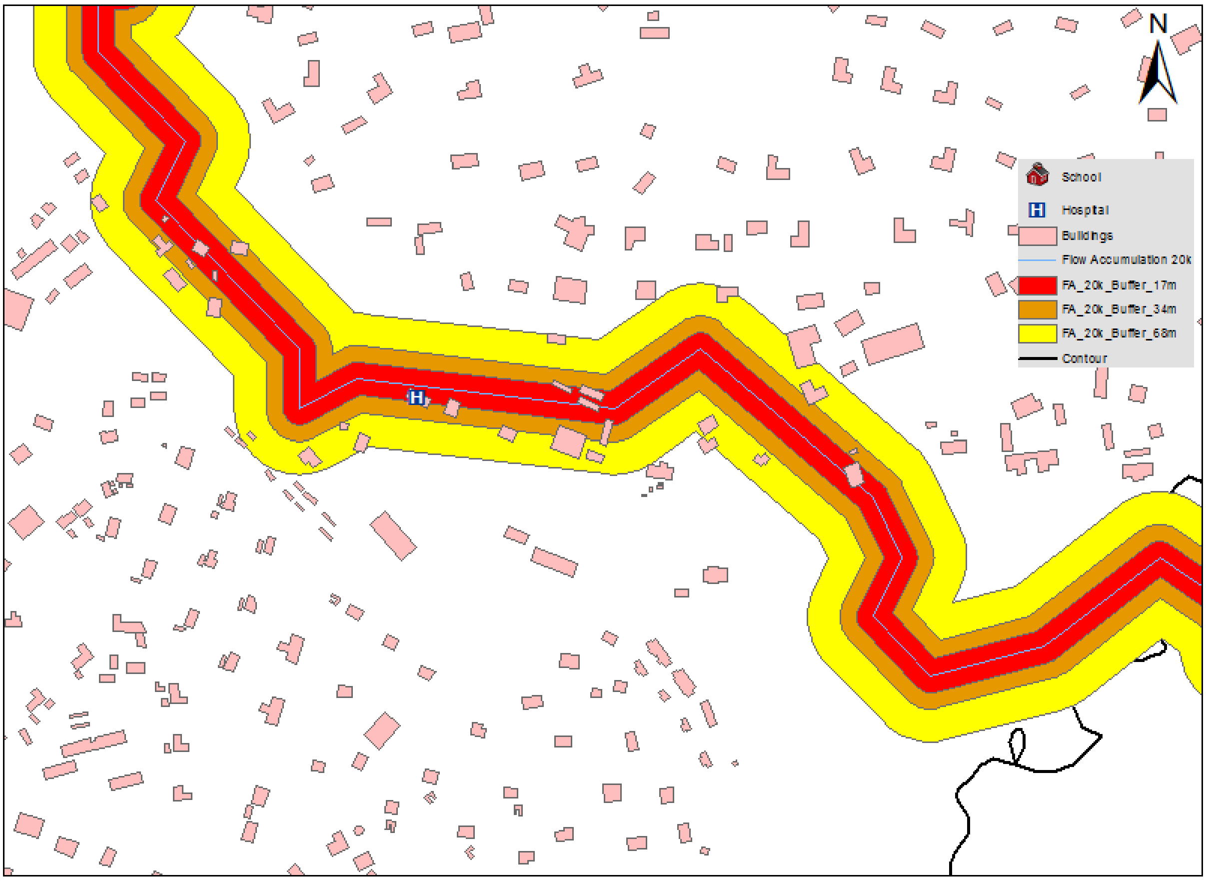


Figure 22 Danger level zones buffer in Zomba Capital

The supplied water from the dam travels underground through pipes for the city. But in the presence of a high intensity of rainfall, the accumulated flow will not travel underground but on the surface through the city's buildings. In between these buildings is the city's hospital, an important building inside the high level danger zone. It is possible due to the spatial resolution size that this building may not be within the red zone, but nonetheless, it is within a perilous area. All the residential buildings that are inside the buffer zones should as well take high precautions and leave their settlements immediately once the flooding event is known to be happening. It could be dangerous to stay in the buildings with weak structures because the strength of the flow could potentially destroy the house and provoke more harm to the people inside.

The next step is to find the nodes of intersection in between the flows. These points could potentially increase the flood effects. For when two different flows are joint in one intersection, the amount of water from both flows will increase into one larger flow. Adding a larger volume of water in the intersection will eventually create more flows in other directions causing to spread the water and flood the area. By using the '*Intersection*' function with only the flow accumulation as input, with the resulting output will be a point type. A point location of all the intersections in between the accumulated flows Figure 23 Nodes of flow intersections (left) and Buffer zones for nodes (right). These nodes will have a buffer of 100, 150 and 200 meters (plus 7 meters of the average width of the rivers in the area), corresponding to low, medium and high danger level zones.

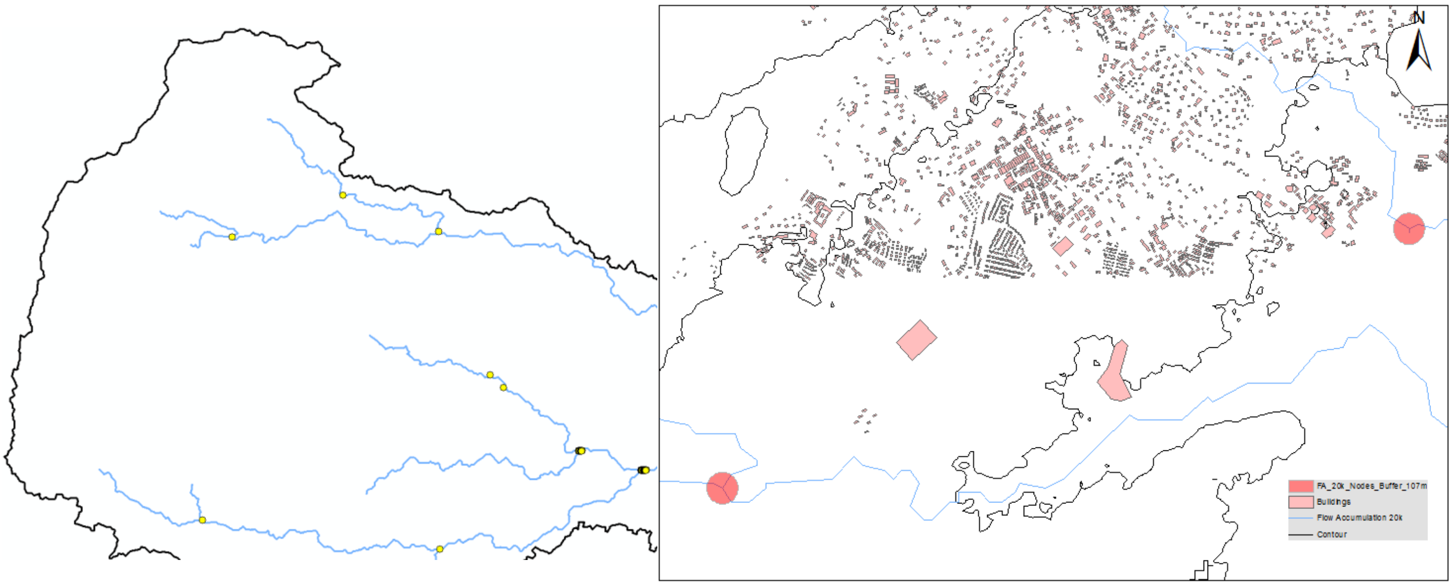


Figure 23 Nodes of flow intersections (left) and Buffer zones for nodes (right)

These buffers will also be included in the danger levels zones for the flow accumulation. Even though they are not inside the city, these buffers could still become an obstacle for the evacuation routes. Having to force the development of a multi-choice for evacuation paths towards the safe zones. The intersection tool will eventually create duplicated nodes, and for each different level of danger zone these need to be merged into one polygon, and lastly a field is created in the table by the name of Value that specifies the values for the different level danger zones (1-Red, 2-Orange and 3-Yellow). The same is done for the previous output of the flow danger zones Figure 22 Danger level zones buffer in Zomba Capital. In the end both these flows and intersection node's buffers will be merged as one Figure 24 Flow Accumulation Danger Level Zones, following the same values given earlier corresponding to each danger level zone.

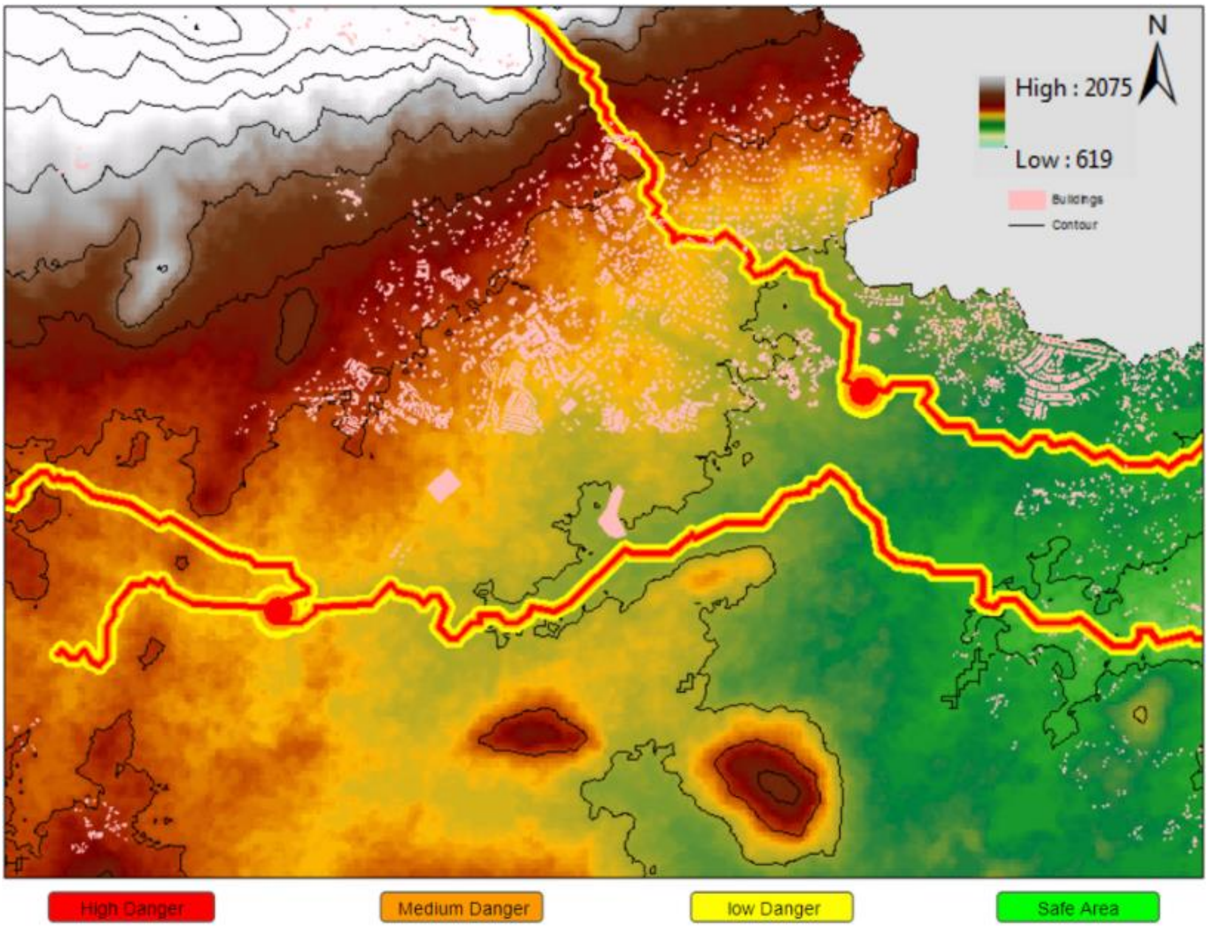


Figure 24 Flow Accumulation Danger Level Zones

According to the map it will be important to check the infrastructures when dealing with the evacuation planning. The size and structure of the bridges will imply either it is safe or dangerous to cross. The types of roads connected to these bridges also need to be taken into account in order to perceive the level of safety for travel. The north part of the city has the flow in the middle of the city as an obstacle, and the most likely option for those people to evacuate is to head to the northwest direction towards outside of the watershed limits, to higher ground of which is not visible in the map. If the high capacity highways or bridges that crosses the river promises to have a strong structure and able to withstand the force of the water flow, then it would be best to use it to cross and follow the route south towards the hills and safer areas.

2.1.2 Slope

The slope can be calculated by using the Digital Elevation Model once it has been “filled” (by using the function *Fill* in ArcMap). Looking at the District of Zomba and the location of the Capital city we can see the slope of the land and the direction of the rainfall drainage represented by the blue arrows Figure 25 Slope - Zomba District.

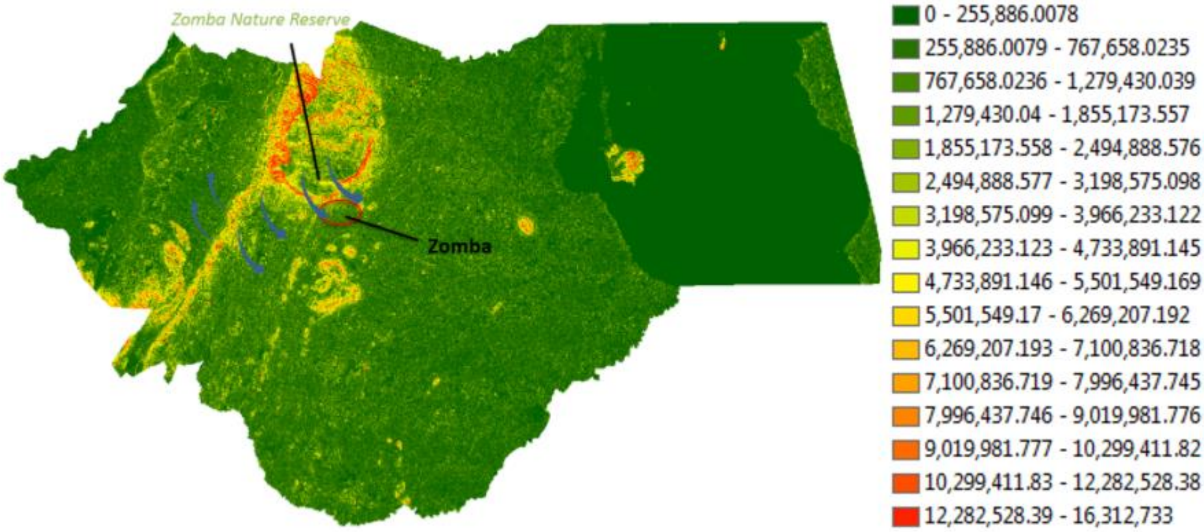


Figure 25 Slope - Zomba District

The red ellipsoid mark is the location of the city Zomba, of which lies under the mountain of which is the Zomba Nature Reserve. The mountain has a high percentage of slope, allowing for the water drainage to flow towards the city, eventually reaching to the streams and rivers that would later on reach to the lake in the East. If it would come to occur a rainfall with great intensity in the raining season, it is safe to assume that the city would become flooded. The following image shows on a lower scale the slope of the land in the city's premises and the direction of the water flow that would take Figure 26 Slope - Zomba Capital:

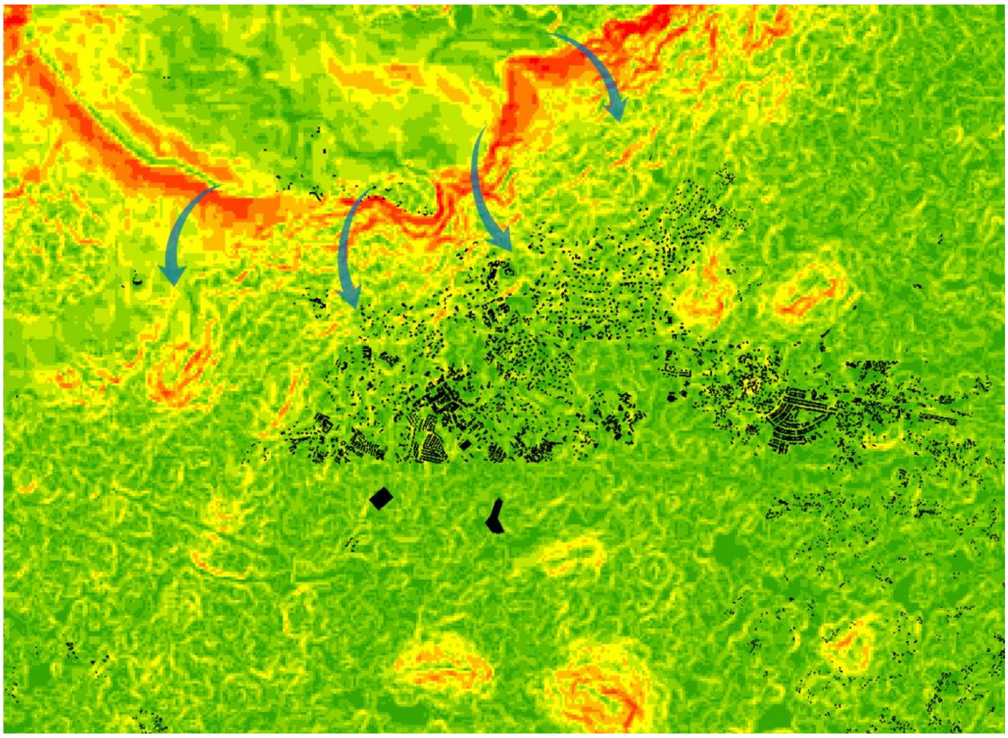


Figure 26 Slope - Zomba Capital

Now we can perceive the level of danger within the percentages of slope. If the land is flat, with low percentage of slope, of which is represented by the green colour, it would be considered as a high danger zone. The low steepness helps to contain the water by decreasing the flow through the streams, resulting into a flood once given the situation where the rainfall intensity is highly great. The areas of where the slope is the highest is also considered as a high danger zone, for it may be dangerous due to weather circumstances for people to travel or stay. From the slope figures, we identify the high danger zones by using the following equation in the *Raster Calculator* function:

Con ((“Slope” <= 1 000 000) & (“Slope” > 8 000 000) , X, Y)

The equation is a conditional selection of where the X represents the value of the being statement true (1) and Y the value of which the statement is false (0). The output is a raster where the cells will have the values 1 and 0, where the value 1 is the selected cells gathered by the statement. By selecting the slope values from below 1 million and higher than 8 million we extract the high level danger zones (Red). The gap between the 6 million and 8 million is the interval that is steep but also able to hold water while draining the water down the streams. By using the following equation this interval would be considered as medium level danger zone (Orange):

Con ((“Slope” >= 6 000 000) & (“Slope” <= 8 000 000) , 1, 0)

The following interval of between the 4 million and 6 million is to be considered as a low level danger zone (Yellow), being slightly less steep than before but still allowing for the water to drain fluently down the streams. The equation to use for this interval would be the same as the previous conditional statement but with the values of 4 and 6 million:

Con ((“Slope” >= 4 000 000) & (“Slope” < 6 000 000) , 1, 0)

The last level to consider is the lowest level danger zone (Green) of which is to be perceived as a safe area, clear of flooding due to the percentage of slope being slightly higher, avoiding the flat areas but also avoiding the steepest areas. This interval can be obtained by using the same equation from previous statements but with the values of 1 million and 4 million:

Con ((“Slope” > 1 000 000) & (“Slope” < 4 000 000) , 1, 0)

In the areas where the slope is high, it is less safe for people to stand and to evacuate by means of transportation, e.g. if an helicopter approaches it would not be able to land in a high slope terrain of which could damage the vehicle and becoming unable to withdraw from the location. Once calculated the different raster’s, each representing their respective danger level zone, the function *Combine* from the spatial analysis toolbox is used in order to blend the raster’s into one, Figure 27 Slope Danger Level Zones.

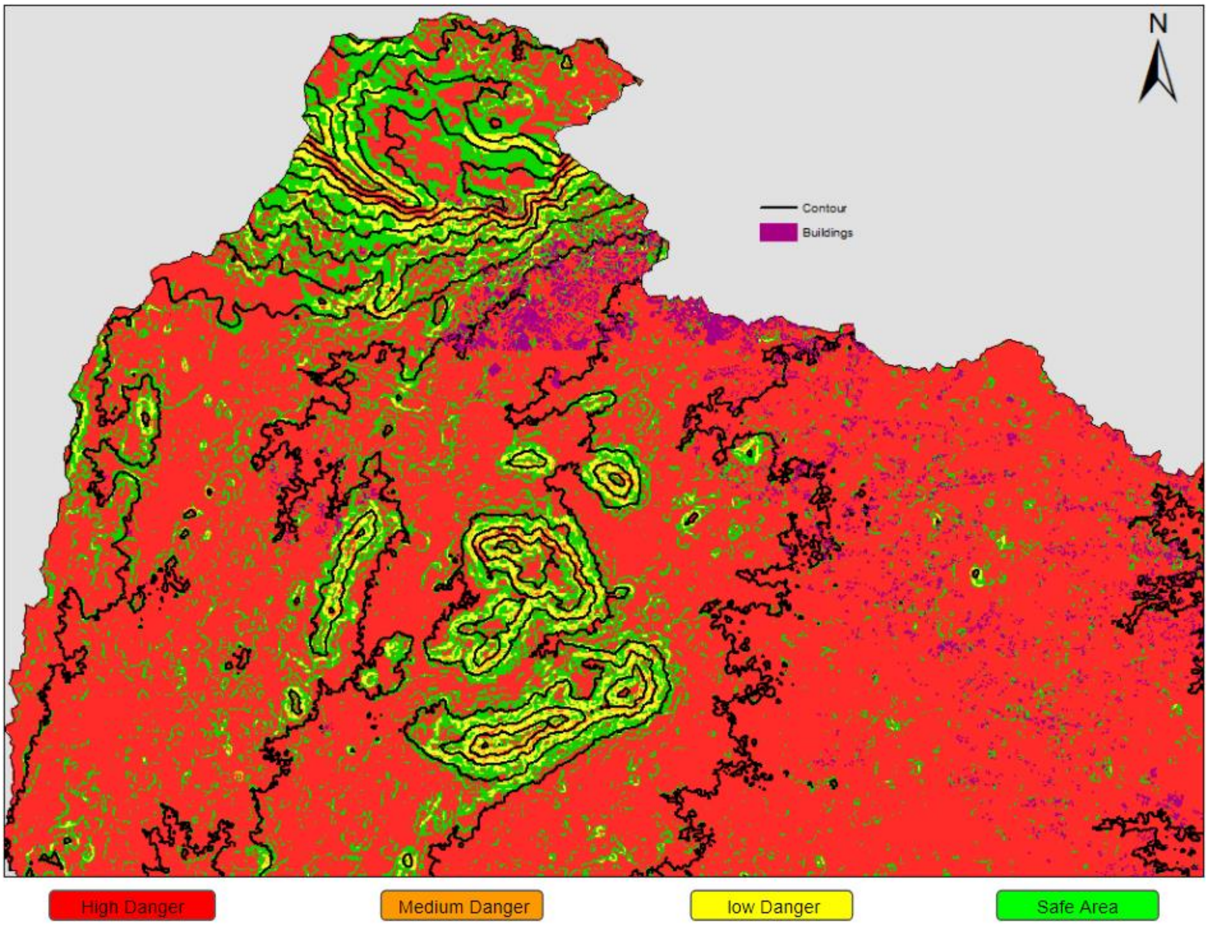


Figure 27 Slope Danger Level Zones

From the output from above it is clear that the slope danger level zones depend on the other factors such as elevation, soil type and land use. It is clear that the low level danger zone (Yellow) in some areas such as the small hills in the south can be considered as safe areas because they are situated in a higher altitude, where a flood will not occur. And the same happens for the medium danger zones (Orange) within the same mentioned areas of higher altitude, could be considered as a lower level of danger in yellow. The city is mostly within the high level danger zone for being in a most flat terrain, facilitating the accumulation of water becoming flooded in the end.

2.1.3 Soil Type

Each soil type have different characteristics, with its own strengths and weaknesses that react differently to water. Some soils, with a similar texture to clay, that has a small particle size, can hold water for a long time and ultimately originating floods by holding large volumes of water from streams. While other types of soil with a similar texture to sandy, with a larger particle size, can absorb the water into the underground and prevent it from spreading into streams. In the District of Zomba we can find at least 10 different types of soil Figure 28 Soil types - Zomba District that have similar or different reactions to water, of which might cause for different outputs of flooding.

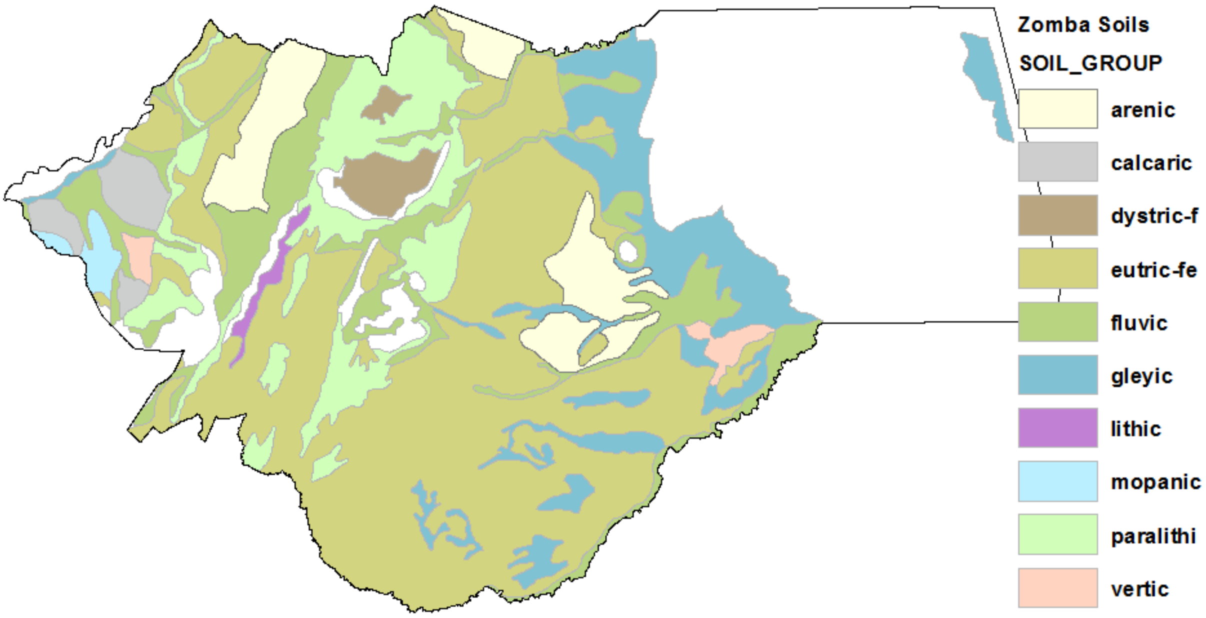


Figure 28 Soil types - Zomba District

Arenic - Is the type of soil of which has a non-gravelly profile (non-loose aggregation of rocks) but of sandy texture. This type of soil has the largest particle size with an approximate of 0.05mm to 2mm. It would absorb the water, leading it towards the underground preventing the overflow to the streams ("5 Different Soil Types – Know Your Soil Type | GROWTH AS NATURE INTENDED™").

Calcaric - The calcaric soil in Zomba has a particle size between sand and clay, allowing for a moderate slow drainage but able to hold some water ("5 Different Soil Types – Know Your Soil Type | GROWTH AS NATURE INTENDED™").

Dystrict-f/Fluvic/Gleyic - These three soils have a similar texture to calcaric soil, with a particle size that allows for a moderate slow drainage and still being able to hold some water that could follow into a stream ("5 Different Soil Types – Know Your Soil Type | GROWTH AS NATURE INTENDED™").

Eutric-fe/Paralithi - Both soils have the balance of all soil materials, silt, sand and clay. It holds tight to water but can drain it easily, allowing for growth of large proportions of vegetation. If the land contains a lot of vegetation it can hold a large quantity of water that would slow the drainage and prevent its flow towards the streams and rivers ("5 Different Soil Types – Know Your Soil Type | GROWTH AS NATURE INTENDED™").

Lithic/Mopanic - With sandy and loamy texture, the air roams freely between the particles, letting the water to be absorbed easily but still being able to hold it. Grants the possibility to growth some vegetation ("5 Different Soil Types – Know Your Soil Type | GROWTH AS NATURE INTENDED™").

Vertic - This soil has a similar texture to clay, having the smallest particles among other soils, with great water storage capabilities, letting the water run freely to streams and waterways if with enough slope ("5 Different Soil Types – Know Your Soil Type | GROWTH AS NATURE INTENDED™").

Taking a closer look to the Capital of the District we can see which of the dominant soil types are within the city premises and determine to what kind of reaction would it have if there would be an heavy rainfall in the area Figure 29 Soil types - Zomba Capital:

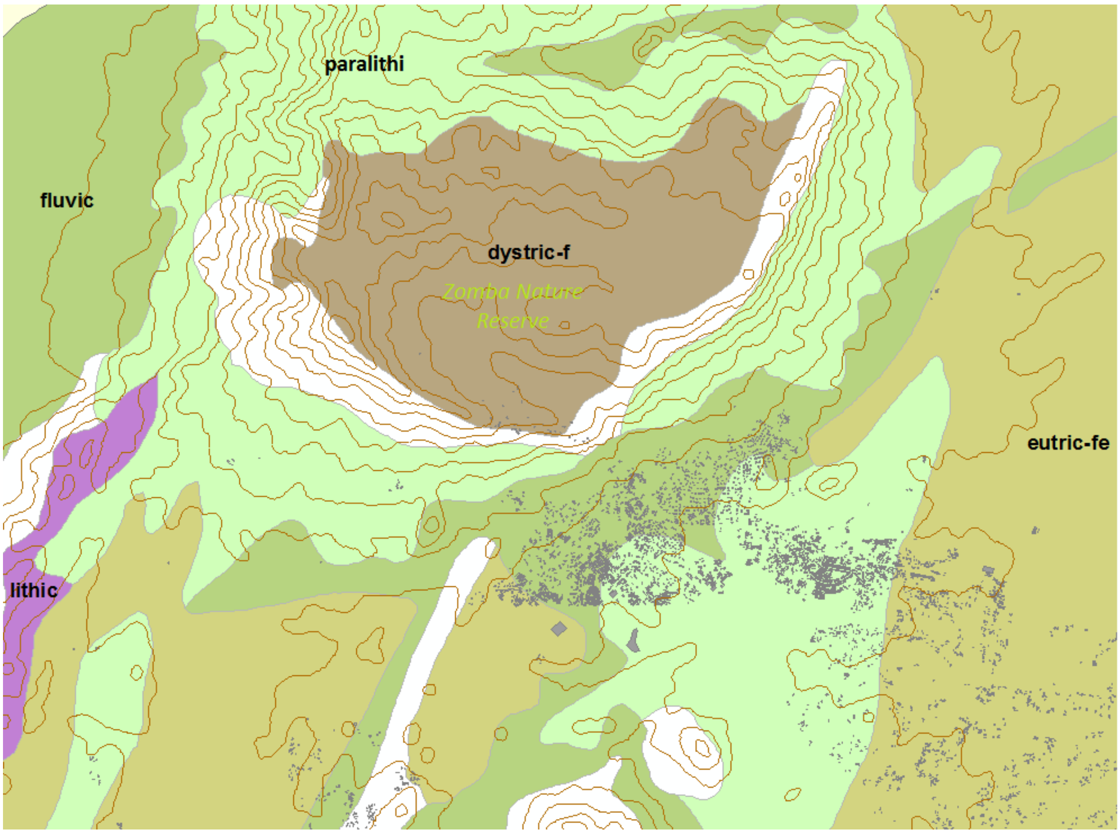


Figure 29 Soil types - Zomba Capital

In the center of the mountain where lies the Zomba Nature Reserve, the soil Dystrict-f has a considerable size of particles in between the textures of sand and clay. Looking from this point towards the south we can see a missing soil type in white of which was not available in the data, nevertheless it is a small portion of land with a high percentage of slope, of which would allow for rainfall to flow towards the streams. Then following to the Paralithi soil group, consisting of sand, silt and clay. This soil shows potential to grow vegetation in large proportions but because of the slope it won't be able to expand many trees and or bushes that could hold and slow the water drainage. Therefore we can assume that the land will not absorb much water and fail to slow down the drainage of the rainfall due to the slope. Next, to where the city starts, the soil Fluvic has a similar texture between sand and clay that would be able to drain a portion of water, but with the presence of buildings and infrastructures the drainage would slow down greatly, allowing for the area to hold a large quantity of water from the rainfall. Depending on the intensity of the rainfall, the area would receive drainage water from the north and likely to trigger the event of a possible flood crisis within the area. The remaining soils surrounding the city share the same texture as the silt, sand and clay. Soils rich of nutrients and low slope to grow vegetation, which would cause for the drained water from the city to hold in the city's limits, increasing the amount of water to be collected by the soil and increasing the flood in the area.

Now we gather the raster's for different levels of danger zones for flooding according to the type of soil. The areas of which contains the soils Fluvic and Dystrict-f are to be considered as high level danger zone (Red). The Eutric-fe and Paralithi are to be considered as low level danger zone (Yellow). And in the areas of which we have no data it would be safer to assume the type of soil to be medium level danger zone (Orange). If there is no data or information from any aspect it is always better to expect the worse from it and therefore classify it as a potential danger zone. The following equation from the function *Raster Calculator* can be used in order to gather the different raster's:

$$Con\ (\ (Soils == A)\ |\ (Soils == B)\ ,\ X,\ Y\ )$$

Where the A and B represents the different soil type's value, but in case we want to select only one type of soil we only use the variable A in the conditional formula alone. The X represents the true output that is the value of 1 and the Y is the false output of which it is the value 0. Once gathered the raster we combine them by using the function *Combine* for raster's spatial analysis. And then reaching into the following output, Figure 30 Soil Type Danger Level Zones:

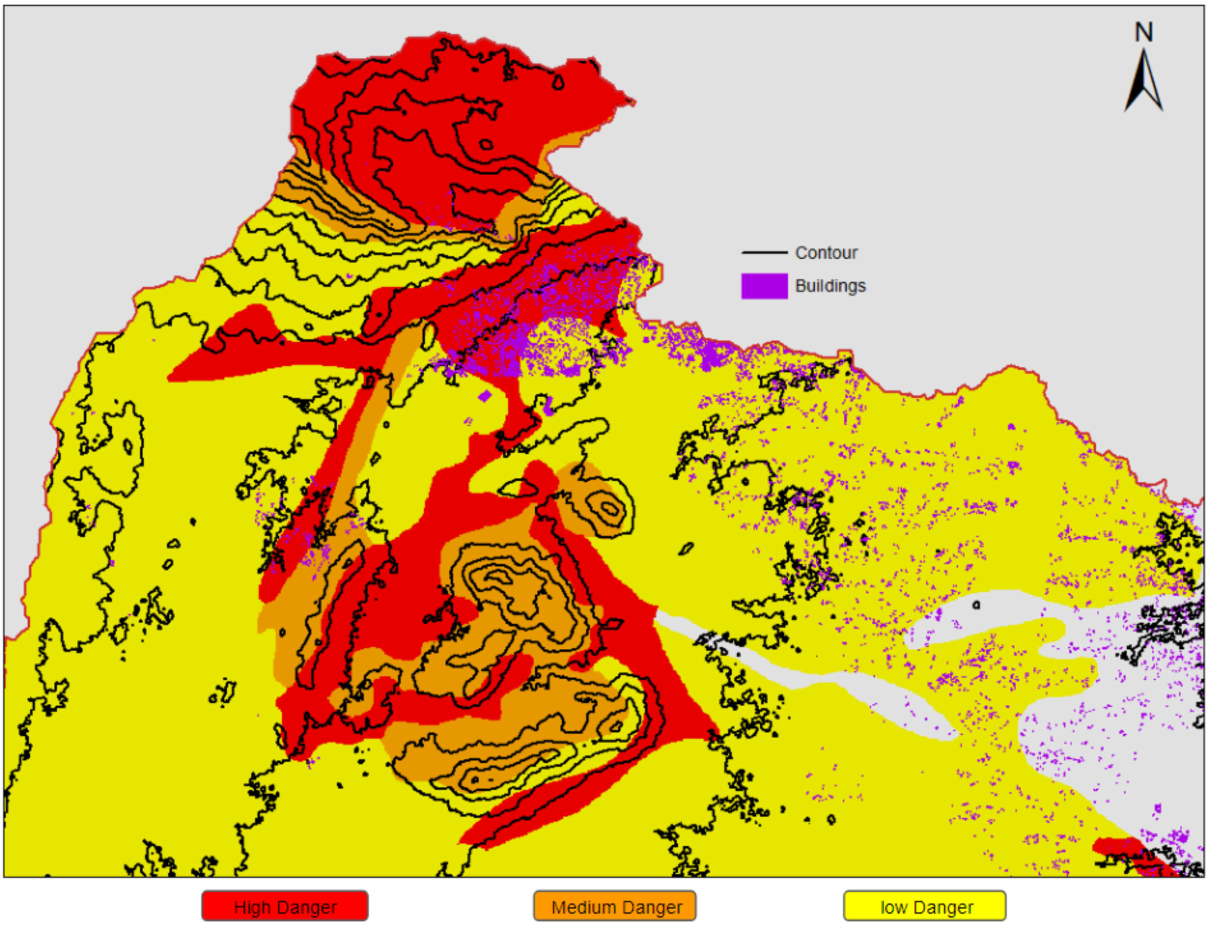


Figure 30 Soil Type Danger Level Zones

The areas that are in white are the type of soils of which we will not focus on, for they are far away from the city and the area would not bring much input for the evacuation planning. The areas in Medium danger level were also the areas that we do not have data and it is unsure to whether it is considered to be safe or not, but when dealing with hazards it is always best to add a margin of error even when it might be a safer area. Much of the city is on top of the high danger level zone, the same result as the slope analysis from above, and the safer areas in the map are the small hills in south of the city as well from the same result of the slope analysis. It is to believe that the soil types are not a dependent factor when dealing with flooding actors. The elevation and slope also have influence in the soil type. Where the slope is not low but neither high and the elevation is in high altitude, the area is to be granted as the lowest danger level zone (Green).

2.1.4 Elevation

Instead of using the OpenStreetMap contour data, by using the Digital Elevation Model from the Malawi Data Portal we can accurately calculate the contour lines within the District of Zomba. By clipping the raster into the admin level 2 borders and use the *Fill* function to remove the small imperfections of the data, we can then use the function *Contour.* The image below Figure 31 Elevation model - Zomba Capital shows the contour lines of the mountain and the premises of the city.

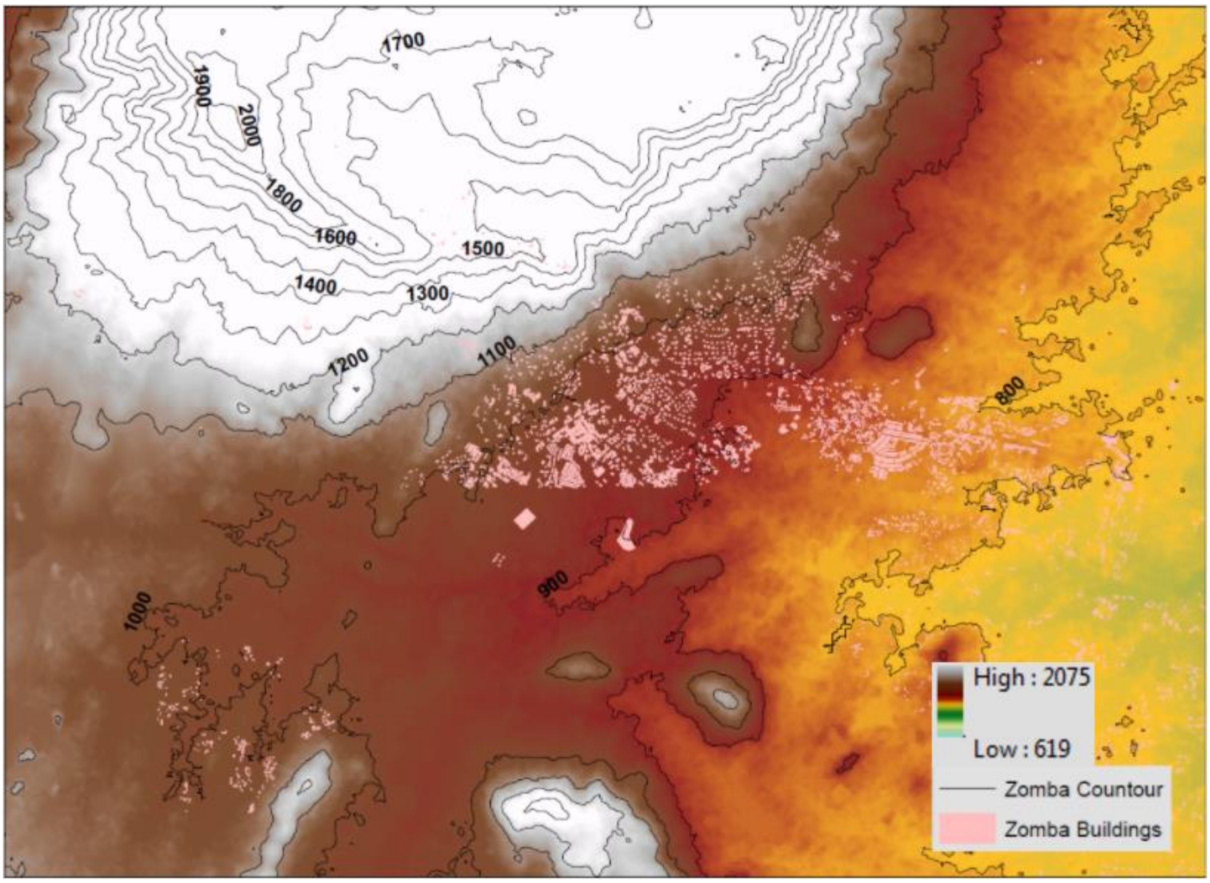


Figure 31 Elevation model - Zomba Capital

The mountain peak is at the 2075 meters high and the lowest altitude is close to the lake by the east. The city is in between the 1100 and 900 meters of altitude, where the majority lies in between the 1000 and 900 meters. There are a few small hills around the city that could potentially be used for a temporary pick up evacuation through air transport such as helicopters.

When retrieving the raster's for different levels of danger zone we need to consider from what altitude is to be treated for the different danger Zone levels. The lower the altitude the more vulnerable is of flooding. But there is not exact assurance of how many meters of altitude is to be considered danger or not. So for this study objective we will express the areas that are above the 1000 meters as the lowest danger level zone (Green), this because since the north of the city that lies between the 1100 and 1000 meters is situated in an area of which the slope is considered both high and lowest danger level zones. And if the slope is considerably high the more quantity there is of water draining than actually being hold in the land and also the soil type has a small particle size, leading to drain a lot of water. So the following level of altitude between the 1000 and 900 is then to be classified as low danger level zone (Yellow) and the next 100 meters of interval to be seen as medium danger level zone (Orange) while the remain levels from 800 to 0 are to be considered as high danger level zone (Red). The same applies for this criteria when using the function *Raster Calculator* and equation to gather the raster's with different danger level zones. The result is as it follows in Figure 32 Elevation Danger Level Zones.

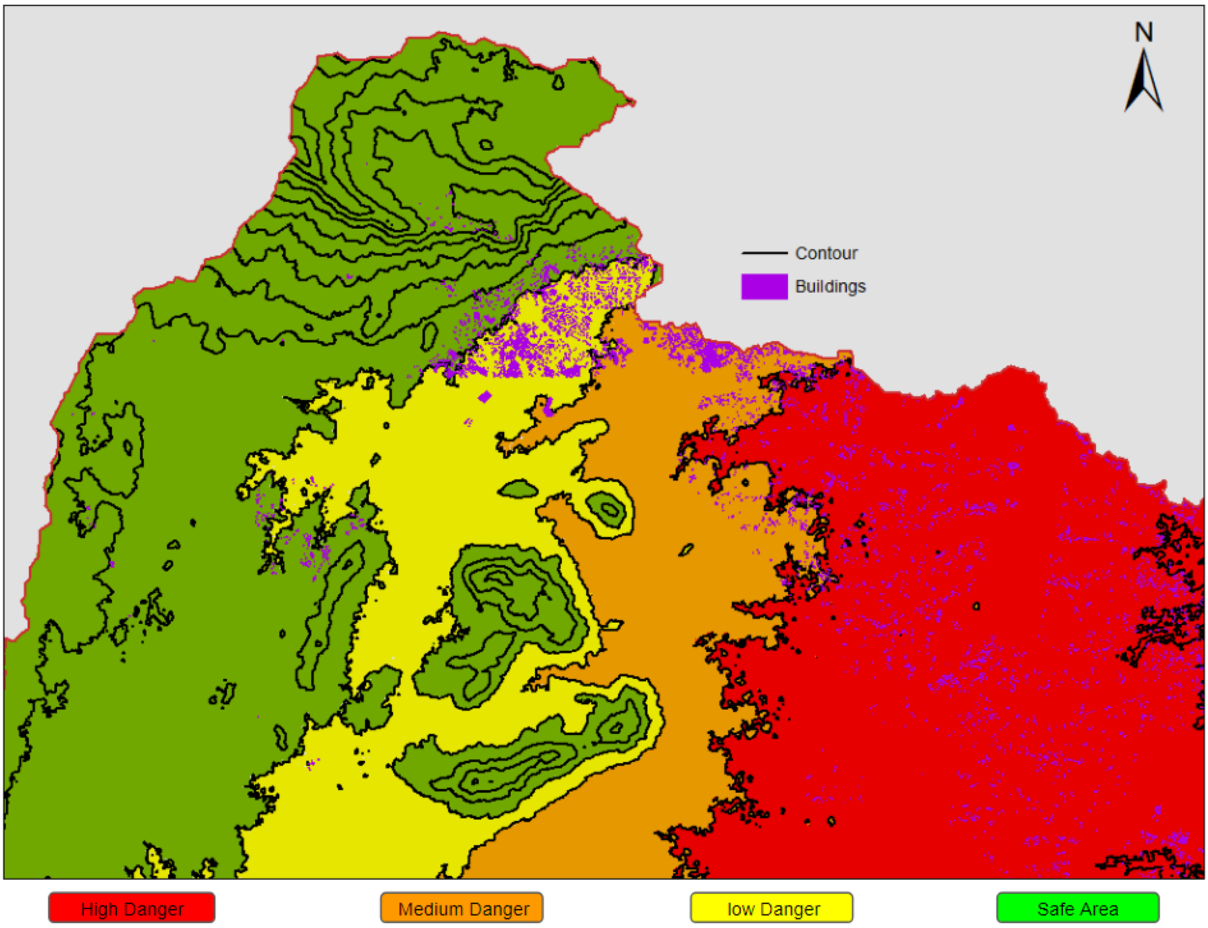


Figure 32 Elevation Danger Level Zones

As suspected, the elevation factor is also not independent when dealing with the remaining flood actors. Even though the area may be at a high altitude, it would not mean entirely that it is a safe area, for it could also have high slope and if there is too much steepness it could be danger for people to stand in.

2.1.5 Land Use

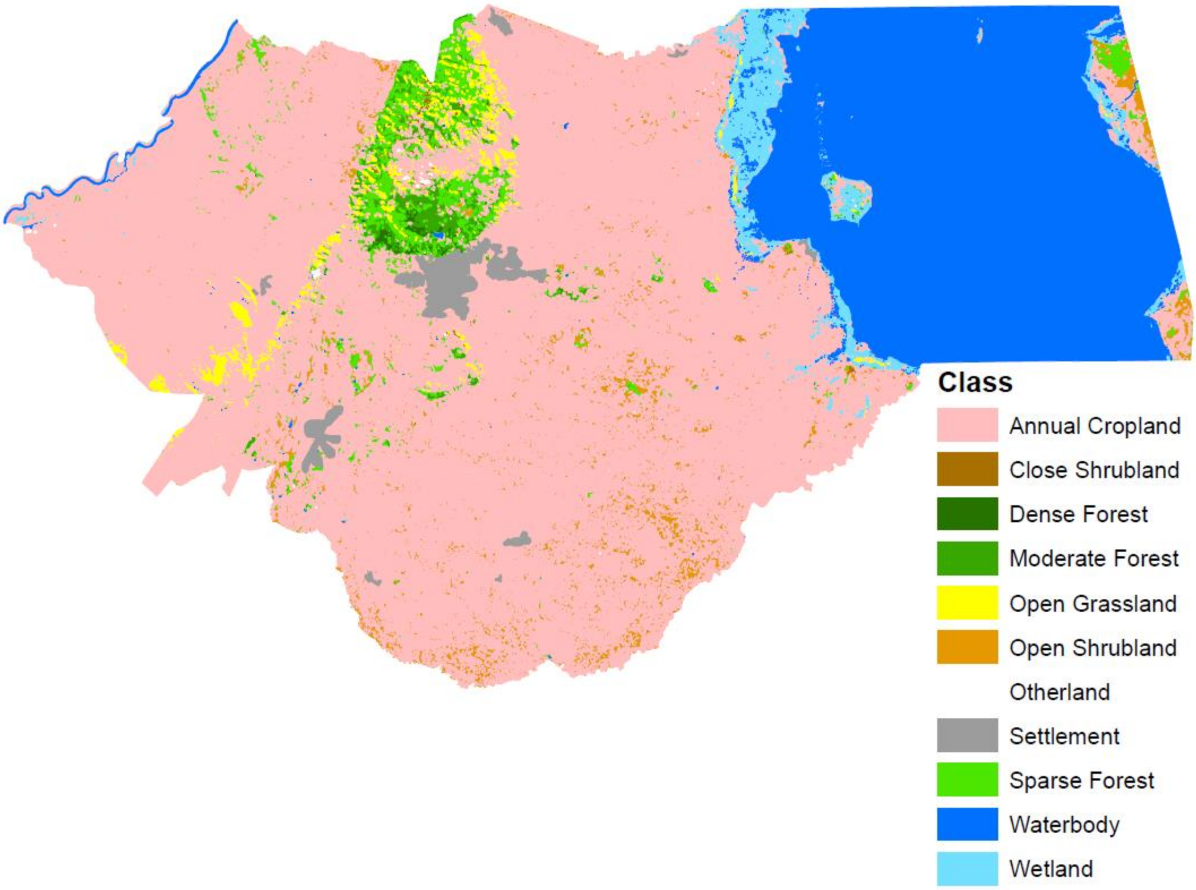


Figure 33 Land Use - District Zomba

The forests are an obstacle for rainfall water to drain towards the streams, holding significant amount of water in the area. But from the Figure 33 Land Use - District Zomba we can see that most of the vegetation lies in the Zomba Nature Reserve, and the surroundings of the city of Zomba are filled with areas that are annually devoted to agriculture to produce food.

If we take a closer look at the city Figure 34 Land Use - Zomba Capital, North of Zomba, there is a water dam called Mulunguzi Dam that is used as a water supply for Zomba city. The existence of the dam may well be another factor to the occurrence of floods once there is a heavy rainfall in the area and the possibility of the infrastructure's inability to hold the water once reached to its full capacity.

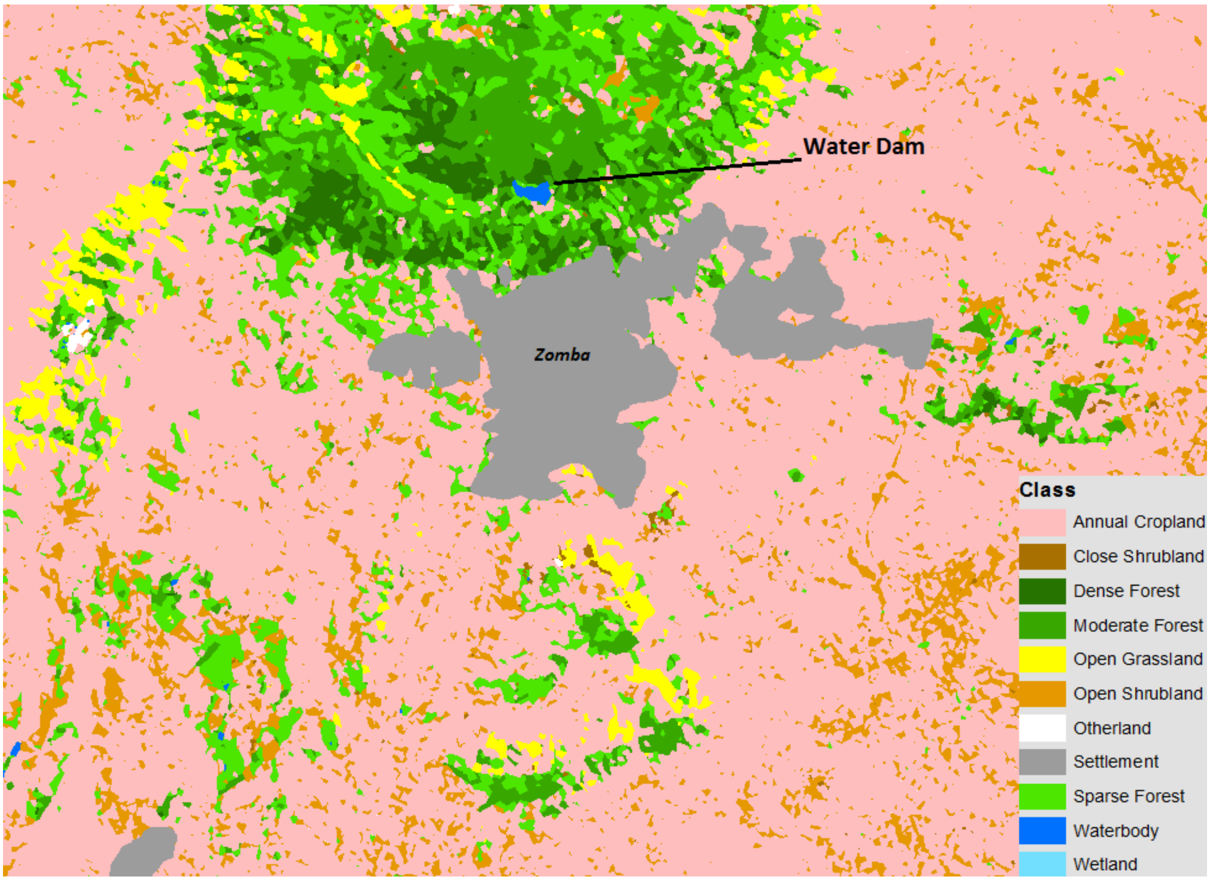


Figure 34 Land Use - Zomba Capital

In the South side of the mountain, towards the city, it would appear that there are some dense forests in the steep areas with high slope. This amount of vegetation would be able to slow down the drainage of water significantly but depending on the intensity of rainfall. And according to the recorded flood events, the rainfall intensity has been greatly high and so the size of the forest did not and would not prevent the devastation of the floods for future crisis events. The remaining surrounding areas of the city have a few small areas of sparse, moderate and dense forests that could hold some of the water that has been drained from the city, increasing the city's vulnerability for flooding. The annual cropland areas are used for agriculture, and therefore it means that they are soils of which will hold water, increasing the chances for flooding. The open/closed Grassland and shrub land are small sized vegetation and since they are sparse in the area, they will not slow down as much the drainage but hold some water, giving also a higher chance for flooding to occur in the area.

Now that we know what could influence the flood events and to what extent, we can use the formulas described above in the previous criteria analysis in the function *Raster Calculator* and say that the areas where we can find settlements, annual croplands, open grasslands, open shrub lands, closed shrub lands and other lands are to be classified as high danger level zone (Red). The sparse forests as medium danger level zone (Orange) and the moderate/dense forests as low danger level zone (Yellow). The raster's will then be merged by using the *Combine* function and the output can be visualised as it follows in Figure 35 Land Use Danger Level Zones.

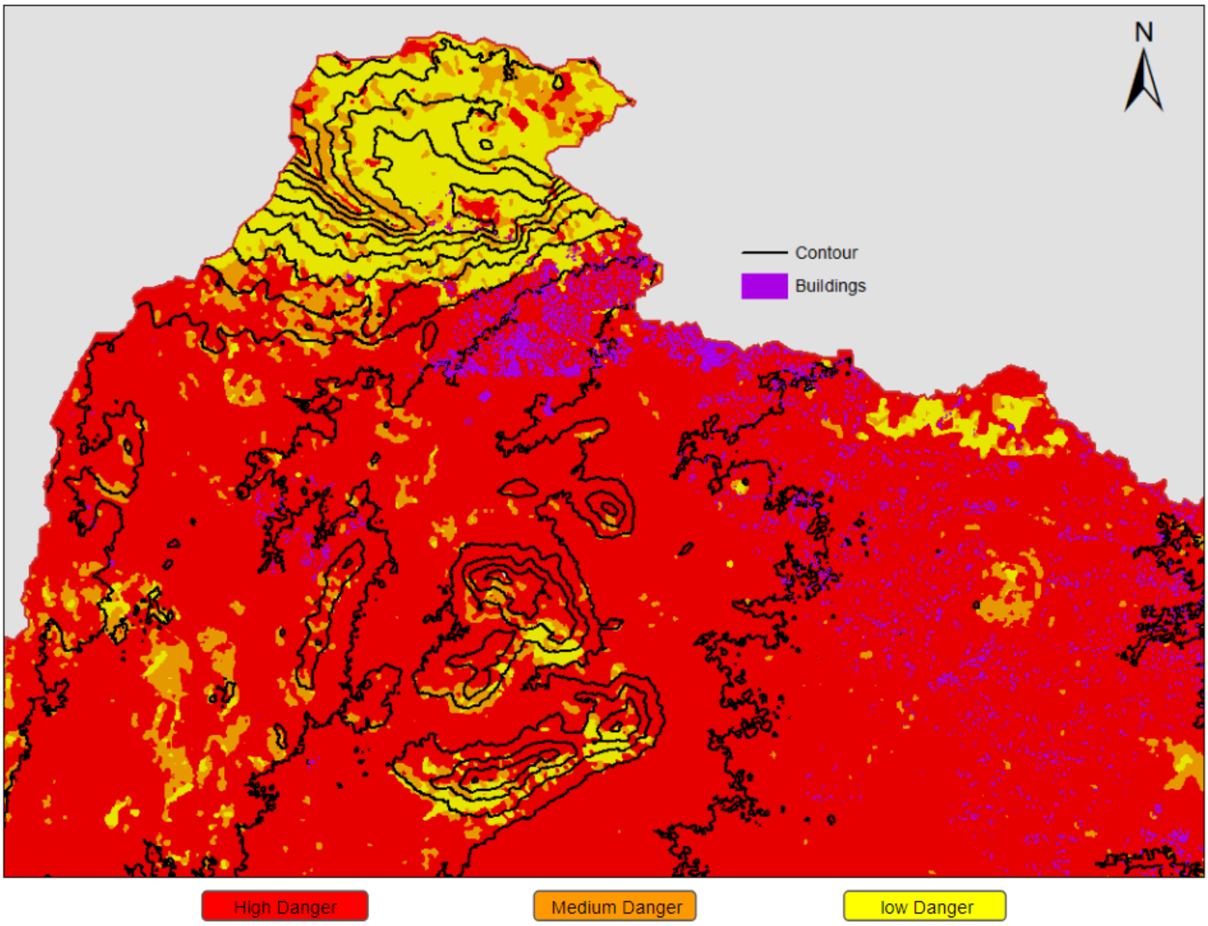


Figure 35 Land Use Danger Level Zones

From the output we can confirm that the same happens with the previous actors. Most areas of high danger level zones are consistent with the other factors, especially within the city. But at south to where the hills are situated it is clear that the land should not be considered as an high level danger zone since they are situated in an higher altitude and with a low level of steepness that allows for people to stand in safety. Therefore the land use is also dependent from the other factors.

2.2 Danger Level Zones

Once finished analysing and evaluating the different potential danger level zones in the chosen basin for the flow accumulation, slope, soil type, elevation and land use, it is time to combine them all as to determine the final output for the different danger level zones within the area. For that we need to reclassify the raster's so that we know what the values are for each danger level zone that represents. For this paper the High danger level zone (Red) value is 1, the Medium danger level zone (Orange) is 2, the Low danger level zone is 3 and the lowest danger level zone that are the safe area (Green) is 4. Since that all the actors are dependent on each other we still need to figure out the weights that each influences for the outcome of the floods. The flow accumulation gathered from the watershed area however will not be included in the analytical hierarchy process.

Starting by setting the first matrix A of *pairwise comparison matrix* for the four variables in which we want to compare. Since there are four variables we would need to have 12 different values for 6 comparisons between them.

The elevation would be considered as the most influential among the other options. If we compare with the slope, in an area at a high altitude where ether there is low or high slope, it would be a safe area because the water always finds a way to flow through the “edges”. But at a lower altitude, where ether it is high or low slope it will always be considered a potential area for flooding. Therefore the elevation is more important than slope (5). When comparing the elevation with the land use, at a high altitude, ether there is a settlement or moderate forest it would be considered as a safer area. But at a low altitude, in a settlement area, it would be at risk for floods while in a dense forest it would be safer. So the elevation is slightly more important than land use (3). With the soil type comes the same conclusion (3), whether the soil has a sandy or clay texture at a higher altitude, it would still be safer but at the lower altitude, the sandy soil could still be safe from floods while the clay texture land would not.

In the analogy between the slope and land use, in most of the circumstances the land use would have slightly more influence (3). Where there is low slope and settlement, it would be a dangerous area, but with a dense forest instead of a settlement it would be a safer area. While in a high slope there would be no settlements and the water would flow downwards and so no risk for flooding. Afterwards, when contrasting with the soil type factor, at an area where soil has a sandy texture, whether there is a low or high slope it would still have lower chances for flooding. Therefore the soil type is also more important than the slope (5).

Lastly for the land use and the soil type, in areas where the land has either sandy or clay texture, if there is a settlement in the area, it would be at high risk for flooding. And if there would be vegetation instead of settlement, it could absorb some of the water, becoming a lower risk for flooding but since the clay texture soil has a very small particle size there wouldn’t be much vegetation to absorb the water. So the land use is more important than the soil type (5).

a_{jk}	Elevation	Land Use	Slope	Soil Type
Elevation	**1**	3	5	3
Land Use	0.33	**1**	3	5
Slope	0.20	0.33	**1**	0.2
Soil Type	0.33	0.2	5	**1**

Table 3 Matrix A

Once figured the value for each criteria, the score for each option is calculated in the next Table 4 Matrix S.

S_{ij}	Elevation	Land Use	Slope	Soil Type	Weight
Elevation	0.535714	0.661765	0.357143	0.326087	0.47
Land Use	0.178571	0.220588	0.214286	0.543478	0.29
Slope	0.107143	0.073529	0.071429	0.021739	0.07
Soil Type	0.178571	0.044118	0.357143	0.108696	0.17

Table 4 Matrix S

In the matrix above we can see the weights for each factor where the elevation has the most influence by 47%, the land use as the second most influential with 29%, the soil type with a significance 17% and the slope with the lowest influence of 7%. These values are added in the function *Weighted Overlay* resulting into the following danger level zones combining the four factors without the flow accumulation in Figure 36 Elevation, Slope, Land Use and Soil Type Danger Level Zones in Zomba Capital.

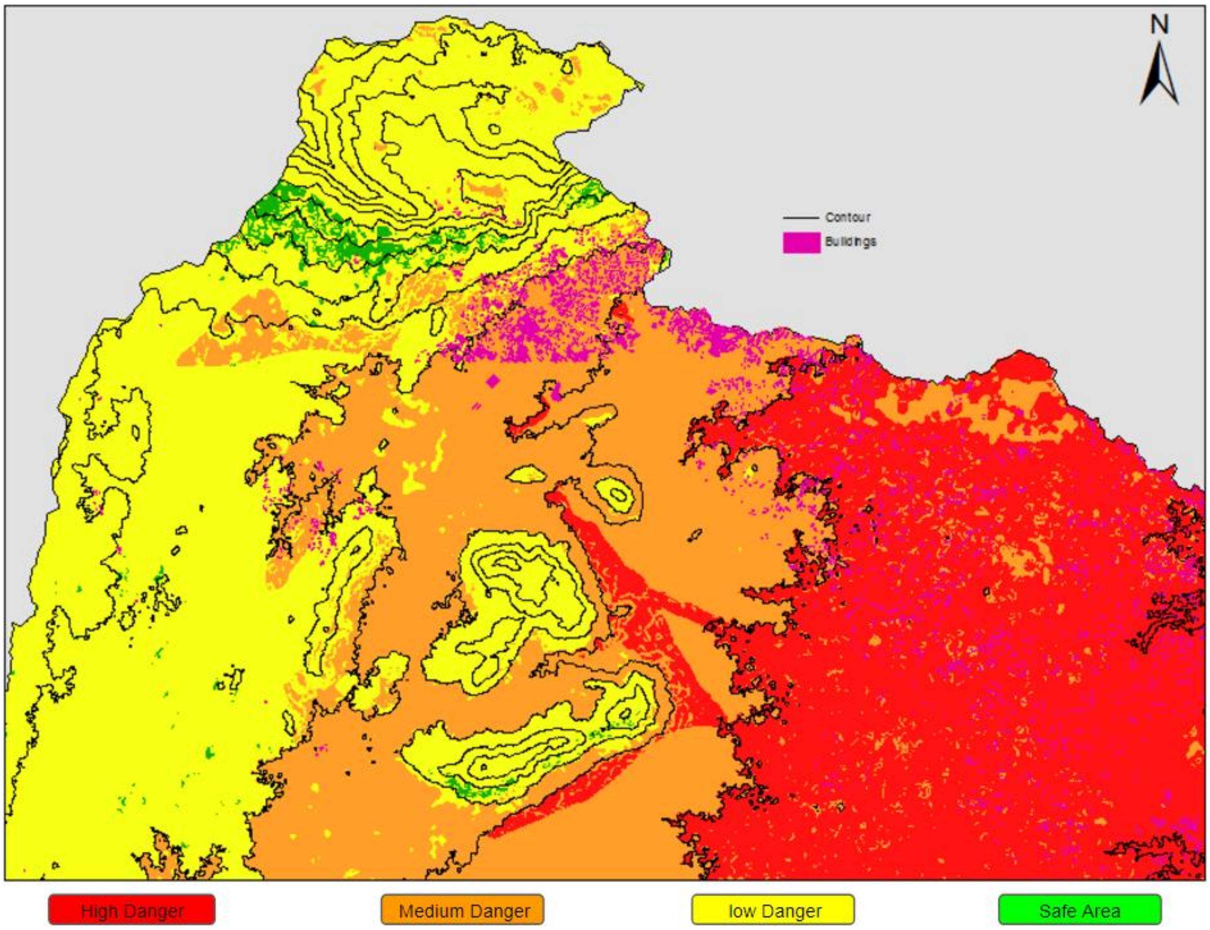


Figure 36 Elevation, Slope, Land Use and Soil Type Danger Level Zones in Zomba Capital

The flow accumulation criteria in this paper's methodology will not be applied in the AHP method neither in the weighted overlay process, for it has a higher value of influence towards all the remaining criteria. It will be joined in the danger level zones map at the end. This estimation is primarily based on the available data and the adaptation to the objective study for the chosen area.

The resulted map in Figure 36 Elevation, Slope, Land Use and Soil Type Danger Level Zones in Zomba Capital, tells us that the settlement area of the city is in a Medium danger level zone area while the lower altitude areas towards the southeast are the most vulnerable areas for floods. Towards north where the natural reserve is, we can see some safe areas in green that are in between the 1300 and 1400 meters of altitude. These areas however should not be considered to be chosen for evacuation areas, for these areas are in the steepness of the mountain from where the rainfall water will flow downwards, and to travel against those flows on foot will prove to be very dangerous to do so. Towards the south of the city there are some hills that are covered in both low and safe areas. These areas should be considered for the population to evacuate from the floods to come.

2.3 Evacuation Route Problem

Before calculating the routes for evacuation, the roads from OpenStreetMap dataset need to be cleaned, fixed, analysed and reclassified. Some roads we can see that are not connected as they should be (Figure 37 Unconnected roads). This error however is easy fix by simply using the function *Integration* on ArcMap. By specifying the maximum distance between the polylines that should be connected (e.g. 6 meters), after measuring the distance between them, the function will extend the vertices of the polylines until it connects and adds a node in the intersection between the lines.

Figure 37 Unconnected roads

According to the OpenStreetMap dataset there are different types of roads within the area. In the next Figure 38 OSM road map of Zomba capital city, the following road types are visible: bridleway, footway, path, track, steps, service and residential, secondary, tertiary, trunk and unclassified.

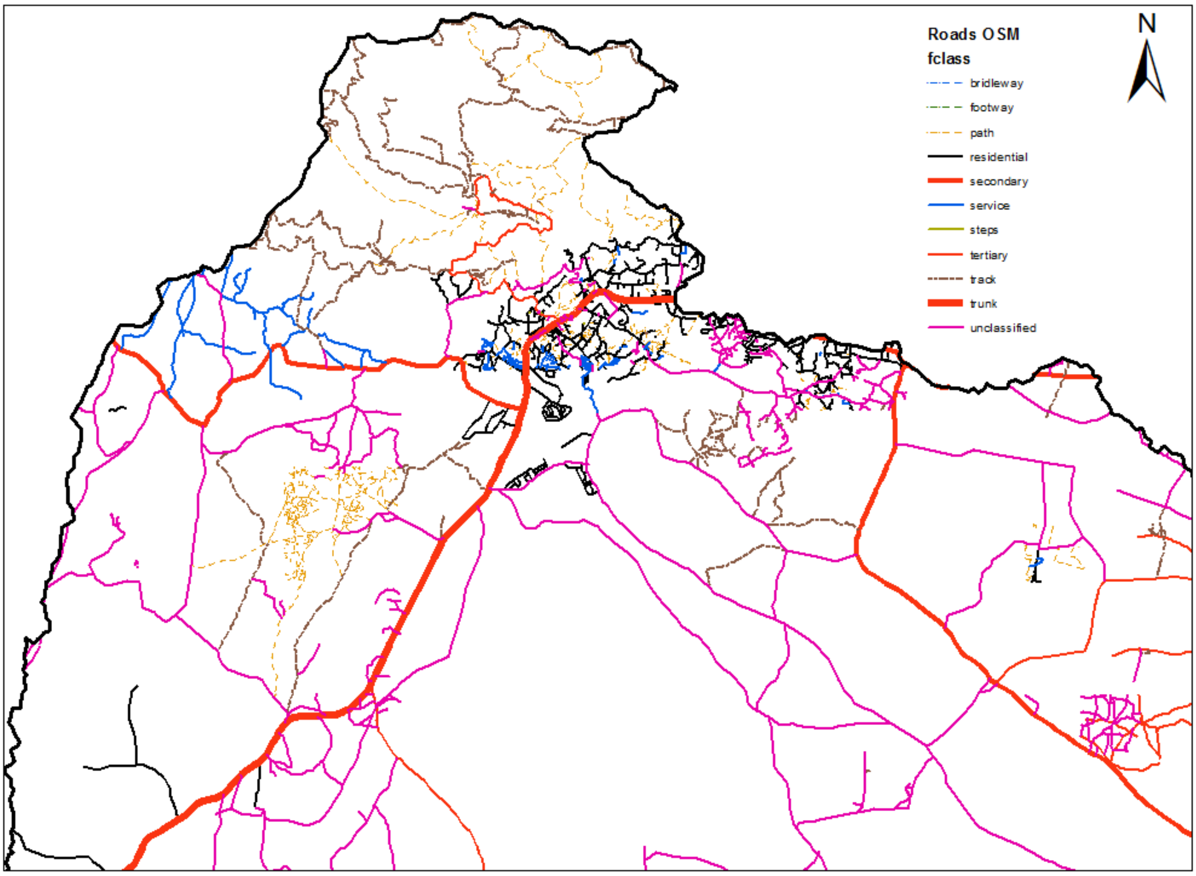


Figure 38 OSM road map of Zomba capital city

The roads that are classified as tracks, bridleways, footways, steps and tracks are considered as trails with minimum capacity for means of transportation. These trails are meant for short distances, with either high or low steepness towards the mountains or simply through alleys in the city. In case of an evacuation event, these trails should not be used for they could potentially cause harm for when the population travels through in with large masses of people, spending more time to travel. If there were to be potential panic during an emergency, these trails would easily become “clogged” with people and provoke more harm among them. The residential and service roads are larger in width and length than the trails but they are still considered as low capacity highway. Nonetheless these roads are connected solely to guide the people from their homes into the higher capacity highways. Therefore it is a valid option to use these roads with the purpose of reaching into the higher capacity highways for the shortest time possible. Of which are the secondary, tertiary and trunk roads, the higher capacity highways that should be prioritized paths for travel. These roads also include bridges Figure 39 Bridge of trunk road outside city of Zomba (source: OpenStreetMap) that crosses the known rivers and other water flows.

Figure 39 Bridge of trunk road outside city of Zomba (source: OpenStreetMap)

One last road class in the shapefile is the unclassified class of which it is very similar to residential and service roads according to the maps from OpenStreetMap in Figure 40 Roads from OpenStreetMap.

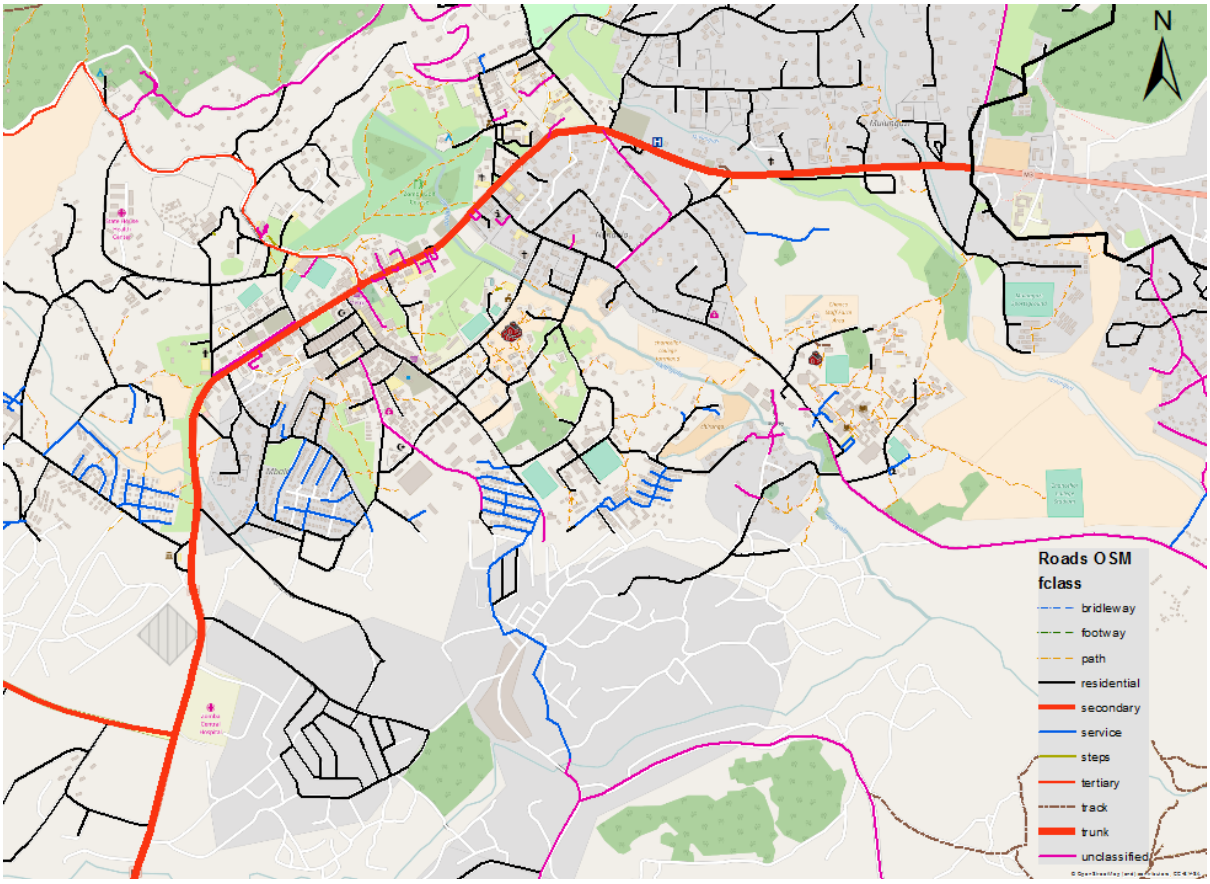


Figure 40 Roads from OpenStreetMap

As much it is visible, these unclassified roads are the extent of either service, residential or one of the five trail's mentioned above. For this paper the unclassified roads will not be taken into consideration for the calculation of evacuation routes, for these roads bring uncertainty about their nature and how they could influence the safety of the people during evacuation process.

First dissolve the roads shapefile, merging all the roads that share the same classification. Extract the residential, service, secondary, tertiary and trunk roads as a feature class within a geodatabase (a geodatabase is required to calculate the routes through network analysis expansion tool). And within the geodatabase, create a feature dataset, where the network dataset will be added. Merge all the five different roads into one single polyline, add a field in the table of attributes called 'Meters' and calculate the length of each polyline through the *calculate geometry* tool. Import the roads layer into the feature dataset as a single feature class. Create a new network dataset with the added roads layer, make sure the attribute for the network dataset's (Meters) usage type is Cost, the units in meters and data type as double. Select the evaluators' source's types as fields with the value of 'Meters' from the field with the calculated length in the table of attributes. Build the network and in the tools select the starting point and the end point location for the route of which the tool *Directions* will resolve the shortest route. The result will be as the following Figure 41 Evacuation Route towards safe areas below demonstrates:

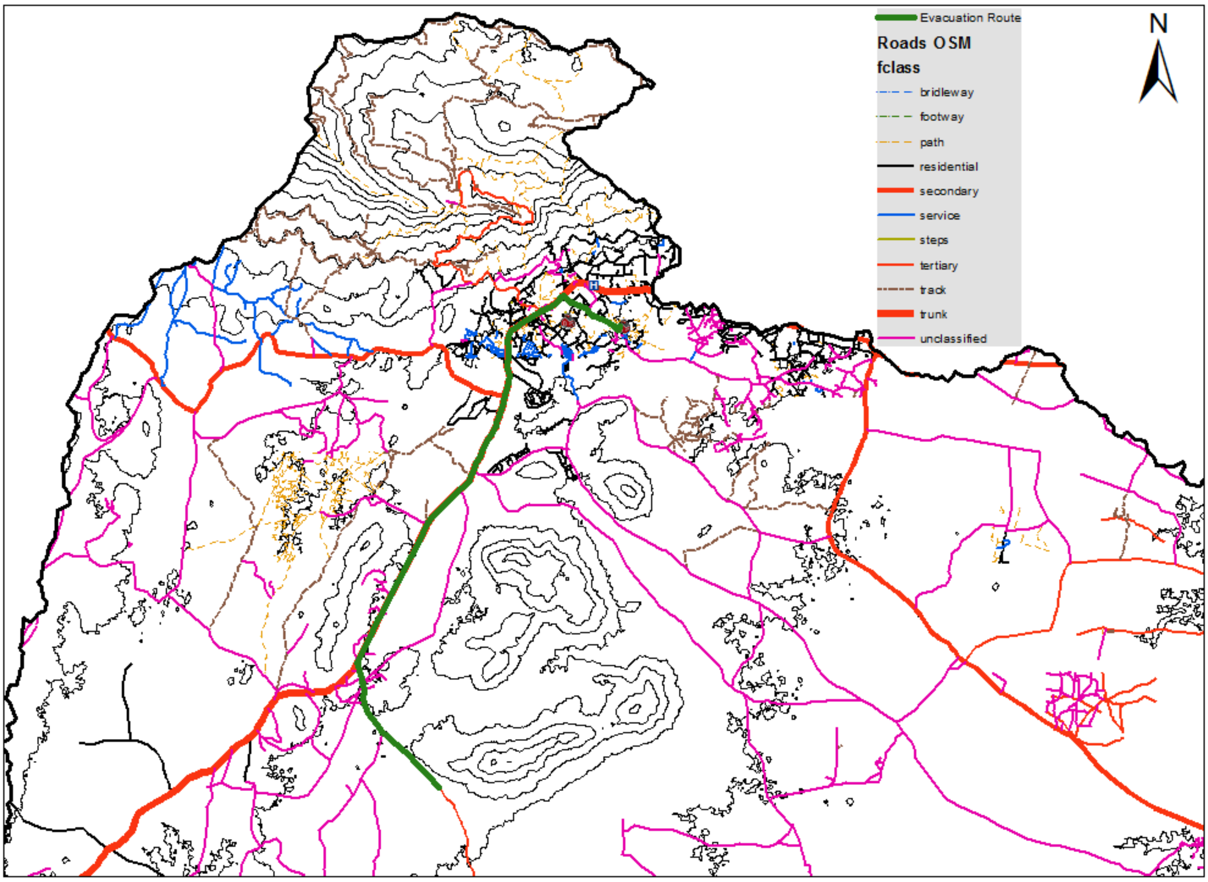


Figure 41 Evacuation Route towards safe areas

The starting point of the route is the location of one of the schools being the strategic build furthest from the high capacity highway, and the destination point is in the area of the safe grounds. The next Figure 42 School evacuation route within the city and the flow accumulation obstacle can show the starting point in more detail:

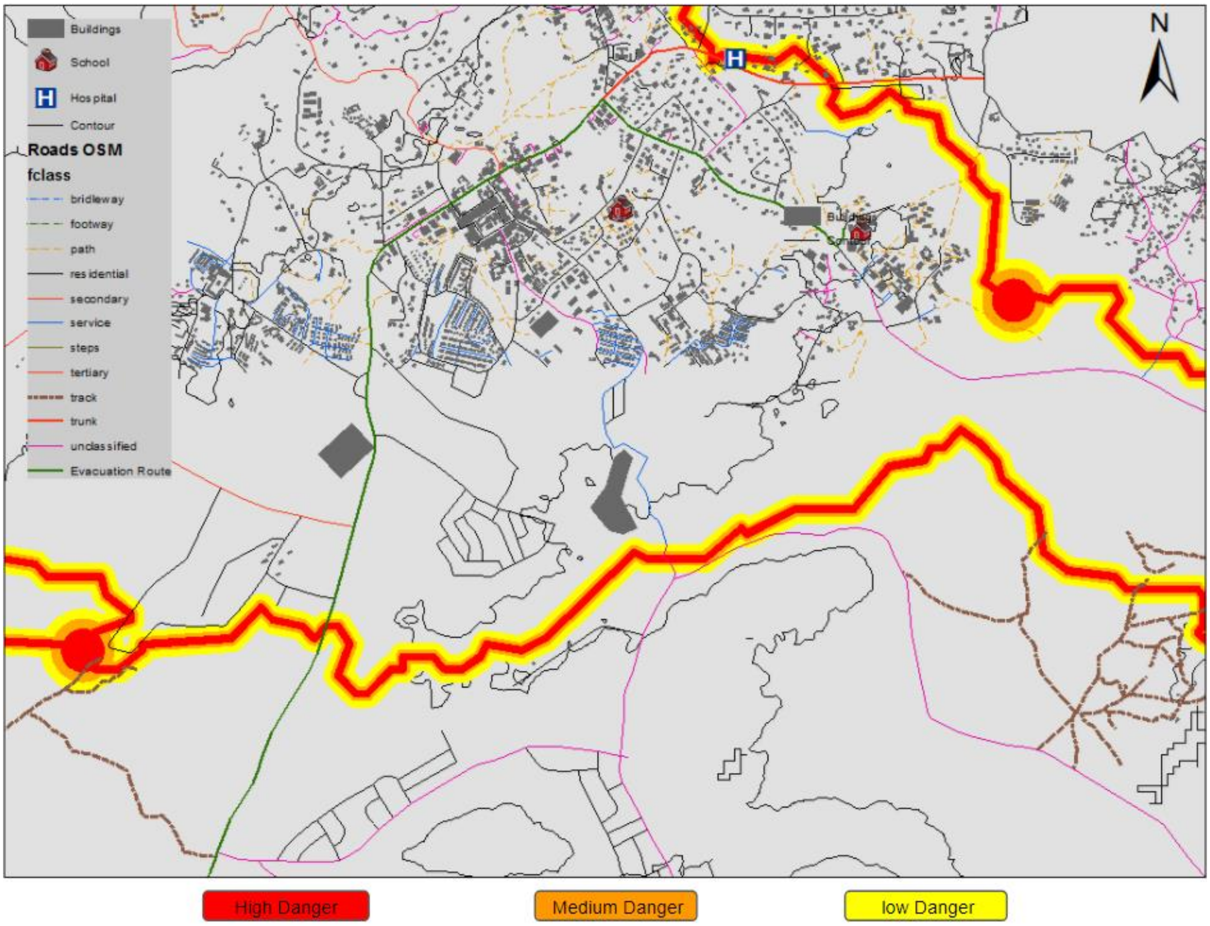


Figure 42 School evacuation route within the city and the flow accumulation obstacle

The network analysis selects the residential road towards to the trunk with a higher capacity for means of transportation leading to south until it reaches to a way out through a tertiary road, finishing to the destination by the same road. Along the way we can find an obstacle of which is the flow accumulation risk zones, through a bridge from the trunk's road infrastructure (Figure 39 Bridge of trunk road outside city of Zomba (source: OpenStreetMap)). The status of the bridge is unknown, it could lead the population through a dangerous passage. Therefore it is required to solve a multi-choice route paths-ways towards the green areas down south. Since the network analysis extension tool is a durable method to calculate several routes due to the low machine's processors capacities, the OpenRouteService is used as a different solution. It is a browser application that allows to solve the fastest routes through different means of transportation, ether by foot, bicycle, or by car. It provides with different sophisticated graphics, measuring the distance, elevation, the segment length for the different types of road, the type of surface and the suitability grades of the chosen routes. If we select the same starting point and destination location point of which was calculated through the Network Analysis, the OpenRouteService application will select pretty much the same route. The application also allows to download the route as a geojson file that can be converted into a shapefile and uploaded in the ArcMap.

3. Results

3.1 Safe Areas

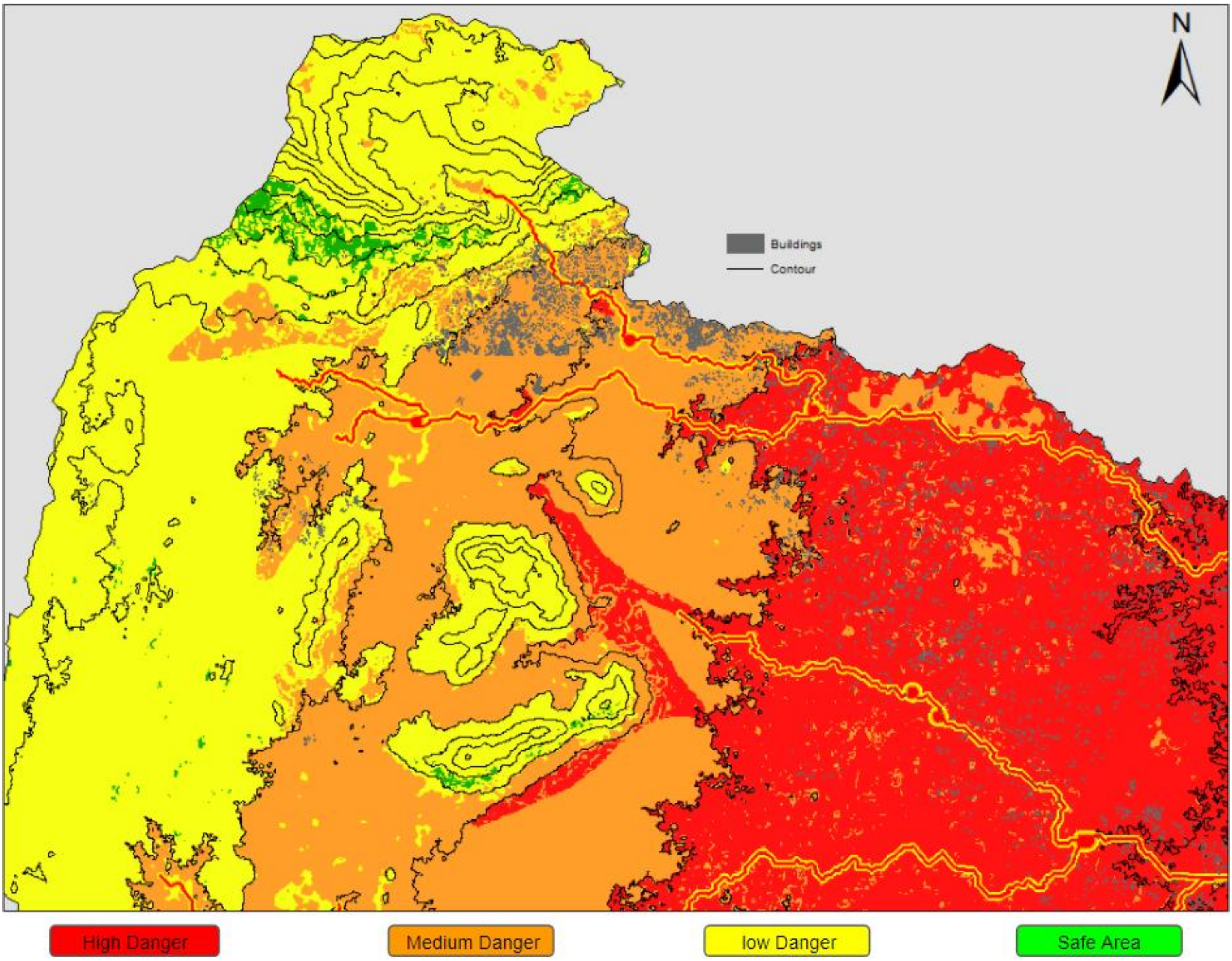


Figure 43 Danger Level Zones of Zomba

The final result of the danger level zones map tells that the city is endangered by the flood risk that could originate from the high intensity rainfall, filling the dam in the mountain, north of the city, that is used to provide with clean water. And follow the same flow but with larger accumulation and volumes of water. The flow crosses the city that will eventually spread throughout the area due to the presence of buildings acting as obstacles and the concrete soils slowing down the water drainage in the surface. Therefore the reason of why it is classified in a medium danger level zone. The flow accumulations act as obstacles for the people to evacuate from Zomba, however if the infrastructures such as bridges are in a conditional state, it would be safe to cross the flows, if not, a new option for a different route is to be calculated in order to reach to the same destination or to another. There are two viable safety areas in the northwest by the side of the mountain and in the south of the city behind the hills. The study of these areas is to be found in the following sub-chapters evacuation plans A and B.

According to Geonames dataset, the populated place of Zomba has 80.932 habitants. This would be the size and scale of the evacuation, and it is important to know if the estimated safe areas are to be large enough to hold 80 thousand people. To do this we generate a polygon in the area of what we suspect that would be the size for the camp with approximately 1.3 kilometres per square. Then generate 80 thousand random points with a 2 meter space between them, and later create a buffer for all the random points with 2 meters of diameter (Figure 44 Southern green area with 48.000 points).

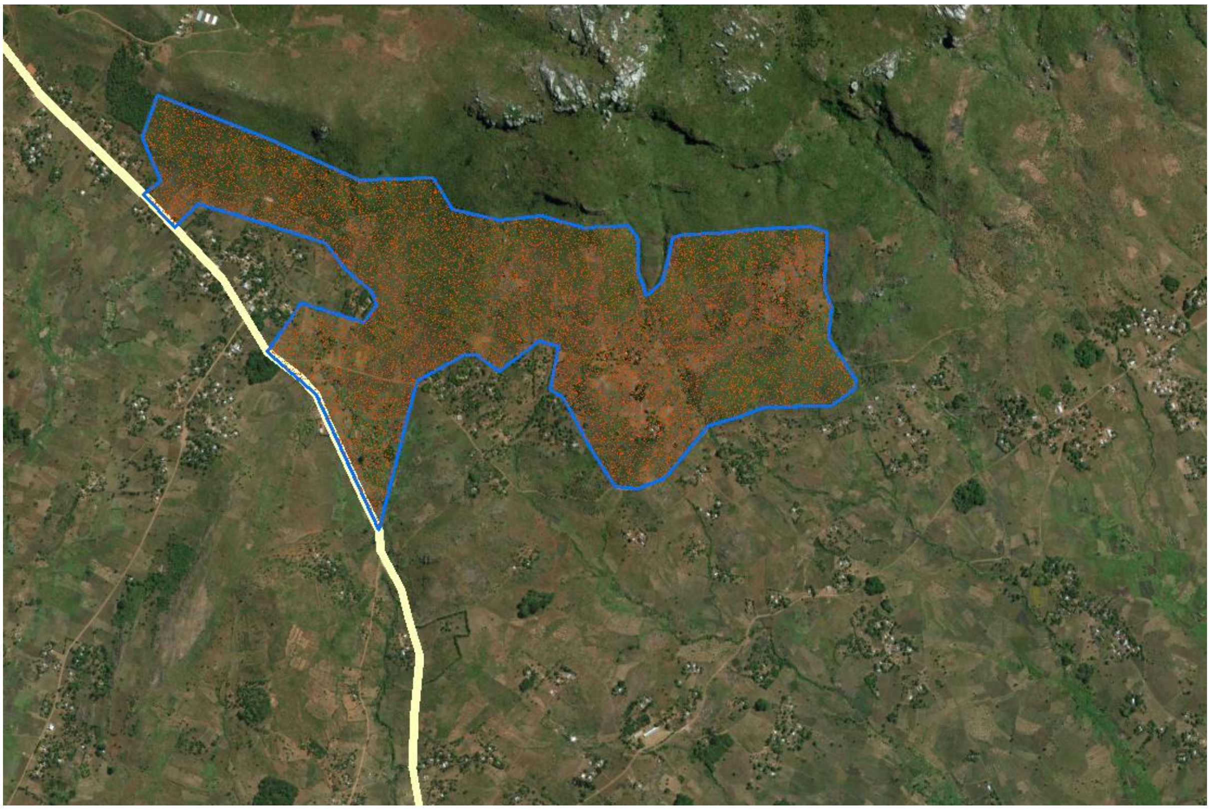


Figure 44 Southern green area with 48.000 points

Figure 45 Zoom of buffer zones

The area would not be able to support the 80 thousand people but it could hold about 48 thousand people (with a radius of two meters space for each) and with possible extension towards the south and inside of the neighbourhood's properties in the area Figure 46 Southern green area with 80.000 points.

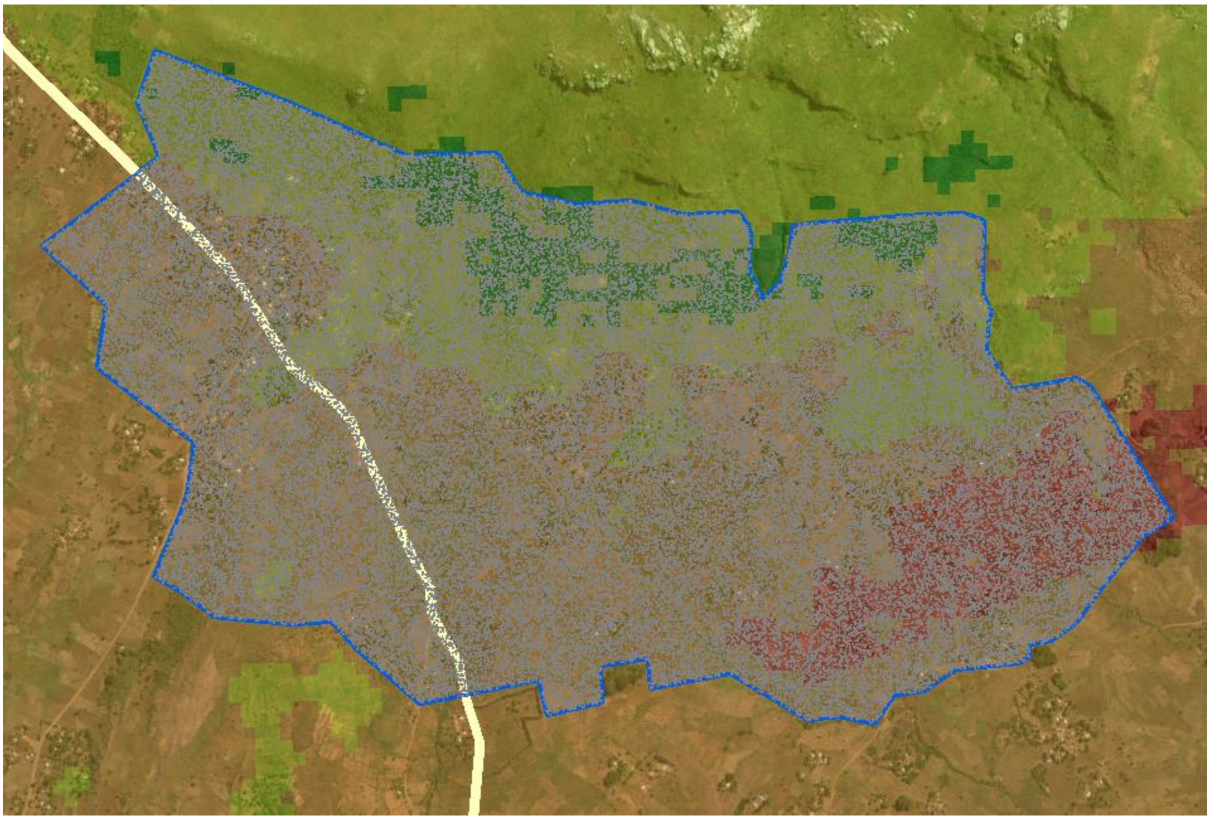


Figure 46 Southern green area with 80.000 points

With the extension (area of 2.8 km per square) it would be possible to gather higher amounts of population but it would have to follow accordingly with the danger level zones in the area. Most of the camp plan is within a medium danger level zone, and according to the estimative, the area would not be large enough to gather more than 40 thousand people. If we look at the north western green area polygon (with 4.5 km per square) (Figure 47 Northern safe area limits) we can see that the area is larger, mostly in safe level danger area, but with large spaces of dense and moderate forests. If it were not by the forests, the area would be suitable to hold 80 thousand people.

Figure 47 Northern safe area limits

3.2 Evacuation Plan A

According to the map above in Figure 43 Danger Level Zones of Zomba, there are green areas in the northwest towards the mountain at the altitude of 1300 and below the 1600 meters. The safe space that has been estimated has about 4.5 kilometres per square total of area, being the largest in the area and able to provide enough room to gather the population from the city, since in reality the space would be larger than the estimated. It is located close to the steepness of the mountain, mostly covered by moderate and dense vegetation and a soil of Paralithi group type, with the balance of all soil materials such as silt, sand and clay, hence the high presence of vegetation. The city's limits is about 4 kilometres of distance to the center of these areas, of which might appeal to be a primary choice for the evacuation, however it might also be a targeted area for landslides[4] due to heavy rains. The image below in Figure 48 Safe areas in northwest shows the satellite images of the area.

[4] "A landslide is the movement of rock, debris or earth down a slope. They result from the failure of the materials which make up the hill slope and are driven by the force of gravity." ("What Is A Landslide? - Geoscience Australia")

Figure 48 Safe areas in northwest

The land is not connected through high capacity highways but by paths and tracks, of which is not a good option for the people of Zomba or humanitarian agents to use as means of transportation of food, shelter or medical supplies. The close distance to the steepness of the mountain may lead to possible threats such as landslides and new water flows yet to appear. The presence of moderate vegetation and the slope percentage may deny the access to the availability of setting a camp in the area. However, if there is a possibility for land clearance from the dense vegetation it could easily provide with enough space for the whole population. But for this study the chance of deforestation will be avoided.

The route in Figure 51 Route A towards the area takes different types of roads, starting by a residential road through 1.5 km of distance into the trunk that follows 600 meters towards the secondary road. After the next 3.5 km in the same road, it will lead into a track for about 920 meters towards the safety area. The time that it takes to arrive to the destination by walking speed takes about 1 hour and 20 mins considering traveling at 1.4 m/s. The suitability of the route can be viewed in the following graph in Figure 49 Suitability of route A.

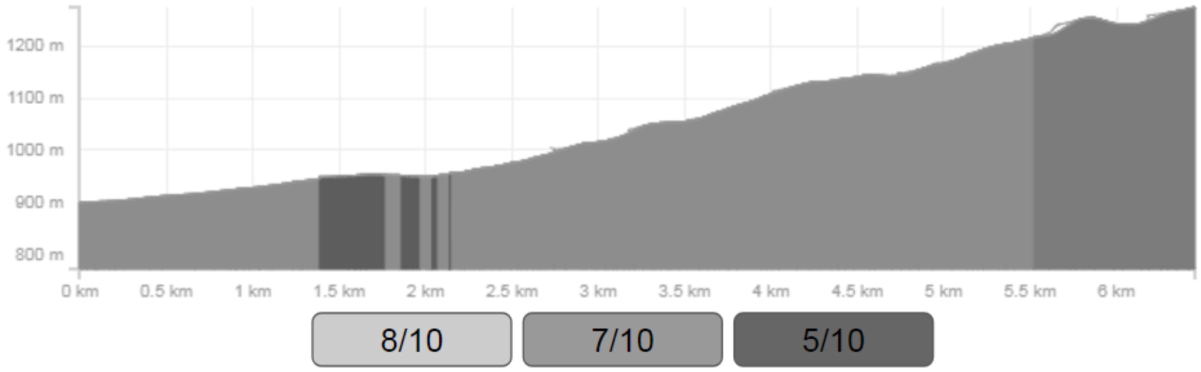


Figure 49 Suitability of route A

About 4.9 km route distance have a rate of 8 out of 10, which is approximately 74% of the whole route. The downside of this route is the 1 kilometre of distance to travel on unpaved roads that are narrower and the high percentage of slope (Figure 50 Slope percentage of route A) to cross, leading the people to evacuate in a lesser efficient way.

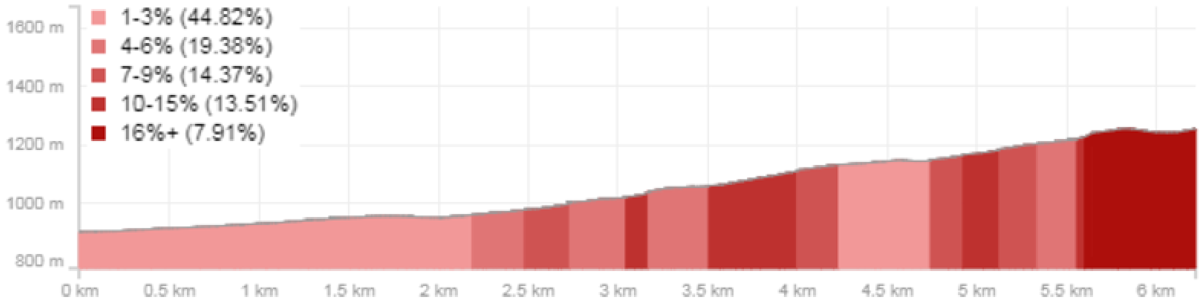


Figure 50 Slope percentage of route A

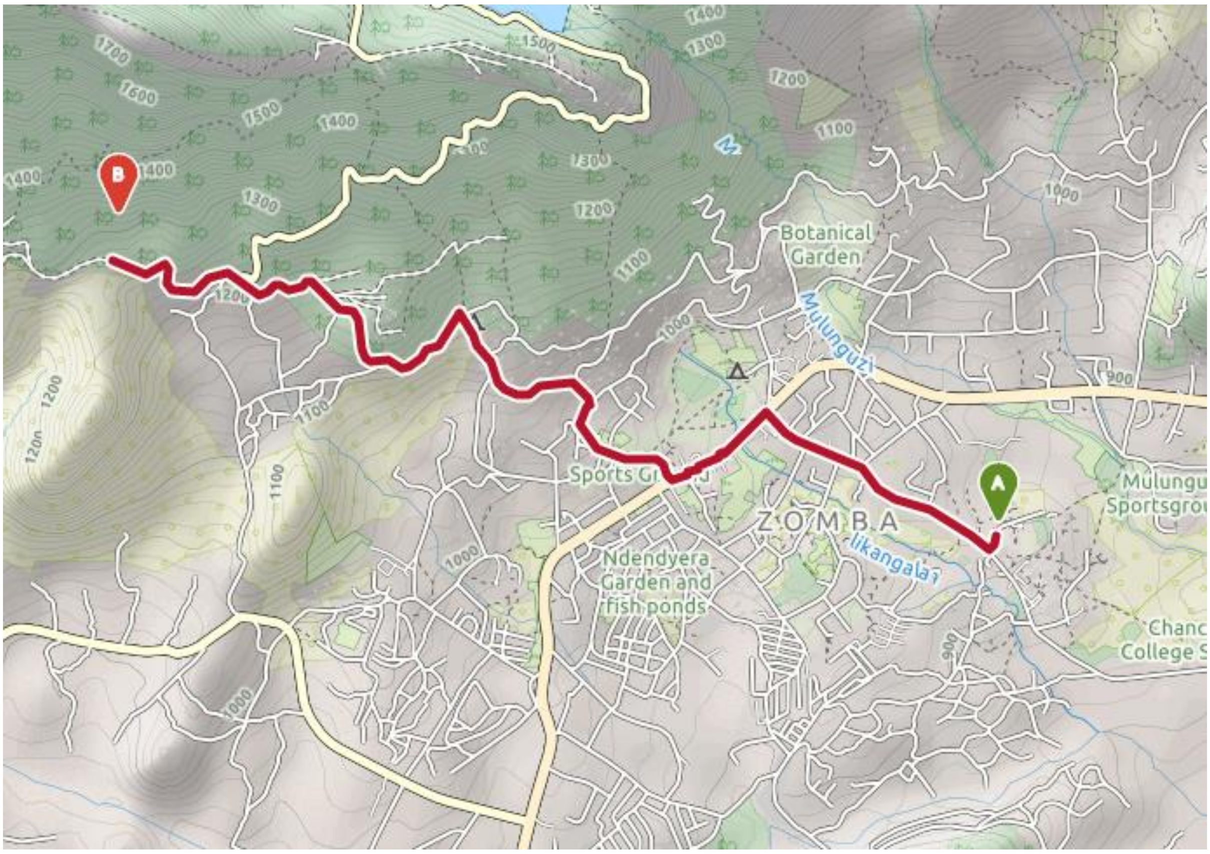


Figure 51 Route A

Even though the distance of travel is short and the route has a good suitability grade, it still faces several disadvantages: The distance of elevated steepness to cross. The presence of a low quality road, with almost 1 km of distance, which connects the area to the higher capacity highway. The existence of a moderate/dense forest, lacking the ability to provide space for humanitarian agents to build a camp to receive the people. And the possible event of a landslide or new flows from erosion to occur within the area.

3.3 Evacuation Plan B

In the south (Figure 52 Safe areas in south), where the estimated safety area is about 1.3 kilometres per square in dimension and at an altitude between the 1000 and 1100 metres. This land could be a viable location for the people to evacuate to, and the humanitarians to meet and deliver the necessities for the people of concern. The targeted area provides with enough space to set up a camp, close to the vicinities of the houses in the area to help support and assist in the matter. It is close to a tertiary road of which is connected to the trunk road, both are high capacity highways able to transport and deliver the necessary means and supplies and also to evacuate people to other areas with access to hospitals, if needed for urgent medical care.

Figure 52 Safe areas in south

This area is about 14.7 kilometres of distance from the city's school, which would take about 3 hours to travel by foot or 14 minutes long to travel by car. The route in Figure 55 Route B from OpenServiceRoute starts off by the residential road of 1.5 km of distance towards the trunk that goes by 9.7 km until reaching to the tertiary road with 3.7 km of distance to the destination point. The 5.6 km of the route has a suitability grade of 8 out of 10 (38% of total distance) and the remaining 9.1 km a grade of 7 out of 10 grade (Figure 53 Suitability of route B). The amount of steepness (Figure 54 Steepness of route B) to ascend is considerably low regarding of the distance to travel.

Figure 53 Suitability of route B

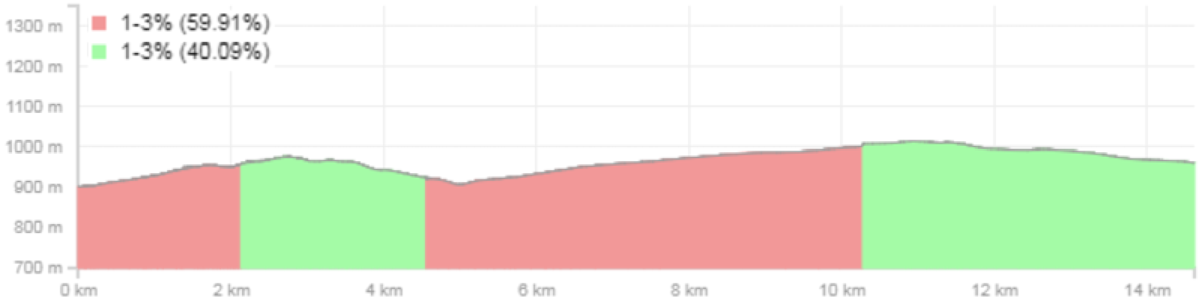


Figure 54 Steepness of route B

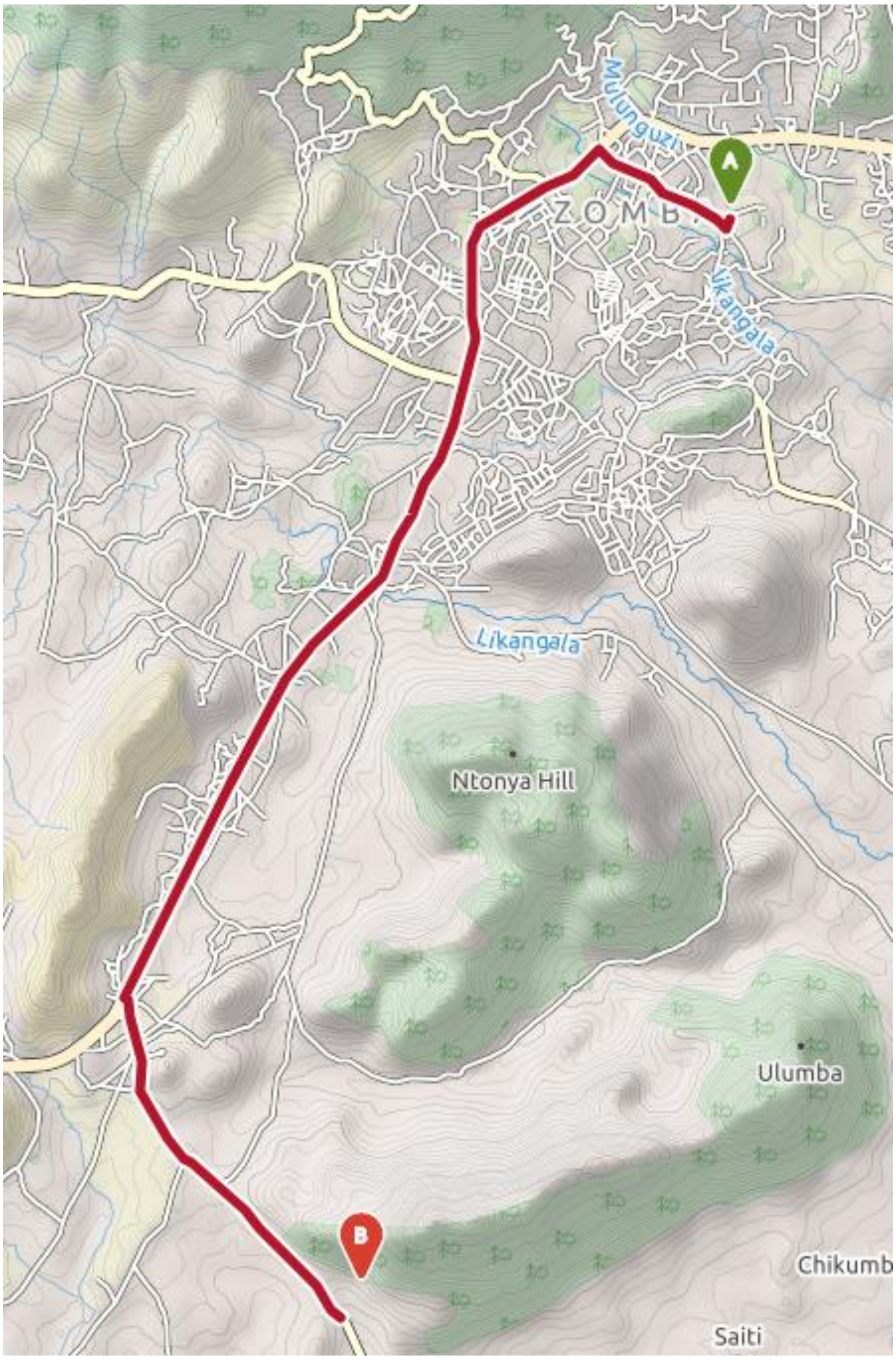


Figure 55 Route B from OpenServiceRoute

The evacuation plan B requires a longer distance to travel but its advantage is the usage of high capacity highways that reaches to the chosen area avoiding to cross the paths, tracks or other lower capacity roads. There is low presence of vegetation in the area that grants the ability to set up a camp and receive the people in need. The area is far away from the mountain and avoids the possibility of a landslide or new eroded water flows to occur in the area. And the route has a good suitability grade, making this route and area of evacuation the most suitable and safest choice. The major problem however is the inability to receive the whole population from the city, being hardly able to hold at least 40 thousand people.

The route is being calculated according to the starting position of the furthest school from the highest capacity highway, but if we calculate the routes for the other schools and hospital the result is as the following map Figure 56 Evacuation routes from different starting points show. All the routes go through the residential roads if needed to, in order to reach to the trunk and evacuate the city towards south, the chosen safety area. If the starting point were somewhere else in the north of the city after the flow accumulation, the people would need to reach the trunk road before crossing the flow. But as it turns out, there are no bridges to cross the flow and the area would be cut off from the city with no option but to evacuate the city through a different path (Figure 57 Optional Route for trapped areas of the city).

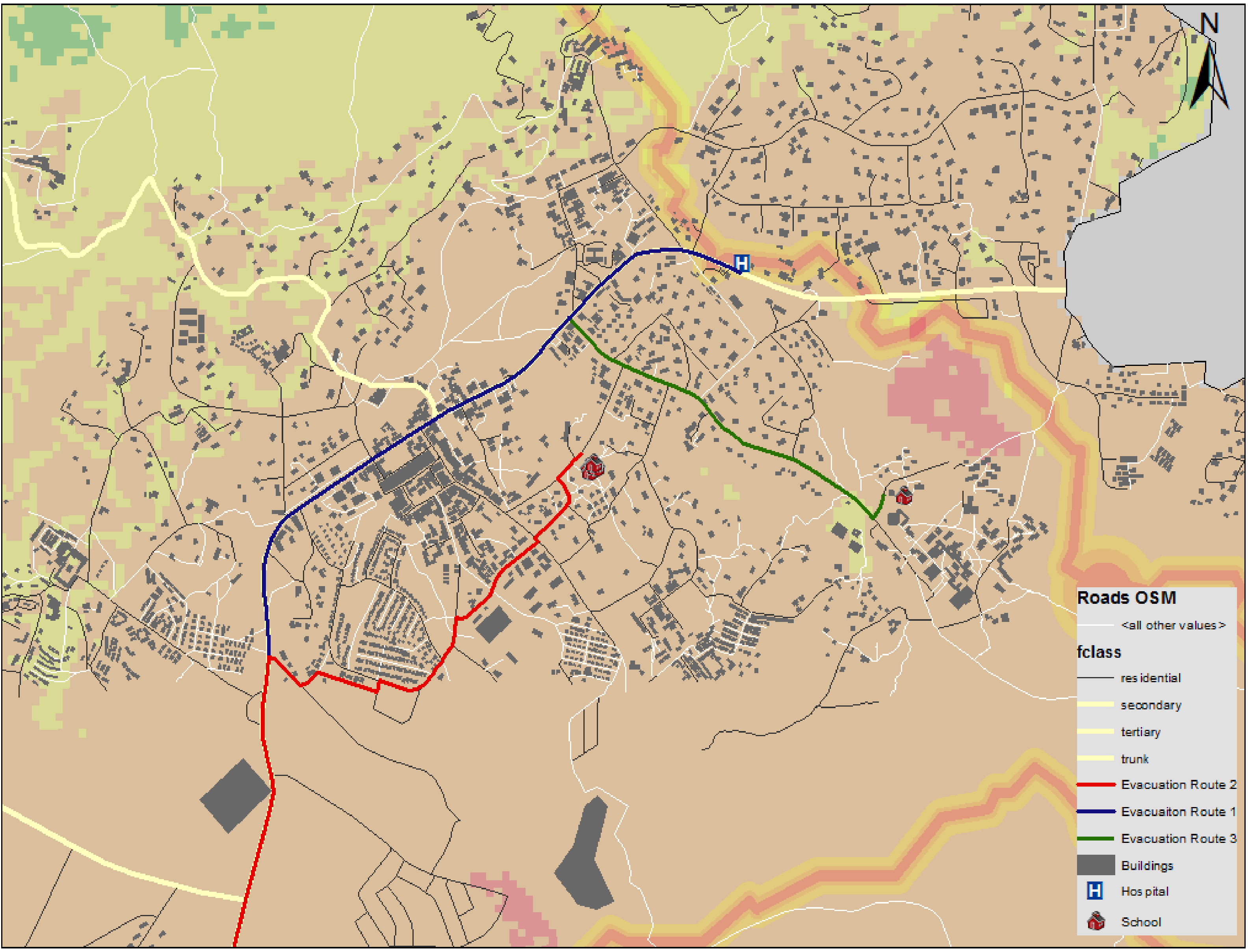


Figure 56 Evacuation routes from different starting points

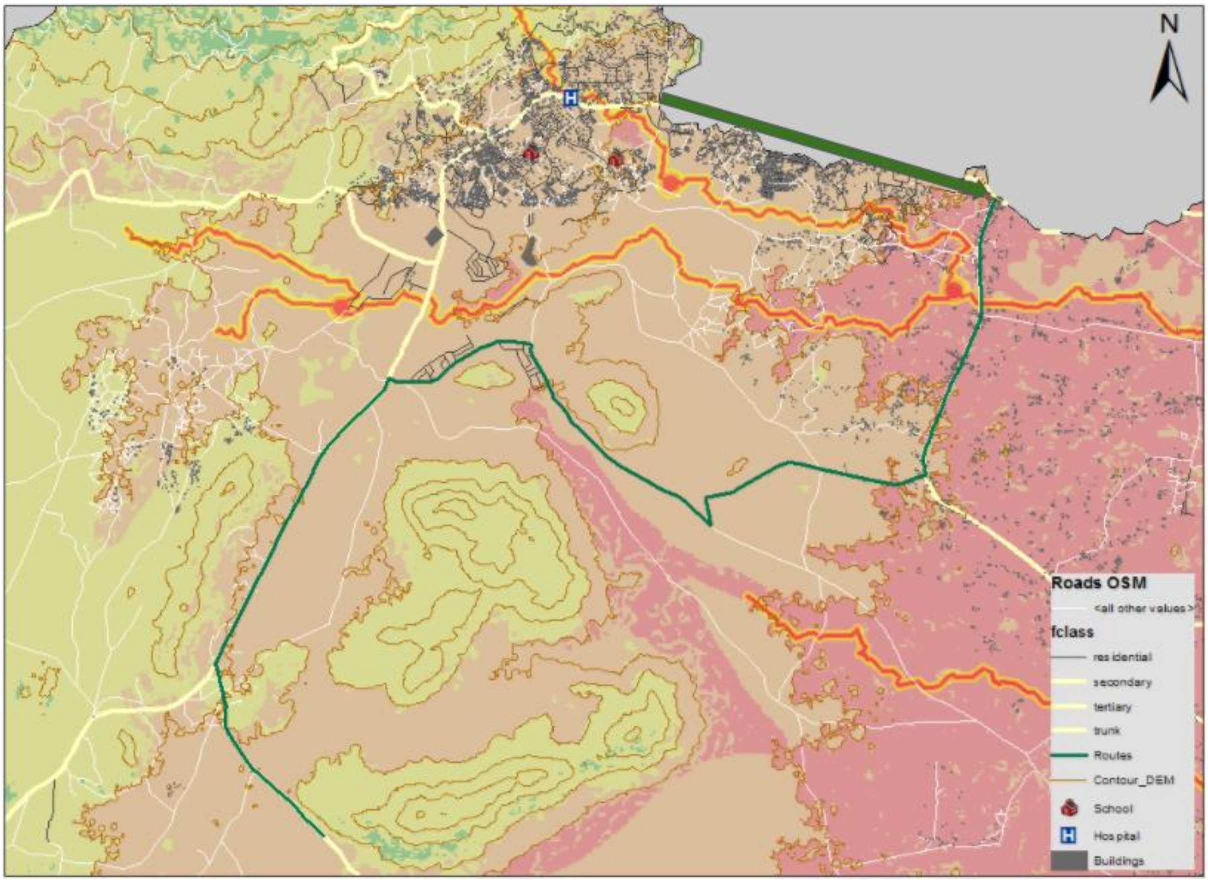


Figure 57 Optional Route for trapped areas of the city

It is possible to see the trunk road between the clipped area of the watershed, and it connects as it is represented by the green arrow in the figure above. The distance becomes the triple but it is a valid route, for it crosses the flow accumulation by using the bridge (Figure 58 Bridge from alternative route (Source: Satellite Imagery Base Map)) and also avoids traveling across other rivers through the tracks and the unclassified roads so to reach to the trunk and continue evacuating towards the destination. Since the bridge is situated far away from the mountain and the city is in the way acting as an obstacle for the water flow, at the moment it reaches, it is lesser faster and in lower quantity, allowing for the people to cross in a safely manner.

Figure 58 Bridge from alternative route (Source: Satellite Imagery Base Map)

The major solution for evacuating the whole city would be to choose both areas with a 60/40 ratio of the amount of population in each area, meaning, the largest green area in the north would gather 48.000 people and the south 32.000 people, with more space to set up camps and outposts. And to decide of which household from the city would evacuate to which area is to consider that the north and west of the city, that are trapped by the obstacle flow accumulation, to evacuate to the southern area using the last calculated route (Figure 57 Optional Route for trapped areas of the city), while the remaining households of east, center and southeast of the city to evacuate to the north-western green area. The routes for each city's zones to evacuate are demonstrated by the following map Figure 59 Evacuation Plan of Zomba City.

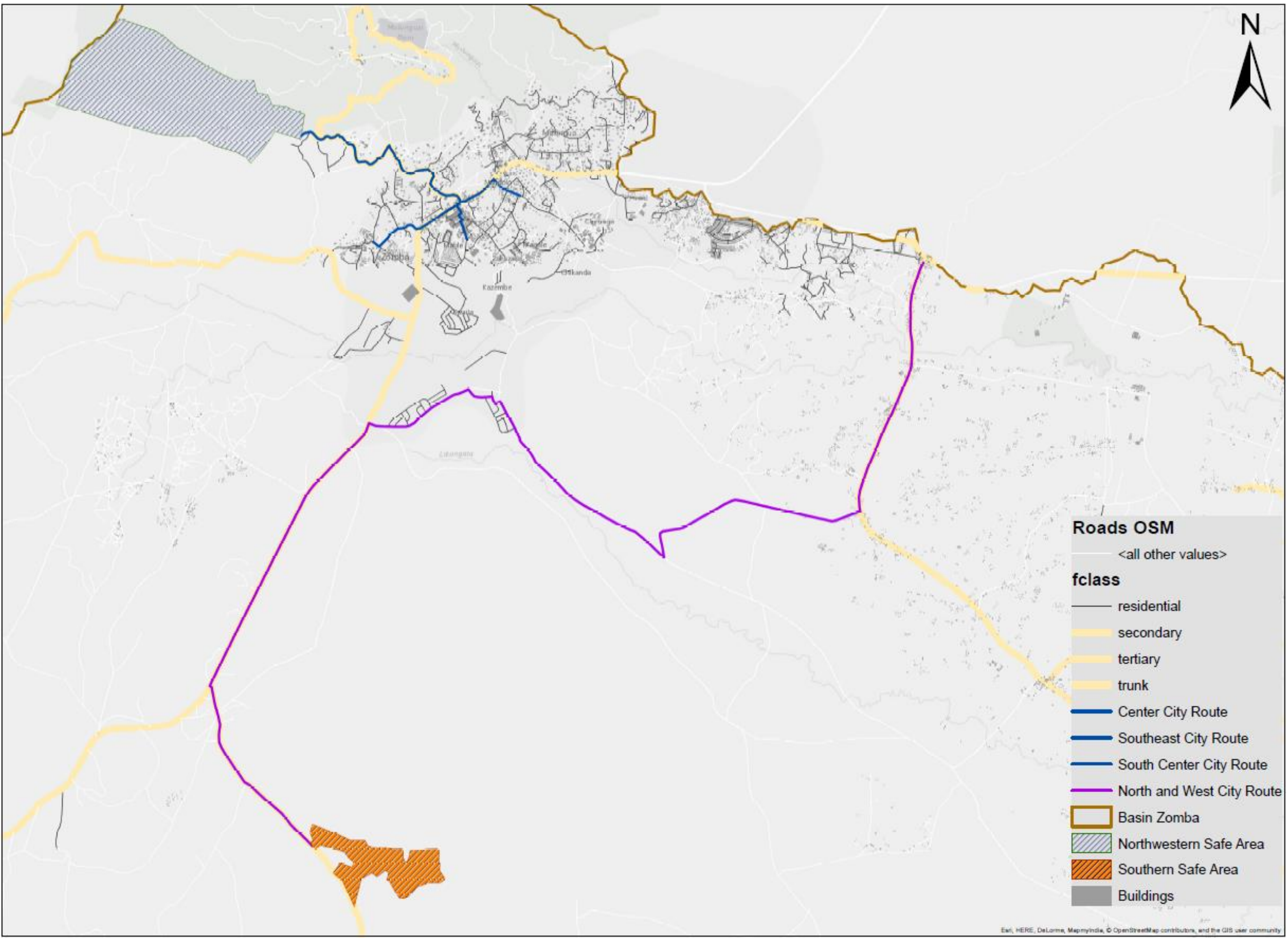


Figure 59 Evacuation Plan of Zomba City

4. Discussion

The bridge (Figure 58 Bridge from alternative route (Source: Satellite Imagery Base Map)) in the purple route mentioned earlier in the results is part of the secondary road that is an high capacity highway, therefore it should meet up with the standards and be able to provide with a safe passage above the river. If it would not be the case, the evacuation would become compromised, so a new route and possibly a new safety area would need to be estimated across different watershed areas to the north. The following watershed in this thesis is the limits of the study area but since the city is in between two different watersheds it would be more efficient and practical to enlarge the study area by two watershed limits and search of more options for evacuating the whole city's population. It would reduce the risk and peril of evacuating large amounts of people towards the safety areas. More options would be added in the situation of a flood event to occur for the humanitarians to plan and decide for what course of action to take and to where allocate their resources to. It would also give the possibility to find further small yet flat areas, safe from danger that allows for the humanitarian and/or government agents to reach and eventually evacuate the people in a more sophisticated manner, either by transportation through air, land or even by sea if the flood level rises to that point.

The two spaces of safety area are not large enough for humanitarians to set a regular size camp and receive such large numbers of population (48.000 in north-western area and 32.000 in south area) due to space limitations from forests, the surrounding neighbourhood's buildings and the limits of the estimated danger level zones. Nonetheless, together they are suitable for establishing a more sophisticated evacuation process, by building a stationary outpost equipped with vehicles with the means of travelling through land or air (e.g. jeeps, trucks, helicopters, etc.). The floods would last according to the level of rainfall intensity. If it's a flash flood then in most case scenarios ("Floods") it would last about 6 hours during the rainfall. Otherwise it could take a week or more until the accumulated water finally starts to recede by its own devices, always flowing downhill. So it extends the possibility of using these estimated safe areas for the people to hold and await until the flash flood recedes or for the humanitarians to arrive with food and supplies.

The efficiency and quality of the work that has been done in this study could improve significantly by applying the following:
The estimation of the danger level zones could boost by adding more criteria's such as Aspect, Rain Intensity, Sewage System Network and other factors that could influence the occurrence and persistence of floods. Replacement for a higher spectral resolution of the digital elevation model with at least 15 metres size pixel. The current DEM being used has a pixel size of 30 metres, which would be enough to work with in such a large study area, but still, it could improve much more if the outputs of the flow accumulation, slope and elevation would be more accurate (Figure 60 Flow accumulation quality).

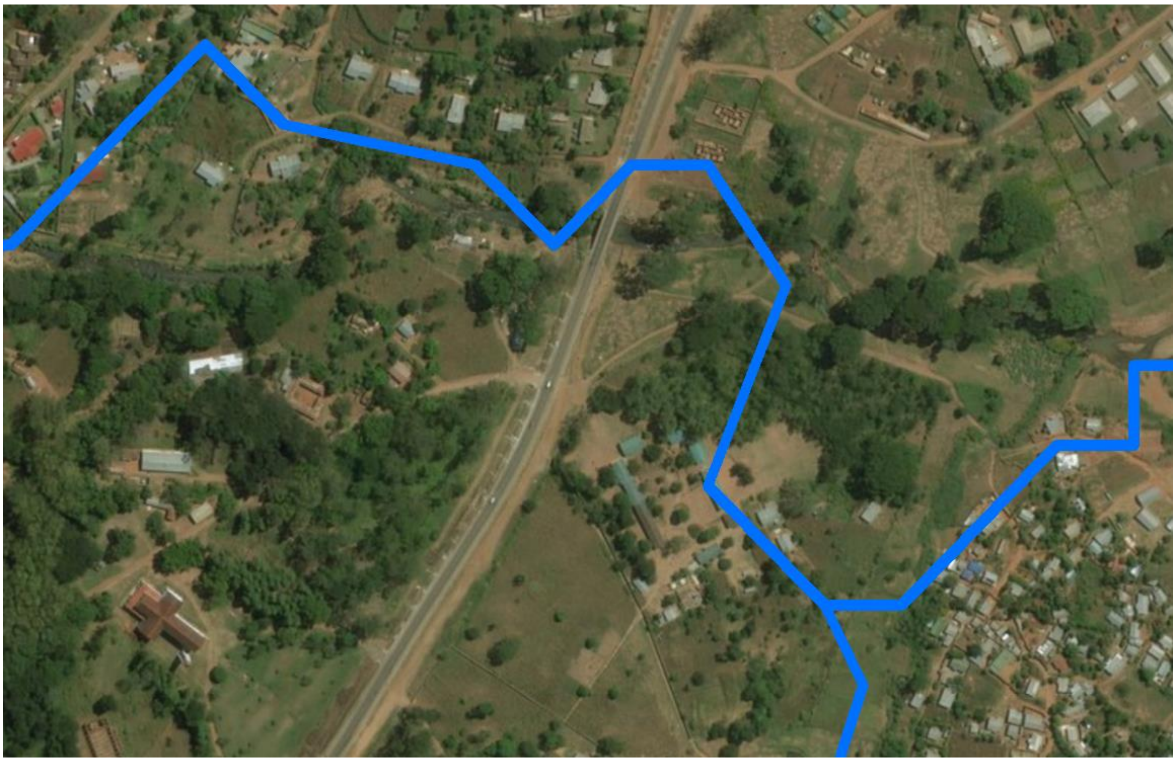


Figure 60 Flow accumulation quality

In addition to the visualization of the danger level zones, an historic estimated flood presences should be added according to the recorded rainfall intensities along the years. This would allow to identify the danger zones of flooding in a much more detailed manner with the possibility of comparing with the resulted danger level zones and confirm the actual threat limits of flooding within the city and its surroundings. This would grant a different estimation of floods and evacuation planning maps for the corresponding incoming level of rainfall concentration predicted by the meteorology stations, sending a warning to the civilians and provide with the right maps that will follow accordingly with the levels of rainfall that could cause another natural hazard event. Providing more time for the people to evacuate and for the humanitarian/government agents to act subsequently.
The calculation of the volume of water that would be present in the city and other areas of interest (where the flood hits harder) according to the levels of rainfall intensity, could add beneficial information for people's awareness of the depths in some areas, identifying potential flows that have enough force to levitate cars, damaging and injuring anyone in the way.
The current criteria's at work for estimating the danger level zones can be improved with further research and discussion for the most optimal range of intervals to identify each danger level: The slope values are not easy to transcribe and measure. They were not calculated by degrees but by percentage values (this because of the presence of an unknown error in the tool) of which the proportions do not correspond at all. The flow accumulation values could also be different, to either include or not the extra load of obstacles in the area according to the extension of research and discussion.

All of the mentioned estimations and calculations in the process and discussion can be calculated with ease using the software Arc Hydro that supports most water resources applications. It provides with sophisticated visualizations of water surfaces, flows, precipitation, temperature and the like. The modelling of a real-time or long term planning designs for precipitation-runoffs (Djokic): Hydrologic modelling - calculates the amount of runoff water from precipitation. Hydraulic modelling - determines the depth, speed and volume of the known water flow quantity that will cover in the area’s shape.

5. Conclusion

The planning and scope of this study is ideal, with the possibility to improve and ultimately meet with the standards for the humanitarian/government agent's decision making, and the necessities for the affected population. The final solution, of choosing both areas to evacuate would be the best approach, as there is no single location that can provide with enough space for the whole city's population, at least from the current selected watershed area. By extending the analysis to an additional watershed area the results could improve greatly. With more ground to cover more additional areas could be classified as safe locations for the people to evacuate to, and the more safe areas there are, the more sophisticated is the evacuation planning. By assigning different routes for each block or zone of the city the less amount of people will use the same route, avoiding for the masses to travel in single, narrower paths, decreasing the chance for panic outbreaks among the frightened individuals.

The GIS tools have proven to be useful to deal with such complexity that involves not just gaining the knowledge of the land and its resources through its analysis, but also improves the decision making for the humanitarians to allocate their supplies, saving more time and less expenditures. The network analysis tool allows for the humanitarians to design evacuation routes according to their own experiences, of which could improve the estimates of the amount of population that would arrive to a certain camp and to identify the right figures of supplies that would be needed to be re-allocated. The data that was used for this thesis is granted for the public use, therefore the humanitarians would be able to apply the same methods, although, it would be of the best interest to invest for higher resolution and better quality data. So possibly in the end they would be able to provide the people with the correct figures and estimates, saving more money for future purposes and needs.
Besides the humanitarian agencies, other identities could benefit from these methods such as the forest engineers, civil engineers, ecologists, hydrologists, flood risk assessors and many more. In the end, the methods applied for this study have achieved the objectives in question with extension for additional improvements and modifications.

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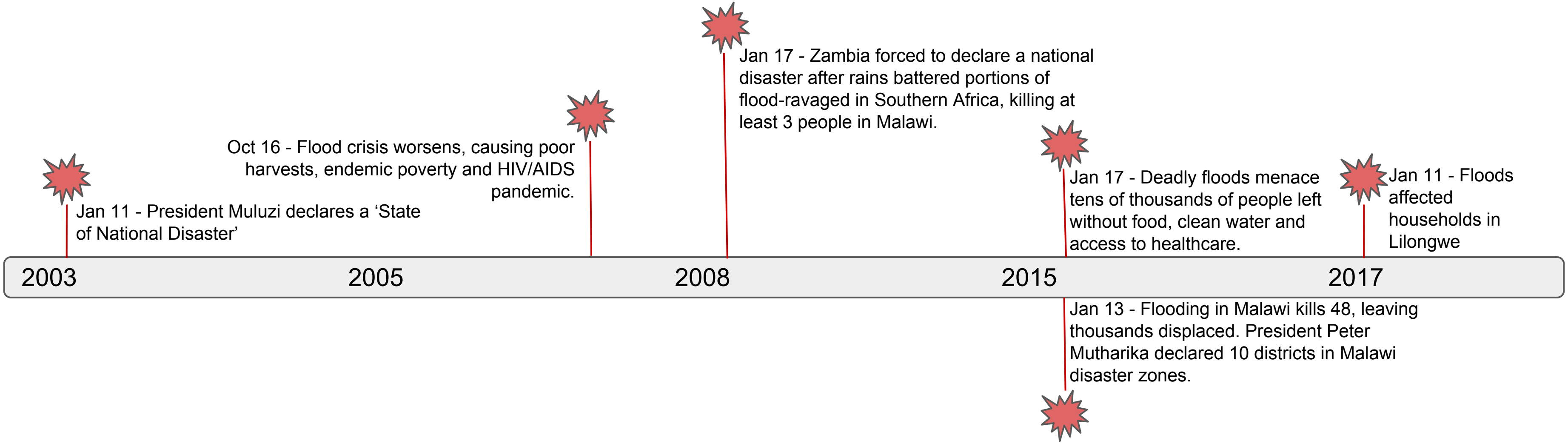
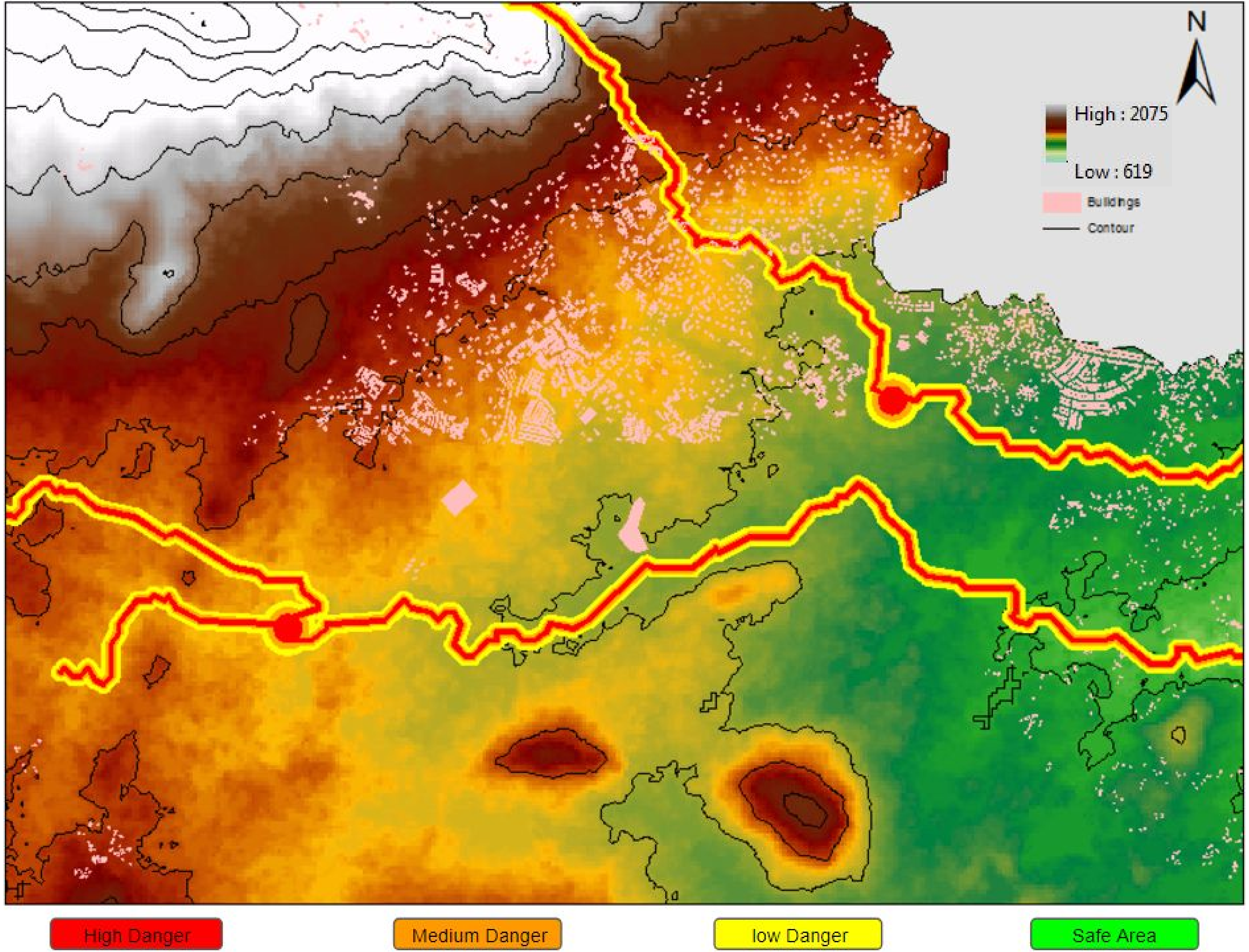
Appendix 1

Floods TimeLine



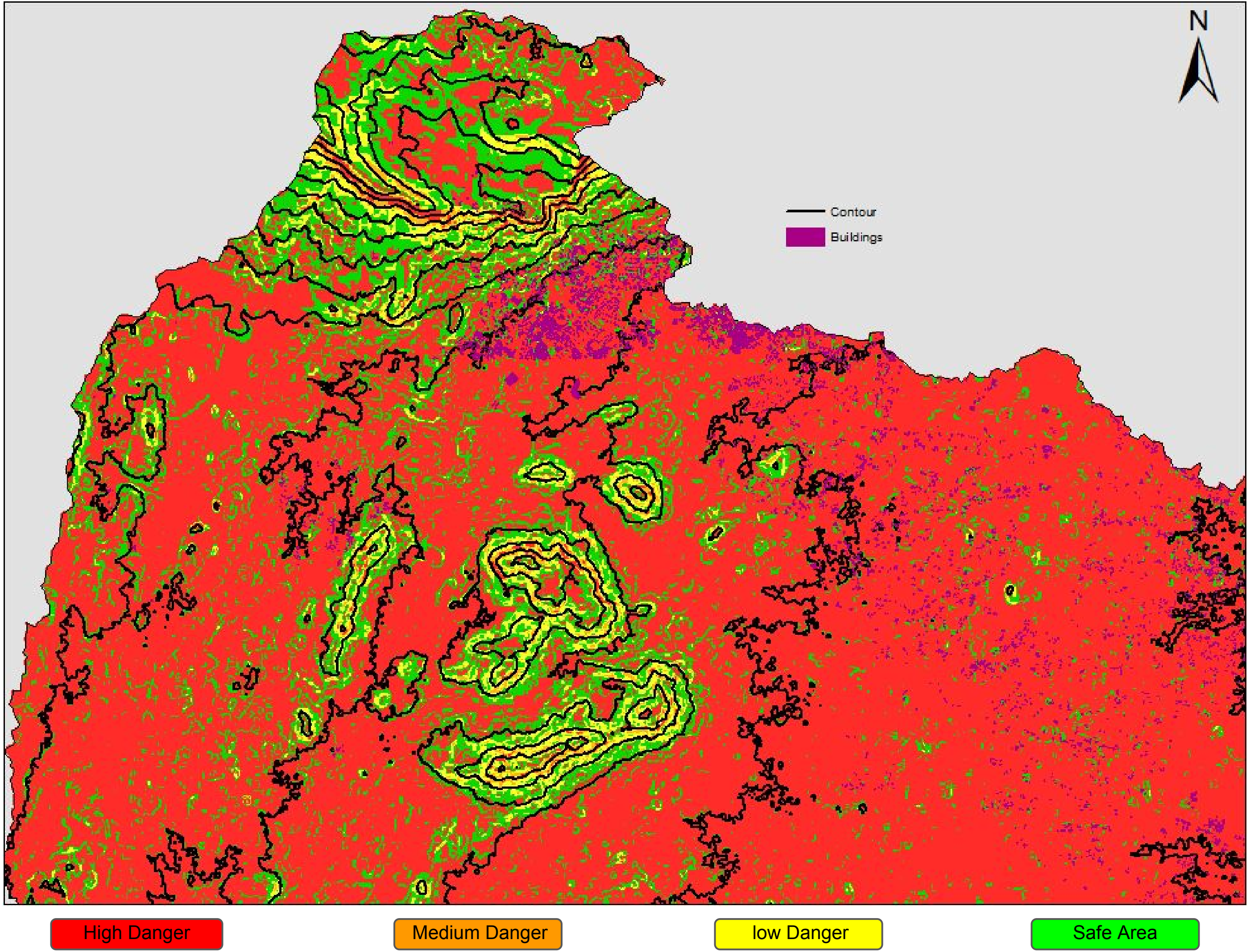
Appendix 2

Flow Accumulation Danger Level Zones



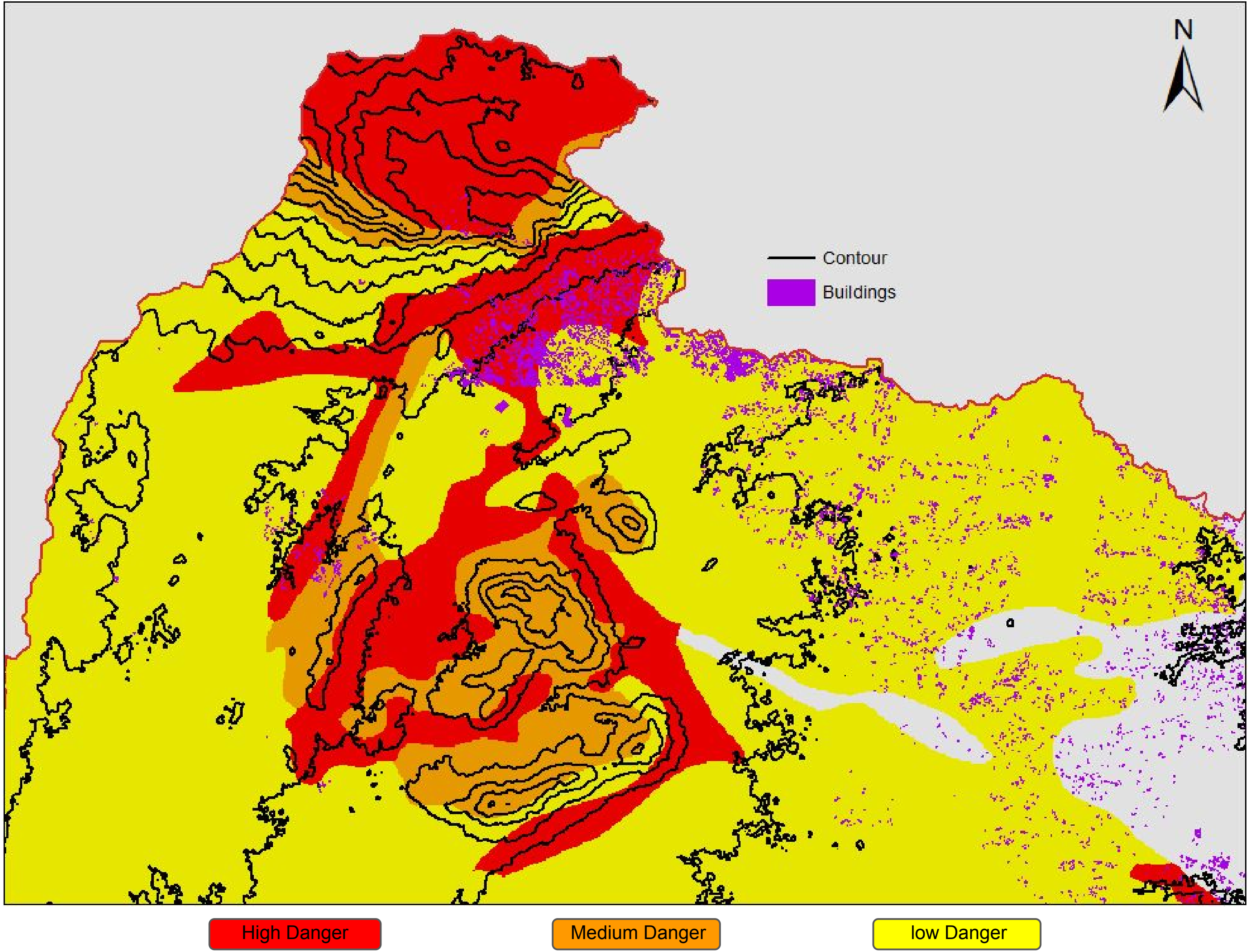
Appendix 3

Slope Danger Level Zones



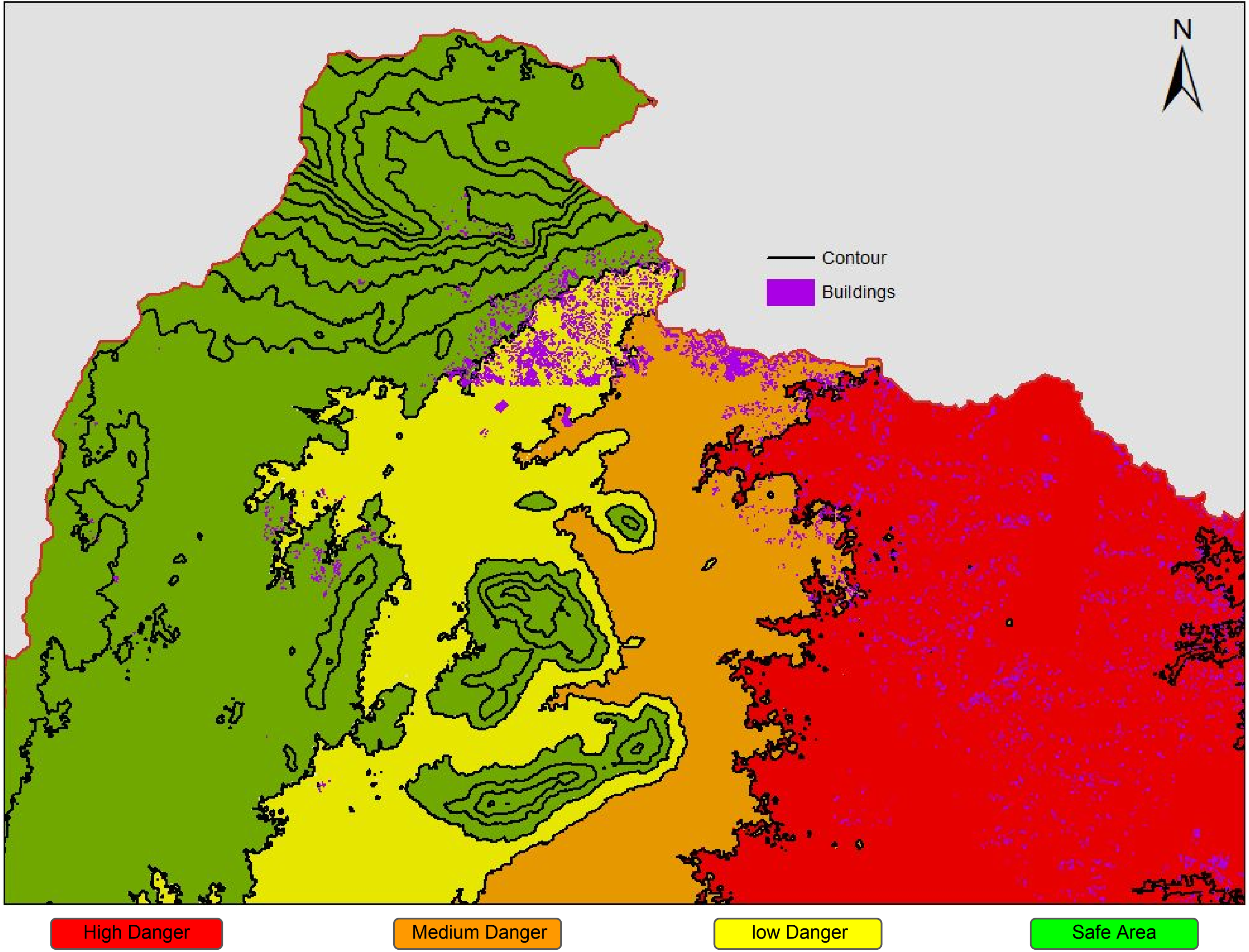
Appendix 4

Soil Type
Danger Level
Zones



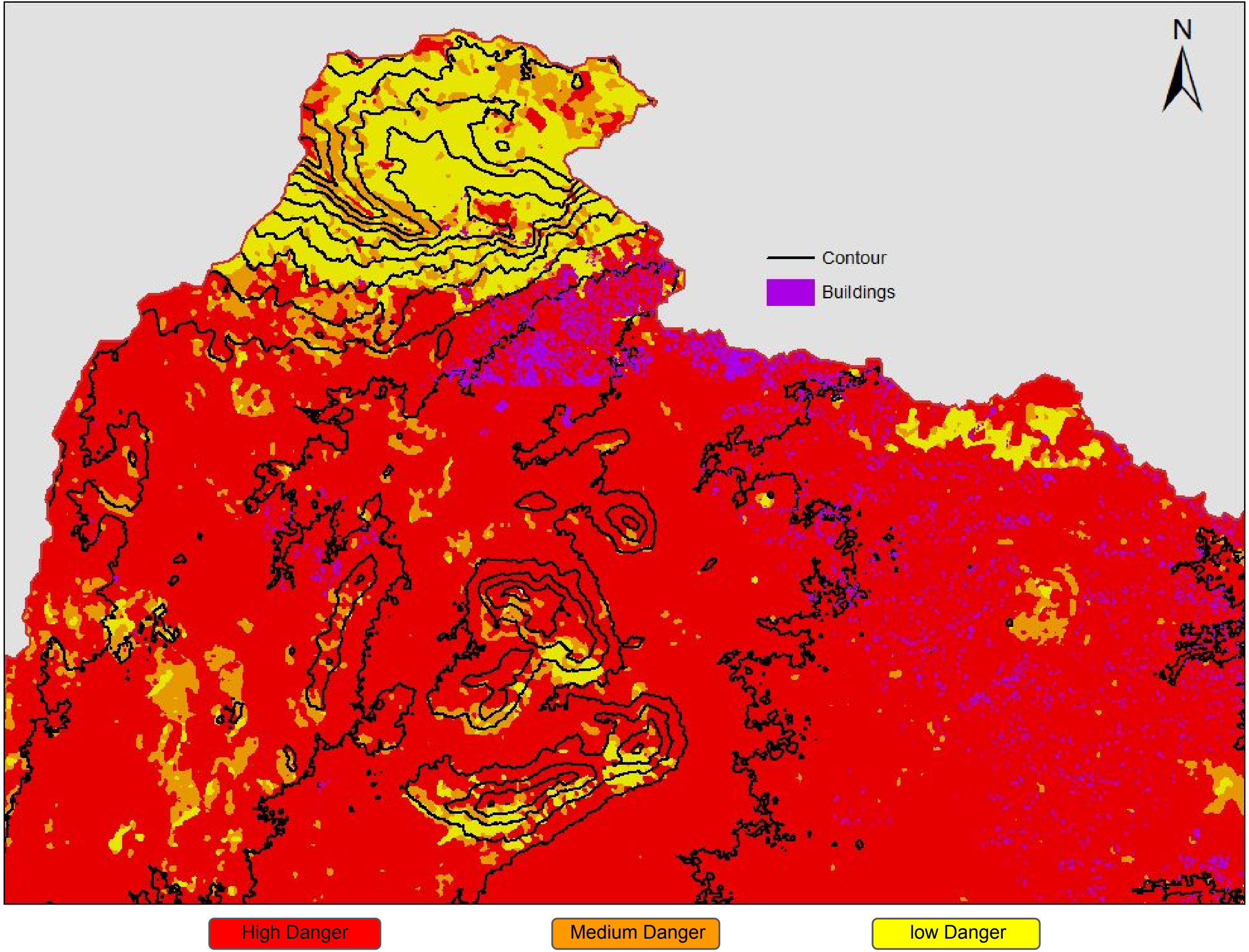
Appendix 5

Elevation Danger Level Zones



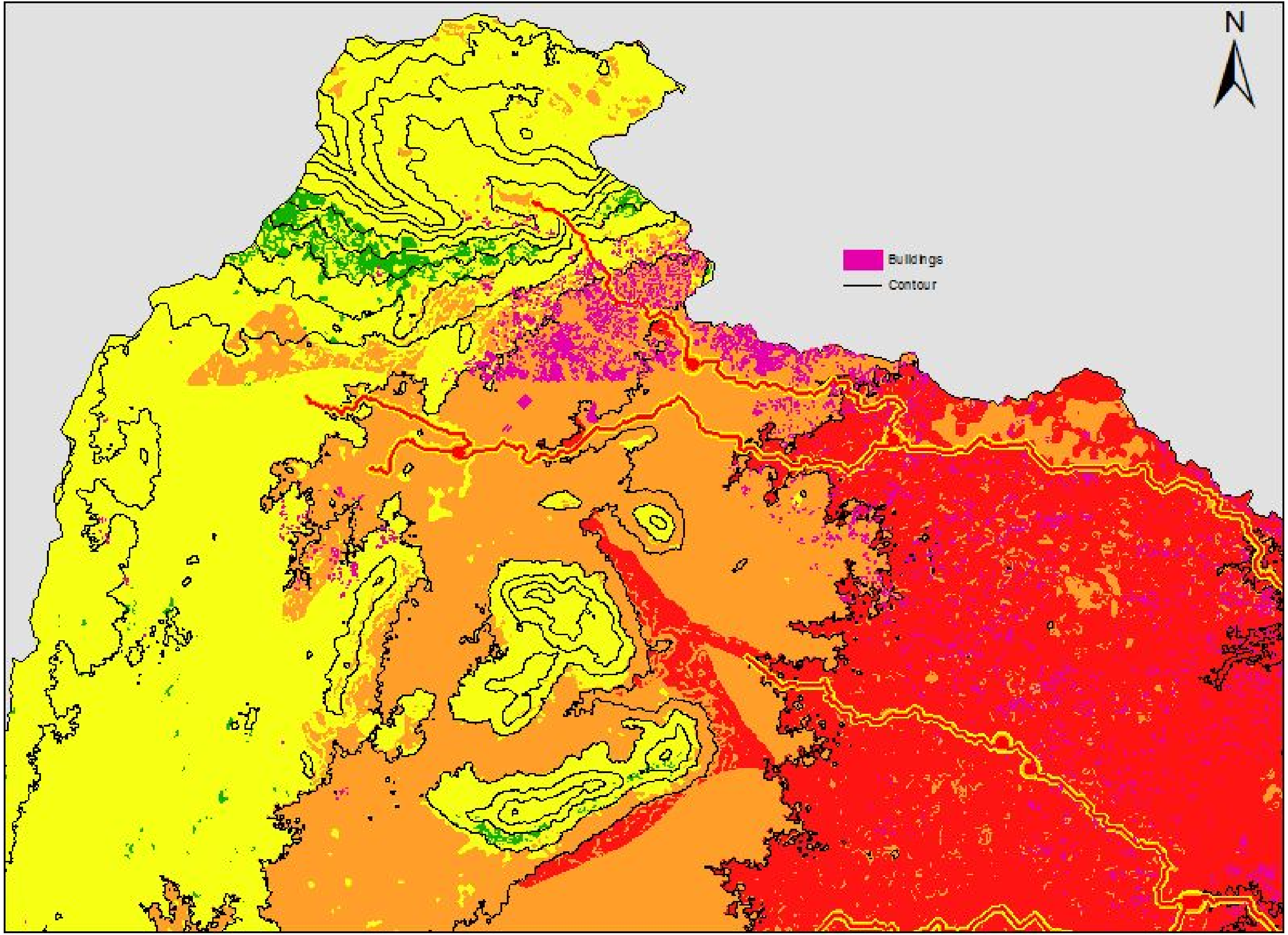
Appendix 6

Land Use Danger Level Zones



Appendix 7

Final Danger Level Zones Map



High Danger

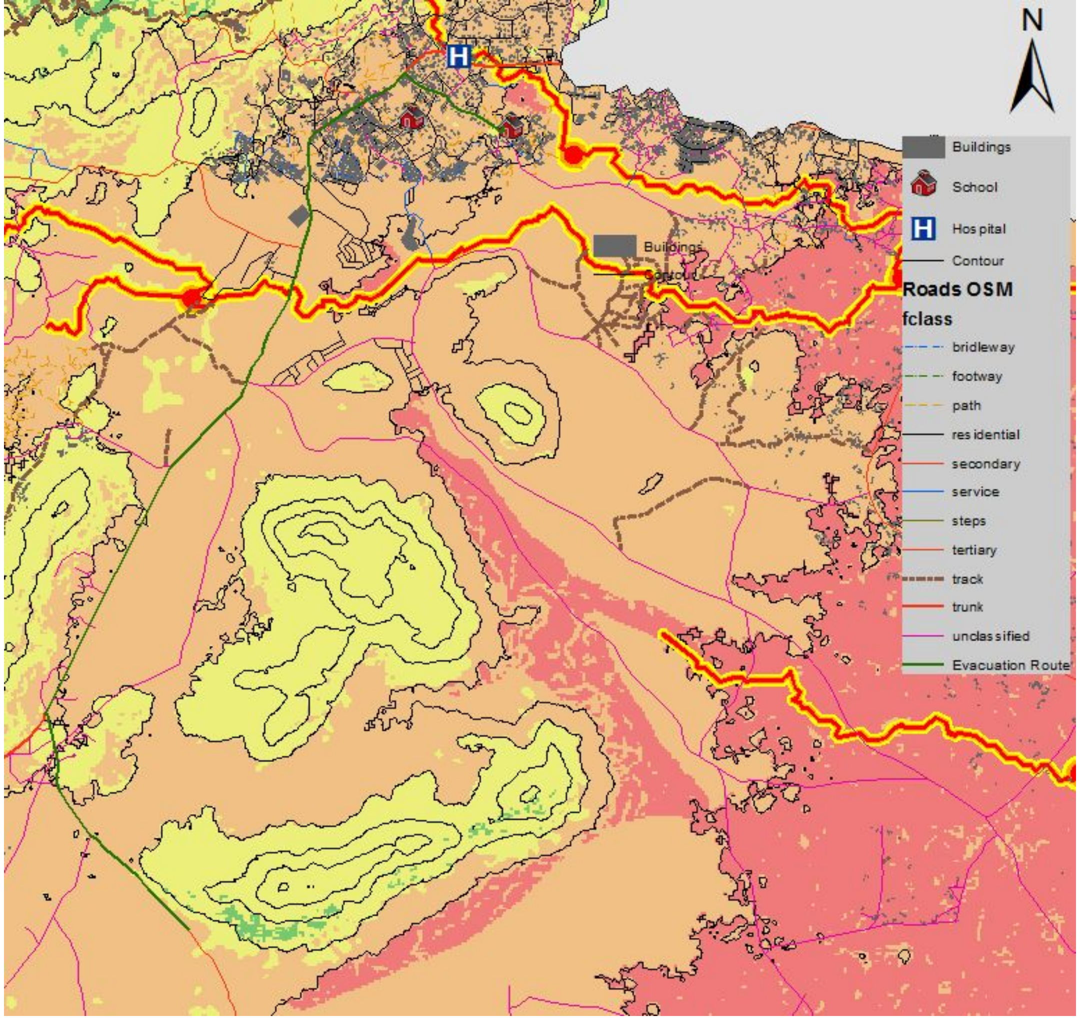
Medium Danger

low Danger

Safe Area

Appendix 8

Initial Evacuation Plan to southern safe area



High Danger

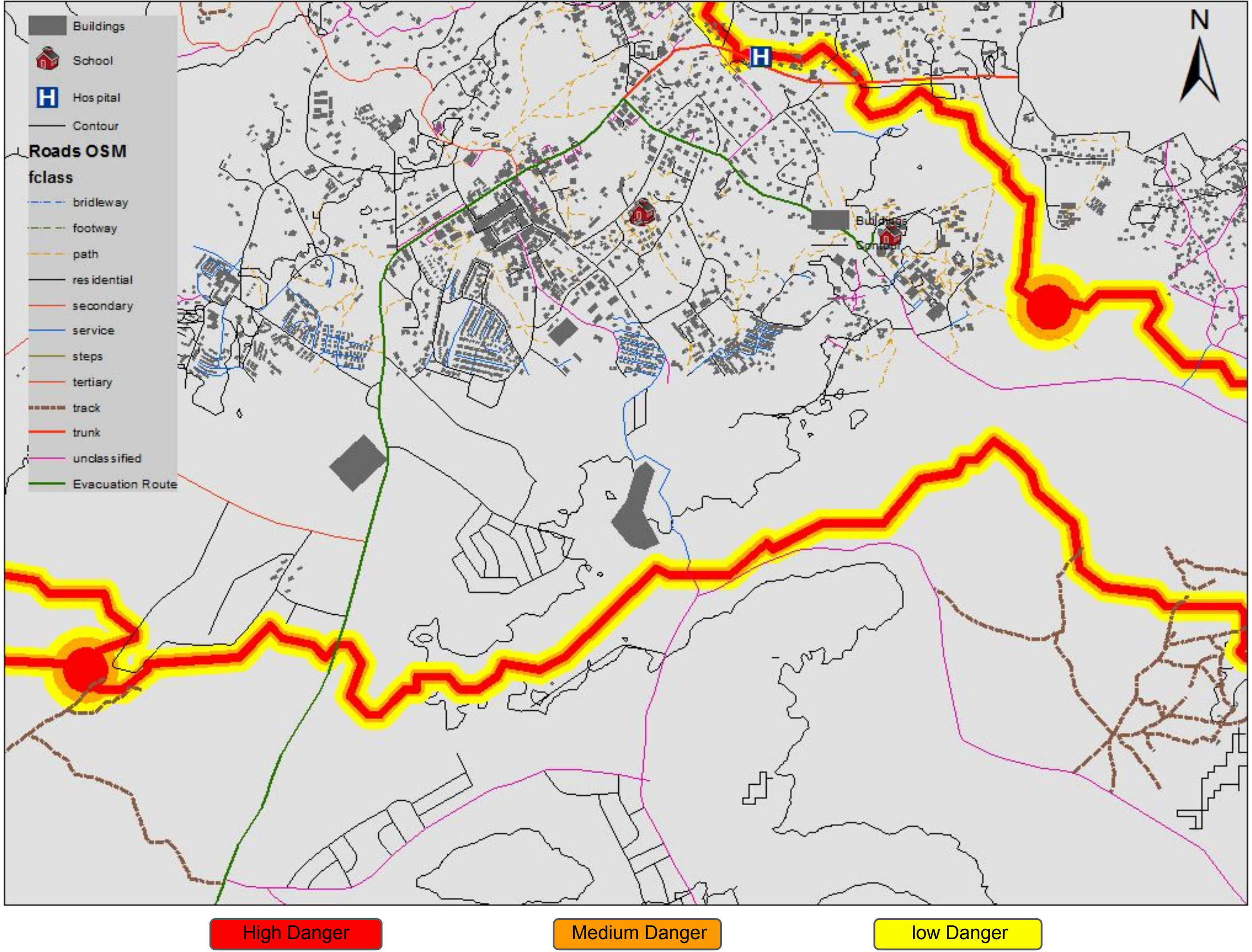
Medium Danger

low Danger

Safe Area

Appendix 9

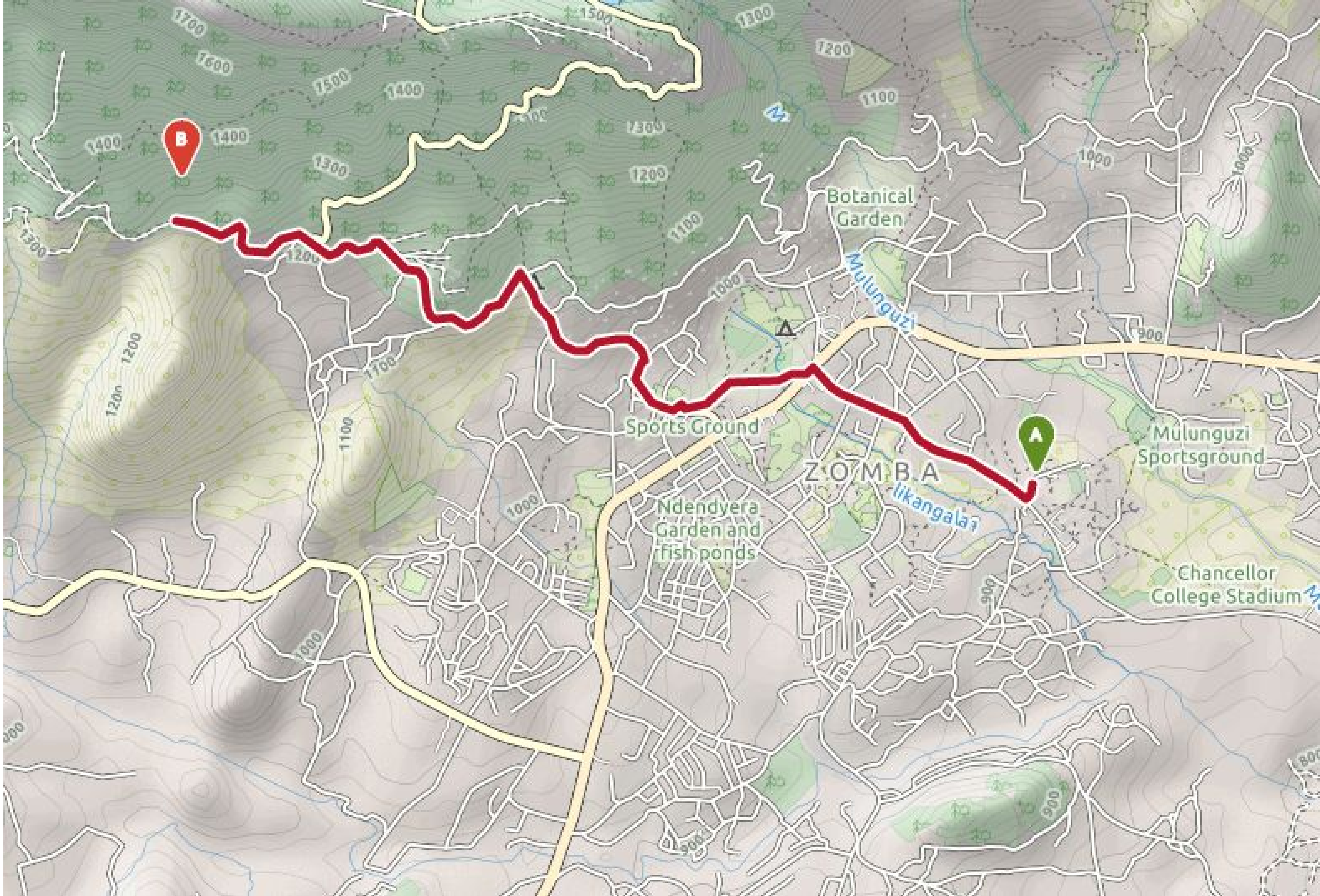
Initial Evacuation Plan to southern safe area (Zoomed)



Appendix 10 North-western Safe Area

Appendix 11

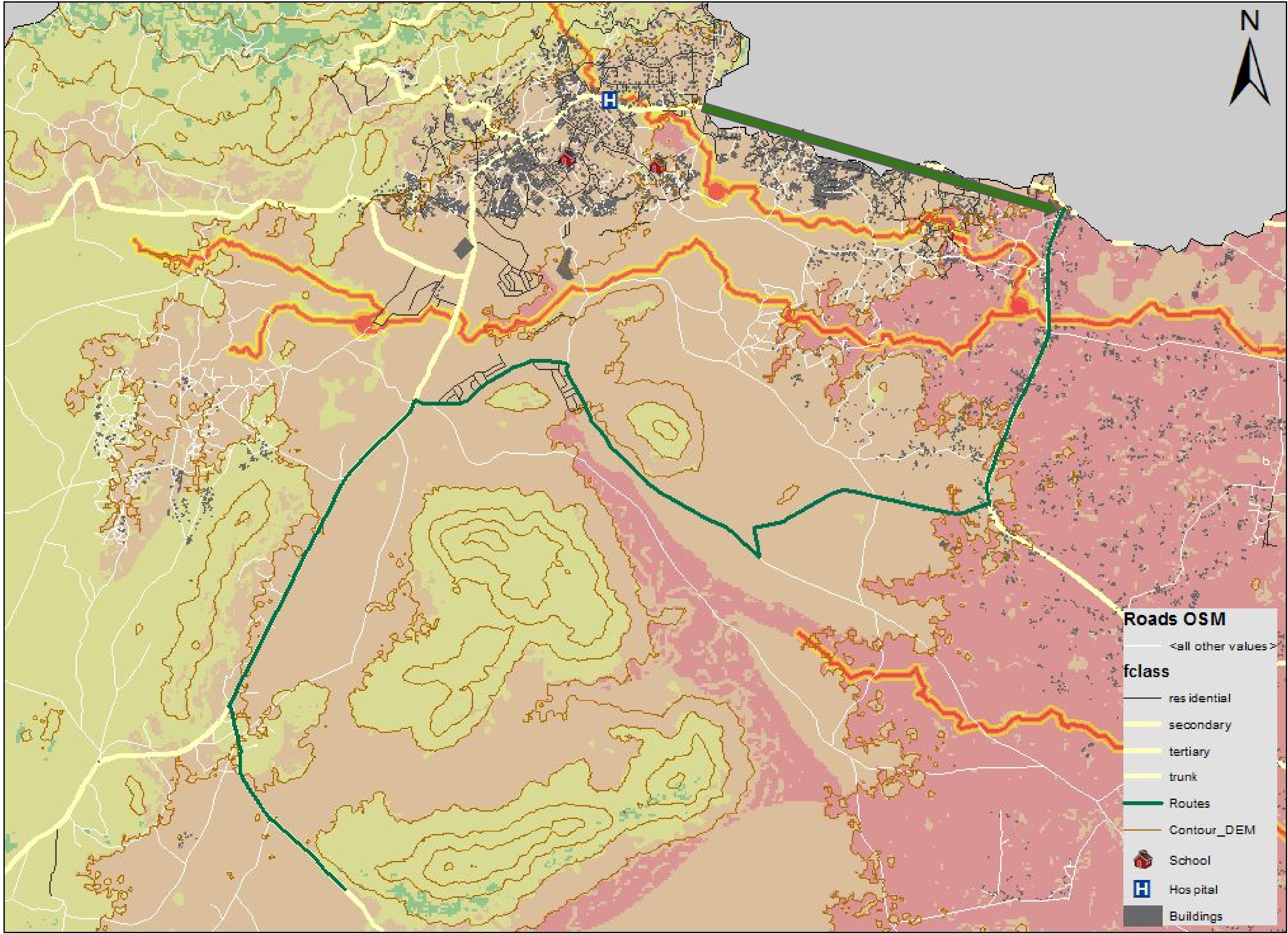
Initial Evacuation Plan to North-western safe area



Appendix 12 Southern Safe Area

Appendix 13

Optional Evacuation Plan to Southern safe area



Appendix 14

Final Evacuation Planning Map