A Study of Landslide Susceptibility on Tobago using GIS Techniques

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A landslide is a type of mass-movement process and it involves the movement of a mass of rock, sediments or debris down a slope and it can be triggered by a number of factors including rainfall, earthquakes, volcanic activity, slope disturbance or change of slope (Cruden, 1991; Varnes, 1996). Landslides represent a natural hazard on the island of Tobago and past events have resulted in loss of live and significant property damage. The landslide events which affect Tobago are typically associated with severe weather conditions; including frequent intense rain showers, which are most likely to occur during the rainy season which lasts from June to December. This study aims to conduct an assessment of the landslide potential on Tobago using the Arc-GIS software in order to identify locations that are at high risk for a landslide event. The results are then compared with locations which have experienced landslide events in the past.

Study area location and description:

Tobago is located in the southern Caribbean at latitude11° 9´N, longitude 60° 40´ with a land area of 300 km^2. The island which has a northeast to southwest elongate shape, is approximately 42 km long and 1 0km wide, Figure 1. Tobago has a hilly topography and the most prominent geomorphic feature is the Main Ridge; a twenty-nine kilometer long elongate northeast – southwest trending high (640 m) which represents the highest part of the island, Figure 2.

Geologically, Tobago is interpreted as a basement high that is the northeastern-most extension of the South American continental shelf (Snoke et al., 2001). The island is considered an allochthonous terrain which represents the easternmost fragment of the Caribbean Mountain system, and this is manifested in the rock exposures of oceanic island arc type crust on the island (Snoke et al., 2001). The southwestern part of the island is relatively flat with a coralline limestone and clastic sedimentary rock exposures. The rest of the island which has a more rugged topography, can be divided into three east-west trending lithologic zones, which are from south to north, the Tobago Volcanic

Group to the south, the ultramafic to mafic plutonic suite, and the North Coast Schist to the north (Snoke et al., 2001), as shown in the geologic map of Figure 3.

The island's location at ~12°N latitude is within the tropical climatic zone, though the tropical climate is moderated by the northeast trade winds. The island experiences two seasons, a dry season which extends from January to May and a wet season from June to December, which also coincides with the Atlantic hurricane season. The island is located just south of the Atlantic hurricane zone however the island's rainy season weather is sometimes affected by tropical storms and hurricanes to the north and there have been a couple instances of storm landfall (CIA, 2009; Encyclopaedia Britannica, 2009). The average temperature on the island is 25°C (77°F) with a minimum of 20°C (68°F) and a maximum of 34°C (93°F). Humidity is generally high with an average of 85-87% during the rainy season (CIA, 2009; Encyclopaedia Britannica, 2009). The mean annual rainfall in Tobago ranges from 1250 mm per year in the southwestern part of the island to over 2500mm per year over the Main Ridge (Central Statistical Office) as illustrated in Figure 4. The bulk of this precipitation occurs during the rainy season months; June to December as illustrated in the graph shown in Figure 5 with smaller amounts during the dry season. It would appear that precipitation plays a significant role in land-sliding events as recorded events have occurred during the rainy season and usually during or following high intensity rainfall occurrences.

Tobago is described as a lush, tranquil and unspoilt Caribbean island, and this is reflected in the Land use map shown in Figure 6. The island is dominated by forests which accounts for ~50 % of the land area and includes the Main Ridge Reserve; designated a protected reserve since 17 April 1776. Much of the remaining land is covered by vegetation including wooded fruit trees and farmed crops in lands designated for agricultural use.

There are five main; though relatively small, built-up centers including Scarborough which is the capital and business center on the island with a population of 17,000 persons, and the residential/tourist towns of Roxborough, Plymouth, Crown Point and Charlotteville. The population density map of Figure 7 illustrates the population distribution with the highest density of people in the southwestern part of the island in the vicinity of Scarborough and lower population density to the northeast in the area of the remote vegetated and forested areas of the Main Ridge.

Surface drainage on the island can be described as radial as rivers drain the Main Ridge area and flow either north or south towards embayments at the coast, Figure 2. These rivers are capable of high discharge and torrential flow during the high precipitation events in the rainy season.

Methods:

In this study six factors were applied in order to assign the risk of landslide events in various parts of the island; slope, geology, rainfall, land-use, proximity to rivers and proximity to faults. The calculation of the landslide risk was done using the following equation.

$$
\begin{aligned}
LandslideRisk = &\left(Slope * Slope\_weight\right) + \left(Geology * geology\_weight\right) + \\
&\left(Landuse * Landuse\_weight\right) + \left(Rainfall * Rainfall\_weight\right) + \left(Rivers * rivers\_weight\right) \\
&+ \left(Fault * Fault\_weight\right)
\end{aligned}
$$

For each of the six factors a raster file was generated for input into the Raster Calculator tool in ArcMap. For each of the six factors that influence landslide susceptibility, five classes were defined to describe the variance of that factor across the island. Each class was given a rank between the values of 0 to 5 with a value of 5 given to the class with the highest susceptibility to landslides; this is described for each class below in Table 1. The six factors were then each assigned a weight in order to account for the varying influence of the respective factors in the susceptibility for landslide events (Table 2). In this study, the slope was considered to be more significant than all other factors and so it was given a higher weighting of 35%. The weights for the respective factors all add up to 1 which will result in a final landslide susceptibility scale that ranges from 0 - 5.

Inputs to the Calculation:

The final risk calculation was done by executing the aforementioned equation in the raster calculator tool of the Spatial Analysis too-set in ArcMap. The data for the six considered factors therefore needed to be entered in the form of raster files. This therefore required some amount of data manipulation and file conversion in order to achieve the required raster format. All imported files as well as files created in ArcMap by digitizing map images were defined or projected as required to the "WGS 1984 UTM Zone 20N" projected coordinate system.

Slope:

The slope data for Tobago was generated from a DEM which in this instance was in the form of SRTM (Satellite Radar Topography Mission) digital topographic data acquired from the CGIAR-CSI website (http://srtm.csi.cgiar.org/). The downloaded SRTM data was uploaded into ArcMap and the "Project Raster" tool in ArcToolbox was used to project the data into the aforementioned coordinate system. The data was then clipped to the outline of Tobago using the "Extract by Mask" tool contained in the Spatial Analyst toolbox; the Tobago outline polygon was the defined mask to clip the raster. The slope file was then generated using the Slope generation tool from the Spatial Analysis tool-set. This produced the slope raster file shown in Figure 8. The data was reclassified on a risk scale or index from 0 - 5, this was done in using the reclassify tool in Spatial Analyst toolset. Mass-movement processes such as landslides are more likely to occur on steeper slopes than on shallower gradients therefore highest slope values were assigned a risk of 5 and the lowest 0 as shown in Table 1. The resulting reclassified map is shown in

Figure 9. It should be noted that there appears to be a relationship in places between the location of steep slopes and the paths of rivers.

Rainfall:

The best rainfall data for Tobago that was accessible for this project was in the form of a contour map of mean annual rainfall shown in Figure 10. The map was imported into ArcMap where the contours were digitized in a feature class file and assigned an isohyet value in defined field of the attribute table. The contour features in the feature class file were then converted to a TIN (triangulated irregular network) using the convert feature to TIN tool in the 3D analyst toolbox, Figure 11. This TIN was then converted to a raster file; while using the Tobago outline shape file as a mask using the Tin to Raster conversion tool in the 3D Analyst toolbox, Figure 4. The rainfall raster file was then reclassified so that the rainfall attribute was classified on a risk scale from 0 to 5 as detailed in Table 1 and the risked slope map is shown in Figure 12.

Land-use:

A land-use map for Tobago obtained from a report of the Central Statistical Office of Trinidad and Tobago was imported into ArcMap. The various land-use features were digitized and assigned the appropriate land-use category in the defined field of the attribute table for the created feature class (Figure 6). The respective entries for land-use in the feature class were then aggregated to the eight variable land-uses using the Dissolve Tool in the Data Management Toolbox, and then the feature class was converted to a raster file using the appropriate Spatial Analyst tool. The raster file was then reclassified in order to assign a land-use risk from 0 to 5 for the respective landslide categories as shown in Table 1 and the risked land-use map is shown in Figure 13.

Geology:

The geology map from Snoke et al. (2001) was imported as an image file into ArcMap. The features of the map including the lithologic units and mapped faults were digitized and classified using the appropriate field of the attribute table to create fault and geology feature class files. The geology feature class file was then dissolved in order to aggregate the polygons associated with the 17 geologic units using the Dissolve tool of the Data Management Toolbox. This feature class was then converted to a raster file using the appropriate tool in the Spatial Analyst toolbox, following which the raster file was reclassified to give each geologic unit a rank from 0 to 5, using the tool for this purpose in the Spatial Analyst toolbox. Based on the basic geologic principle that young sedimentary rocks are much more easily eroded and subsequently mobilized during a mass movement event when compared with igneous or metamorphic rocks (Press & Siever, 1986), the Quaternary and Pliocene sedimentary units were assigned the highest risk. The gabbro-diorite units have been observed in the field to weather to weak crumbly grains while still remaining in-situ and in close proximity to more coherent volcanic Bacolet Formation (Alvarez, 2001). Sites of active creep-type mass-movement processes were observed to occur in areas underlain by the weathered gabbro-diorite lithology. This igneous unit was therefore assigned a risk of 4. The volcanic rocks which appear more resistant to erosion were assigned a risk of 2 and the more resistant metamorphic rocks of the Main Ridge were given the lowest risk, as described in Table 1. The risked geology map is shown in Figure 14.

Proximity to rivers:

The effect of confined surface drainage in the form of rivers which are responsible for incision which sets up steep gradient in close vicinity to the channel as well as the role of water in lubricating the near surface soil/sediment layers are considered by applying a risk to areas in close proximity to rivers. A map of the rivers in Tobago was imported into GIS and a feature class was created to contain the digitized rivers. The multiple ring buffer tool from the Analysis Toolbox was then used to set up 25, 50, 75 and 100 meter buffer zones from the axis of the respective channels. The feature class file was then converted to a raster which was reclassified to assign a risk from 0 – 5 to the respective buffer zones shown in Table 1. The risk of land-sliding associated with the proximity to rivers is shown in Figure 15.

Proximity to faults

The effect of a fault on the surrounding rock is two-fold; there is the fault gouge or brecciated zone which is a weaker, fragmented, more easily eroded and displaced zone relative to undeformed rock, as well as the enhanced permeability of this zone to flowing water which increases the risk of erosion and mobilization of sediments (Twiss & Moore, 1992). The faults were digitized from the source geologic map and a feature class generated. This feature class was then used to generate buffer zones of 50, 100 and 300 meters from the respective faults using the multiple ring buffer tool from the Analysis Toolbox. The resulting feature class was then converted to a raster using the feature to raster tool and then a new reclassified raster file was generated in order to assign a risk from 0 - 5 for the respective buffer zones, Table 1. The map of the risk of landsliding due to proximity to faults is shown in Figure 16.

Results & Discussions

The calculated Landslide Risk map (Figure 17) shows a distribution of landslide risk across the island but there appears to be a relative concentration of highest risked areas between the villages of Goodwood and Speyside. The highest risked areas appear to be just south of the Main Ridge High and in close vicinity to faults and rivers located in areas of high rainfall and relatively steeper slopes. Based on the visual comparison of the maps, land-use appears to have less of an influence than the other aforementioned factors.

Geology also appears to have a dampened effect though the high risk zone appears to correlate with the class 4 geology risk. Locations of recent landslide events have been gathered from press reports and these are shown in Figure 18. There have been events in the calculated high-risk zone between Goodwood and Speyside including a catastrophic event which is reported to have buried houses and vehicles and resulted in 2 deaths (Trinidad Express, 2004). There are also some events in the south-central part of the island which are in medium-risk zones. This study would suggest that the employed method and calculation did capture the areas that have a high potential for land-sliding. There are also a couple events which are in low-risk areas, for example the event near the village of Castara. This may suggest that the natural environment is a bit more dynamic than this static model or that there may be risks below the resolution (spatially) of this calculation which have not been captured and may have been averaged in this calculation.

Conclusions

The results of this study would suggest that the application of ArcGIS methods of map overlay and summation is an effective tool in examining earth-science problems. The results of any such study will however be improved by consideration of actual empirical data which may guide the definitions of classes more robustly as well as the consideration of the weighting of the respective factors.

Table 1 Index for the defined classes for the respective variables which are used in the landslide risk calculation

Class	Slope	Rainfall (mm)	Landuse	Geology	River Proximity (m)	Fault Proximity (m)
0	0° - 2°	-	-	-	> 100	> 300
1	2° - 8°	1250 - 1750	Swamp, Coconut	Amphibolite, Mt. Dillon Fm, Parlatuvier Fm, Argillite	-	-
2	8° - 16°	1750 - 1950	Forest	Bacolet Fm, Goldsborough Fm, Argyle Fm	25	50
3	16° - 24°	1950 - 2150	Tree-crops	Biotite-tonalite, Ultramafic rocks	50	100
4	24° - 32°	2150 - 2350	Crop, pasture, sugar-cane	Gabbro-diorite	75	200
5	32° - 40°	2350 - 2500	Built-up areas	Rockly Bay Fm, Mongomery Fm, Quaternary alluvial, Volcanogenic sedimentary rocks, Undifferentiated volcanic and sedimentary rocks	100	300

Table 2 Table of the weights assigned to the respective variables used in the landslide risk calculation

Factor	Weight
Slope	35%
Rainfall	10%
Landuse	15%
Geology	15%
River Proximity	15%
Fault Proximity	10%

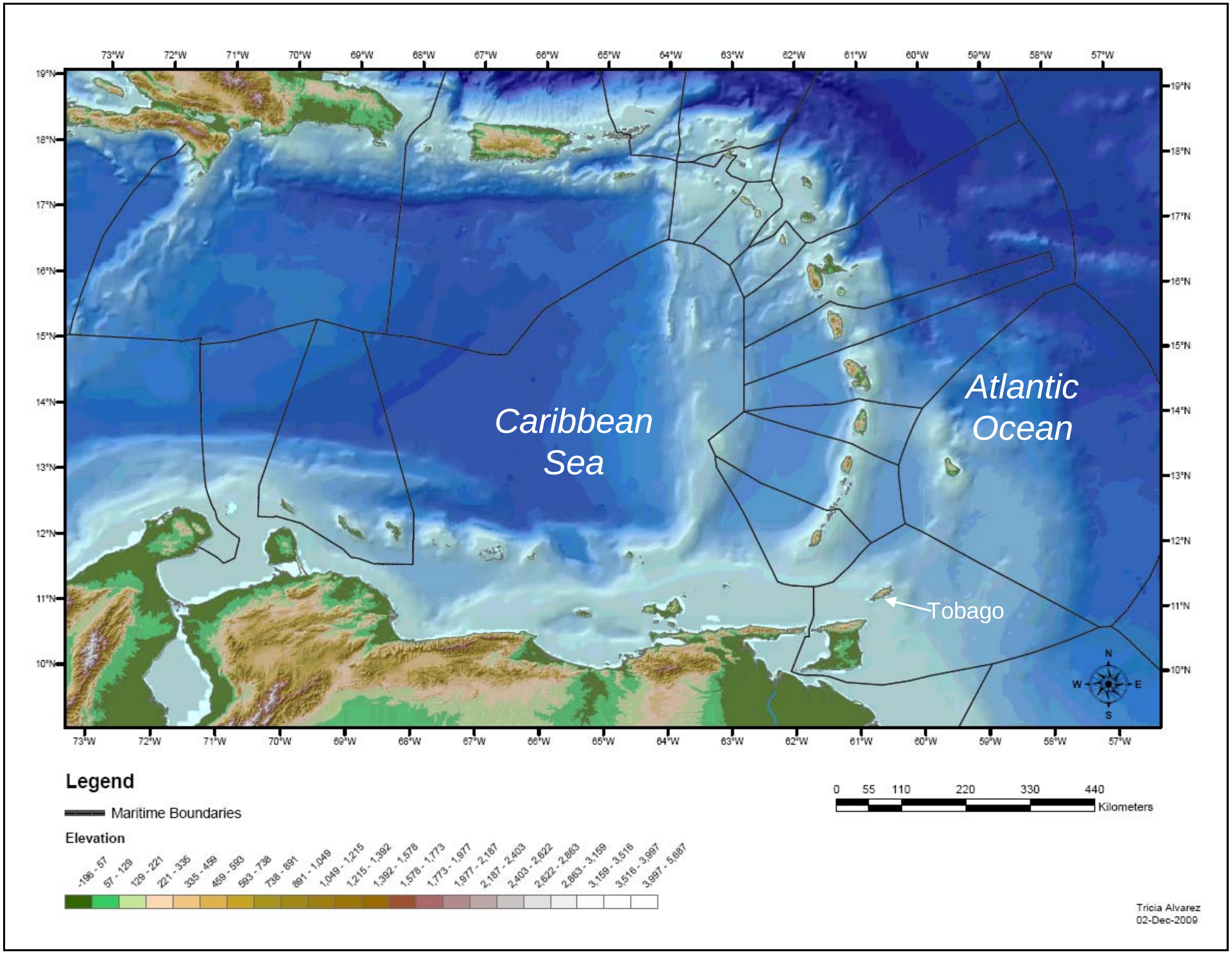

Figure 1 Regional map of the Caribbean showing the location of Tobago, W.I.

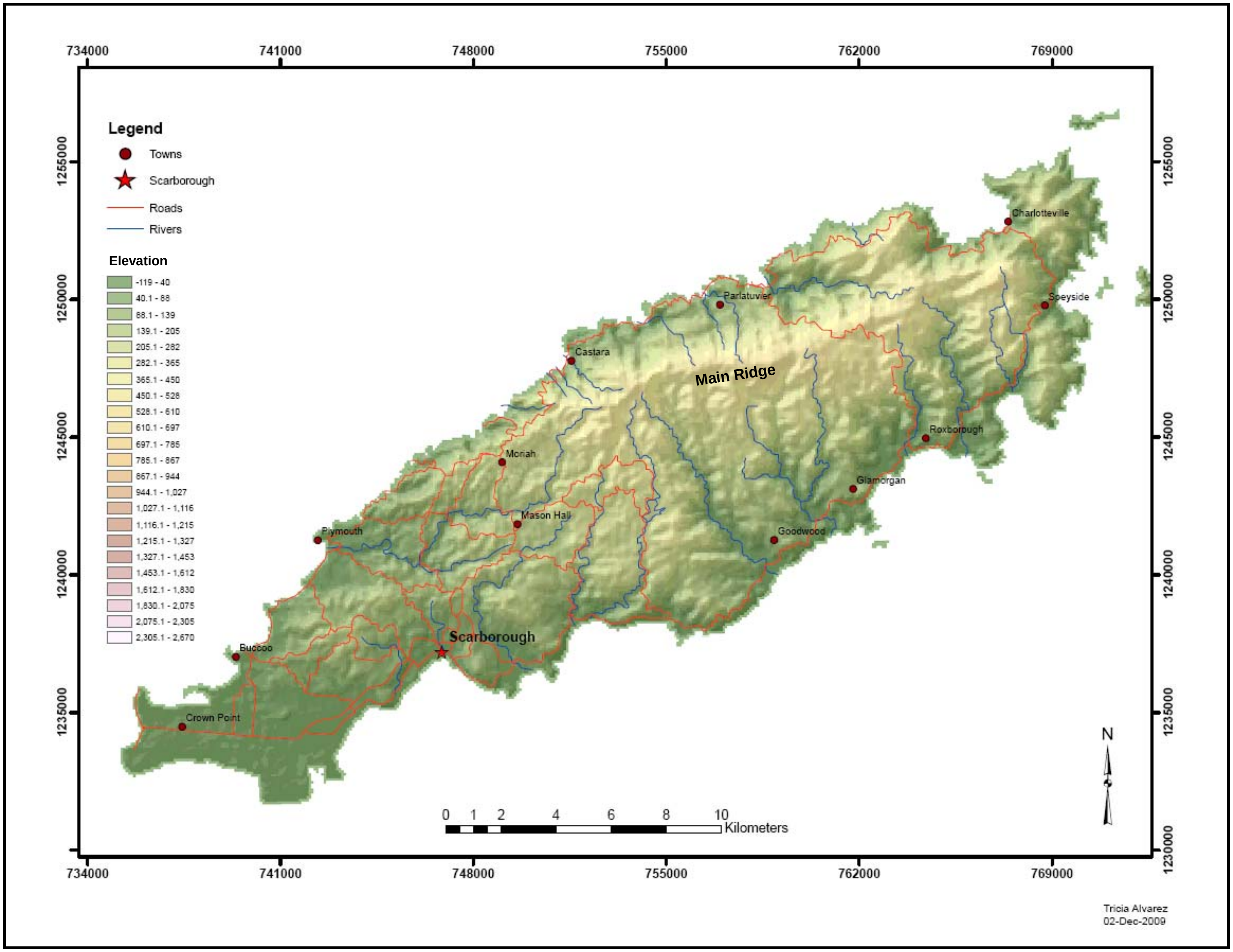

Figure 2 Topographic Map of Tobago, W.I.

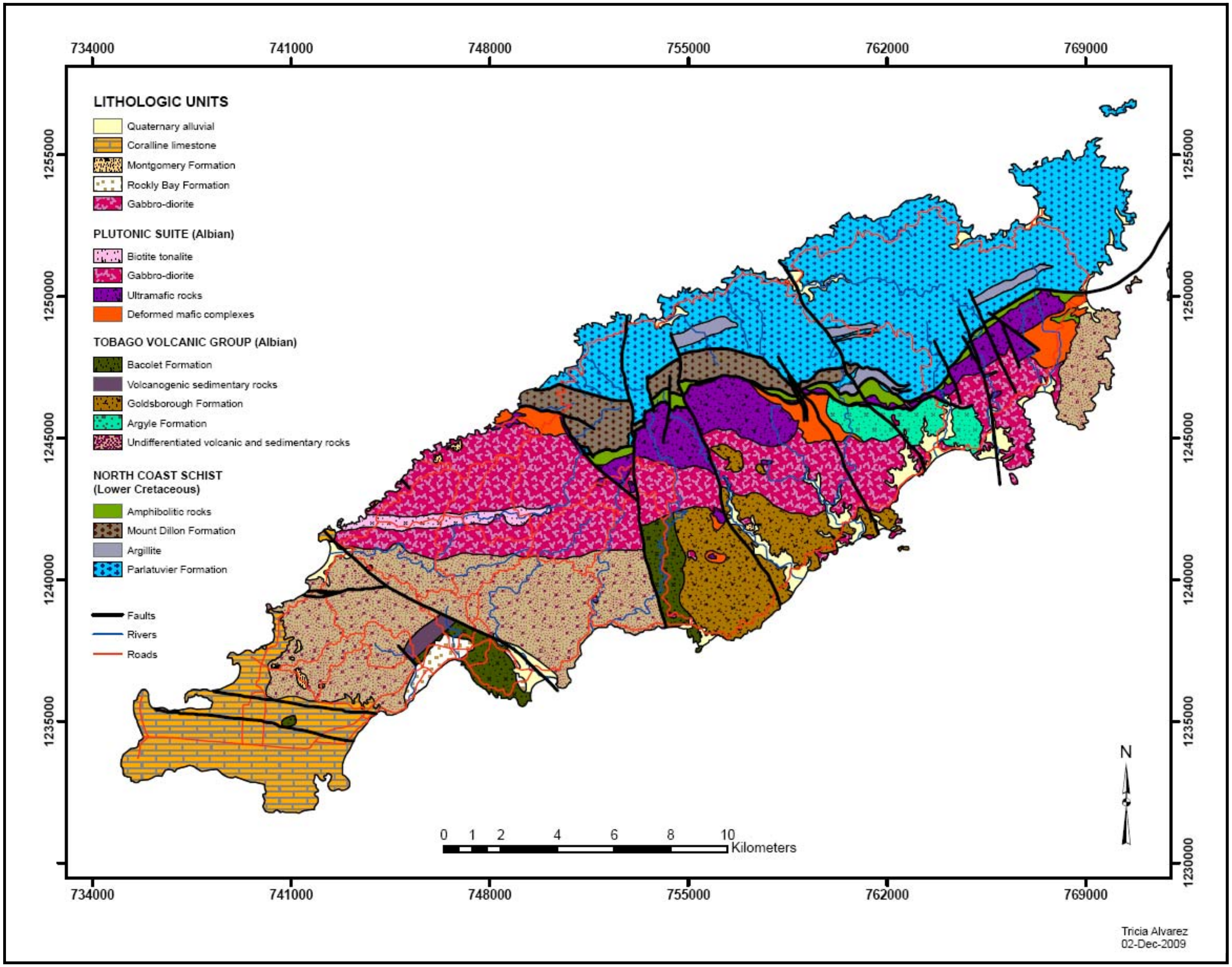

Figure 3 Geologic Map of Tobago, W.I.

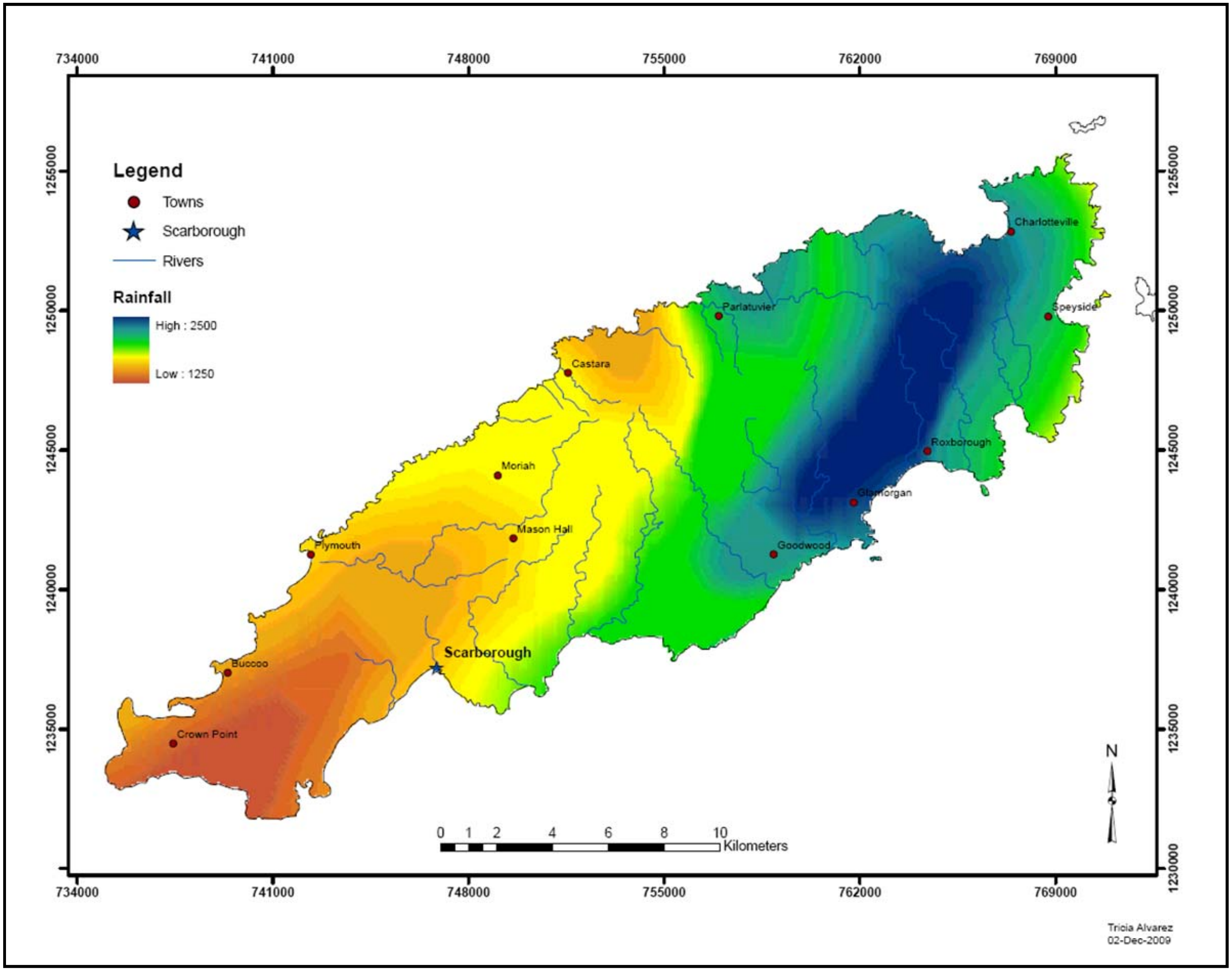

Figure 4 Map of Tobago, W.I. showing rainfall distribution (rainfall values are given in mm)

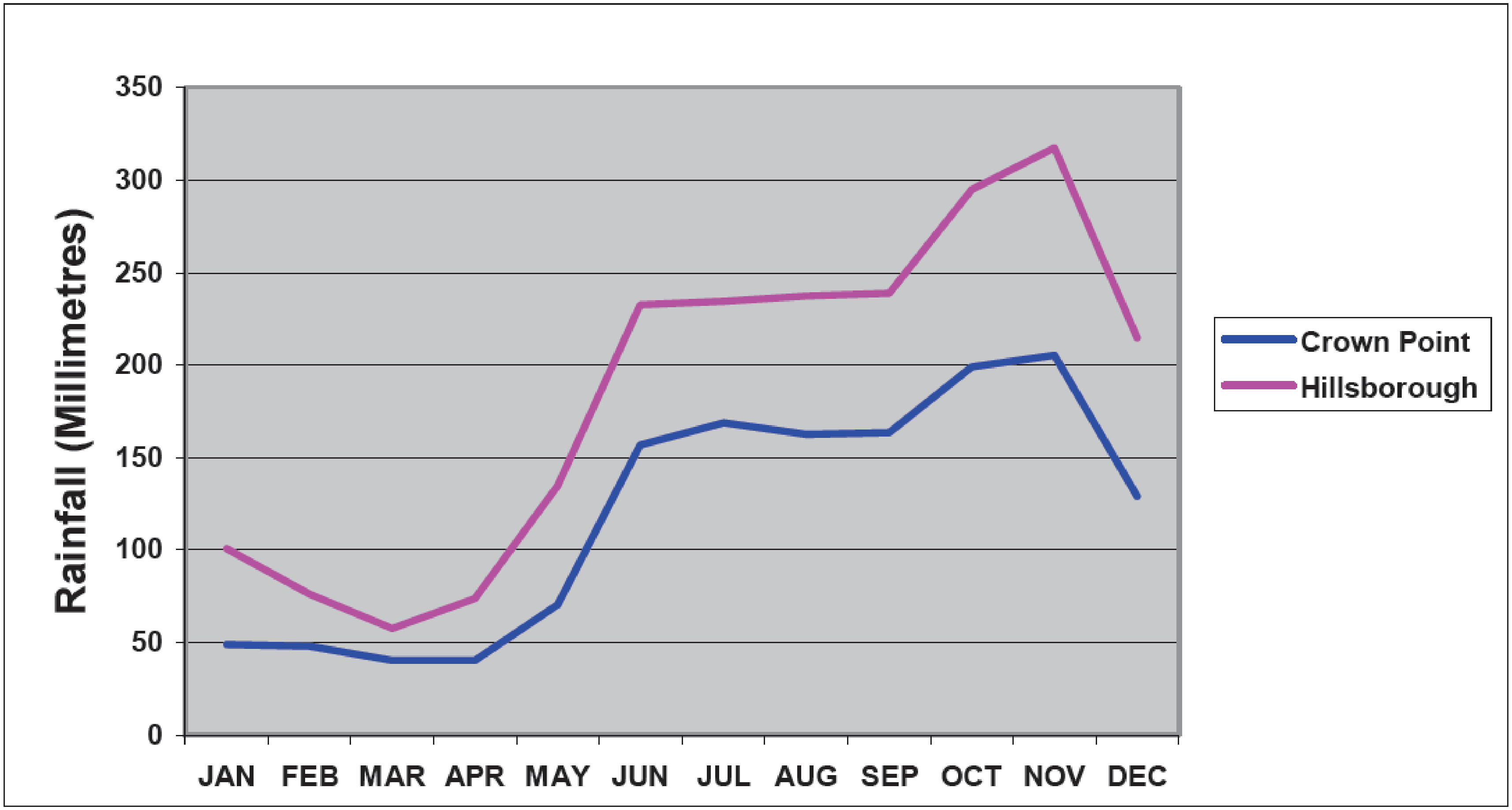

Figure 5 Graph illustrating the long-term monthly averages of rainfall in Tobago based on measurements at two stations for the period 1971 - 2000 (Taken from Central Statistical Office document)

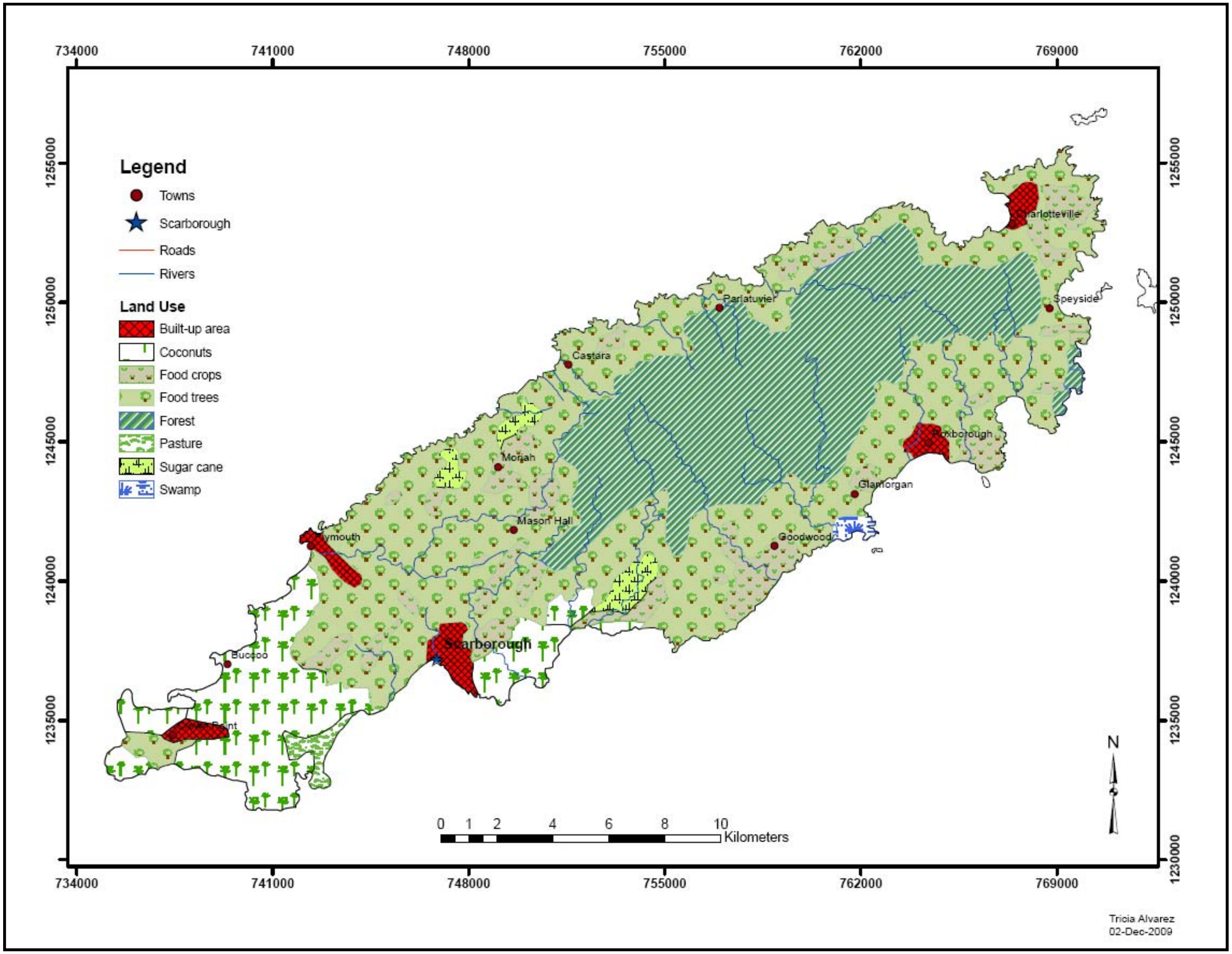

Figure 6 Map of Tobago, W.I. showing land-use map patterns

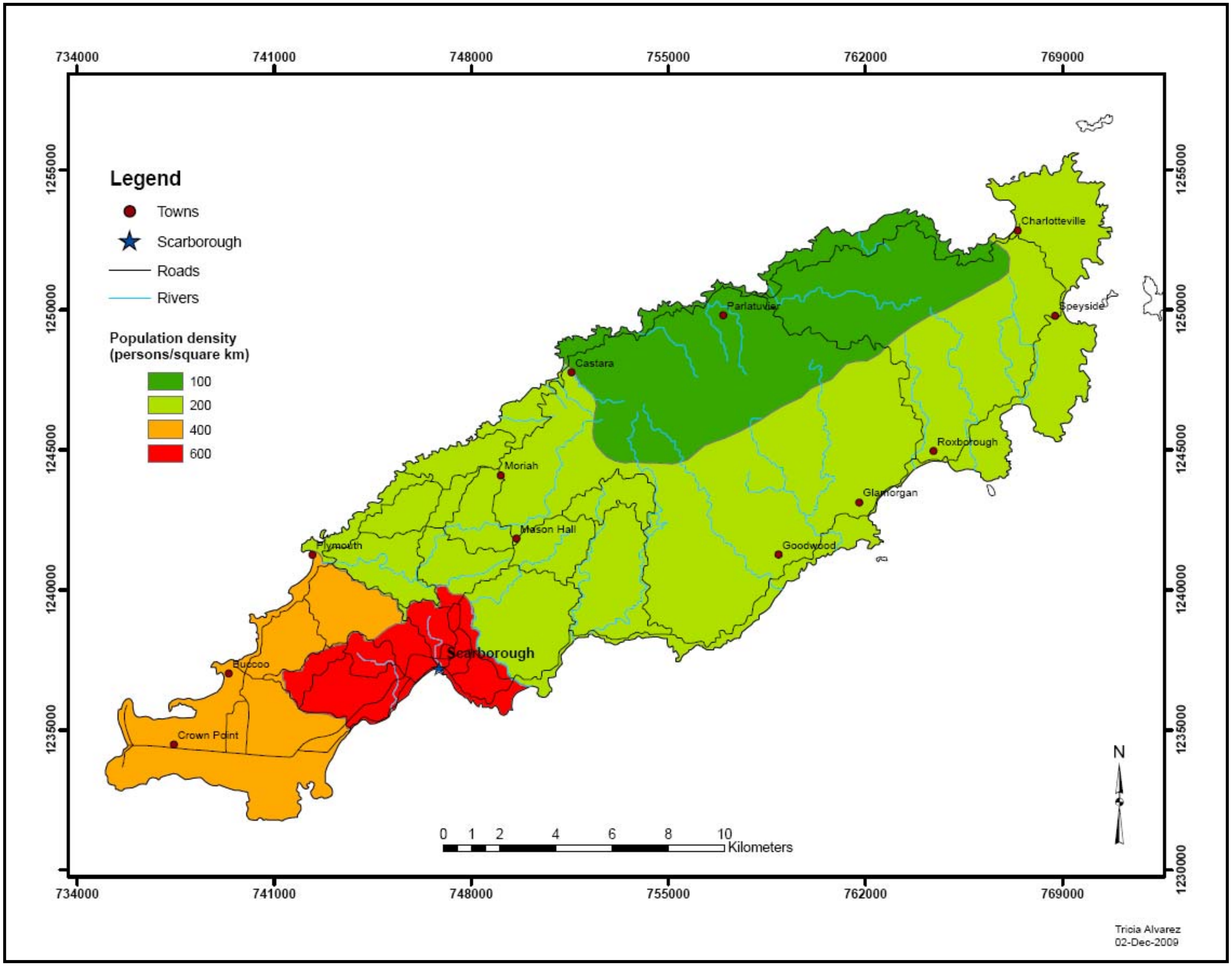

Figure 7 Map of population density of Tobago, W.I.

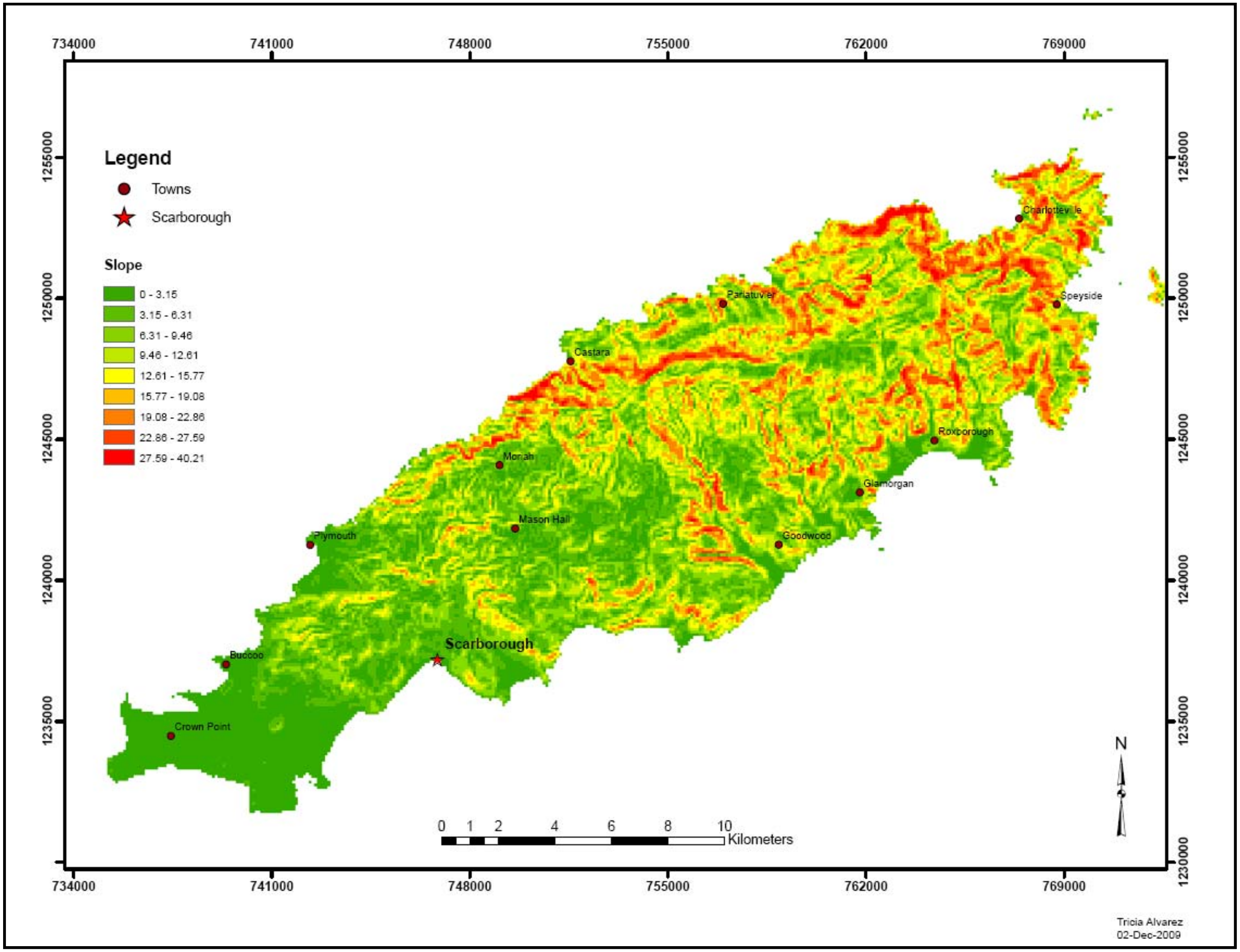

Figure 8 Map showing the distribution of slope angle on Tobago, W.I.

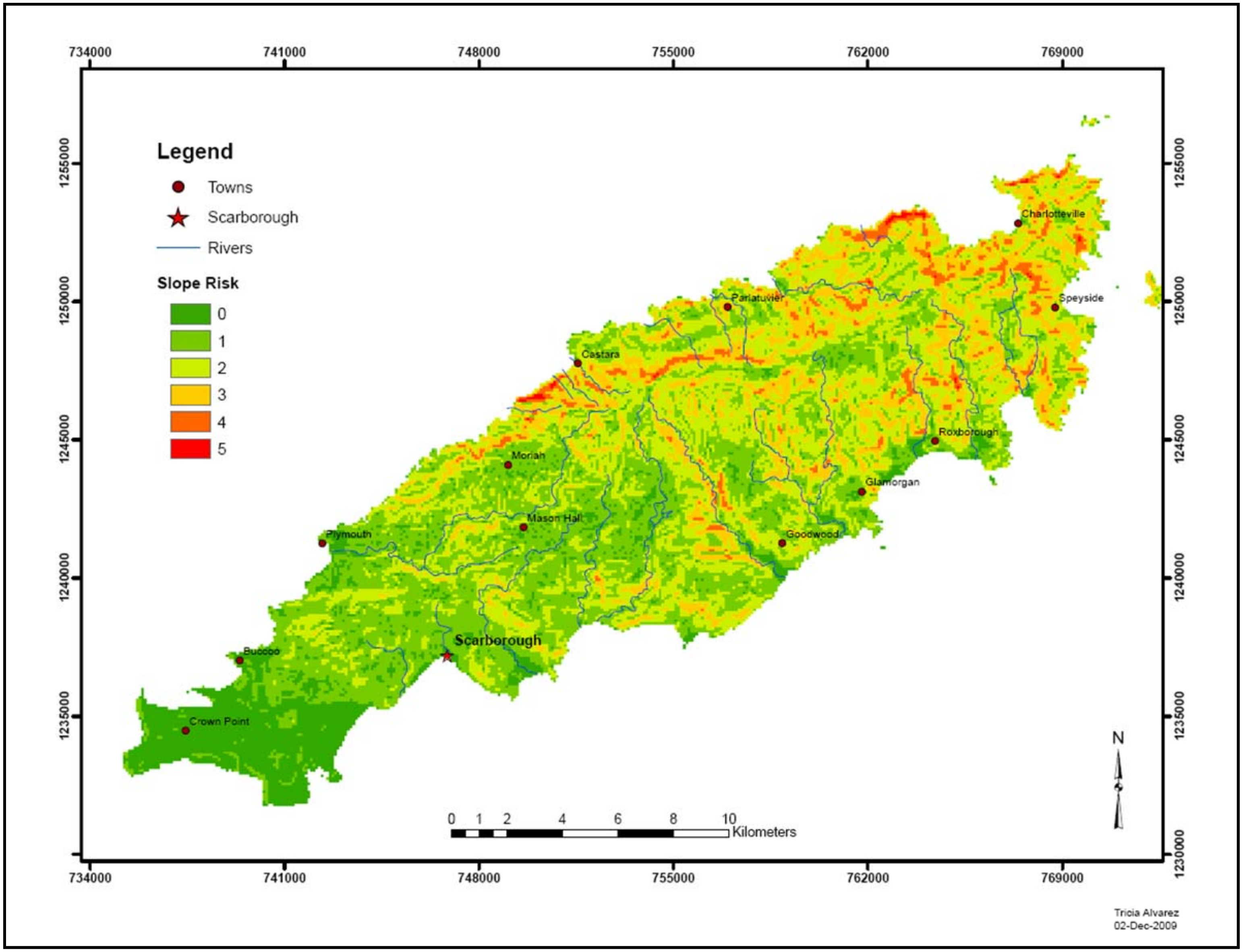

Figure 9 Map showing the reclassified slope pattern on Tobago, W.I.

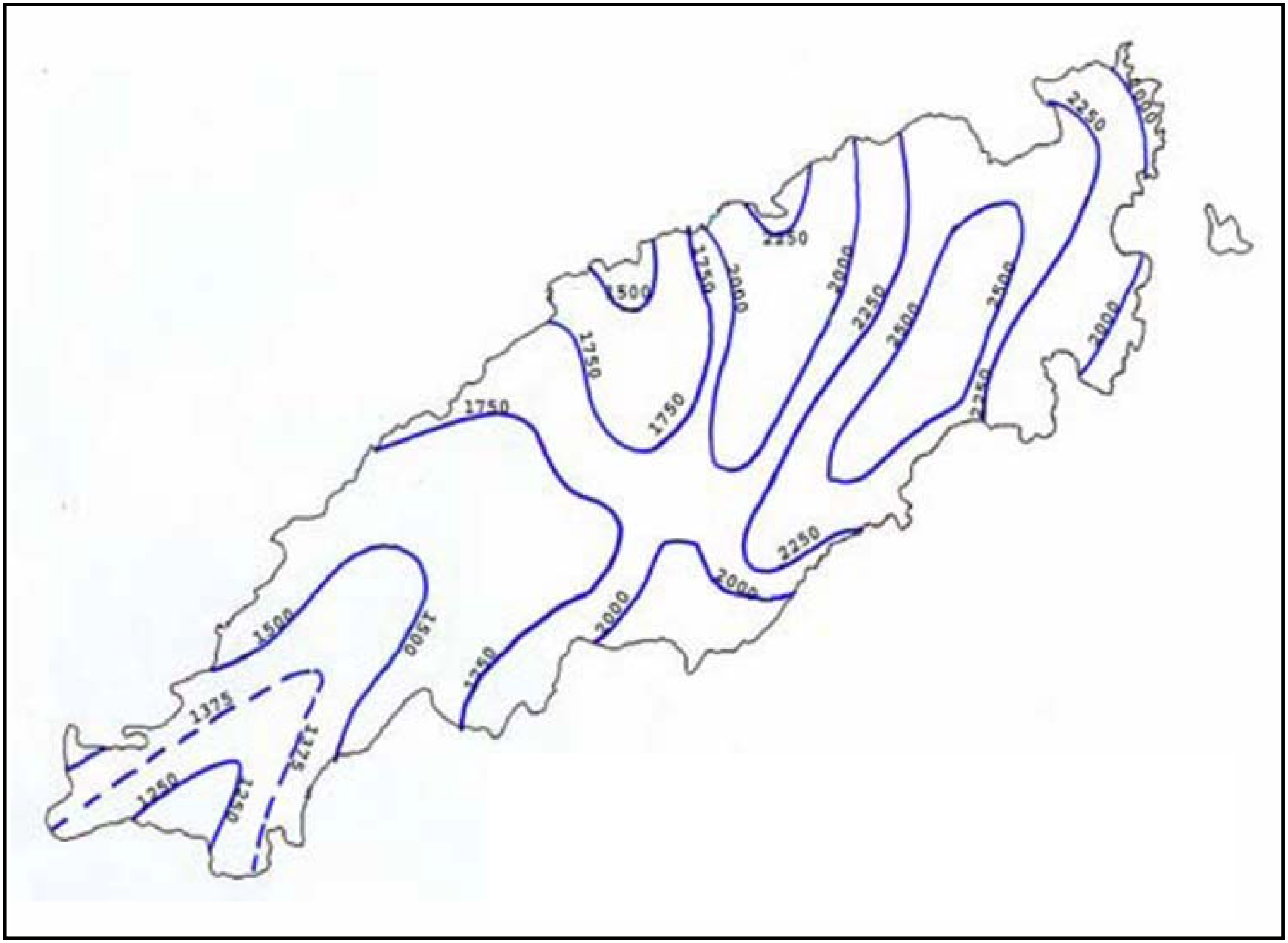

Figure 10 Map of Tobago, W.I. showing isohyet based on annual rainfall over the period 1971 - 2000. (Taken from Central Statistical Office document)

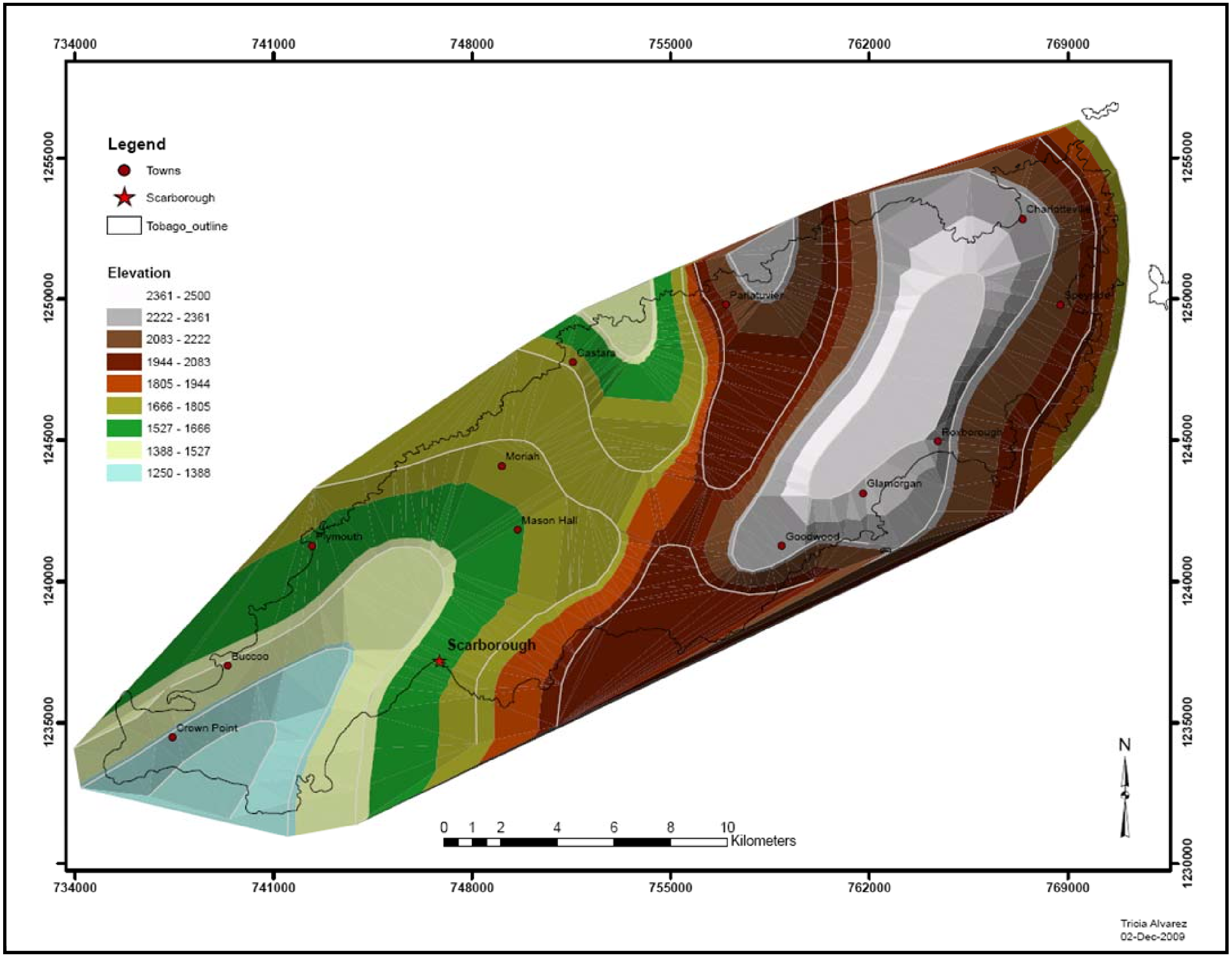

Figure 11 Map of Tobago showing the Triangulated Irregular Network (TIN) generated from the rainfall contours feature class

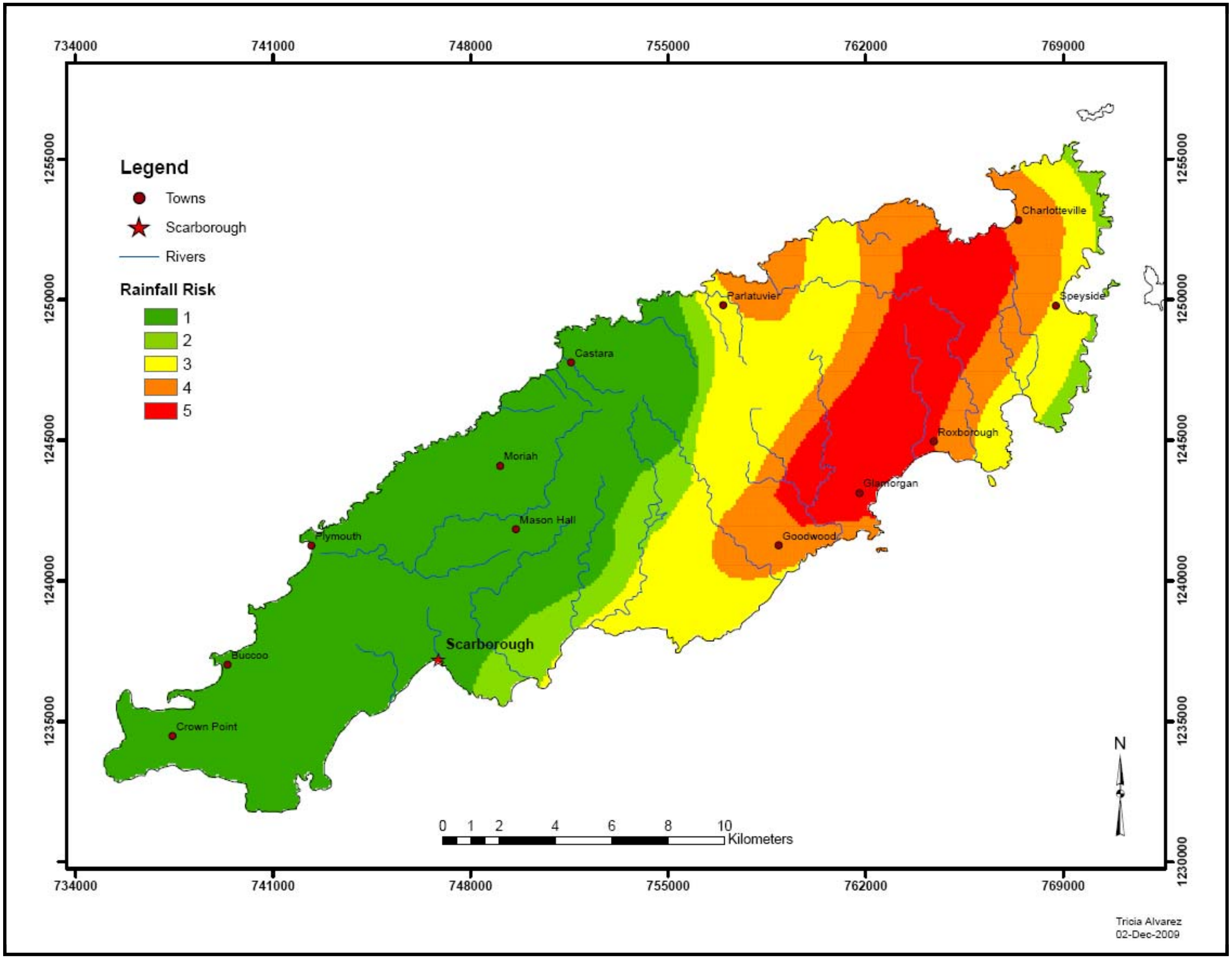

Figure 12 Map of Tobago showing the reclassified risked rainfall distribution

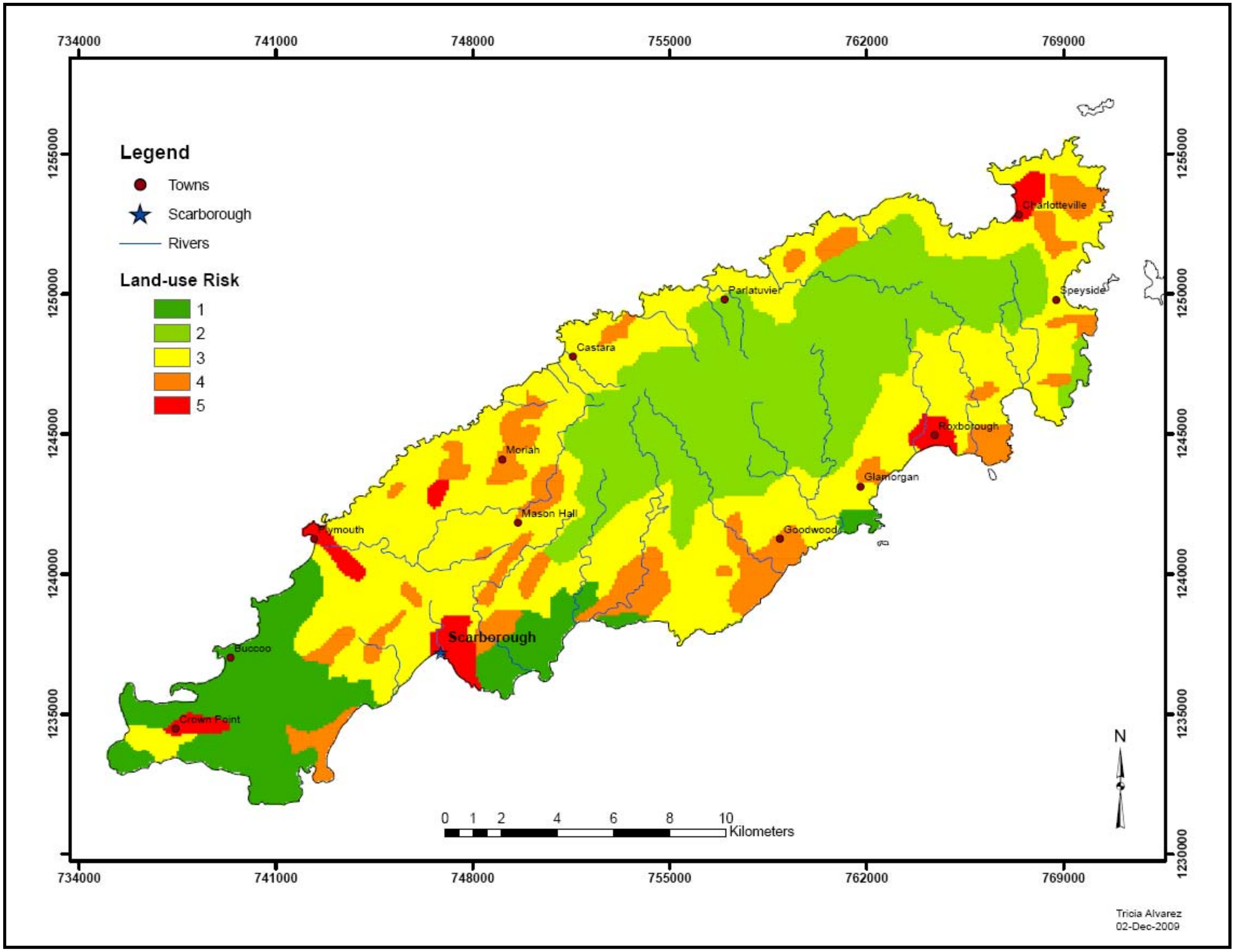

Figure 13 Map of Tobago showing the reclassified land-use patterns

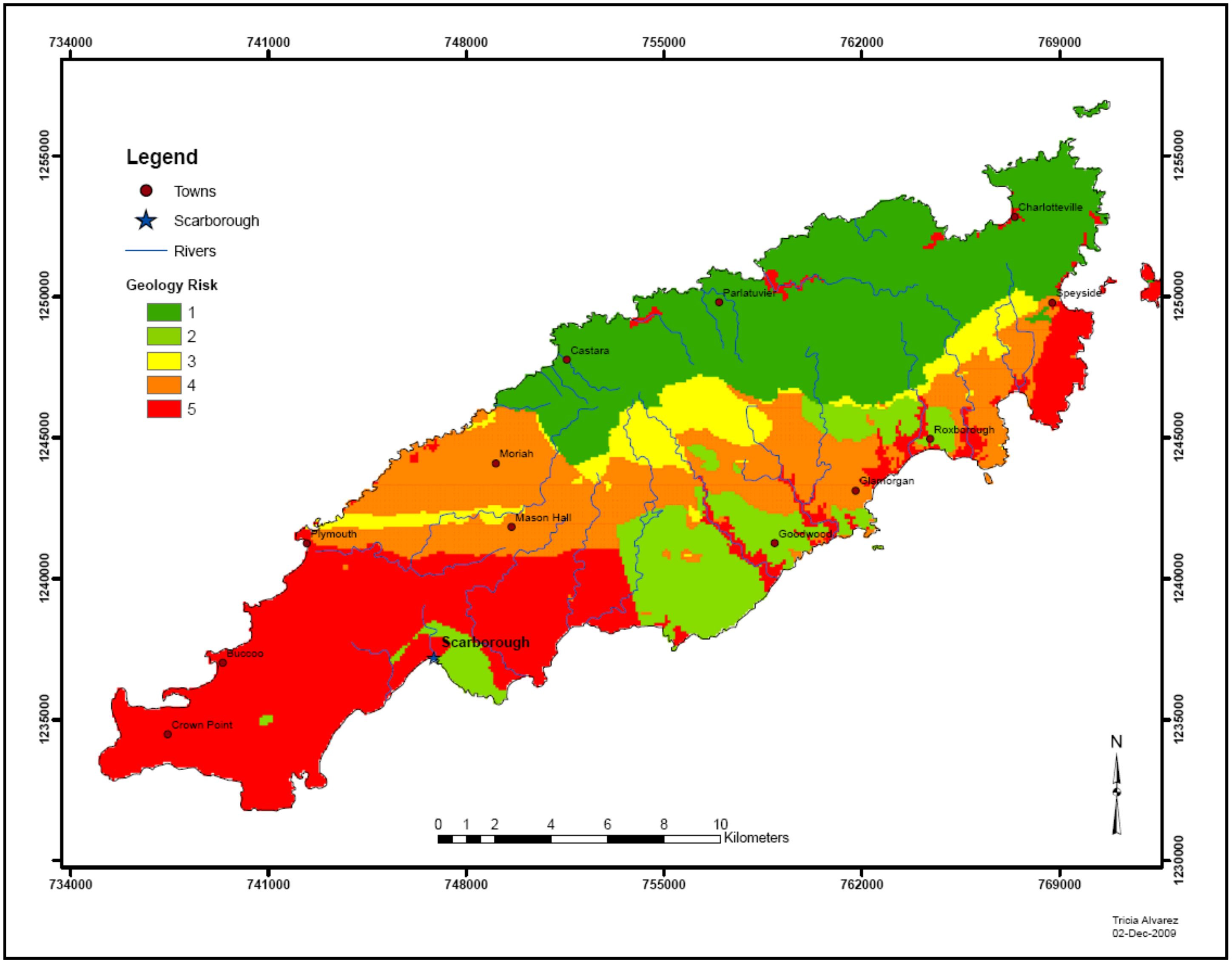

Figure 14 Map of Tobago showing the reclassified geologic susceptibility to land-sliding

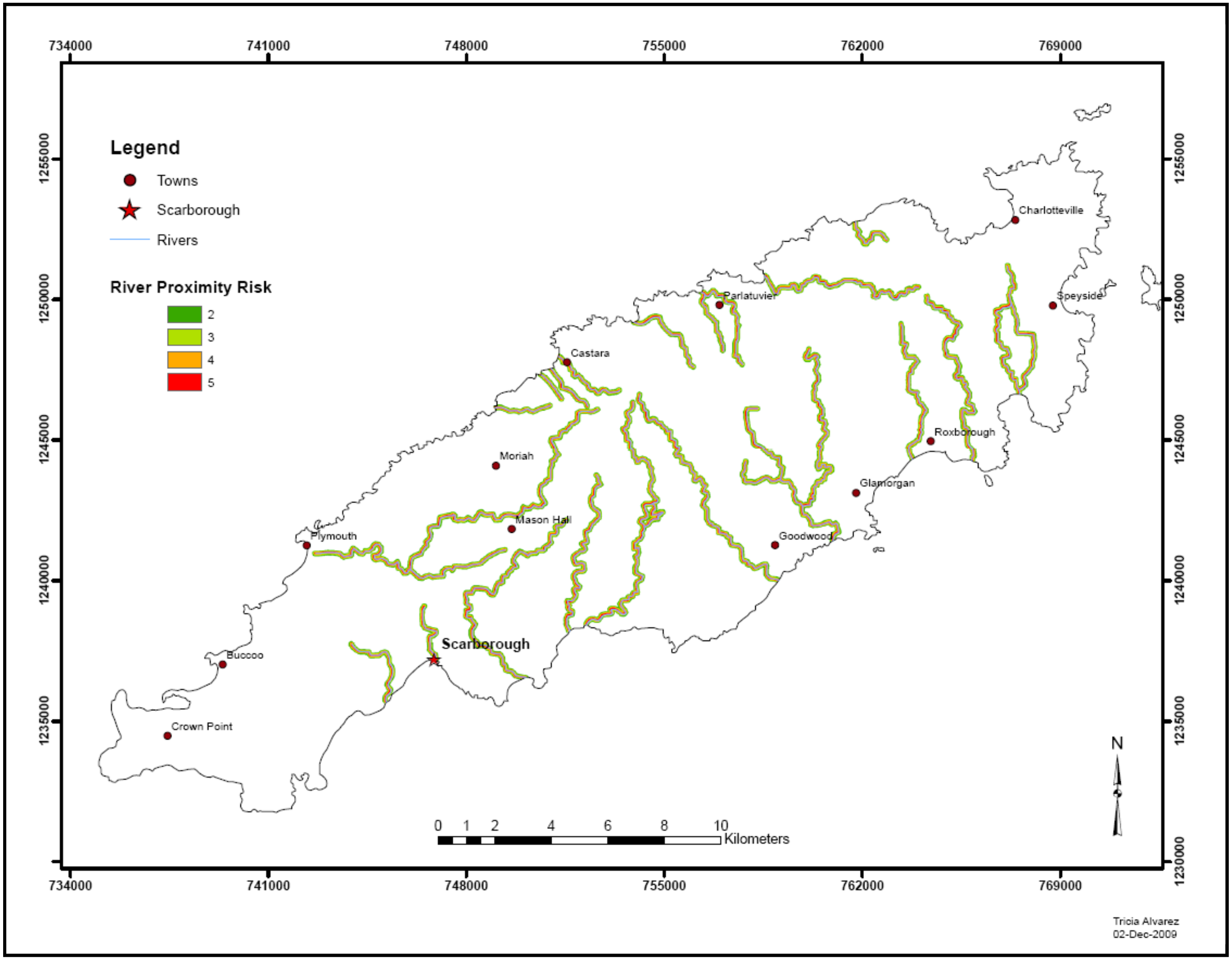

Figure 15 Map of Tobago showing the risk associated with proximity to rivers

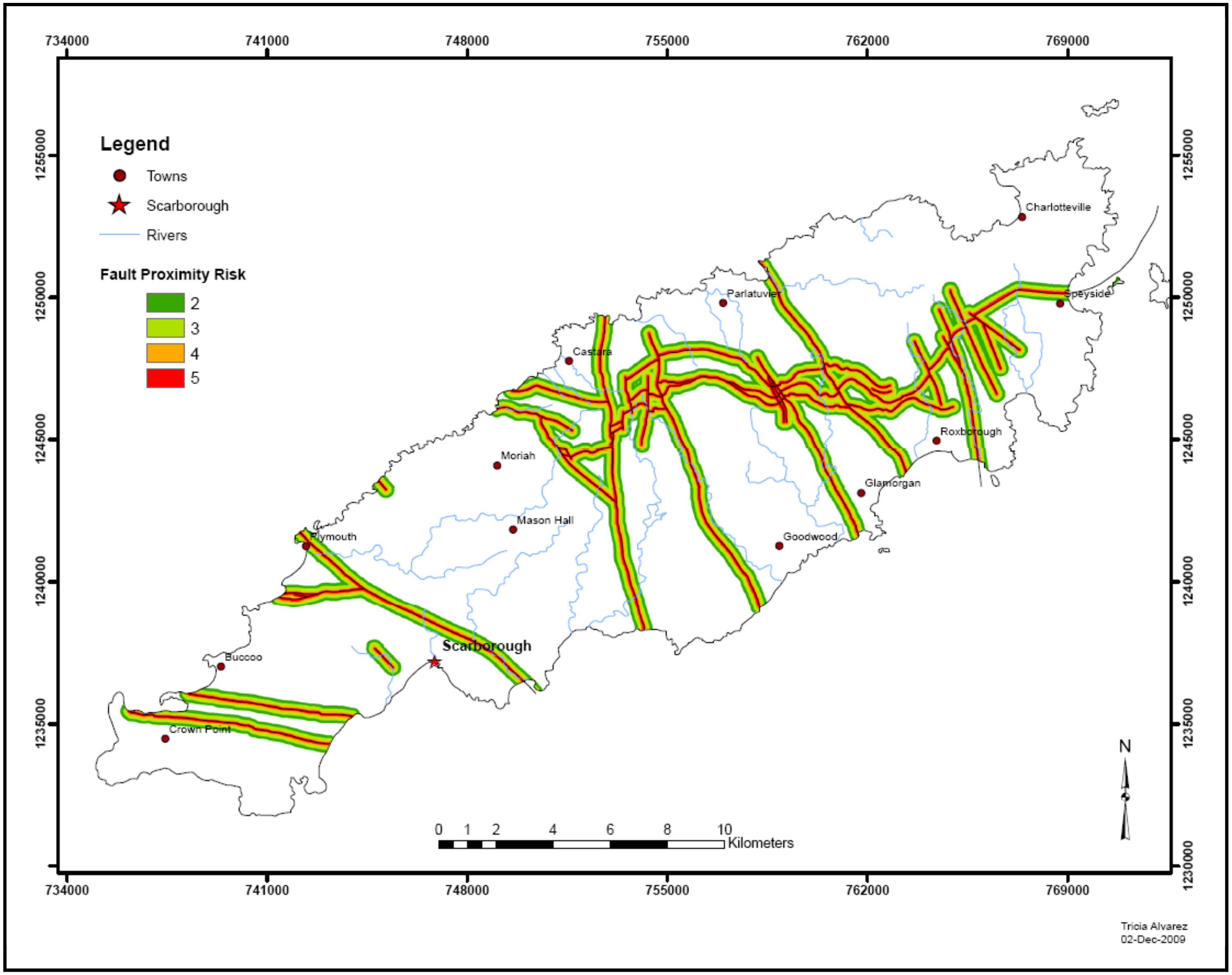

Figure 16 Map of Tobago showing the risk associated with proximity to faults

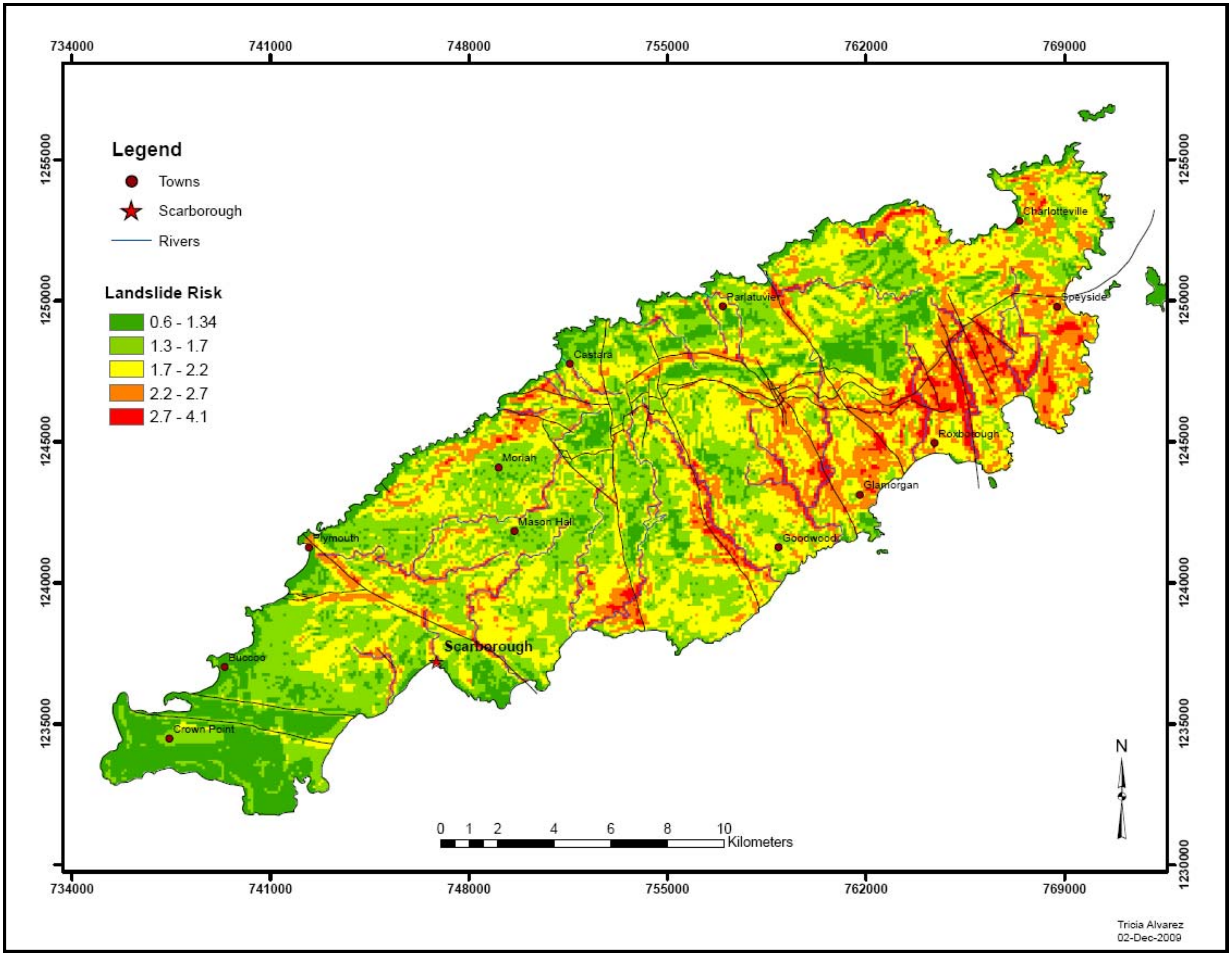

Figure 17 Map of Tobago showing the landslide risk based on the calculation of the variability of six risk factors

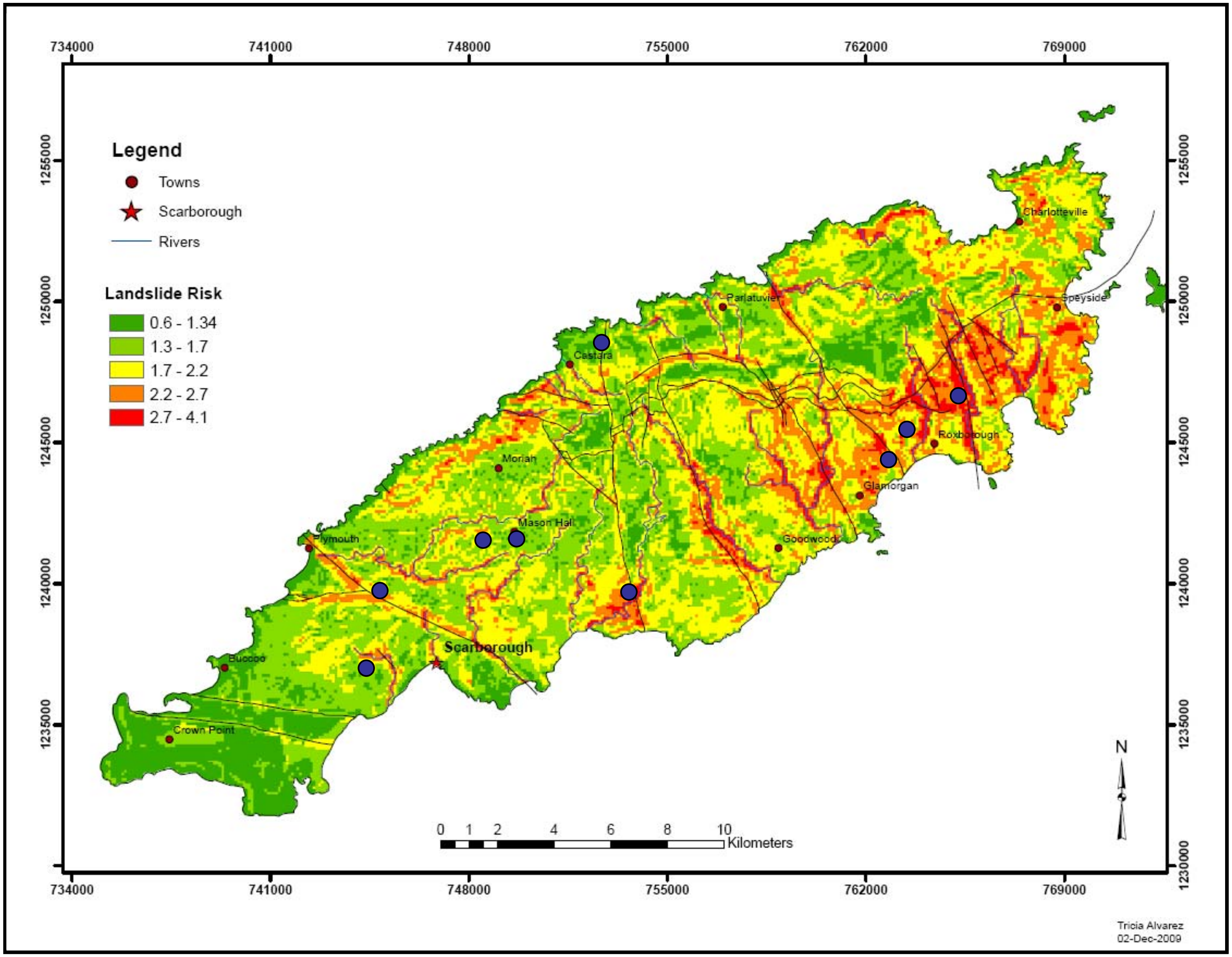

Figure 18 Map of Tobago showing the landslide risk based on the calculation of the variability of six risk factors with the location of previous landslide events shown by blue circles.

References

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