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Mapping Flood Vulnerable Areas in Quetzaltenango, Guatemala using GIS

Prosper Issahaku Korah* & Francisco Mariano Juárez López
Department of Spatial Planning and Environment, Faculty of Spatial Sciences, University of Groningen, Netherlands
*Corresponding Author's Email: pikprosper@gmail.com   franciscojuarezlopez@gmail.com.

ABSTRACT

It is estimated that with the onset of climate change, flood risks will not subside in the future and the intensity and frequency of floods will threaten many regions of the world particularly urban areas. Current spatial plans used for guiding the development of urban areas have also been criticized for failing to match dynamism and unpredictable manifestations for instance climate change and flooding. Given this premise, there is a growing call for the need to integrate flood risks management strategies and spatial planning. This represents a proactive approach to dealing with both the probability and consequences of flooding in cities. As an important step towards this integration, this study sought to map flood vulnerable areas in the city of Quetzaltenango, Guatemala using GIS. The hydrology and weighted overlay (spatial analyst) techniques were used to analyse the materials for the study. The results showed the whole city was at risk of being inundated. The areas at high risk of flooding were at the core of the city whereas the no and low flood vulnerable areas were non-habitable. The study recommended the recovery of forest through afforestation among others as some flood mitigation strategies.

Keywords: GIS, Vulnerability Maps, DEM, Flood risk, Land Cover, Quetzaltenango

1. Introduction

According to Khan et al (2011), floods are among the most repetitive and overwhelming natural hazards, which impact human lives and destroy property worth millions of money (see also Uddin et al., 2013; Pradhan, 2009). It is estimated that with the onset of climate change, flood risks will not subside in the future and the intensity and occurrence of floods will threaten many regions of the world (Jonkman and Dawson, 2012). Urban areas are susceptible to flooding because of the nature of their landscape which is often predominantly pavement and impervious surface thus resulting in anthropogenically induced flooding (Campion and Venzke, 2013; Masgrau and Palom, 2012; Chen et al., 2009).

According to Oyesiku (1997), the ability to promote liveable and safe urban environments depends on the rights and methods of dealing with land. Urban planning therefore becomes critical in mitigating and preventing flooding. Plans based on traditional urban planning however have been criticized for their rigidity when faced with changes in context (Rauws and de Roo, 2011; Alfasi & Portugali, 2007; Alfasi, 2006, Alfasi, 2004). Plans produced under traditional land use planning are unable to deal with non-linear manifestations in urban areas (Alfasi, 2006). These plans are always rendered obsolete when faced with phonemenon such as climate change and flooding. This means flooding and its impacts always seem to be beyong the capacity and resources of the city management authorities (Nwaka, 2005). In instances of flooding, city authorities are forced to take 'reactive' measures instead of being 'proactive' (Rauws et al., 2014).

This has triggered the discussion on the need to make urban areas resilient. Resilience concept is seen as a new approach to incorporate uncertainty into planning, particularly natural disasters such as climate change and flooding (Davoudi, 2012; White, 2010). Making urban areas resilient to flooding means they are prepared for both the probability and consequences of flooding (Restemeyer et al., 2015). In order to reach this objective, there are calls for a new strategic policy that integrates flood risks management and spatial planning (Woltjer and Al, 2007).

An important step towards this integration is the ability to map flood vulnerable areas in the city and strategic visions with short-term actions put in place (Albrects, 2004). However, much research has not gone into the mapping and identification of flood vulnerable áreas in cities of developing countries (Ishaya et al., 2008; Ifatimehin and Ufuah, 2006). In Guatemala, little has been done in terms of mapping flood vulnerable areas in the cities. Geographic Information System (GIS) has been successfully used to map flood vulnerability areas and for evaluating the impacts of floods (Dawod et al., 2014; Youssef et al., 2010; Fernández and Lutz, 2010). The main aim of this study is to identify the most vulnerable areas to flooding in the city of Quetzaltenango and propose mitigation approaches for averting the negative impacts of flooding. This study, in essence, is an invaluable contribution towards reducing the impacts of floods in Quetzaltenango because it will serve as input for the integration of flood risks management strategies and spatial planning in the city.

1.2 Study Area

Guatemala is a country that experiences flooding. In the year 2011, the country suffered its worse inundation with several lives, infrastructure and property affected (International Federation of Red Cross and Red Crescent Societies (ifrc), 2011). The city of Quetzaltenango, Guatemala is the second most important economic region and the second largest city in the country. It has a population of approximately 250,000 inhabitants. The location of this city (see figure 1) which is in the western highlands and surrounded by mountains and Santa Maria Volcano (highest peak of 3600 meters) above sea level and with no major river running through it to serve as natural drainage channel makes the whole city vulnerable to flooding. Flood mitigation can only be effective when areas at high risk of flooding are identified and measures are put in place for preparedness, effective prevention and response.

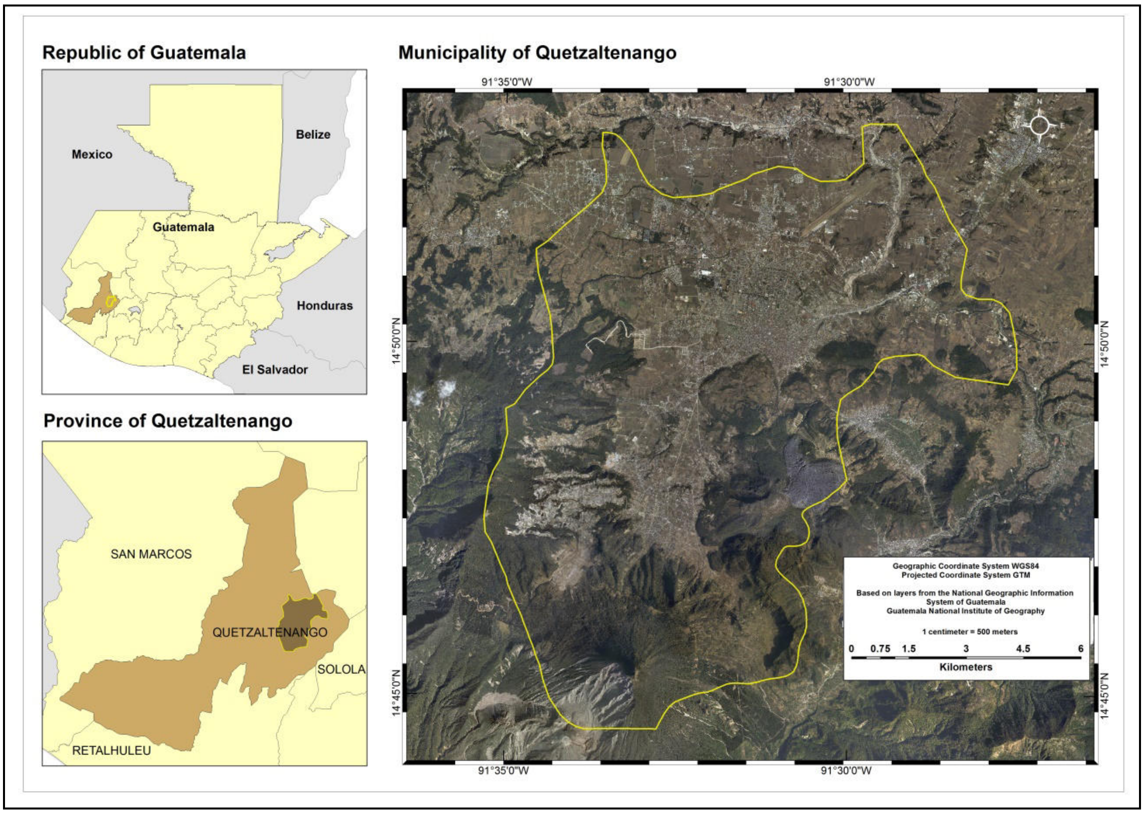


Figure 1: Study area

2.1 Materials

Layers were derived from National Geographic Information System of Guatemala, Guatemala National Institute of Geography. These were clipped using the *clip tool (data management)* to the boundary of the study area. Furthermore, some of the layers were projected from Universal Transverse Mercator into the Guatemala Transverse Mercator -GTM- projection system, using the Geographic Coordinate System WGS 1984. The materials for this study are shown in table 1

Table 1: Data requirements for the analysis

Spatial Data	Attributes	Type
Guatemala regional borders	Area/Polygon	Shapefile
Guatemala Municipal Borders	Area/Polygon	Shapefile
Quetzaltenango City area	Area/Polygon	Shapefile
Contour lines	Height (m)	Shapefile
Digital Elevation Model (DEM)	Elevation	Raster
Land cover map	Land cover type	Raster
Precipitation	Amount of rain per year	Shapefile
Satellite imagery	Orthophoto	Raster

The contour lines obtained from the Guatemala Geographic Information System, were at a distance of 100 meters and it was clear that this will not lead to the desired outcome. Therefore it was necessary to make use of the software Global Mapper, version 15. The aim was to use remote sensing techniques to derive contour lines at a more accurate distance. The use of Global Mapper was essential because it enabled connection to the SRTM worldwide elevation data (3 arc-second resolution), and the ASTER GDEM worldwide elevation data (1.5 arc-second resolution). These applications were used to load the elevation data for Quetzaltenango City and then the contour lines were generated at a distance of 3 meters, and used for the analysis.

2.2 Methods

The main analysis techniques were the hydrology (spatial analyst) tool and weighted overlay techniques in ArcGIS 10.2. The analysis process is further explained below.

2.2.1 Slope (spatial analyst) tool

Slope is the rate of maximum change in z-value from each cell. For degrees, values range between 0-90. This tool was used to determine the slope degrees, the higher the slope degree, the higher the runoff, and the lower the slope degree, the higher the probability that these areas will receive much water in case of runoff.

2.2.2 Fill (spatial analyst) tool

This tool was to fill all depressions in the DEM in order to carry out hydrology analysis. This ensures perfection in the data to avoid false depression areas. This enabled the generation of correct flow direction within the basin as well as flow accumulation.

2.2.3 Flow Direction (spatial analyst) tool

The depressionless DEM derived from the fill was used to generate a flow direction raster. The flow direction shows the possible direction of water run-off on the elevation model.

2.2.4 Flow Accumulation (spatial analyst) tool

This tool was used to determine the flow accumulation using the flow direction raster as input. Output cells with a high flow accumulation are areas of concentrated flow and were used to create stream channels/network

2.2.5 Stream to feature (spatial analyst) tool

This tool was used to create stream networks from the flow accumulation. This shows the possible channels of water in case there is runoff.

2.2.6 Buffer (analysis) tool

This tool was used to create distances around the stream networks. A buffer distance of 200 meters was generated and all property within the buffer zone were considered to be at very high risk of inundation

2.2.7 Topo to raster (spatial analyst) tool

This tool is used to interpolate a hydrologically correct raster surface from point, line, and polygon data. This was used to drive surface from the rain data which was line feature in order to enable reclassification.

2.2.8 Reclassify (spatial analyst) tool

This tool was used to reclassify the entire factors that affect flooding such as the slope, flow direction; land cover and precipitation into a common scale (refer to table 2)

2.2.9 Weighted overlay analysis

This was used to overlay the slope, flow direction, land cover and precipitation raster datasets which have been reclassified into a common measurement scale and weights each of them according to its importance to produce the final risks map. Two scenarios were generated

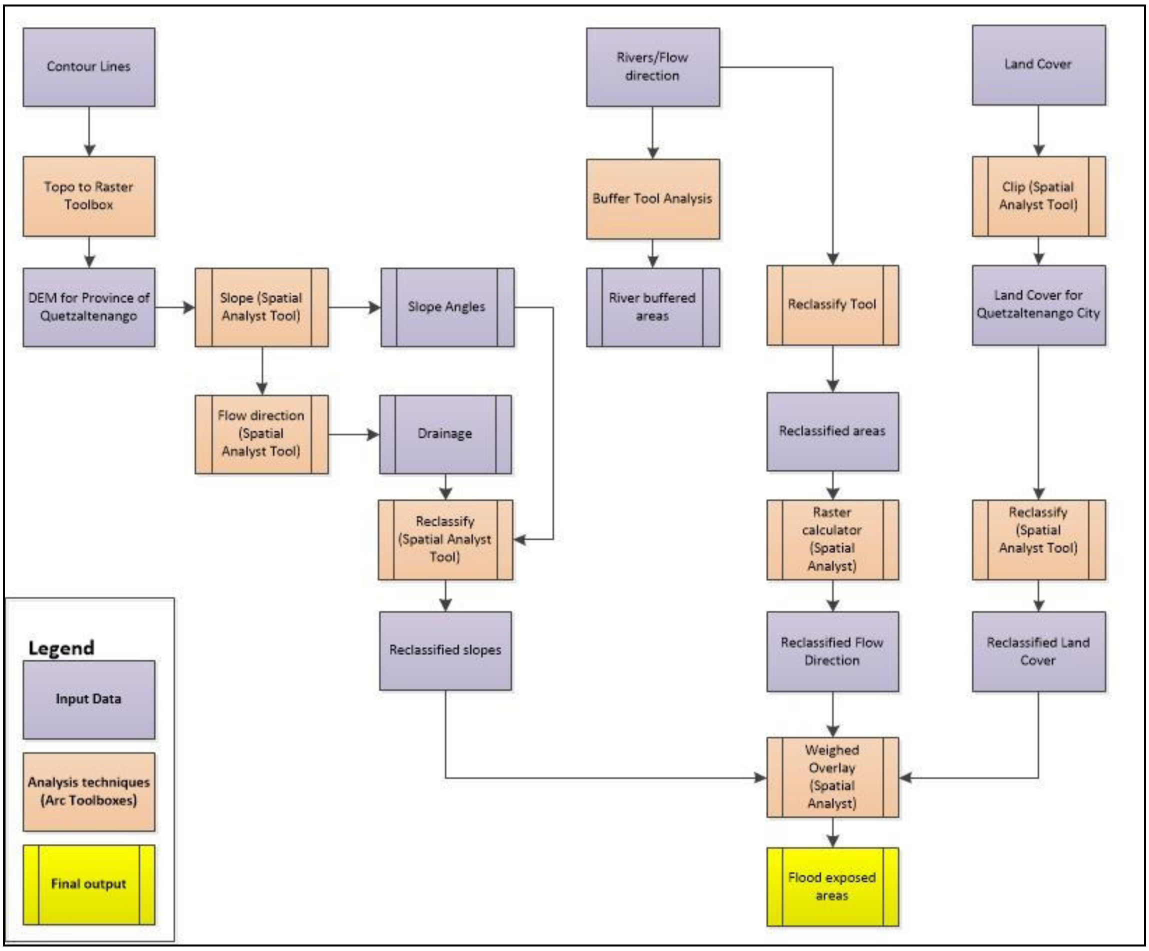


Figure 2: Flow chart of analysis techniques

3. Results and Discussion

The final outcome of the analysis shows a raster output of the areas within the city that are prone to flooding

Table 2: Values and scale of the various layers

Factors affecting flooding	Values	Scale	Interpretation
Slope (degrees)	0-9	4	High Vulnerability
	9-23	3	Moderate Vulnerability
	23-51	2	Low Vulnerability
	51-85	1	No Vulnerability
Land cover	Without Forest Cover	4	High Vulnerability
	Degrading Forest Cover	3	Moderate Vulnerability
	Recovering Forest Cover	2	Low Vulnerability
	Forest Cover	1	No Vulnerability
Flow Direction	1-28	4	High Vulnerability
	28-80	3	Moderate Vulnerability
	80-136	2	Low Vulnerability
	136-255	1	No Vulnerability
Precipitation(mm)/ yr (used only in second scenario)	698-1011	1	No Vulnerability
	1011-1326	2	Low Vulnerability
	1326-1640	3	Moderate Vulnerability
	1640-1954	4	High Vulnerability

3.1 Elevation and Slope

The elevation and slope influence the direction and amount of surface runoff in a particular area. The results show that some areas are very high in terms of slope degrees while others are very low. Figure 3 shows the reclassified slope of Quetzaltenango City.

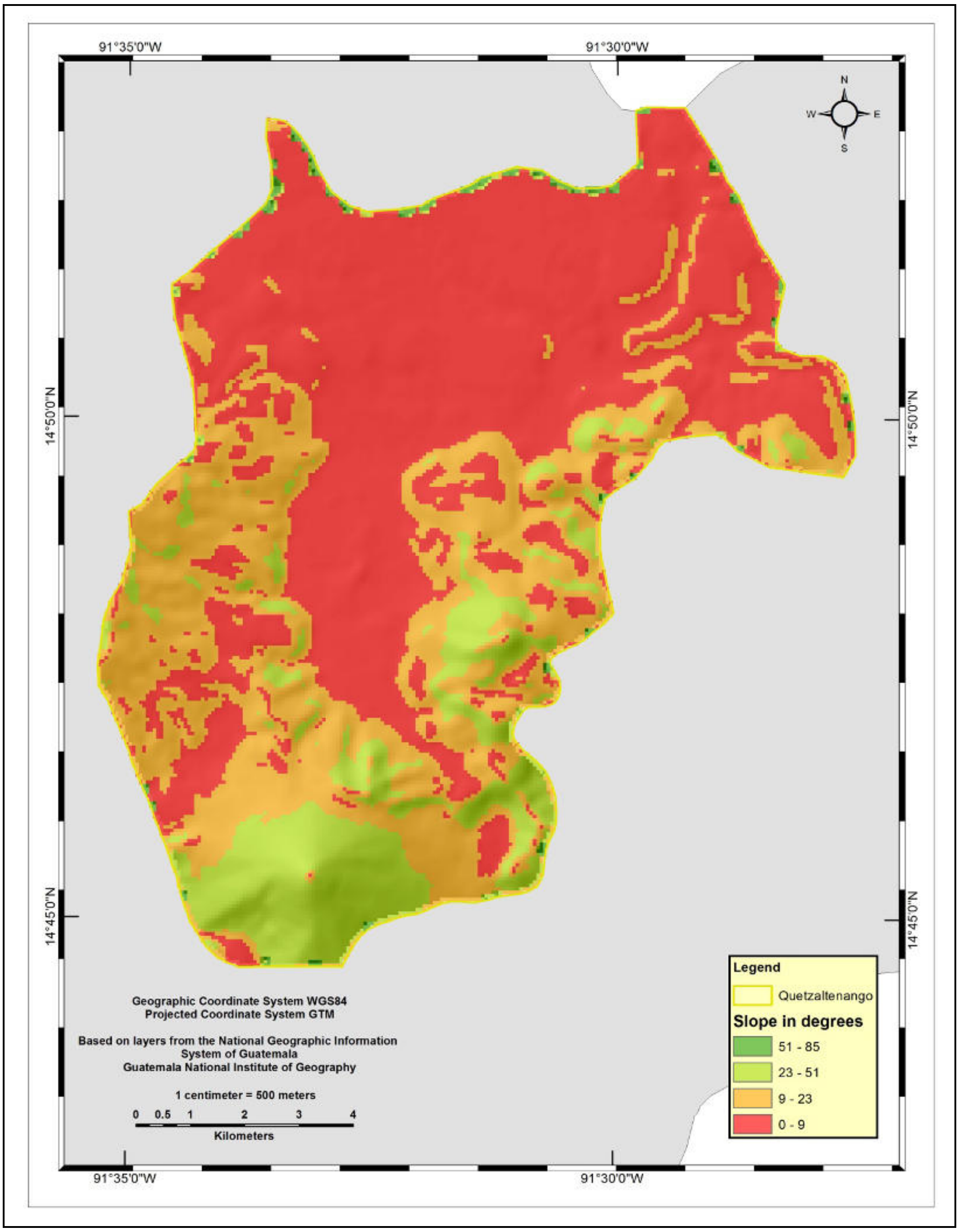


Figure 3: Map of reclassified slope

The low slope areas are depicted with the pink colour, which unfortunately is where development is possible and where the city is located. This means that any surface runoff will be directed towards the city and built up areas. This confirms the earlier assertion that the whole city was at risk of flooding.

3.2 Land cover

The land cover influences both the speed of surface runoff and water retention. Land-cover like vegetation or forest has a significant impact on the capacity of the soil to act as a water store. Runoff of rainwater is much more likely on bare fields or areas without vegetative cover than those with a good forest cover. The availability of forest cover reduces the speed of water from the sky to the soil and decreases the amount of runoff, additionally forest cover improves significantly the soil's capacity to infiltrate the water, and therefore the runoff tends to be reduced. On the other hand, impervious surfaces such as pavement, absorbs almost no water at all and thus increases runoff. The results show that the built up areas are without forest cover and this supports the findings of Campion and Venzke (2013) that urban areas are susceptible to flooding because of the nature of their landscape, which is predominantly pavement.

3.3 Drainage analysis

The drainage analysis involves the determination of the flow direction and flow accumulation. The flow direction shows the possible runoff of water from the elevation model. The flow direction raster was used as in input for the generation of the flow accumulation. The flow accumulation shows the possible stream channels in an event of water runoff. The map below shows the flow accumulation

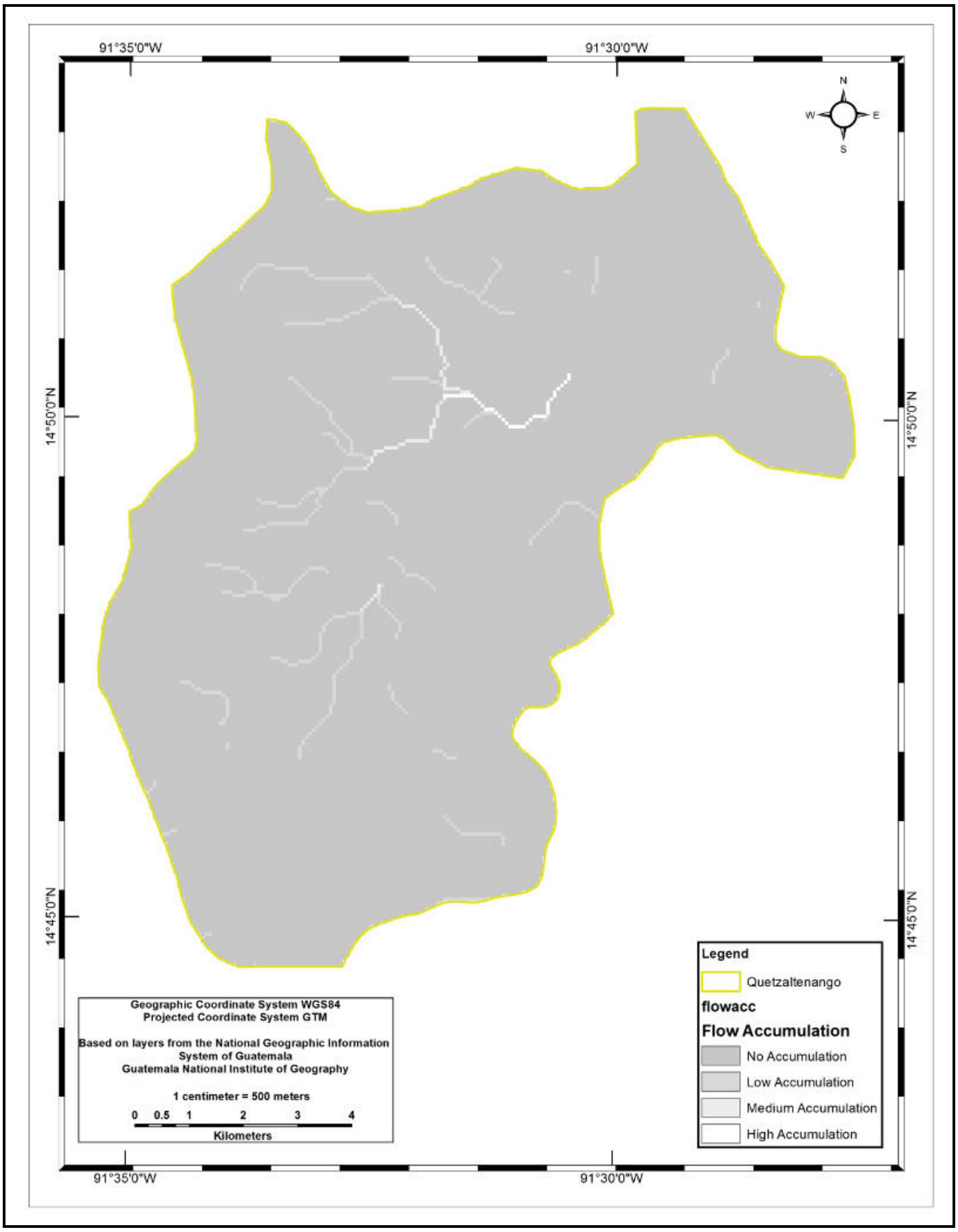


Figure 4: Flow accumulation map

The areas with high cells accumulate much water in terms of runoff. In order to obtain the stream network or channels, the flow accumulation raster was reclassed under the symbology (classified) in the layer properties to obtain only two classes. The two classes namely: 0-2000, and 2000-7770 were further reclassified as: 0-2000 (no data) and 2000-7770 (1). The resultant output was used as input to generate the stream networks. The stream network was buffered at a distance of 200 meters and all the property within this buffered zone could be visualized

3.4 Rainfall Distribution

Floods are associated with excess rainfall, and any water that cannot immediately percolate into the ground flows down slope as runoff. The quantity of runoff is connected with the amount of rain an area experiences. The results show that the rainfall values for the study area ranges between 800mm and 1800mm per annum.

3.5 Final flood risks maps

The maps shown below were produced after a combination of several layers based on their level of influence on flooding. The maps show vulnerable areas with values ranked from 1 to 4, in terms of the level of vulnerability. For scenario one, slope was assigned an influence of 25%, Landcover (40%) and flow direction (35%). With scenario two, slope was assigned an influence of 15%, landcover (35%), flow direction (20%) and rainfall (30%)

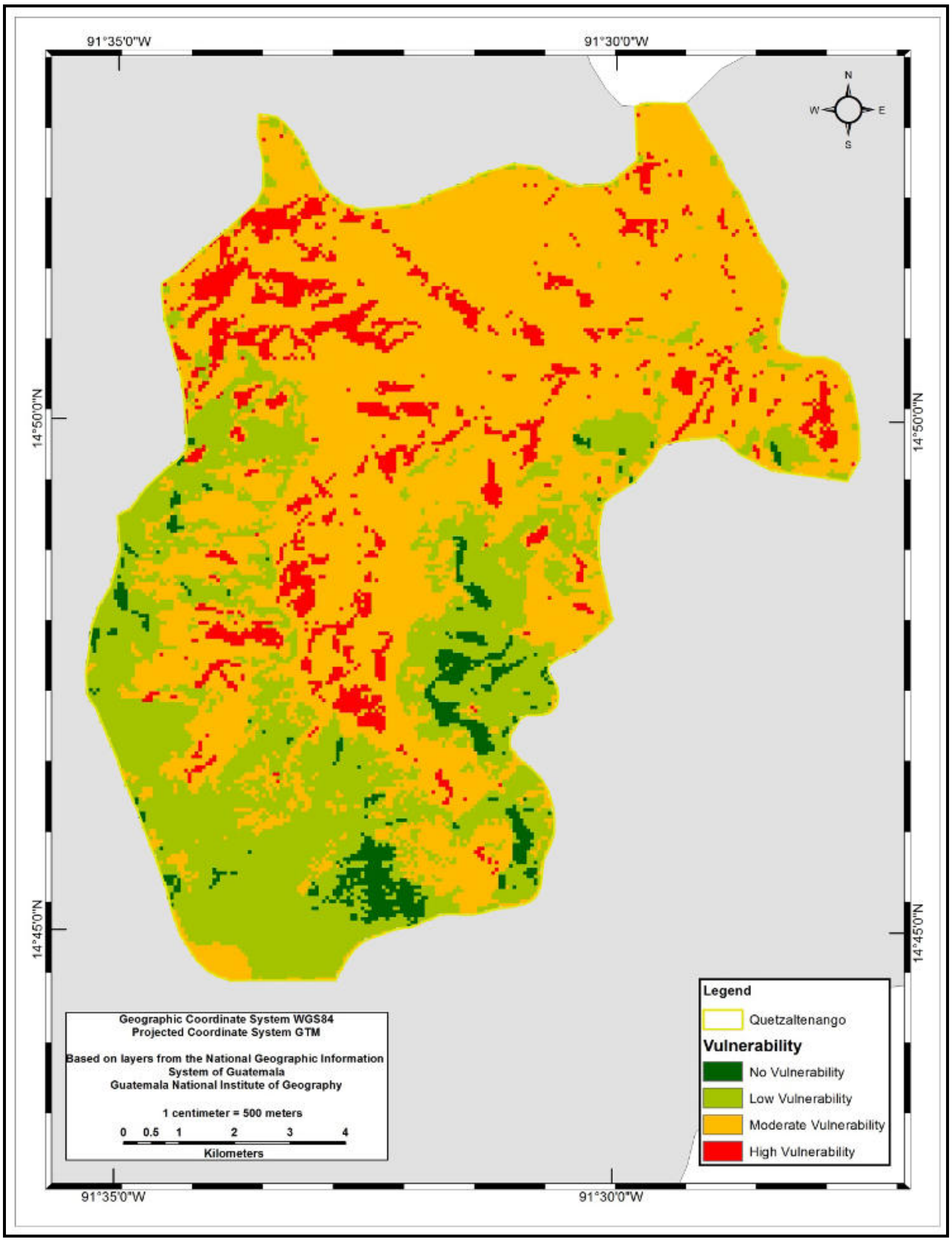


Figure 5: Flood vulnerability map (scenario one)

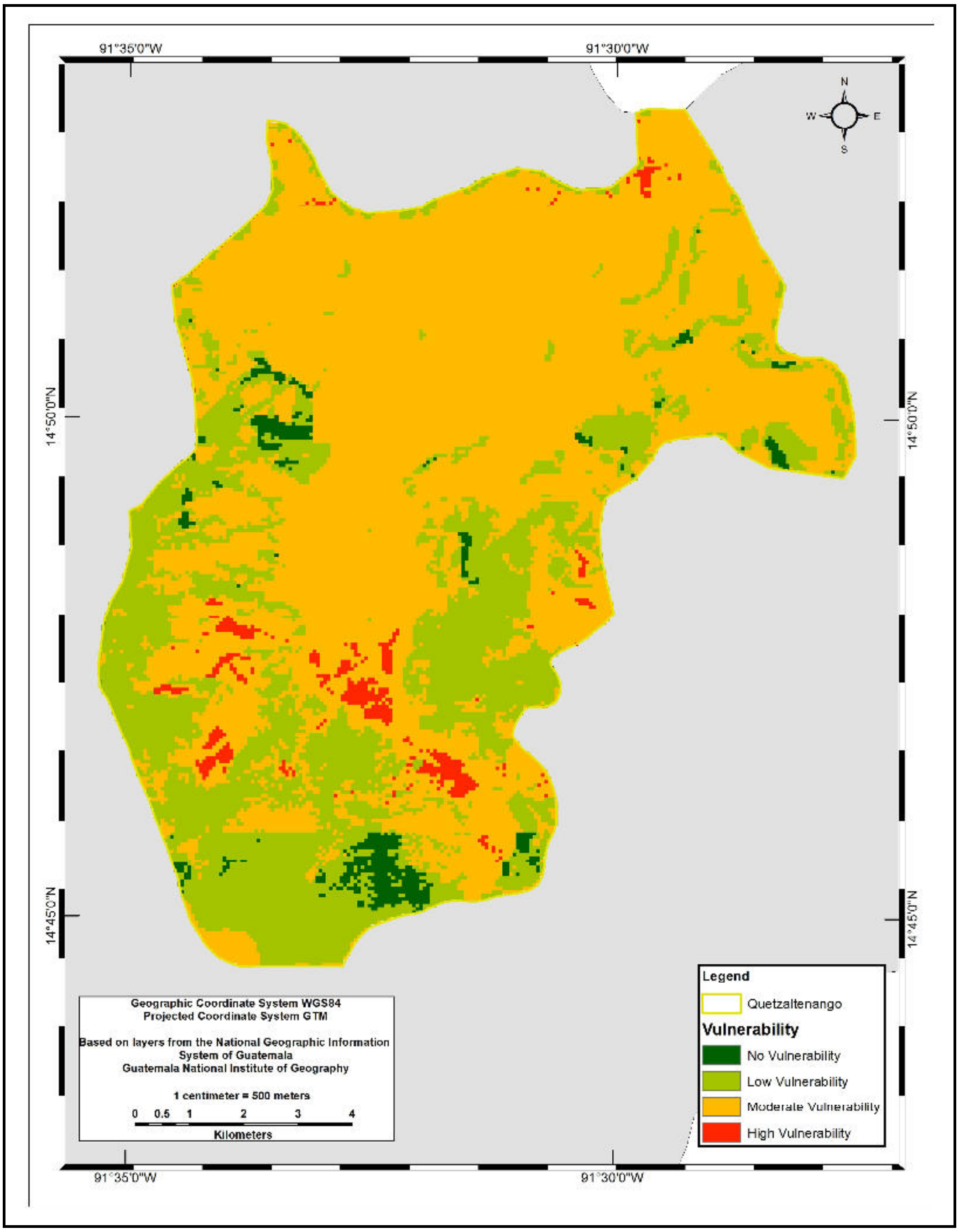
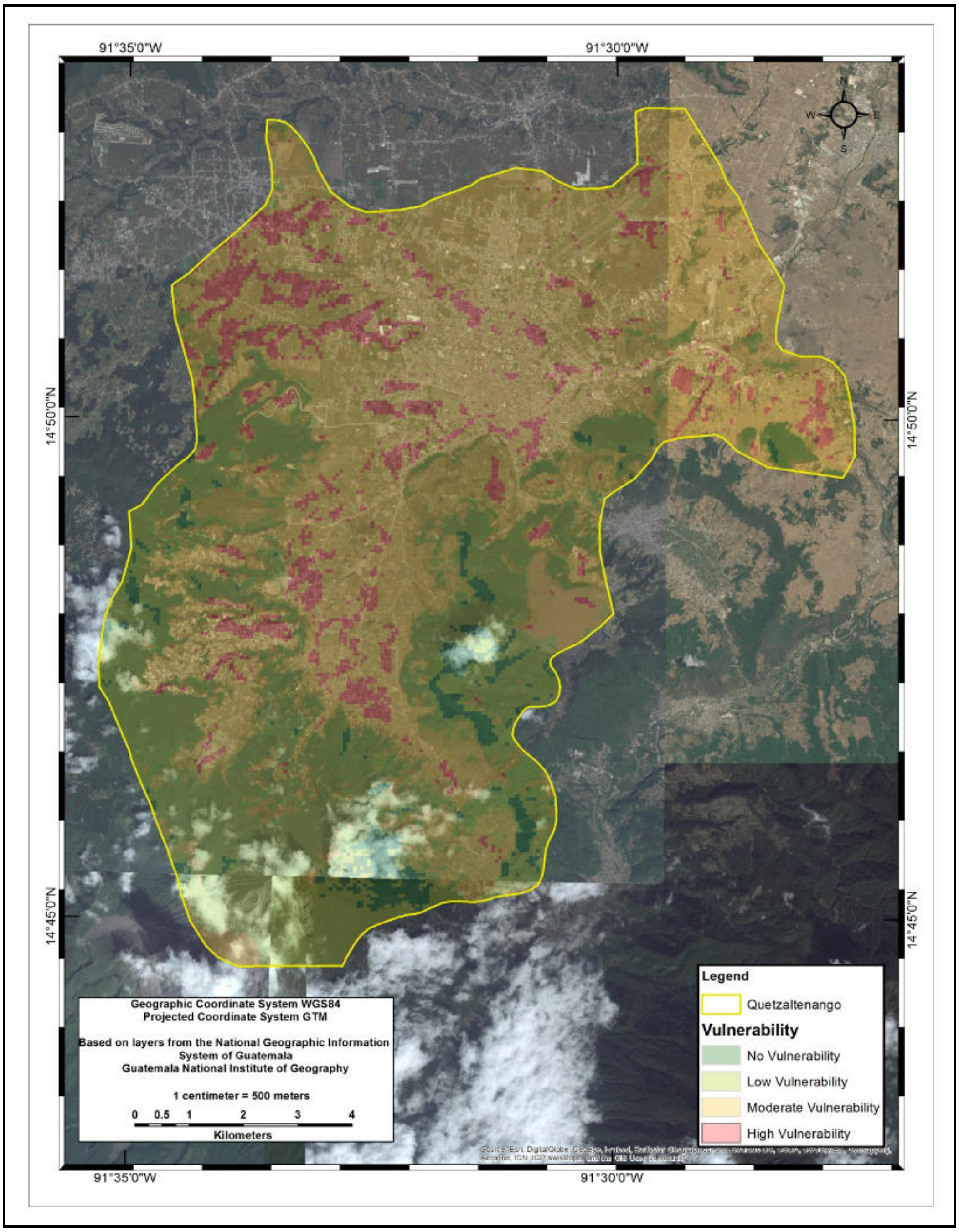


Figure 6: Flood vulnerability map (scenario two)



Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, [illegible] Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 7: Overlay of flood risks map and satellite imagery

The flood vulnerable maps show that the moderate and high zones are all within the built-up areas of the city meaning the lives of the inhabitants are in great danger of flooding.

4. Recommendation and conclusion

4.1 Recommendation

First, the city authorities should prioritize solid waste management in the highly vulnerable areas to prevent choking of the available natural watercourses. This will serve as a mitigation approach to flooding since choked drains will prevent free flow of runoff in the city's drainage system and eventually cause flooding.

Secondly, the analysis showed that in the north-eastern side of the city there are less vulnerable areas than in the north-western side; however, it is very important to notice that the north-western side is not densely populated yet. It is therefore highly recommended that the city authorities should stop authorizing housing development in and around this area until at least proper drainage infrastructure is built and a basin management plan is formulated. This will help reduce the number of people and property at risks of flooding in the future decades.

Some areas especially around the volcano and mountainous areas are also degrading in terms of forest cover. This is particularly perilous given that these areas are high and dissipating their vegetative cover means the amount and speed of runoff from these areas will increase. This puts the people and property at a very high risk of being inundated, especially since the city is growing and getting densely populated. From the forgoing, it is essential that trees are planted by the city authorities at these areas as well as preventing sprawling and unauthorized developments in these areas.

In the future, further research can be directed at assessing the impacts of potential floods on socio-economic activities in Quetzaltenango using GIS as well as a network analysis to determine the best routes for evacuation and emergency response purposes.

4.2 Conclusion

In conclusion, flood risk is not likely to subside anytime soon because of its association with climate change. What can be done however is to be able to identify the areas that are at high risk of flooding which will be the basis for prioritizing mitigation measures and to create awareness for prevention and preparedness. This research has demonstrated that GIS is a powerful tool when it comes to mapping flood vulnerable areas because is robust and is able to combine large and different data at the same time (weighted overlay) to produce a desired output. This research will be of relevance to policy makers and can serve as reference for spatial planners in Quetzaltenango, Guatemala in their quest to integrate flood risks management and spatial planning.

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