Hazard Risk Assessment for the Island of Grenada

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Abstract

The country of Grenada is prone to many natural hazards such as flooding, mass movements, and hurricanes. Past attempts to lessen the impacts have been more reactive than proactive in nature. Through the use of infrastructure, precipitation, historic flooding, landslide inventory, and other datasets, this project identifies areas at risk of these hazards, and areas that are socially vulnerable to these hazards. Four different layers are created, displaying the areas of Grenada at risk of storm surge flooding, landslide susceptibility, social vulnerability, as well as overall hazard risk. This research, analysis, and presentation of this data through a web map application and website can be used as decision-making tools for the government and disaster management organizations, and can also be used as an interactive visualization for the residents of Grenada.

WEBSITE URL HERE: https://q-schen.github.io/gp481/final.html

WEB MAP URL HERE: https://q-schen.github.io/gp481/map.html

Keywords: Hazard, Disaster Risk, Disaster Management, Hurricane, Flooding, Storm Surge, Mass Movement, Landslide, Social Vulnerability, Web Map Application, Leaflet, GIS, Accessibility

Introduction

Grenada's location in the Caribbean Sea exposes the island nation to a wide variety of natural hazards. However, at-risk areas are not well documented and public knowledge of disaster risk is not wide-spread, specifically in regards to hurricanes, flooding, and mass movements (Collymore, 2011). The project provides a solution in the form of a web map application that allows users to explore the main island for at-risk areas, and a website that allows users to access explanations of the analysis and links to external disaster management resources.

The government of Grenada and its citizens are the main audience for this project. This initiative seeks to raise awareness of risks that flooding and mass movements pose to life and property. The web map application is a visual and interactive tool for stakeholders to consider in their planning of infrastructure development and emergency preparedness responses. It also has the potential to contribute towards the development of a new national disaster plan.

Beyond the general public and government of Grenada, other regional and international organizations may also be interested in the web product. The results provided by our application have the potential to support and better coordinate emergency response, as well as improve existing policies and programs. Economic investors, especially operators in Grenada’s two main industries of tourism and agriculture, could also be interested in our project’s results: with areas in jeopardy identified, the development of tourism and agriculture infrastructure could change to mitigate the devastating impacts of disasters (Government of Grenada, 2013a).

Our company has conducted a multi-criteria analysis of major natural hazards for the country of Grenada. The project has identify areas at risk of storm surge flooding and landslides, as well as areas of social vulnerability. This information is presented to stakeholders in the form of an interactive web map application to support local awareness, government emergency management, and disaster planning organizations. The project also promotes publicly available and digestible information with its mobile friendly web products. The web map application allows users to explore the main island for at-risk areas, given the local geography and other factors, and the application is accessible through the Internet using either a desktop or mobile browser.

The project has involved the collection of data, namely those of local physical geographical features, local human geographical features, and other datasets such as historical landslides and storm events. However, the main analysis involved the overlaying of the different spatial datasets to create secondary data. With these secondary datasets, a multicriteria evaluation was conducted to show at-risk areas and their risk and vulnerability levels. From the resulting layers and datasets, the web map application displayed those outcomes, and allows users to overlay those layers to observe varying qualities of impact.

Hypothesis

With a more accessible and readily available method to present risk hazards to the public, a more informed decision can be made. This should help to reduce people's risk to storm surge, landslides and social vulnerability which in turn will hopefully better prepare the country of Grenada for greater success in the future.

Literature Review

In order to ensure that a web map application of hazard risk assessment is necessary and relevant for Grenada, it is imperative to have an understanding of existing literature that has been conducted in the area. Similarly, evaluating the effect of climate change, current and potential risk mitigation measures, and the role of participatory geographic information systems (PGIS) is important to provide a background of the hazard risk in the area - as well as how PGIS can improve risk mitigation. In this literature review, there are a few significant changes that are explored in greater detail, flooding, weather, and mass movements. Climate change has a serious effect on these factors greatly increasing the risk to the people of Grenada.

Background

The country of Grenada, as part of the Caribbean region, is vulnerable to a variety of hazard types, including flash-flooding, earthquakes, tremors, landslides, mudslides, and hurricanes. These events have occurred in greater frequency due to climate change (Collymore, 2011). Collymore (2011) notes that there has been a notable increase in deaths and severity of severe weather events, as well as earthquakes, in the last few decades. The Global Circulation Model (GCM), a model produced by the Intergovernmental Panel on Climate Change (IPCC) to predict the potential annual increases in rainfall and evapotranspiration due to human caused climate change by 2100, has broken down the potential changes to climate change into three possible future scenarios; a carbon intensive situation, a carbon neutral situation and a carbon decrease situation. In the carbon intensive situation, large amounts of carbon are continued to be dumped into the atmosphere increasing the global temperature immensely, about 5 degrees Celsius, and in turn the annual rainfall. This would have the greatest effect on natural disasters. In the neutral situation, the same amount of carbon is released into the atmosphere, as of 2015 levels, representing a global temperature increase of about 2 degrees Celsius. This effect will have a moderate increase in annual rain precipitation values and natural disasters. The decrease situation notes a decrease in the amount of carbon being released into the atmosphere, as of 2015 levels, with an overall global temperature increase of about 1 degree Celsius. This situation represents the smallest increase in global annual precipitation but overall still represents an increase over current levels. Each method uses the GCM to try to downscale predict how much more precipitation a specific region will receive. This overall change in climate affects how the response to flooding, weather and mass movements react. With greater climate change, more events will start to occur which has to potential to increase the number of deaths. This increases the need for future risk management and active preparedness.

Flooding

With increases of recurrence of severe weather events the potential for flash-flooding also increases. Higher chances of flash-floods on Grenada will start to arise as water infiltration decreases and run-off increases (Pratomo, Jetten, & Alkema, 2016). The negative impacts of these hazards can be seen economically, socially, and environmentally, as there are great costs associated with rebuilding, relocating, and recovering the affected areas and residents. For example, the cost associated with the damages from Hurricane Ivan in 2004 was $889 million USD, which was 200% of the GDP of Grenada at the time, according to the Caribbean Disaster Emergency Response Agency (2005). This highlights a need for the Government of Grenada to improve risk management measures to account for climate change, as well as to create tools that will allow all stakeholders to engage with risk mitigation in an accessible manner.

Mass Movements and Climate Change

Monitoring the effects that increased precipitation has on mass movements becomes essential with climate change. A study completed by Crozier (2010) tries to classify the direct changes and potential slope stability responses to climate change. Crozier (2010), categorizes potential changes due to climate change into 6 sections – increased in precipitation totals, increases in rainfall intensity, shift in cyclone tracks and other rain bearing weather systems, increased variability in precipitation and temperature, increased temperature and increased wind speed and duration. Crozier (2010) had concluded that slope stability is demonstrably influenced by climate, in particular the amount of water within the slope, which is indirectly a function of precipitation, drainage conditions and other less direct inputs (Crozier, 2010).

The role of GIS

Participatory geographic information systems (PGIS) is one example of a locally integrated disaster management approach that uses GIS. One study aimed to explore PGISs as methods to assess community risk and vulnerability, and found that a PGIS could be a useful tool in recording local spatial knowledge to help identify households of higher vulnerabilities (Canevari-Luzardo et al., 2015). In their study, Canevari-Luzardo et al. (2015) took the input of community members to identify household characteristics and associate that information with a map that also showed areas at risk to natural hazards, and together they were able to identify the households that were most vulnerable and at risk to the local natural hazards. The study was able to show the Grenadian government that mapping and household vulnerability were useful tools in disaster planning, and even allowed the community to communicate needs to the government and share how they felt the maps and information could be used before, during, and after a disaster (Canevari-Luzardo et al., 2015). Although it was conducted at a small scale, this research was able to demonstrate how community participation could uncover community priorities and educate locals on where the natural hazards were so that they would be more effective in their future responses. Although our project and web map application does not include direct input from local communities, collaborating with local communities is an avenue for future improvements for this project.

Another article by Weis et al. (2016) looks at using GIS and vulnerability indicators to identify areas in need of more proactive management. In this article, the researchers assess the socioeconomic vulnerability of coastal communities in Grenada to flooding and sea level rise with a vulnerability matrix, composed of three main categories: exposure, sensitivity, and adaptive capacity. By mapping out where the vulnerable communities are in Grenada, the study recommends where the government should direct its investments of time and resources to reduce the different indicators of vulnerability to short-term flooding and long-term sea level rise events (Weis et al., 2016). The study pushes for a proactive approach from the government with its results, which disaster planning and management focus areas can be derived. This study is very similar to the PGIS study, but does not take a localized, community driven participatory GIS approach on the issue. It may be more effective and more persuasive if a study was conducted that combined the two methodologies of the above two studies, to achieve a more comprehensive and data-driven look into the issue of vulnerability to natural hazards.

Risk Mitigation Measures

The Government of Grenada has a National Hazard Mitigation Policy (2003) that immediately addresses and outlines goals, challenges, and interventions for hazard mitigation measures. Overall, this policy created an integrated framework for hazard risk reduction and mentions the implementation of projects that would improve the existing risk mitigation measures. By integrating risk reduction into policy, more initiatives and activities may be sustained and created, towards the goal of "capacity building and increasing natural resilience to hazard risks" (Government of Grenada, 2003). However, it is questionable as to whether these subsequent programs that were launched have been successful in reducing the impacts of hazards. Academic literature has noted that disaster management policies and programs in Grenada, as well as the Caribbean as a whole, need to be improved in order to be effective (Collymore, 2011). An article exploring Grenada found that current "public assistance programmes … cannot meet existing demand, especially in times of hardship," that there is a “significant gap in resources to support natural hazard management [in] the absence of hazard maps” (Barrientos, 2010). Collymore (2011) also noted that past disaster management programs initiated in the Caribbean have largely been responsive in nature, highlighting the need for a more “comprehensive consolidated framework” on the country-wide level. These authors indicate that further study and initiatives can be made by the Government of Grenada, to ensure that public safety is protected during a large scale hazard event.

Study Area

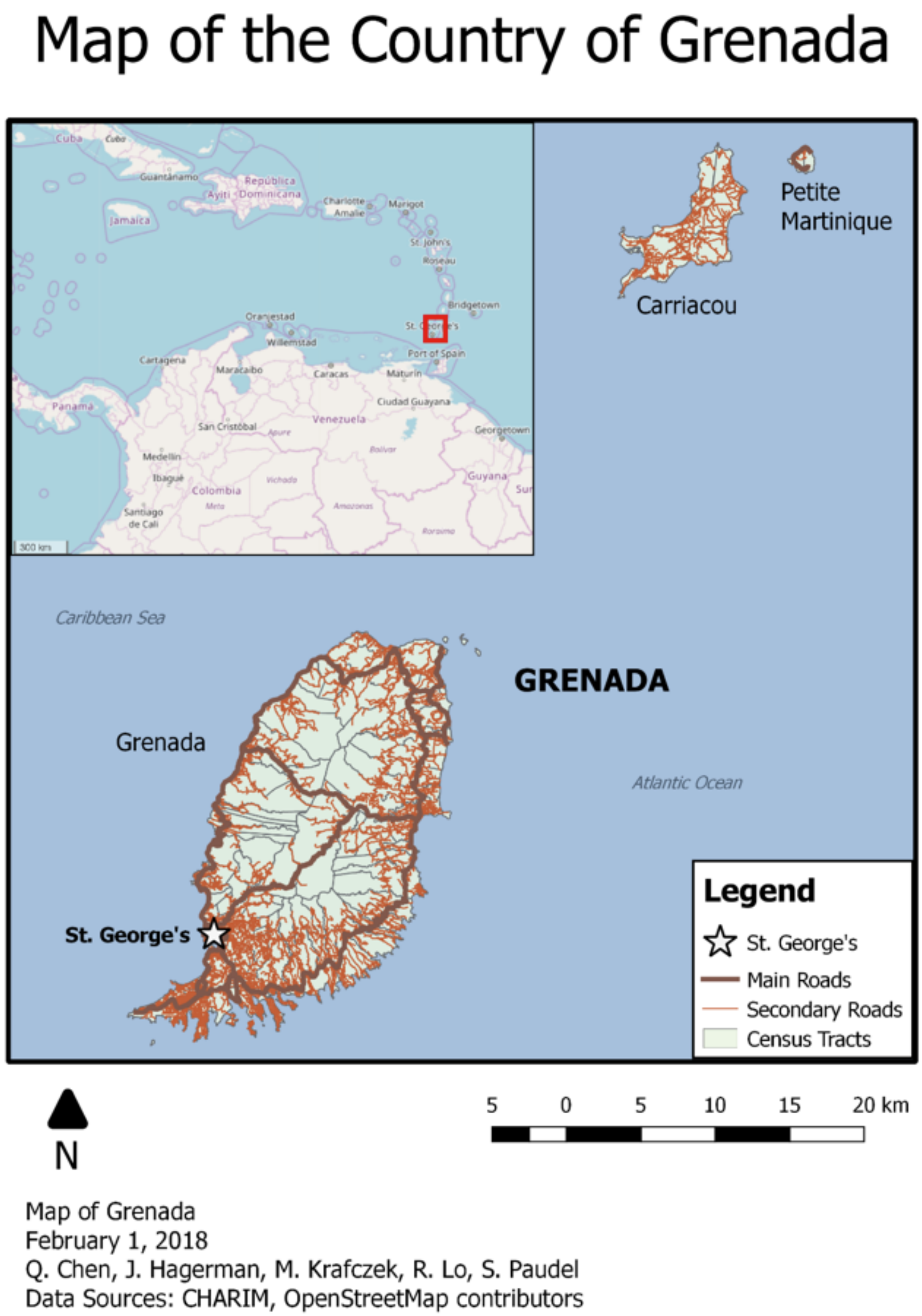

Figure 1- Map of the Study Area, Grenada

Grenada is located in the southeastern part of the Caribbean Sea, part of the Lesser Antilles, and as seen in Figure 1, is composed of the largest island, Grenada, and two dependent islands, Carriacou and Petite Martinique (Government of Grenada, 2013a). The population is 111,724 (July 2017 est.), and its capital city, St. George's, is located on the largest island (CIA, 2017; Government of Grenada, 2013a). As most of the country's land and population are located on the island of Grenada, it has been chosen as the study area of this project.

First a colony of France and then Great Britain, the country of Grenada achieved independence and joined the British Commonwealth in 1974. The official language is English, with French Patois as the other major language (Government of Grenada, 2013a). It is known historically for its trade resources of sugar and spices, but more recently tourism has led the economic growth in regards to foreign direct investment (Government of Grenada, 2013b).

The island of Grenada is susceptible to a wide variety of natural hazards (Government of Grenada, 2013a). As early as the 1800s, there have been records of Grenada experiencing earthquakes and tsunamis caused by tectonic and volcanic activity (Van Westen, 2016a). Two major hurricanes, Hurricane Ivan and Emily, have caused significant destruction, leading to over $889 million USD and $110 million USD in damages respectively (Van Westen, 2016a). Grenada also experiences landslides and flooding every year that have destroyed infrastructure and caused harm to life (Van Westen, 2016a).

Software and Data Sources

There was enough data available to create the project's risk and vulnerability layers, however the quality of the analysis results could be improved with better data. The majority of the data was from Caribbean Handbook on Risk Information Management (CHARIM). The CHARIM website provides physical and human geographic data and other risk-related information on various Caribbean countries. It is funded by the European Union (EU) and managed by Global Facility for Disaster Reduction and Recovery. With permission, we also used building-related data that was not publicly available, which was provided by Kristen and Rob. Additionally, data were also gathered through literature reviews, as well as reports from National Centers for Environmental Information (NCEI), the World Bank, OpenStreetMap (OSM), the Government of Grenada, National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the Central Intelligence Agency (CIA). The majority of the data used for this project can be seen in the table below.

Table 1 - Data used for creating various layers

Layer Created	Data sets	Source	Description
Social Vulnerability	Infrastructure	Kristen and Rob	Buildings in Grenada and their construction materials
Social Vulnerability	Demographics	CHARIM	Census and demographic data Social Vulnerability
Storm Surge Landslide Susceptibility Social Vulnerability	Basemap	OSM	Basemap layer from OpenStreetMap
Storm Surge Landslide Susceptibility Social Vulnerability	DEM	CHARIM	5M resolution

Landslide Susceptibility	Rivers	CHARIM	River network for the entire country
Storm Surge	Flood Data	CHARIM	Current areas of flooding
Storm Surge Landslide Susceptibility	Rainfall Data	NCEI	Daily to yearly rainfall statistics
Landslide Susceptibility	Landslide Susceptibility	CHARIM	Current potential areas of risk

Once the required data were obtained, they were processed and analysed using various tools and software. The software used for data cleaning included Microsoft Excel, Python, and QGIS. The software and web services used for analysis purposes were: ArcGIS, QGIS, Ogre, GeoJSON.io, Github, Photoshop, and GIMP. The majority of the data that were in a tabular form were cleaned using Excel and QGIS; however, for any datasets that were too big to be cleaned manually in Excel were cleaned using Python scripts. Excel was also used to compute the matrix analysis seen in Appendix 1. Once these data were cleaned and analysed using Python and Excel, they were imported into ArcMap and QGIS to be used for spatial analysis. The steps for analyses can be seen under Methodology section. After the analysis process, the web services Ogre and GeoJSON.io was used to convert shapefiles to GeoJSON files. These GeoJSON files were then uploaded onto GitHub. Photoshop and GIMP were used to create the logo and colour the analysed raster data, all of which were uploaded onto GitHub. Lastly, GitHub and GitHub Pages were used to host and display the data, the website, and the web map.

Methodology

Overall Hazard Risk Layer

The overall hazard risk layer was created by combining the results of the storm surge, social vulnerability, and landslide susceptibility layers. The Weighted Sum tool was used in ArcGIS to merge a raster version of each of the three layers together. The layers were weighted equally in the tool, although the social vulnerability layer had a higher scale (from 0 to 6) whereas the physical layers had a lower scale (0 to 3 at highest). It was accepted that the social vulnerability layer could be weighed more, due to the greater amount of factors used to generate it. The resulting hazard risk layer contained the sum of all three layers, creating a total of 9 classes of risk.

Storm Surge Layer

The storm surge layer was built using the openly available DEM provided by CHARIM. Although we originally planned to build a flooding layer that incorporated the wind speeds of category 1-5 hurricane winds, we decided to create a layer that identifies areas susceptible to hurricane-based flooding brought about by a storm surge. The Saffir Simpson scale removed the influence of wind speed as a storm surge factor, as it was found that wind speed was too unpredictable of a factor to generate consistent storm surge results.

The five steps of how the storm surge layer was completed is outlined below.

1. The DEM
2. Raster Calculator and buffer tool
3. 3, 6, and 9 metre values for storm surge
4. Raster to polygon
5. Merge
6. Euclidean distance for service areas of hurricane shelters

First, the DEM was loaded into ArcGIS. After that a raster calculator was completed along with a buffer tool to create the layer. Next, the data was separated into three layers, one each for 3, 6 and 9 metre height values for storm surge. Later, the three rasters was converted into polygons shapefiles for the web map application, and the three rasters were also merged together to form a final storm surge layer to be used in further analysis. Finally, the euclidean distance tool for service areas of hurricane shelters was added and the total risk to the population was produced.

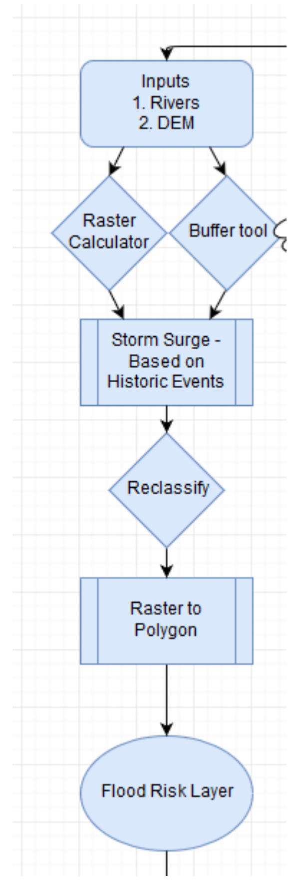

Figure 2 - Methodology for Flood risk

Landslide susceptibility layer

There were 6 major steps taken in the producing of the landslide susceptibility layer. These steps are outlined below.

1. Input DEM (Digital Elevation Model) layer
2. Use the slope tool
3. Compare the historical landslide data and the location of current structures
4. Reclassify the information into three classes
5. Export each layer into three different PNG files to be used online
6. Produce final map

The DEM that was used in this process was taken from the data collected by CHARIM. Using the Slope tool in ArcGIS, the DEM was classified to show changes in elevation from 0 degrees, being flat, to 90 degrees, being straight up. This data was then compared and classified against historical data along with existing locations of houses, to show that certain areas may be at higher risk of landslides, but if no buildings are located there, then there would be no harm to the local population. After that, the layer was reclassified into three categories: 1 for slight risk to landslides, 2 for medium risk to landslides, and 3 for high risk of landslides. The resulting raster was then exported into three different PNG files, one for each class, to be displayed on the web map application. The final raster layer was also ready to be used in further risk analysis.

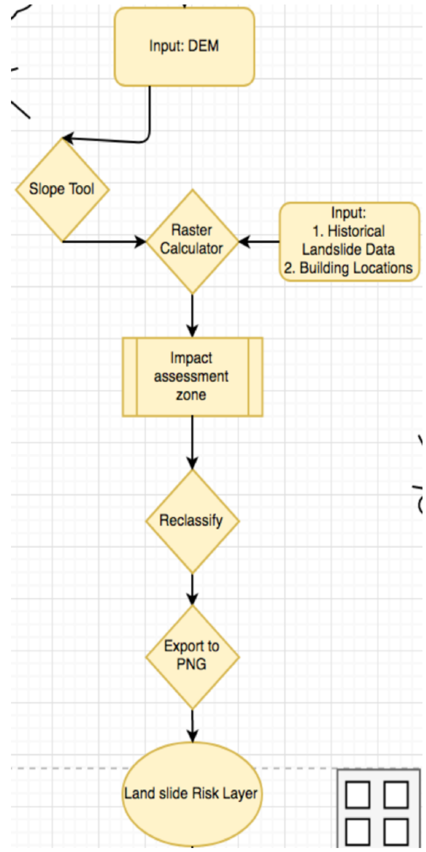

Figure 3 - Methodology for Landslides

Landslide can happen at any time. Even with the lowest risk, there is still potential for a landslide to occur. Comparing the methodology behind our landslide susceptibility layer to the one produced by the CHARIM, our process is less complex, and it is also easier to update and change, as it does not require a large bank of data to be collected. Additionally, in order to decide the final criteria tree for the CHARIM landslide data, several scenarios were tried as a sensitivity analysis to determine the best combination and ordering of the factor maps. These were compared to how different methods of standardization can affect the results. This makes the process extremely time consuming to recreate if new data were to arise.

Social vulnerability layer

To create the social vulnerability layer, a multi-criteria analysis was conducted using three different datasets: demographics (age), material construction of all buildings, and the distance of each enumeration district (ED) from hurricane shelters. The scope of the data was kept at the enumeration district level. The analytical hierarchy process (AHP), which utilizes pairwise comparisons between subjects (Dandapat & Panda, 2017), was used to determine the relative risk that one subcategory in the three datasets was compared to others. These decisions were made according to a 9 point scale, where 1 was equal risk and 9 was an absolute higher risk favouring one subcategory. The comparative importance of each point on the AHP scale is further described below:

Table 2 - Semantic scale of the AHP method. Source: Ramanathan (2001)

Comparative importance	Definition	Description
1	Equal importance	Two indicators equally influence the parent decision
3	Weak importance	One factor is moderately influential over the other
5	Essential or strong importance	One decision factor is strongly favoured over the other
7	Demonstrated importance	One decision factor has significant influence over another
9	Absolute importance	Evidence favouring one decision factor over the other is the highest order of affirmation
2, 4, 6, 8	Intermediate	When compromise is needed, values between two adjacent judgements are used
Reciprocals	If A_i is the judgmental value when i is compared with j, then A_J has the reciprocal value when compared to A_I	A reasonable assumption

The resulting pairwise comparison matrices compute the priority vectors, or the weight, of each criterion based on the normalized points in each column. This was achieved by dividing each cell value by the sum of the column, and then by averaging the resulting values in each row of the criteria. Furthermore, to evaluate the efficacy of the comparison decisions made, a consistency ratio was also computed-- a value equal to or less than 0.1 indicates that the decisions are consistent (Dandapat & Panda, 2017). All of the AHP matrices used in this analysis had a consistency ratio of less than 0.1.

Once all three of the categories produced a normalized social vulnerability risk factor, in the form of a percentage of total risk for each category, the percentages were then added together for each ED to produce the total social vulnerability risk. The resulting total was then also converted into a percentage of the sum of risk, creating a percentage of social risk with the inclusion of demographics, material construction, and distance from hurricane shelters.

Demographics

The demographic data used included the population of Grenada and was grouped in the following categories: ages 0 to 4, 5 to 64, and 65 and above. As these age ranges are very broad, it is difficult to determine each age group's social vulnerability—for example, the age group 5 to 64 includes children, as well as adults. As such, we created an additional range to separate children from the adult and young adult population: the range of age 5 to 14 and 15 to 64. To do this, we used the Central Intelligence Agency's (2017) data on Grenada's population to determine the general percentage of people aged 0 to 14, which was 24%. The total population of each ED was then multiplied by this percentage, and then the number of age 0 to 4 citizens that was already in the data was subtracted from that overall number to isolate the age 5-14 population. Next, the new age 5 to 14 group was subtracted from the overall age 5 to 64 group, creating the age 15 to 64 group. The group of age 65 and higher was not changed. This calculation was replicated through all EDs to determine the general population ranges for each district in the data.

Each age range was then inputted in an AHP comparison matrix. As ages 0 to 5 and 65 and above are dependents and vulnerable groups, it was determined that they were the most vulnerable populations. These were followed by the age 5 to 14 group, which comprises of children and teenagers, and the least vulnerable was determined to be the age group 15 to 64, which contains adults. The table containing the comparison decisions made for demographics is shown below, with the full AHP table available in Table A in Appendix 1:

Table 3 - Demographic AHP matrix

Criteria	Age 0 to 4	Age 5 to 14	Age 15 to 64	Age 65 and over
Age 0 to 4	1.00	6.00	9.00	2.00
Age 5 to 14	0.167	1.00	3.00	0.20
Age 15 to 64	0.111	0.333	1.00	0.13
Age 65 and over	0.500	5.000	8.000	1.00

The priority vectors were then multiplied to the total population of each age group for each ED in the data. The sum of all the resulting age group values generated the overall social vulnerability risk factor of the ED. To normalize these values with the other two categories, each ED social risk factor was turned into a percentage of the total risk.

Material Construction

The data used for the material construction category was provided by Kristen and Rob. The amounts of different materials used in each building were estimated for each ED in the data. Although the data was originally offered at the individual building level, the remainder of our data was at the ED scale-- it was therefore scaled upwards to be used comparably with the other social vulnerability factors. The materials available were separated into four criteria: aggregates, timber, concrete, and steel. All four categories were inputted in an AHP matrix, where the decision was whether one material is more vulnerable than another. Concrete and steel were found to be the least vulnerable, while timber was the most vulnerable in Grenada. These were chosen because of Grenada's susceptibility to landslides and hurricanes—concrete and steel are less likely to degrade and have higher structural integrity when exposed to shocks (Sawab et al., 2016). On the other hand, timber is more vulnerable to fire and decay, causing it to be more affected by natural disasters (Thomas & Ding, 2018). Aggregates are materials used to bind and reinforce other elements, and as such had a neutral preference in the AHP matrix unless it was compared with timber-- it was considered less vulnerable than timber, but more vulnerable than steel and concrete.

The decision matrix for the material construction layer is shown below in Table 3, and the full AHP matrix can be found in Table B in Appendix 1.

Table 3: Material construction AHP matrix

Criteria	Timber	Aggregate	Steel	Concrete
Timber	1.00	5.00	6.00	8.00
Aggregate	0.200	1.00	3.00	4.00

Steel	0.167	0.333	1.00	2.00
Concrete	0.125	0.250	0.500	1.00

Similar to the demographics category, the priority vectors generated for the material construction were multiplied with the total amounts of each material found in each ED. The results of each material were added together in each ED to create the degree of risk, and then turned into a percentage to normalize the risk factor with the demographics and distance from shelters categories.

Distance from Hurricane Shelters

Distance from hurricane shelters was included as a category because of Grenada's high susceptibility to hurricanes. After generating the centroid of each ED, the distance to the closest hurricane shelter from each centroid was calculated. These distances were then converted into percentages of the sum of all distances. This criteria was not inputted into an AHP matrix, as it was determined that the greater the distance to a shelter was, the greater the social risk-- the farther away a shelter is, the more difficult it is to access services or safe areas once a hurricane strikes. The percentage of total distance was used as-is with the demographics and material construction layers to produce the overall social vulnerability risk factor.

Development of the Web Map Application

The methodology for the web map application and final website products were broken down into nine phases. There were eight phases for the development of the web map, which were the Design Phase, Initial Coding Phase, Data Loading Phase, Layer Styling Phase, Popups Phase, Legends Phase, Plugins Phase, and Final Coding Phase; there was one phase for the development of the website, which was simply called the Website Development Phase

Web Map Workflow Diagrams

Below are the workflow diagrams for the web map application, which groups the eight web map phases into four main focuses: Design and Initial Coding Processes in Figure 4, Layer-Related Processes in Figure 5, Leaflet Plugin Processes and Leaflet Final Processes in Figure 6. The processes, decisions, and data are colour-coded to show which phase each step belongs to.

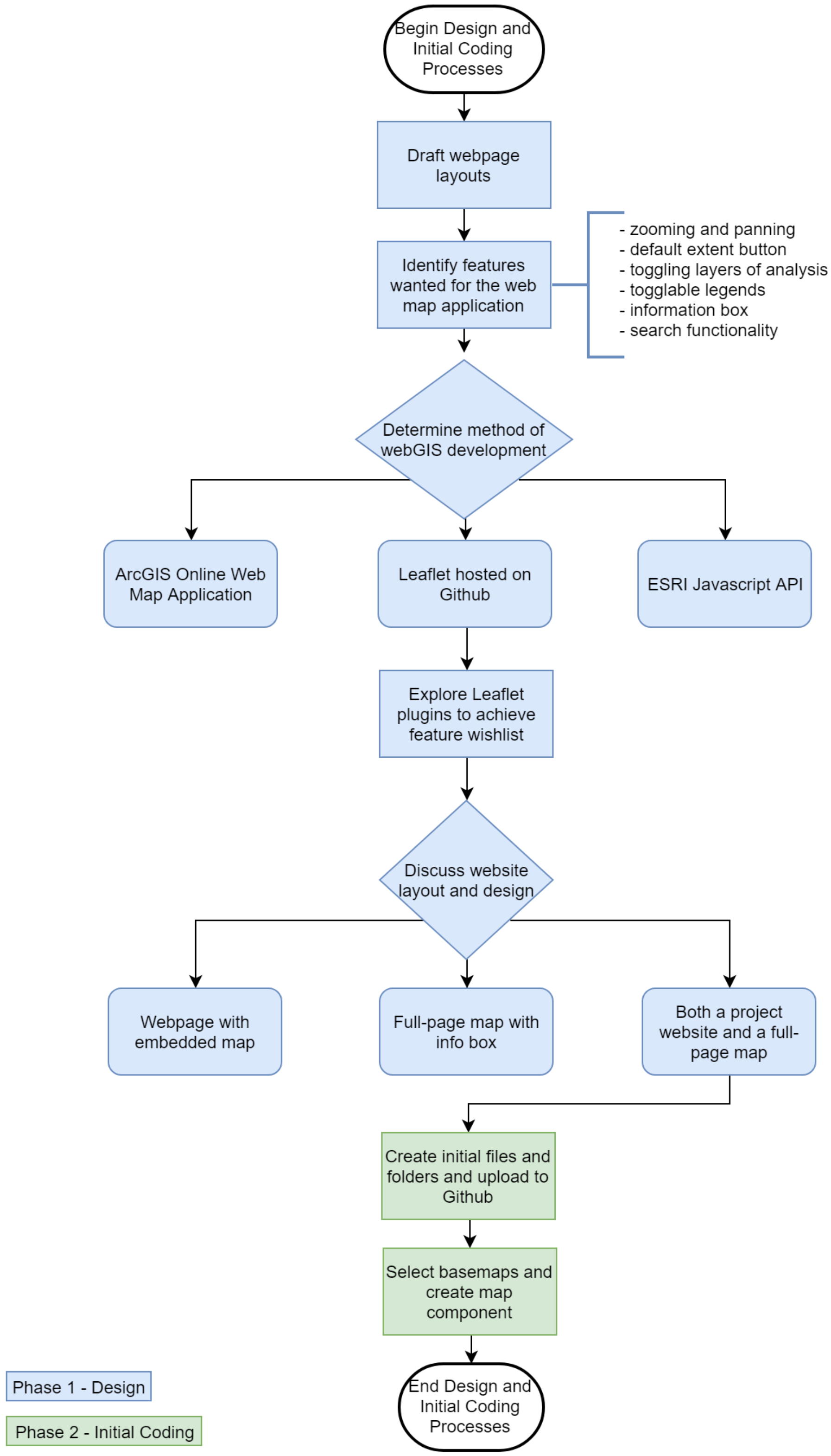

Figure 4 - Design and Initial Coding Processes

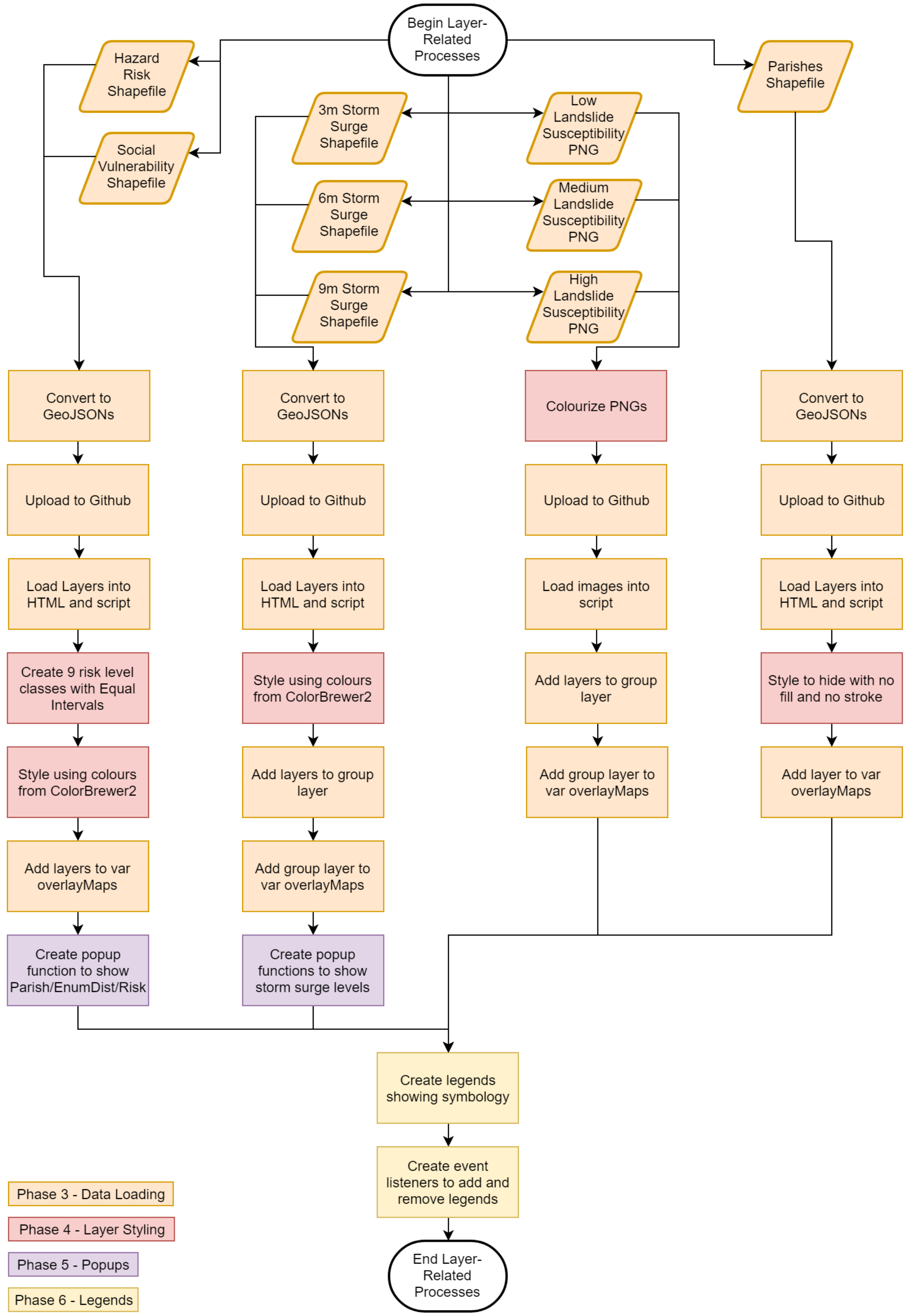

Figure 5 - Layer-Related Processes

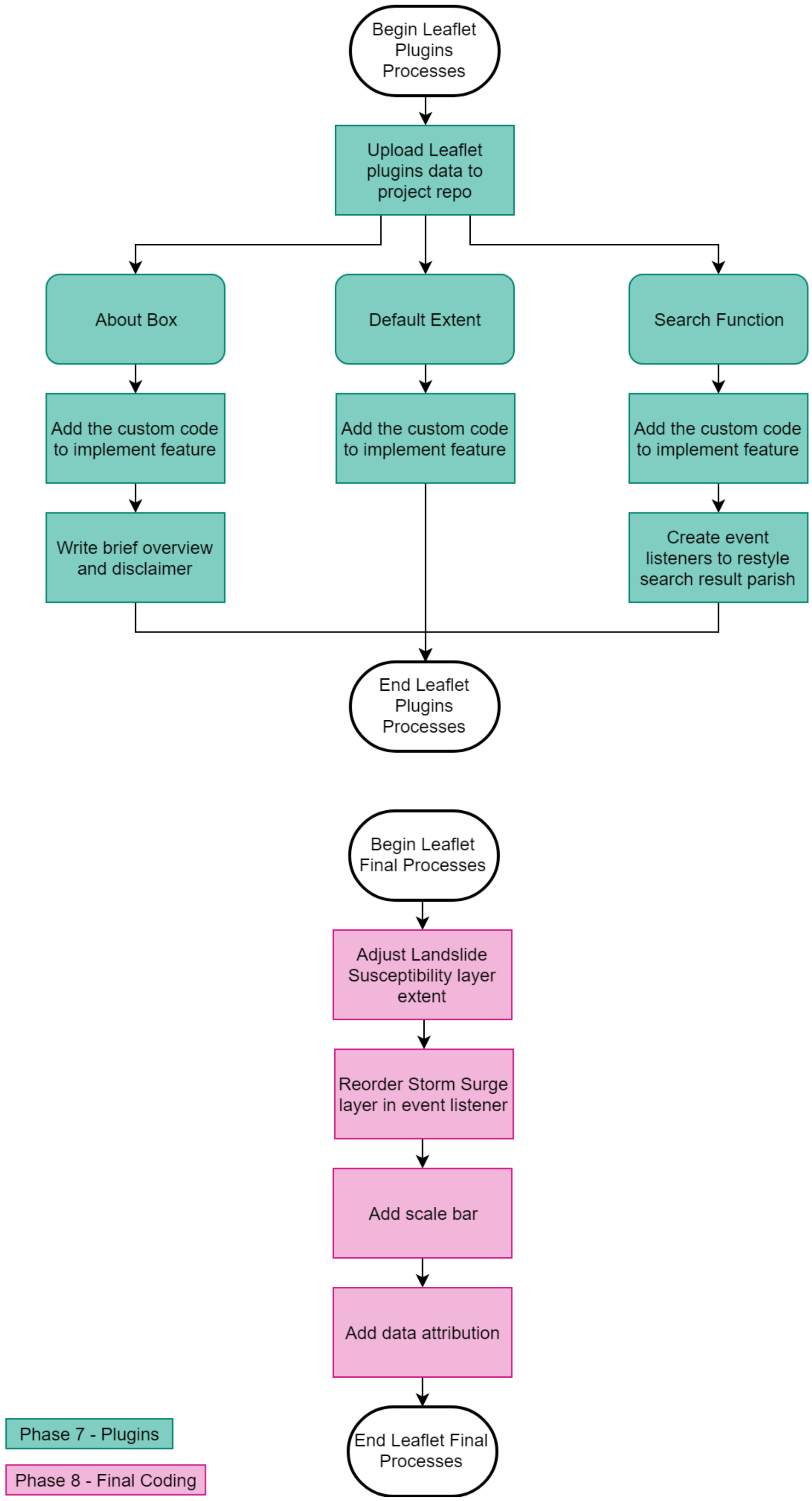

Figure 6 - Leaflet Plugin Processes and Leaflet Final Processes

Design Phase

We began our web development with design, in order to identify what we wanted our final product to look like and what we wanted it to do. We created a draft layout of a webpage, which put the web map on the same page as the project information and external resources. This was our first version draft layout of the web map application. We then discussed what features we wanted the web map to have in terms of interactivity, and determined that we wanted users to be able to toggle analysis layers on and off, to be able to return to a default zoom with a button, and to be able to search and highlight parishes on the map, in addition to a few others seen in Figure 1. We considered and discussed different development methods, such as using ArcGIS Online and the ESRI Javascript API, but it was eventually decided that the web map would be developed with Leaflet hosted on Github. We chose to develop with Leaflet because we wanted to use more free and open source technology and methods for our project. Additionally, the Leaflet JavaScript library was more feature flexible than ArcGIS Online, less complex than ESRI Javascript API, and in combination with Github, allowed for code collaboration and good version management. Our developer was also familiar with Leaflet web map development, and so the choice of using Leaflet to create our web map was an easy one.

Following the decision of developing with Leaflet, we explored and browsed through existing Leaflet plugins to look for those that could achieve our functionality wishlist, and also to add any other plugins that we would be interested in for our web map. We found that with Leaflet, toggling layers was a built-in function with the base Leaflet source script, and that there were plugins for a default extent zoom and search functionality. We also found a plugin for a prefacing About box, which generated discussion and created two more layout drafts. Eventually, we finalized our web product design to be a full-page web map with an associated website that would host all the project information and external resources. With our final design, we were able to make the web map its own component, and highlight it as the main product, while supplementary material was presented in a linked website. This decision closed the Design Phase.

Initial Coding Phase

Moving into the Initial Coding Phase, files and folders were created an uploaded to Github, specifically the HTML and script files, and a folder for data. Within the HTML file, we sourced Leaflet and our plugins, and created a map div that is also a mobile-friendly size, and referenced our working script. Within our working script, we selected a few basemaps from Leaflet Extras (https://leaflet-extras.github.io/leaflet-providers/preview/) and added them to the basemap control, and created the Leaflet map component and added the basemap control to the map, resulting in a basic web map product.

Data Loading Phase

The analysis sections of the Methodology outlined how our analysis layers were created, and most of those layers were exported as shapefile layers. As seen in Figure 2, the social vulnerability, storm surge, overall hazard risk, and parish layers were made available as shapefiles to be converted and inputted into our web map application. It was ideal to export those analysis layers to shapefiles because there is well-established and clear documentation on how to convert shapefiles to GeoJSON files, and on how to add GeoJSON layers to Leaflet (http://leafletjs.com/examples/geojson/). Our developer was also already very familiar with how to use GeoJSON layers in Leaflet. Other than the GeoJSON layers, the landslide susceptibility layers were exported to PNG and loaded into Leaflet as PNGs, and will be discussed later in this phase.

We converted the shapefiles to JSON using a free web service Ogre, located at https://ogre.adc4gis.com/, and converted the JSON files to GeoJSON using http://geojson.io/, which also allowed us to check the spatial data on a quick web map and the attribute data in a table on the side. This allowed us to do data quality assurance on the converted files, and also allowed us to fix any possible problem sources, such as changing field names to not have spaces. After converting the files to GeoJSON and saving them with the `.geojson` file extension, we opened them in Notepad++ to manually add each file's data to a variable within the file, for example `var socialvul = […].`

Following this, we pushed the data onto Github and source the data as Javascript in our HTML before the working script, and within the working script, loaded each of the data into Leaflet as individual layers using the variable name declared in the GeoJSON files. For the storm surge layers, we added the three layers of storm surge data into a storm surge layer group variable. We added the storm surge layer group and all the other GeoJSON-based layers to the variable `overlayMaps` (with the exception of the parishes layer), and added `overlayMaps` to the Leaflet control. With that, there were now layers that the user could toggle on and off.

As mentioned before, the landslide susceptibility layers were exported to PNGs after the analysis had been completed. Originally, they had also been converted from raster to polygon and exported to shapefile, much like the storm surge layers, but we found that the resulting GeoJSON file size was too big for our web application, at over 10 times the size of the other GeoJSON files. The landslide GeoJSON file negatively impacted performance in such a way that the basemaps and other layers took extremely long to load and the map could not be panned or zoomed. This massive reduction in performance was due to the application trying to load the multiple high-resolution polygons of the data.

The landslide susceptibility layers exported as PNGs were comparable in size to the other analysis layers and did not impact performance as negatively. They were exported to PNGs because Leaflet only support image overlays of JPEGs and PNGs using its `L.ImageOverlay` methods, and we wanted to retain the data for transparent values to show the basemap under cells with no data, which JPEGs cannot achieve but PNGs can (https://www.sitepoint.com/gif-png-jpg-which-one-to-use/).

`L.ImageOverlay` required the developer to provide the PNG image as a URL, and the geographic bounds of the image as the latitude and longitude coordinate pairs of the southwest and northeast corners of the image. Those latitude and longitude coordinate pairs were acquired from the original raster layer in our GIS software, which will later cause a problem that is resolved in Phase 8, the final coding phase. Before loading in our PNGs however, we had to skip forward to the Layer Styling Phase for the landslide susceptibility layers because the exported PNGs were coloured black, and could not be styled in Leaflet. Each PNG was recoloured in graphics editing software (both Adobe Photoshop and GIMP were used), following a colour scheme chosen from Color Brewer 2.0 at http://colorbrewer2.org/, and then uploaded to Github to produce URLs. The coloured PNGs were then loaded into Leaflet, and the three PNG layers were put into a layer group for landslide susceptibility and added to the `overlapMaps` variable.

Layer Styling Phase

While the PNG styling took place before the loading of the landslide susceptibility layers, the GeoJSON layers were loaded and then styled. The developer had to style the GeoJSON layers for their feature type, be they points, lines, polygons, or a combination; otherwise, Leaflet would impose a preprogrammed default style on all the layers and features.

Generally, the GeoJSON layers followed the same methodology for styling, with the exception of the parishes layer that will be discussed later. After loading in the GeoJSON layers, we created styling functions that would define the main style attributes for that feature type, such as fill colour and fill opacity for areas, and weight, opacity, and colour for strokes (outlines). These styling features would take in layer features as the argument. Functions were also created for the social vulnerability and overall hazard risk layers, and classify and colour those layers by class. These two layers were expected to be visualized as choropleth maps; they both have 9 equal interval classes, based on the weighting criteria established in the making of the hazard risk layer. The colour schemes of all the layers were determined using a popular online tool for cartographic colour advice, Color Brewer 2.0 at http://colorbrewer2.org/, which also had recommendations for colour-blind friendly colour schemes.

Our colour schemes were all chosen to be colour-blind friendly. The landslide susceptibility layers were coloured orange to dark red to represent the danger of landslides and the earth. The storm surge layers were coloured blue to represent water flooding the land. The social vulnerability layer was coloured yellow to dark green to represent the dependent demographics and the other factors that contributed to the analysis of that layer. The overall hazard risk layer was coloured light pink to dark purple to represent the combination of all the other analysis layers.

The parishes layer had dramatically different styling compared to the other GeoJSON layers, as the parishes are not meant to be displayed to the user until they successfully complete a query with the search function. The parishes layer was loaded into the web map to provide parish boundary highlighting for the search function, so the default styling for the parishes layer has no fill and no stroke. When a search for a parish is successful, the parish polygon of interest takes on a new styling of no fill and a thick black stroke. Upon exiting the search function, the parishes layer and the searched parish polygon all return to the original no fill and no stroke style. This interactive change of styling is made possible with the `setStyle` functions that are added to the search function's event listeners, which will be discussed later in Phase 7, the Plugins Phase.

Popups Phase

In this phase, we created the popups for our three GeoJSON analysis layers, by creating functions that can access the attribute data of interest stored in each layer. Those functions retrieve the attribute data and add them to the contents of the popups. The social vulnerability and overall hazard risk layers were both presented in Grenada's enumeration districts, and so the popups of those two layers indicate the parish, enumeration district, and the vulnerability or risk level of each polygon. The storm surge popups indicate if the user has clicked on a 3m, 6m, or 9m storm surge level area, and this is because it is hard to tell what the level is for some parts of the map.

Legends Phase

To make the web map more understandable, we created legends for each analysis layer to show the colour symbology and to quickly show what the colours mean. We defined the colours of each legend, as well as the text description for each colour block, and then added each legend to the map with each layer. We added Cascading Style Sheet information to the HTML file to produce clean-looking legends, as sourced from the official Leaflet choropleth map example (http://leafletjs.com/examples/choropleth/). We wanted legends to show and hide when their respective layers were toggled, and we were able to do this by creating Javascript event listeners. Every time a layer is enabled, the associated legend is added to the map, and every time a layer is disabled, the associated legend is removed from the map.

Plugins Phase

As mentioned in the Design Phase, we wanted to achieve some functionality that was only possible through the implementation of plugins, specifically the creation of an About box and button, a button for returning to the default extent, and a search feature. Leaflet and its plugins have their own script and CSS that must be accessed through by calling through the HTML file, in order to use their functions and settings. This phase describes how each plugin works and how they were incorporated into the web map application.

About Box

There is a Leaflet plugin called infoButton that can be added to the Leaflet controls, and the developer can customize the text that is displayed. For our About box, we included a brief backgrounder on the project, a disclaimer for the appropriate intents and uses of the web map, and a link back to the main project website. This About box is seen at the very beginning of a user's experience with the web map application, in order to push forward the purpose and disclaimer of the map before they actually use it. The user can view the About box again by clicking on the ? (question mark) button. Implementation of this plugin was in two main steps: writing up the text content and adding the appropriate code to the Leaflet control.

Default Extent

The plugin for the default extent created a button that allows users to return to the defined "default extent", or the initial map view on load, which was defined in the initial coding of the Leaflet map. By clicking the house icon button, the user can return to the default zoom and map centre. The implementation of this plugin was very simple, and just required a few lines of custom code to enable the button.

Search Functionality

We wanted to give the user the ability to search for a parish of Grenada and be show the parish on the map. The search plugin we chose allowed us to achieve this feature, given that it is coded after the parishes layer data is loaded. It is implemented at the end of our working script, and also involves adding the search button to the Leaflet control. In some custom code, we defined two actions for when the search is successful: to zoom in and centre on the parish, and to outline the border of the parish in black, as previously mentioned. We also defined one action for when the search box is collapsed, which is to reset the parishes layer's style to no fill and no stroke, also as previously mentioned.

Closing Coding Phase

In this last phase of the web map application development, we addressed some errors and made some small additions to the code. One of the two main problems we had to fix was the landslide susceptibility PNGs geographic position. The exportation of the raster data to PNG had changed the extent of the layer, so that the PNG was wider than the original raster. The extent we used in the loading of the PNGs to the web map were of the original raster, so the resulting image on the map was squashed. We resolved this problem by manually adjusting and checking the latitude and longitude coordinates of the southwest and northeast corners of the PNGs, which can be seen in the code.

The other main issue we had was with the order of the storm surge layers. We found that the popups would only show for the 9m storm surge, and it was determined that Leaflet was loading the 9m storm surge on top of the other two layers, preventing the user from clicking on the 3m and 6m storm surge layers and opening their popups. The solution we implemented was to use the legends' event listeners to bring the storm surge layers to the front, in the right order for user interaction.

We had two small additions made to the code at the end, which was to add a scale bar to the map, and also to add data attribution to CHARIM to the map.

As the web map development was a very iterative process, at the end of every phase, the updated product was presented to the rest of the team for user experience quality assurance, and modifications were made as they occurred. Generally, only major data-related errors and issues were communicated with the analysts of the datasets, due to the project's division of labour, time constraints, and each individual's understanding and level of expertise of the dataset's analysis methods and of the web map development. The two errors described in this phase actually occurred and were resolved at different stages, but they fell under this phase for the improvements they made to the presentation of data and user experience.

Website Development Phase

The website was built with Hypertext Markup Language [HTML], Cascading Style Sheets [CSS] and JavaScript. HTML is used to create electronic pages to display on the web, CSS is used for designing the HTML page with various layouts. Javascript is used for actions to be performed by the website. Each page is created in a separate .html and .css pages. All the code written for the website and web map application can be found at the following link: https://github.com/q-schen/gp481

The format of the website contains 5 components: Home, Project, Resources, About, and Contact. The website was created to have multiple sections to address one of the project's goals, which was to present at-risk area information to stakeholders in the form of an interactive web map application to support local awareness, government emergency management, and disaster planning organizations, as well as promote publicly available information.

The Home page is the first webpage everyone loads into. It shows the logo, the 5 selectable components, and a brief message describing the reason for this project. It has the logo spinning and briefly pausing at 50% rotation. The animation is also stopped if mouse is hovered over it. This is done by using the code:

```
@keyframes rotate {
0% {transform: rotate(0deg);}
50% {transform: rotate(180deg);}
100% {transform:rotate(360deg);}}
```

Then calling this code under logo style as:

```
animation-name: rotate;
animation: rotate 5s infinite;
```

Lastly adding this code to hover:

```
animation-play-state: paused;
```

The code *@keyframes* represents animation and rotate is the name given to that specific keyframe. The code: *0% {transform: rotate(0deg);}*, means that at 0% of given time, it holds the initial position of 0 degree (upright position of the image). 50% represents the half way time, and at half way time it holds the position at 180 degrees (when the word "Grenada" is at top and "AeGIS" is at bottom of the logo). Lastly, 100% represents the completion of given time, and it rotates full 360 degrees back to its initial position. Therefore, every time the animation is called, it rotates a full circle based on the given time. To animate the object, it must be called where we give design style to logo. Under the style, animation-name: rotate, calls the animation rotate keyframe. Then *animation: rotate 5s infinite*, gives the rotate 5 seconds to complete its full animation, and does this infinite time (always). Lastly, adding the code *animation-play-state: paused*;, pauses the animation when mouse is hovered over it. This process was explained because it was an interesting way of animating within CSS. Not all of the code used to build the website and the designs will be explained in this report, however, they can always be viewed on GitHub.

The second component of the website, Project, has a link to our full report, and goes over the project briefly. This component includes the sections: Introduction, Background, Study Area, Final Product, and Conclusion. Introduction and Background and Study Area were added to give a brief overview of what the project is about and why Grenada was selected. The Final Product section includes the link to the web map application, as well as brief explanations in regards to what each layer represents. It also mentions what different values represent within the each layer. Lastly, the Conclusion section states a brief conclusion of this project.

The third section is the Resource section, which was created to promote and provide publicly available disaster management information that can be of help to the citizens of Grenada. The websites selected here all provide support and information to Grenada or hazard preparedness. There are two sections to the Resource page: links to resources for hazard mitigation, and links to disaster and hazard research conducted in Grenada.

In the links that provide resources for hazard mitigation; the first link is the home page of National Disaster Management for Grenada (NADMA), which provides an emergency update as soon as the page is loaded. This update changes with the occurrence or approach of different hazards and disasters in Grenada. NADMA also has various disaster management information for the citizens of Grenada. Since NADMA provides a variety of information on disasters and also gives emergency updates, it was selected to be the first link on Resource page. The second link is also to NADMA, but this link goes directly to the list of emergency shelters. Although NADMA also has emergency shelters on the top right of its home page, in the event of a disaster, people do not have the time to browse around for additional information. Thus, our website provides a direct link to the shelters list. The third link is to the official website of the U.S. Department of Homeland Security, which provides information in regards to what to do before, during, and after a disaster occurs. This gives information on how to be prepared for disasters and what to do to improve personal safety during disaster events. For these reasons, this website was listed third on the Resource page. The final link for hazard mitigation is NOW Grenada, which is a website that publishes events and news on Grenada. In an event of a potential hazard, it is important to have news that can help identify areas that are more dangerous or safe. However, compared to NOW Grenada, NADMA has emergency updates and other information on their page, and the U.S. Department of Homeland Security has information on how to be safe. Therefore, NOW Grenada was placed as the fourth link in regards to resources for disaster mitigation.

The second section on the Resource Page holds links to research conducted on Grenada. The first link on this is report done by Think Hazard, GFDRR, and The World Bank Organization. It provides information on various areas of Grenada which are prone to different types of hazards. Although the quality of this research does not measure up to the second link, the quantity of disasters covered is much greater. The second research link provided is done by

CHARIM. This research provides intensive research on flooding in Grenada, but it only shows flooding risks.

The two sections provide some resources and information on hazards and proactive disaster management. Additionally, these sections will be updated regularly as additional research found or conducted in Grenada, which should be useful to the citizens of Grenada.

The fourth section is the About Us page. This page was created to show the credibility of our team and our research. It gives recognition to the candidates working on this project.

The fifth component of the website is the Contact Us page. To create this page, the first step was to create an AeGIS email, which was created in Gmail. The password-recovery for Gmail was linked to one of our personal emails. This Gmail password was then shared with the group so that everyone can view the feedback provided by visitors of the website and update with information if required. Since the Gmail account is new and may not be checked as often, it was set to forward to our personal emails. This way if there is a feedback, it will come to the Gmail as well as personal email. If the contact us page gets spammed, the forward option will be removed in future, and it will be checked in regular intervals. Once the email was set, the code to open the email is short. Only the html code is required for this to work, the entire code is:

Contact Us.

From this code, when they click the contact us, it will open the user's default mail application in their computer with the email: AeGisGrenada@gmail.com on the To: section.

With these five components completed, it was hosted on GitHub pages to provide Grenada with additional resources in hazard vulnerability.

Results

Web Map Application and Website

The final website can be viewed from: **https://q-schen.github.io/gp481/final.html**. We were able to achieve our wishlist of features for the web map by developing with Leaflet and Leaflet plugins, as seen in Figure X, including toggling our analysis layers, having a working default extent button, being able to search by parish, and having an About screen. We were also able to display all of our analysis layers and their legends, which are the overall hazard risk, social vulnerability, landslide susceptibility, and storm surge layers. The list of layers can be seen in Figure X below. The website we developed presented all of the project information, including important background information and explanations for the analysis layers, and also provides links to external resources for local users looking for more hazard and disaster management information. In addition, the web map application and website are both mobile-friendly, and the web map should also be colour-blind friendly, as advised by the colour schemes selected from ColorBrewer2. Overall, the final web products are accessible by the public on all devices with a browser and Internet connection.

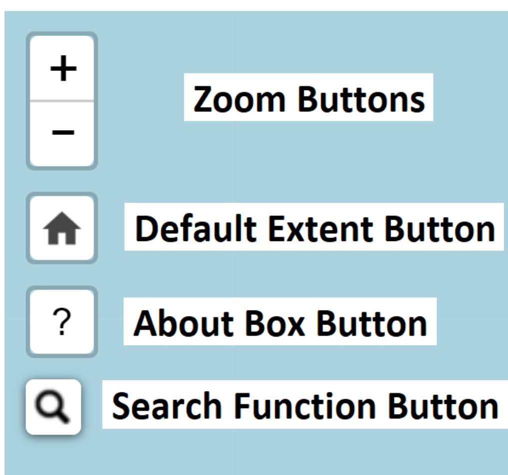

Figure 7 - Web Map Feature Buttons

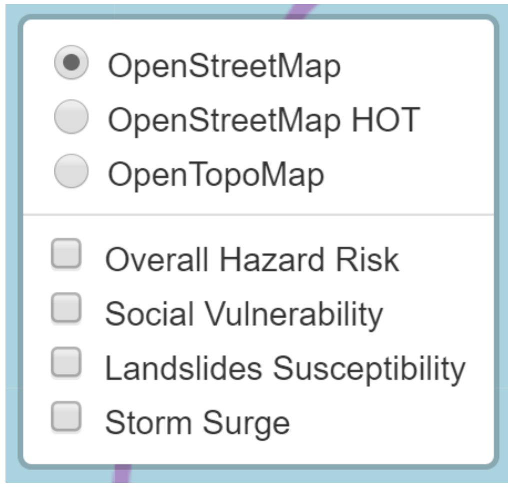

Figure 8 - Web Map Layer Toggle Control

Landslide Susceptibility

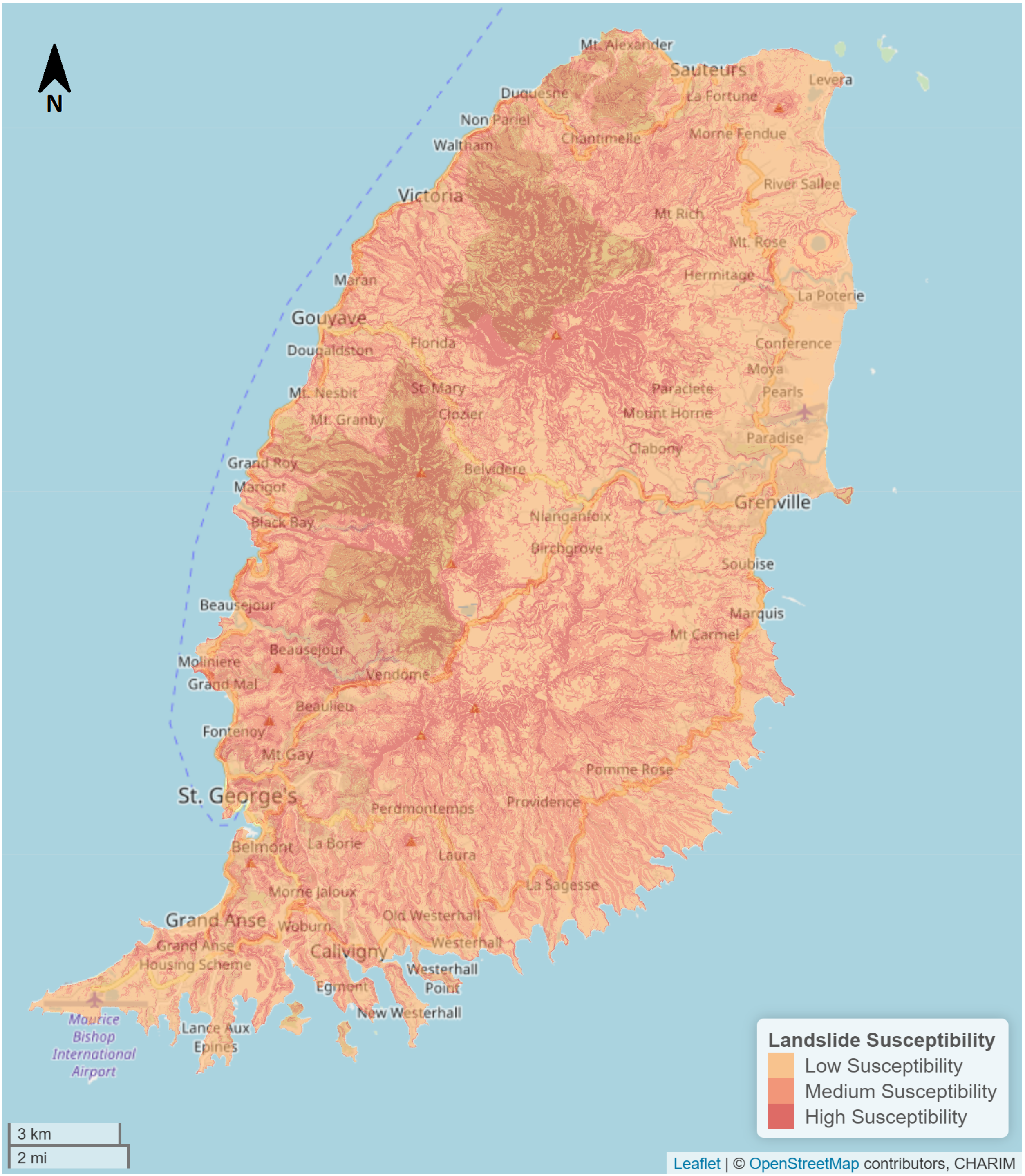

Figure 9 - Map of Landslide Susceptibility Layer

As seen in Figure 9 above. There was generally low landslide susceptibility along most of the coastal areas of the island. However, there was high landslide susceptibility further inland in the northern half of the island, and some of the northwestern coast. Portions of the southern half of the island also had higher landslide susceptibility, shown in somewhat radial spatial patterns. In the northern half of the island, high landslide susceptibility appears in a trellis spatial pattern.

Storm Surge

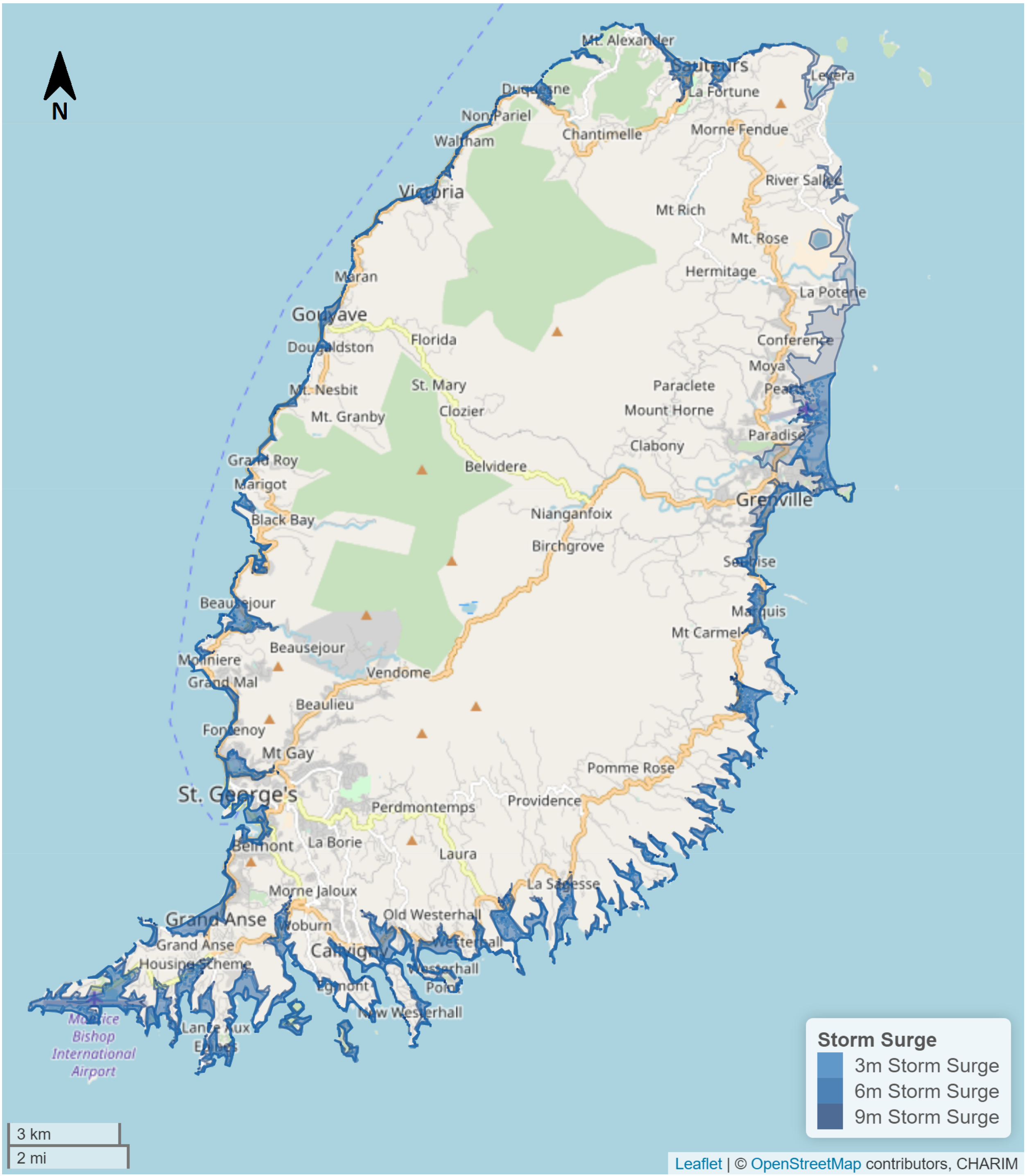

Figure 10 - Map of Storm Surge Layer

As seen in Figure 10 above. Most of the major coastal towns and cities are partially or wholly submerged in a 9m storm surge event. Large areas of the northeastern coast, north of Grenville, are submerged in 6m and 9m storm surge conditions. Several inlets of the south coast will grow and submerge land in 3m and 6m storm surge levels, and nearly all of the Maurice Bishop International Airport is submerged in 6m storm surge conditions. Half of the St. George University main campus is at risk of flooding under 3m storm surge, and all of the Grand Anse campus is underwater in the same 3m storm surge scenario. The majority of the island is not at risk of any level of storm surge.

Social Vulnerability

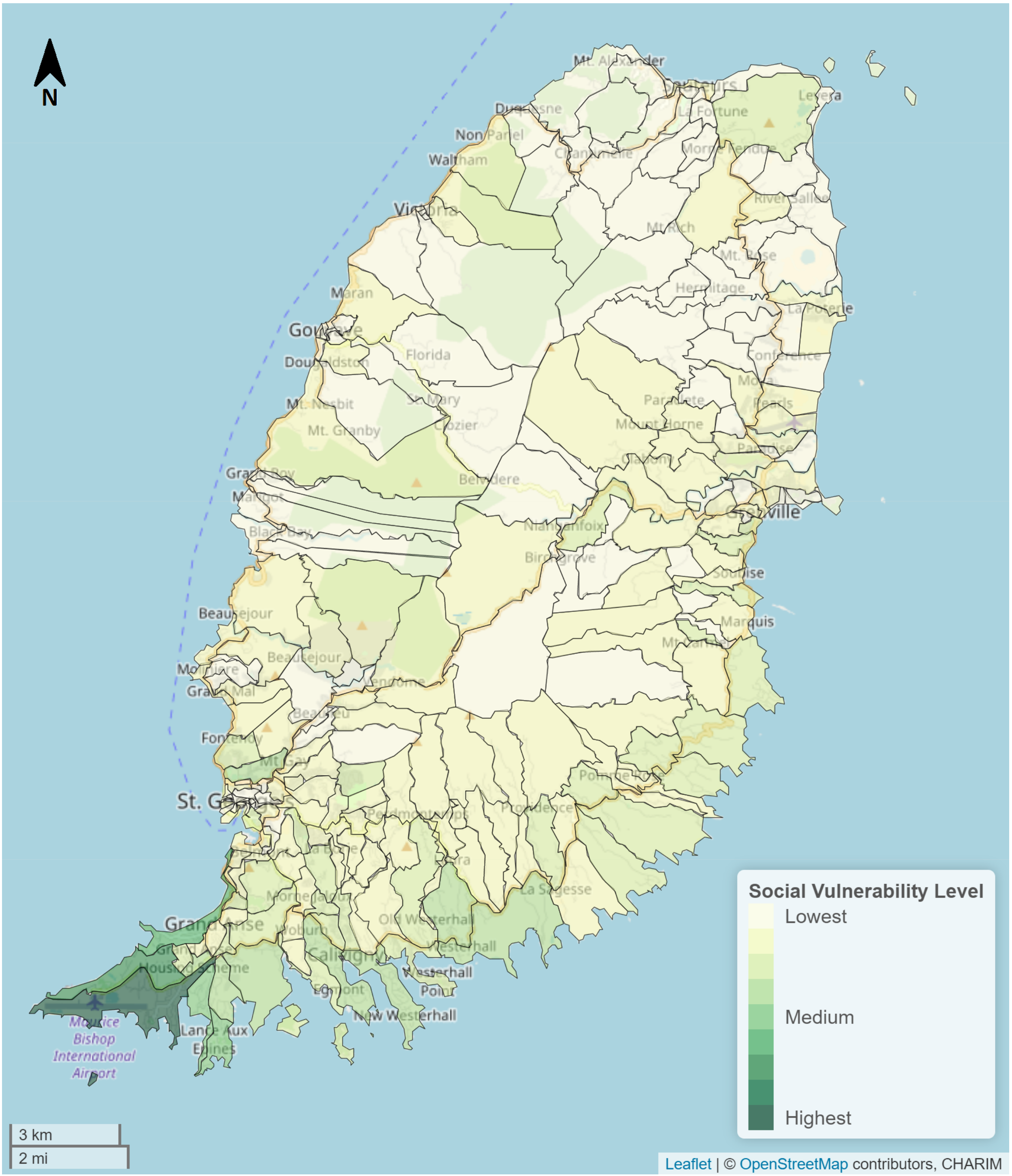

Figure 11 - Map of Social Vulnerability Layer

As seen in Figure 11 above. The highest social vulnerability levels are the southwest enumeration districts of the island, around Grand Anse and the Maurice Bishop International Airport. Outside of that area, the southern coast has medium to low social vulnerability. There is not a lot of variation in social vulnerability around the island; the rest of the enumeration districts are mostly of low social vulnerability.

Hazard Risk Map

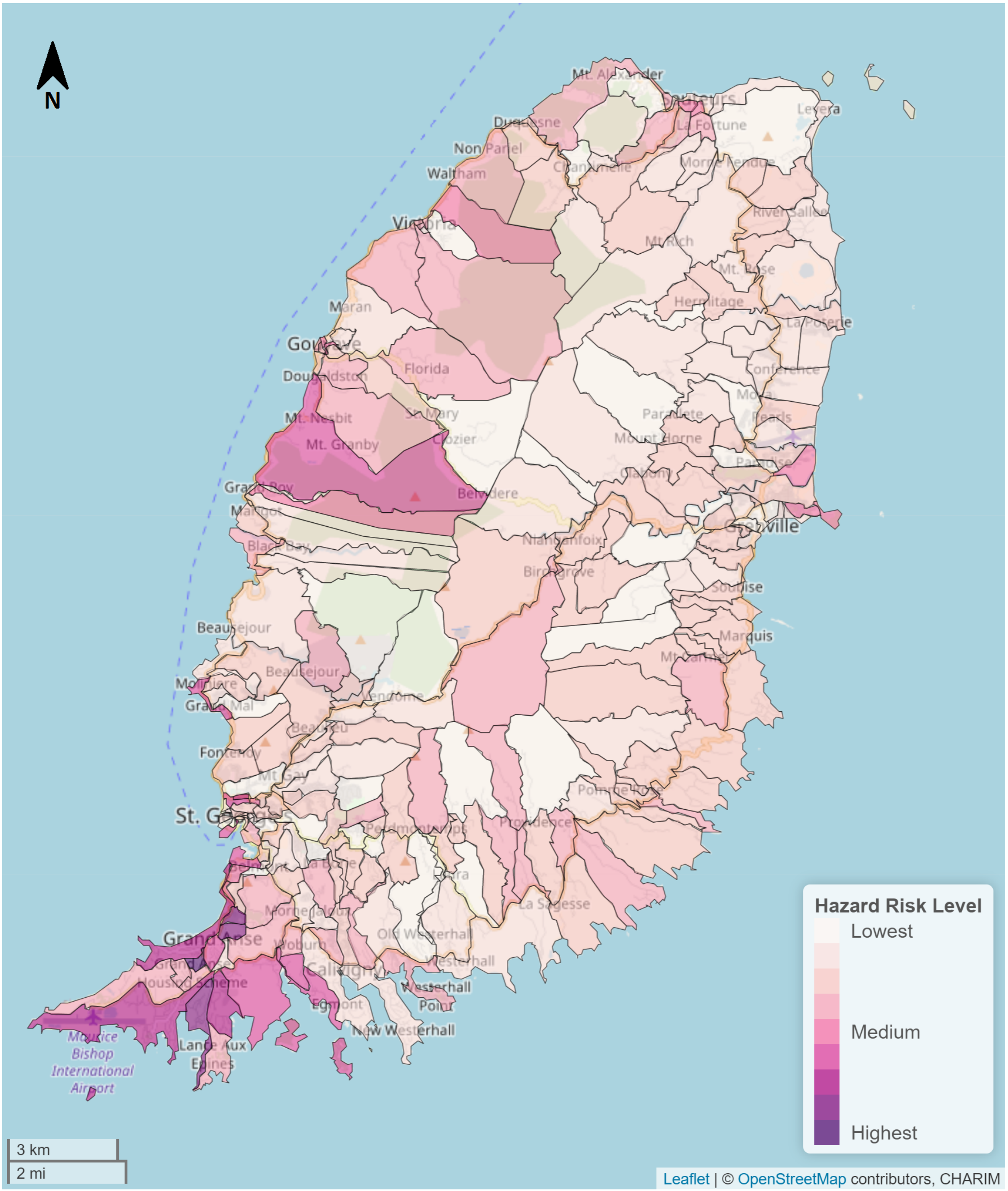

Figure 12 - Map of Storm Overall Hazard Risk Layer

As seen in Figure 12 above. The highest overall risk levels can be seen in the southwest enumeration districts of the island, around Grand Anse and the Maurice Bishop International Airport. There is also medium to high overall risk levels along the northwestern coast, north of Grand Roy.

Discussion

The importance of the web map application cannot be understated especially in the current climate uncertain times. With the strengthening of Atlantic hurricanes as a direct result of climate change, it is vital that the people of Grenada have quick access to information on possible hazard risk areas, specifically hazards influenced by hurricanes such as landslides and storm surge flooding.

Layers Discussion: Storm Surge

The web map application reveals key areas of interest. The storm surge layer highlights areas under threat of 3, 6 and 9 metre storm surges. In 2004, Hurricane Ivan produced a 3 metre storm surge on the island, and for this reason, the height of 3 metres was chosen for the base value of storm surge (Organisation of Eastern Caribbean States, 2004). Also, the largest storm surge for an Atlantic hurricane was determined to be 9.26 metres in height, as a result it was chosen as the highest storm surge value (Masters, n.d.). In order to produce a worst case scenario for Grenada this value was used. Finally, the 6 metre value was chosen as a median break point value to identify risk areas for medium intensity storm surges.

The storm surge layer identifies some key areas of interest. The parish of St. George located on the south west side of the island contains a series of enumeration districts on the southern tip of the island that are largely covered by a storm surge, of any level. However the major concern is the Maurice Bishop International Airport located in this region. Under a 6 metre storm surge, the airport is shown to be flooded over and patches of the runway are even covered under 3 metre storm surge conditions. This is problematic because of the high probability of such a flood event taking place, as seen with Hurricane Ivan. If the airport becomes inaccessible, evacuation procedures and the ability to receive external aid and emergency services will be greatly hindered.

Although not available visually in the web map application, it was also noted that the hurricane shelters on the island were all located on the northern half of the island, and also on the west side. This means that those located on the south and east side of the island have no access to storm shelters. On top of that, it was found that under a 3 metre storm surge, three hurricane shelters would be flooded, and therefore rendered useless. One recommendation derived from this is for the Government of Grenada to reconsider the locations of existing hurricane shelters, as well as to consider the construction of hurricane shelters on the southern half of the island.

Layers Discussion: Landslides

The landslide susceptibility layer is an important analysis layer in regards to hazard risk because the island of Grenada is home to a dormant volcano. Due to its volcanic past, the island has a diverse elevation profile, making it more susceptible to landslides (Tsutsui et al., 2007). The landslide susceptibility layer can be viewed as a stand alone layer in the web map application, in order to identify small changes in landslide susceptibility across the island. This layer was also incorporated into the overall hazard risk layer which determines the overall hazard risk level of each enumeration district. It should be noted that the incorporation of the landslide susceptibility data into the overall hazard risk layer involved the scaling up of that data, resulting in a loss of accuracy.

Layers Discussion: Social Vulnerability

The social vulnerability layer revealed a series of trends that could be the result of many factors. For example, a higher level of vulnerability can be seen on the south side of Grenada. This was likely the result of a higher density population in the area. Furthermore, there are a higher number of dependents and elderly, which are the two groups that heavily influenced the demographic criteria in the social vulnerability layer. Another reason for the high susceptibility in this region is possibly because the town is located in this area. More buildings generally means higher amounts of timber in the area, and that particular type of construction material significantly increases vulnerability. Finally, the distance to hurricane shelters was used as a factor to determine social susceptibility to hazards. All of the shelters are located on the north side of the island which fits with the spatial pattern seen because the south side has no access making the area more socially vulnerable. This also reveals why the northwestern side of the island is light in colour and has an overall low social vulnerability. Since the high concentration of all the criteria were on the south side, the other parts of the island are not as vulnerable. Generally, the interior of the north side is where the agricultural sector is located, which is why there are fewer people and buildings. This in turn means there is a lower social vulnerability risk in this region.

Layers Discussion: Overall Hazard Risk

The overall hazard risk layer identifies the enumeration districts more at risk to hazards based on the combination of social vulnerability, landslides susceptibility, and storm surge. The values for each risk level were weighted equally compared to each other. This was done because all factors were deemed to have a significant impact on survival, and also because weighing each factor equally allows for the opportunity to understand how each analysis layer would affect the overall hazard risk. This can be seen in the St. John and St. Mark parishes within the overall hazard risk layer. The northwest region of the island can be seen as a darker pink compared to the rest of the island. When compared to the social vulnerability layer, the same area is a low risk value (almost white). This means that the social vulnerability is not the major influence for risk in this area. Instead it is the landslide susceptibility layer that increases the hazard risk for these parishes. Landslides are a major influence in this area because the dormant volcano is located here, causing the most significant changes in elevation.

The overall hazard risk layer also identifies the most at-risk areas on the island. Unsurprisingly, it is the southern part of the St. George parish. High social vulnerability, storm surge potential, and distance from hurricane shelters identify this area as the most at-risk area of the island. This means that in the event of a hurricane, this is mostly likely the priority region for emergency services and aid.

Limitations

The project had some limitations on its analyses. The limitations have been broken down into three categories: physical hazard layer limitations, social layer limitations, and data limitations.

Physical Hazard Layer Limitations

Some of the limitations of the physical hazard layers include the availability of data and the accuracy of the available data. While we created a storm surge layer, we were not able to create a flooding layer as originally planned due to lack of river flooding data. Data on river flooding could be extremely useful in creating a layer just for flooding, and in turn informing the local population of that hazard risk. Unfortunately, there has not been data collected or publicly available on the base flow of the rivers of Grenada, so we cannot yet estimate the flooding risk of these rivers. The landslide layer has a similar situation in regards to data. Assumptions such as soil type, land use, and increases of precipitation due to climate change has led the landslide data to have potential error. With different soil types, the adhesion properties and filtration properties change across the island. A more compact soil will allow for more environmental change to affect it before it results into a landslide. Additionally, if the land use of an area changes, for example from forest to farming, this will expose the ground to more weather conditions and increase the chances for a landslide. Finally, as more precipitation starts to accumulate and fall, there will also be a greater chance of landslides occurring. If the soil is already supersaturated, more water is unable to filter through the soil, causing overland runoff. This also increases the potential for a landslide to occur. Given our storm surge and landslide susceptibility layers, there is still room for improvements. With more research and data collection, more accurate physical hazard risk layers can be produced.

Social Layer Limitations

The social susceptibility layer also had some limitations. Firstly, the material construction data used to calculate the susceptibility was available at the household scale, but the data was generalized and brought up to the enumeration district level for the social vulnerability layer. Only after the material construction data was generalized could the social vulnerability and overall risk layers be generated. This limitation decreased the data quality for the social vulnerability layer, but it was a necessary sacrifice in order to generate the final results. The comparison between vulnerability of different building materials was also generalized. It did not account for the fact that some buildings may inherently have better engineering and construction, and therefore be less vulnerable.

Demographic data limitations also lead to generalizations in the social vulnerability layer because there were only four age categories available. The largest age category grouped an age range of 50 years together. The grouping overlooks possible vulnerability changes because a 20 year old will likely be less susceptible than a 60 year old individual.

Finally, the social susceptibility incorporated the distance to storm shelters to help determine susceptibility. However, we did not take into account distance to the locations of other services such as emergency services (hospitals, police and fire stations) and government offices, that could have also influenced the social vulnerability of the enumeration districts.

Data Limitations

In a few circumstances, development of the analysis layers was restricted as a result of lack of data availability. Originally the storm surge layer was to include a river flooding layer based on precipitation values taken from hurricane data and weather stations. However, in order to calculate river flood areas, we required the average stream flow level and flow rate. Normally. this is information is gathered from stream gauges located at either end of the river. This data was unavailable as only one stream gauge was found, which does not allow for the calculation of stream height change or flow rate. As a result, we did not generate a river flooding layer. Another situation in which data availability influenced the analysis layers is the lack of economic data. In order to achieve a more holistic social vulnerability layer, the economic data for each household would be ideal to incorporate. This would have helped determine how economic means influence susceptibility to hazards. Unfortunately, household economic data was unavailable for the country and as a result it had to be removed as an potential factor to the social vulnerability layer.

Future Development

Although we were pleased with the results of our analyses and the presentation of the web map application, next steps for further analysis and development have been discussed.

Future Development: Analysis

Currently, the web map application allows the user to view the four different analysis layers. For the future, we hope to increase the number of analysis layers available to the user, such as a services layer. This services layer that would include the locations of hurricane shelter and emergency services. This would help users identify where shelters and services are, so that they can find the aid and safety closest to them and plan accordingly. In the same vein, we hope to develop a network analysis of the locations of emergency services, to identify service area zones. This will assist emergency services with response time management and help the government identify underserved areas of the island. In order for this future development to take place, we will need access to accurate road network data, as well as the locations of emergency services.

Another analysis layer considered for future development was the river flooding areas due to increased rainfall. As mentioned in the data limitations section, current streamflow levels and rates are unavailable due to a lack of monitoring stations. However, if in the future more stream flow instruments are installed, or the data becomes available, a flood analysis layer will be added to the web map application. The river flooding layer will be helpful because the increased rainfall brought about by storms and hurricanes often overflows riverbanks and as a result puts many buildings at risk of flooding.

Finally, in the event that higher quality demographic and economic data become available, it will be incorporated into the social vulnerability layer. This will increase the accuracy of the social vulnerability layer as the economic capacity of a household will influence the level to which each household is able to recuperate after a disaster event. Also, as of right now the demographic data is broken down into four classes only (0-4, 5-14, 15-64 and 65+). The four classes provide some general information, however the age group of 15-64 is quite broad, and may contain different levels of vulnerability based on age characteristics. If and when the demographic data improves, updates can be made in order to accurately identify new social vulnerability levels for the enumeration districts. All of the future developments discussed for analysis are important because the data the layers were built on are dynamic. The data will change with time, and thus dataset updates and future developments are key to ensuring the web map application stays relevant and useful.

Future Development: Web Map Application and Website

Future development phases have also been outlined for the web map application and website. Currently the web map allows the user to search for a parish and the map will highlight and zoom to that parish, and the user can click on enumeration districts to open popups with risk data. While this is helpful, we would like to remove the use of popups to instead create a dynamic statistics box in the lower right corner that changes if the user hovers over or clicks on an enumeration district.

Another future consideration for the web map application is to allow the basemap labels to appear overtop the hazard analysis layers, as currently all basemap labels lie underneath the analysis layers. Making this change would allow the user to more easily identify the places they are interested in, and even someone unfamiliar with the area could pick out key landmarks and towns to determine where they are, and what their risk level is.

Future development considerations have also been made for the website. The website currently provides resource links such as emergency procedures, hazard preparedness documentation, and more. In the future, more local and national-level resource links would be added in order to assist in the understanding of risk potential and existing aid programs. In order to provide the updated resources, the goal would be to open communication between the AeGIS team and local governments. Doing so would ensure that both the website and web map application stay up to date and and thus be able to better serve the community well into the future.

Conclusion

The country of Grenada is prone to various natural hazards such as flooding, mass movements and hurricanes. There are varying levels of social vulnerability for the areas at risk of those hazards. As mentioned in the discussion, the storm surge layer shows how areas with denser populations are more at risk, and also impacts a critical location, the Maurice Bishop International Airport. If a flood caused by storm surge were to occur in the southwest part of the island, an important source of aid, the international community, would be restricted due to the sudden unavailability of the airport. There are also visible risks to economy seen from the landslide susceptibility analysis in Grenada. The landslide susceptibility layer shows areas with high and low landslide potentials, and majority of the high areas are on the sides of mountains and the dormant volcano. These mountainous areas are normally used for agricultural purposes, and therefore have the potential for higher economic losses. Lastly, social vulnerability layer shows where the people are most vulnerable, due to building materials, demographics, and other factors. The most vulnerable area is also on the southwest region of the island, which also had a high flooding risk for 3 metre storm surges. In addition to this, there are no hurricane shelters in this region of the map. Due to denser population, large flood extent coverage, and no hurricane shelters, the southwest region is the most vulnerable area in Grenada. This can also be seen in the overall hazard risk layer.

The analysis results produced in this report can be used by the government, emergency management organizations, and disaster planning organizations. They can also be used by the people of Grenada to realize at-risk areas. The web map application allows for zooming, searching, and panning capability, so that the user can explore and determine exactly how vulnerable their area of interest may be.

The overall goals set at the beginning of the project were accomplished. A web application was created to display the at-risk areas, and made this information available to everyone with a browser and Internet access. A website was also built to promote publicly available resources to citizens of Grenada. The application part of the project has been completed, therefore, the next process is to contact the government and media of Grenada to make this information localized. It is expected that once the population has more resources and information available, it will increase their awareness of hazard risk, which will provide them more options to better prepare themselves in case of a disaster event.

References

Barrientos, A. (2010). Vulnerability and social protection in small island states: the case of Grenada. *Social and Economic Studies, 59*(1-2)*,* 3-30.

Bull, DK. (2013). Earthquakes and the effects on structures: Some of the lessons learnt. *Australian Journal of Structural Engineering*, *14*(2), 145–166.

Collymore, J. (2011). Disaster management in the Caribbean: Perspectives on institutional capacity reform and development. *Environmental Hazards*, *10*(1), 6–22. https://doi.org/10.3763/ehaz.2011.0002

Crozier, M. J. (2010, April 29). Deciphering the effect of climate change on landslide activity: A review. *Geomorphology*(124), 260-267.

Dandapat, K., & Panda, G. K. (2017). Flood vulnerability analysis and risk assessment using analytical hierarchy process. *Modeling Earth Systems and Environment*, *3*(4), 1627–1646. https://doi.org/10.1007/s40808-017-0388-7

IPCC. (2007). *A Report on the INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE.* Sweden: INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE.

Etehad, M. (2017, September 7). How Hurricane Irma became the second-strongest Atlantic hurricane on record. Retrieved from http://www.latimes.com/nation/la-na-hurricane-irma-explained-20170906-htmlstory.html

Government of Grenada. (2003). *Grenada national hazard mitigation policy.* Retrieved on February 1 2018 from http://www.caribank.org/wp-content/uploads/2012/03/GRN_national-HMitigation_policy.pdf

Masters, J. (n.d.). U.S. storm surge records | Weather Underground. Retrieved from https://www.wunderground.com/hurricane/surge_us_records.asp

Organisation of Eastern Caribbean States. (2004, September 7). *Grenada:Macro-Socio-Economic Assessment of the Damages Caused by Hurricane Ivan*. Retrieved from http://www.gov.gd/egov/docs/reports/Ivan-Report-07-09-04.pdf

Pratomo, R., Jetten, V., & Alkema, D. (2016). Rural flash-flood behaviour in Gouyave watershed, Grenada, Caribbean Island. *Geoplanning: Journal of Geomatics and Planning, 3*(2), 161-170. doi:http://dx.doi.org/10.14710/geoplanning.3.2.161-170

Ramanathan, R. (2001). A note on the use of the analytic hierarchy process for environmental impact assessment. *Journal of Environmental Management*, *63*(1), 27–35. https://doi.org/10.1006/jema.2001.0455

Sawab, J., Luu, C. H., Nie, X., Lim, I., Mo, Y. L., & Li, M. (2016). Structural integrity of steel plate ultra high-performance concrete modules. *Journal of Structural Integrity and Maintenance*, *1*(3), 95–106. https://doi.org/10.1080/24705314.2016.1211236

Tsutsui, K., Rokugawa, S., Nakagawa, H., Miyazaki, S., Cheng, C., Shiraishi, T., & Yang, S. (2007). Detection and Volume Estimation of Large-Scale Landslides Based on Elevation-Change Analysis Using DEMs Extracted From High-Resolution Satellite Stereo Imagery. *IEEE Transactions on Geoscience and Remote Sensing*, *45*(6), 1681-1696. doi:10.1109/tgrs.2007.895209

Appendix 1

Table A: Full demographics AHP matrix

Reciprocal Matrix					
Criteria	Age 0 to 4	Age 5 to 14	Age 15 to 64	Age 65 and over	
Age 0 to 4	1.00	6.00	9.00	2.00	
Age 5 to 14	0.167	1.00	3.00	0.20	
Age 15 to 64	0.111	0.333	1.00	0.13	
Age 65 and over	0.500	5.000	8.000	1.00	
Sum	1.78	12.33	21.00	3.33	
Normalized Matrix					
Criteria	Age 0 to 4	Age 5 to 14	Age 15 to 64	Age 65 and over	Priority Vector
Age 0 to 4	0.563	0.486	0.429	0.602	0.520
Age 5 to 14	0.094	0.081	0.143	0.060	0.094
Age 15 to 64	0.0625	0.027	0.0476	0.038	0.044
Age 65 and over	0.281	0.405	0.381	0.301	0.342
Sum	1.00	1.00	1.00	1.00	1.00

Lambda Max	4.1438640		N = 4	
Consistency Index (CI)	0.0359660			
Consistency Ratio (CR)	0.0399622			

Table B: Full material construction AHP matrix

Reciprocal Matrix					
Criteria	Timber	Aggregate	Steel	Concrete	
Timber	1.00	5.00	6.00	8.00	
Aggregate	0.200	1.00	3.00	4.00	
Steel	0.167	0.333	1.00	2.00	
Concrete	0.125	0.250	0.500	1.00	
Sum	1.49	6.58	10.50	15.00	
Normalized Matrix					
Criteria	Timber	Aggregate	Steel	Concrete	Priority Vector
Timber	0.670	0.759	0.571	0.533	0.634
Aggregate	0.134	0.152	0.286	0.267	0.210
Steel	0.112	0.051	0.095	0.133	0.098

Concrete	0.084	0.038	0.048	0.067	0.059
Sum	1.00	1.00	1.00	1.00	1.00
Lambda Max		4.236439134		N = 4	
Consistency Index (CI)		0.059109783			
Consistency Ratio (CR)		0.065677537			